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Effects of aramid-fibre toughening on interfacial fracture toughness of epoxy adhesive joint between carbon-fibre face sheet and aluminium substrate

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ABSTRACT

Brittle epoxy adhesive joints, between the carbon-fibre/epoxy face sheets and aluminium substrate, were toughened using randomly-distributed short aramid fibres. In this study, effects of the epoxy adhesive thickness on interfacial fracture toughness of the adhesive joints, with and without short aramid-fibre toughening, were investigated. Short aramid fibres of 6 or 14 mm in length with an area density of 12 g/m^2 were inserted between the carbon-fibre face sheet and aluminium substrate during the laminating process. Two and six layers of aluminium foils were inserted at the interface to form the controlled thin and thick adhesive joints, which are around 20 and 70 μm in thickness. The two "composite adhesive joints", with different volume densities of short aramid fibres, reversed the adhesive-thickness influence on the interfacial toughness in comparison to that of the plain epoxy adhesive joints. However, both "composite adhesive joints" with low and high aramid-fibre densities resulted in significant improvement in the interfacial toughness. Analytical models, together with optical and scanning electron microscopy observations, were used to explain the experimental findings, and relevant toughening mechanisms.

1. Introduction

Carbon-fibre epoxy composites are widely used in various industries, including automotive, aerospace, marine and civil construction [1–3], because of their high specific stiffness and strength, and excellent fatigue and corrosion resistance. However, carbon-fibre composites also have their disadvantages, noticeably the poor energy absorption and much-reduced compressive strength and stiffness after impact due to delamination [4]. Various combinations of carbon-fibre epoxy composites with metal substrates can overcome many disadvantages associated with carbon-fibre composites and metals, if used separately, and offer engineers with new composite-structure options taking the full advantages of both carbon-fibre composites and metals, e.g. carbon-fibre metal laminates [4,5], carbon-fibre metal-foam sandwich [6,7] and carbon-fibre reinforced steel and concrete structures [3,8]. Clearly, epoxy adhesive joints between the carbon-fibre epoxy composites and metal substrates are preferred for simplicity in forming of the composite structures, and also because of the fact that a strong interfacial bonding between the carbon-fibre-epoxy composite face-sheet and epoxy adhesive joint is almost assumed.

Essential to all laminar composite structures, interfacial bonding in those aforementioned carbon-fibre and metal sandwich structures is critical to their structural performance. The long-term structural integrity of epoxy adhesive joints can become a concern, because of the brittle nature of epoxy, and potential delamination between the carbon-fibre face sheet and metal substrate due to contact, low energy impact or accidental excessive loading, or even corrosion at the metal surface in contact with carbon fibres [9]. The bending and out-plane properties and performances of laminar carbon-fibre metal sandwich structures are often limited by interfacial adhesive toughness and strength rather than stiffness or strength of carbon-fibre or metal substrate.

Therefore, the primary objective of this study is to investigate the feasibility and effectiveness of strengthening and toughening of brittle epoxy adhesive joints using tough and flexible aramid fibres. Short aramid fibres are preferred as relatively uniform fibre distributions within thin adhesive joints can be achieved, and also because protruding free fibre ends can enhance fibre-bridging and crack-defection, not only within the epoxy adhesive joint, but also along the two side-interfaces, close to the carbon-fibre face sheet and the metal substrate.

Because of the metal core in the sandwich structures, common through-the-thickness toughening technique for carbon-fibre epoxy composites, such as Z-pinning [10], are not suitable to the interfacial toughening of carbon-fibre aluminium-substrate sandwich composites. However, surface treatments [11,12] and

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interleave strengthening techniques [6,13] can still be applied to the carbon-fibre aluminium-substrate sandwich composites.

Recent studies by Yasaee et al. [14,15] on comparisons between various interleave methods, including thermoplastic and thermoset adhesive films, and short aramid fibre interleave, showed that the short aramid fibre interfacial toughening compared favourably with the other interfacial techniques in both Mode-I and Mode-II delamination toughness measurements. Sohn, Walker and Hu studied and proposed both experimentally [16,17] and analytically [18] that the randomly-distributed in-plane short aramid fibres were also able to provide through-the-thickness toughening against delamination because of the protruding free fibre ends and twisting of flexible aramid fibres in the thickness direction. Interfacial toughening from the "composite adhesive joints" had recently been adopted to reinforce the interface between carbon-fibre/epoxy face sheet and aluminium-foam core, showing up to 80% increased in the interfacial toughness with a merely 0.18% increase in the structure weight [6]. The key interfacial toughening mechanism, fibre-bridging, was well-documented in various fibre composite systems [19,20].

Those aforementioned studies [6,7,14–18] have shown consistently the effectiveness of short aramid-fibre interfacial toughening in various carbon-fibre composites. Based on the recent experimental and analytical studies on the carbon-fibre and metal-foam sandwich structures, it can be postulated that the short aramid fibre interfacial toughening is also capable of enhancing interfacial toughness of adhesive joints between carbon-fibre face sheets and metal substrates.

It is known that the interfacial fracture toughness of an adhesive joint also depends on the adhesive thickness, geometry and properties of substrate materials even if crack growth is limited within the adhesive joint [21–24]. Interfacial cracking between the substrate and adhesive joint is another concern, as shown by a recent Finite Element Analysis by O'Mahoney et al. [25], which dealt with the influence of adhesive curing process and surface preparation. For the aramid-fibre toughened adhesive joints concerned in this study, the adhesive thickness determines the volume fraction of short aramid fibres within the "composite adhesive joints" even if the areal density of short aramid fibres is maintained constant. Obviously, the volume fraction of short aramid fibres is related to the degree of fibre-bridging during the crack extension and subsequently the interfacial fracture toughness. Therefore, the adhesive thickness effect on aramid-fibre toughened epoxy adhesive joints will be different to that of pure epoxy adhesive joints.

Therefore, the current study needs to consider the interactive effects of adhesive joint thickness and short aramid-fibre toughening, i.e. to recognise the existence of a "composite adhesive joint" of finite thickness between the carbon-fibre face sheet and metal substrate. For simplicity, this study is limited to the epoxy adhesive joint, same as that used in the carbon-fibre face sheets, and no other chemical is used to enhance the bonding with the metal substrate. However, the principle of a fibre-toughened "composite adhesive joint" can apply to tougher adhesives, and to cases where the metal substrates are chemically treated to enhance the interfacial bonding.

2. Carbon-fibre aluminium laminate preparation

2.1. Materials

In this study, 200GSM 2×2 twill weave carbon-fibre fabric was used as the face-sheet material. Alulight closed-cell aluminium foam with twill-weave pattern was used as the metal substrate, which has a solid surface finish, sealing all internal pores, as shown in Fig. 1. Therefore, the interfacial bonding depends purely on the surface pattern and roughness of the aluminium-substrate surface.

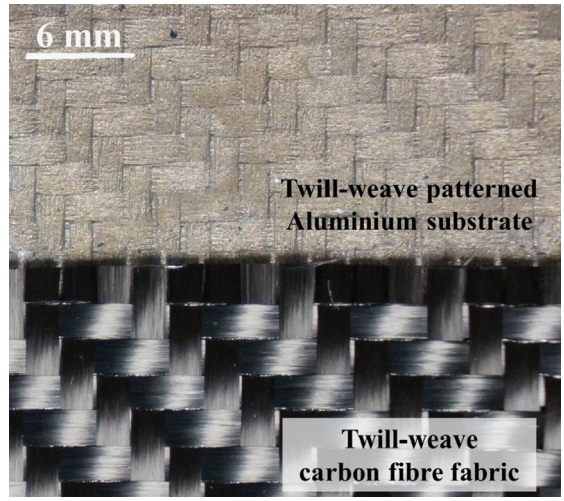

Fig. 1. Comparison of the twill-weave carbon-fibre fabric and the aluminium-foam substrate with similar twill-weave pattern. The aluminium foam can be considered as a "dense" aluminium substrate, because the foam structure is not exposed on the surface.

The West System z105 epoxy resin was mixed with slow hardener 206 using the recommended ratio of 5:1, and then impregnated the carbon fibre fabrics and the surface of aluminium substrate. Ten plies of carbon fibres were used to make the face sheet, and short aramid fibres were only inserted into the interface between the carbon-fibre face sheet and aluminium substrate. Enough resin was needed to ensure the complete wetting of interleave short aramid fibres. Commercial carbon-fibre pre-pregs were not used in this study to avoid potential incompatibility of epoxy resins in the pre-pregs and adhesive joint.

2.2. Short aramid fibre preparation

The short aramid fibres employed in this study were prepared from Kevlar 49 developed by E.I DuPont. The Kevlar 49 fibre was chopped into two different lengths, 6 and 14 mm, after considering the interfacial toughness measurements for various aramid fibre lengths from our previous study [6]. The chopped aramid fibre strands were then stirred in a blender with a blunt blade to produce well-dispersed cotton-like aramid fibres [6]. The cotton-like short aramid fibres were then used to make thin tissue with even fibre distributions of desired densities. As an example, a 12 g/m^2-density short aramid-fibre tissue impregnated by epoxy resin and cured without pressure is shown in Fig. 2, where the random distribution of short aramid fibres and free fibre ends are visible.

2.3. Manufacturing of fibre metal laminates and adhesive thickness

The aluminium-substrate surface was firstly degreased using acetone and then cleaned with water. Both the carbon-fibre face sheets and aluminium substrate were impregnated by the same epoxy. The thin aramid-fibre tissue was then placed on the carbon-fibre face sheets. Because of its low density, wetting of the aramid fibre tissue was sufficient from the epoxy adhesive on both the carbon-fibre face sheets and the aluminium substrate.

Epoxy-impregnated carbon-fibre face sheets with the thin aramid-fibre tissue and the aluminium substrate were then placed in a steel mould. The pre-crack was introduced by inserting aluminium foils. The thickness of epoxy adhesive joint was also controlled by inserting either two or six layers of 12-μm-thick aluminium foils, forming thin and thick "composite adhesive joints".

After the assembly, compressive moulding was performed to cure the laminar composite under a constant curing pressure of