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Characterisation of metal–thermoplastic composite hybrid joints by means of a mandrel peel test

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ABSTRACT

Fastener free metal–carbon fibre reinforced thermoplastic composite hybrid joints show potential for application in aerospace structures. The strength of the metal–thermoplastic composite interface is crucial for the performance of the entire hybrid joint. Optimisation of the interface requires an evaluation method for these hybrid structures. This work demonstrates the applicability of a mandrel peel test method for this purpose. The suitability of the mandrel peel test for certain hybrid joints is evaluated. Furthermore, a series of parameters in mandrel peel test are assessed in order to optimise the evaluation of the performance of metal–thermoplastic interface.

1. Introduction

Joints exist in transitions between composite parts and metal features or fittings in aerospace structures. A technique called one-step consolidation shows a potential to manufacture fastener free metal–carbon fibre reinforced thermoplastic composite joints. During this process, the metal parts are essentially co-consolidated with fibre reinforced thermoplastic composite prepreg. The thermoplastic resin, already present in the prepreg, is thus used for bonding and no additional adhesives are employed. In addition, since the thermoplastic composite plays both the roles of adhesive and adherend, the surface cleaning process, is limited to treatment of the metal only. A reliable experimental method is required to evaluate the interfacial strength between the metal and the thermoplastic composite in order to further develop the technology. Generally, the performance of such hybrid joints can be evaluated by either the stress required to break the joint, i.e. the joint strength, or the energy required to propagate the crack at the joint interface, i.e. the joint toughness. The remainder of this section shortly introduces several typical test methods based on these two evaluation criteria.

1.1. Strength based test methods

The strength of the hybrid joint is directly measured by the force required to break it. This force could be the normal load as measured by the tensile butt test (ASTM D2094) [1,2], or the shear load as evaluated by the so-called lap shear test (ASTM D1002) [3–6]. The measured strength, however, not only depends on the degree of adhesion and the mechanical properties of the adhesive and adherends, but also on the specific geometry of the joint [7]. The influencing factors are the adhesive layer thickness, fabrication induced geometry change, the stiffness of the adherend and the bonded overlap area [8–10]. Furthermore, the stress distribution within the bonded area for both the tensile butt joint and lap shear joint is non-uniform [7,11]. These features complicate the evaluation of the measurement result. It is, therefore, difficult to compare results from different researchers. Moreover, the non-uniform stress distribution can influence the locus of failure thus hindering the analysis of the joint failure mechanism. In conclusion, since the strength based test methods cannot accurately evaluate the metal–thermoplastic interfacial behaviour, these are not employed in this research.

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1.2. Energy based test methods

The interfacial fracture toughness refers to the energy required to separate the interface in two individual surfaces. This energy only represents the fracture behaviour of the interface and should be independent of the joint geometry [7]. For identical adherends, the double cantilever beam (DCB) test is employed for measuring the interfacial fracture toughness under mode I loading [12–14], while the end notch flexure (ENF) test is suggested to characterise the fracture toughness under mode II loading [12]. The peel tests, measuring the energy required to peel off a relatively flexible adherend (peel arm) from a rigid adherend (fixed arm), are the most common test methods to measure the fracture toughness between different adherends under various load modes [15–20]. The peel tests could be classified by the different fixture configurations. Several commonly used peel tests are the 90-degree peel test (ASTM D6862) [20–22], the floating roller peel test (ASTM D3167) [16,23] and the climbing drum peel test (ASTM D1781) [24]. A peel experiment is attractive for the current application, as specimens can be designed quite economically. A single ply of unidirectional (UD) fibre reinforced thermoplastic tape can be co-consolidated on a metal substrate. Subsequently, it can be peeled off to quantify the interfacial fracture toughness.

For the previously introduced peel tests, the peel arm is inevitably bent with a certain curvature during the peeling [17]. However, in cases of measuring a relatively tough interface (fracture toughness > 1 kJ/m^2 for a 0.15 mm thickness UD tape) by using standard peel test, the curvature of the peel arm at the peel front could be too large which causes the carbon fibres in the tape to fracture before the peel arm is peeled off [25]. This phenomenon of tape fracture prior to peel off may also occur in the floating roller peel test and climbing drum peel test, since the conformation of the tape to the roller and drum may not be achieved [15].

This paper proposes a mandrel peel test which peels the specimen at a designated peel arm curvature, thereby avoiding tape fracture. The following sections elaborate on the mandrel peel test. Firstly, the test itself is outlined including a description of the required specimens and a discussion on the effects of residual stresses and test parameters. Subsequently, an experimental study on titanium – C/PEEK hybrid joints is presented. An experimental procedure is finally proposed based on the theoretical and experimental analysis.

2. Mandrel peel test for metal–thermoplastic composite joints

2.1. Principle of the test and specimen preparation

The mandrel peel test was first proposed by Kawashita et al. [26] to measure the fracture toughness of a metal–epoxy–metal peel specimen. Fig. 1 schematically shows the configuration of the mandrel peel test. The flexible peel arm is bent around a mandrel which is a bearing able to rotate around a shaft fixed on a fixture. A tensile force F_p is applied in order to peel the peel arm from the fixed arm. An alignment force F_a, provided by a pneumatic piston or a dead weight, is applied to the sliding table in order to achieve conformation of the peel arm to the mandrel. Kawashita's work reported that the mandrel peel test is able to measure the plastic work in the metal peel arm of a fibre metal laminate, which simplifies the test considerably compared to a standard peel test in which this contribution to the measured force is estimated using a modelling approach [17,26]. Grouve et al. used the test to solve the inapplicability of the standard peel test on the thermoplastic composite UD tape peel arm [25]. The curvature of the peel arm can be controlled, which maintains the elongation of the carbon fibres in the peel arm below its fracture limit, thereby preventing tape breakage. Based on this, the interfacial fracture toughness between a carbon fibre reinforced polyphenylene sulphide (PPS) UD tape and a C-PPS woven fabric laminate has been successfully measured [25].

As the test allows peeling of a tape without breaking it, the mandrel peel test is employed to measure the fracture toughness of thermoplastic UD tape-metal interface. A titanium alloy-carbon fibre reinforced polyetherketoneketone (C/PEKK) hybrid joint is employed as an example. The hybrid peel specimen is fabricated from grade 5 titanium alloy (Ti–6Al–4V) strip as the fixed arm and C/PEKK UD tape as the peel arm. The configuration and dimensions of the peel specimen are shown schematically in Fig. 2:

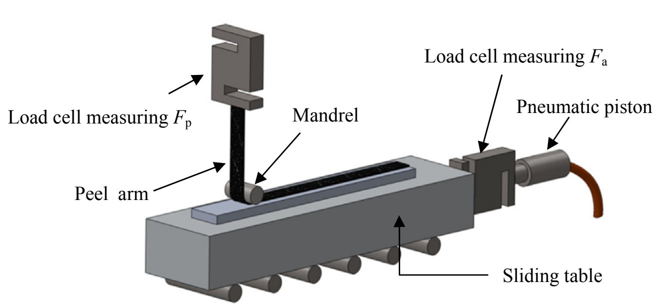

Fig. 1. A schematic representation of the mandrel peel test.

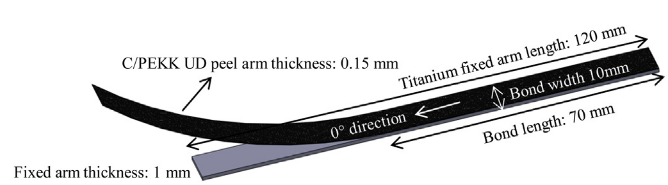

Fig. 2. Dimensions of the mandrel peel specimen.

2.2. Interfacial fracture toughness calculation

The fracture toughness G, measured by the mandrel peel test, is expressed as the strain energy change per unit area of crack growth [25]:

$$G = \frac{1}{b}\left(\frac{dU_{ext}}{da} - \frac{dU_d}{da} - \frac{dU_s}{da}\right) \tag{1}$$

where U_{ext} is the external work, U_d is the energy dissipated during the test and U_s is the strain energy stored in the peel arm. The crack area change is $b\,da$ in which b is the width of the peel arm and da is a crack length increment.

The change in external work due to the crack growth da is:

$$\begin{aligned} dU_{ext} &= F_p da - F_a da + F_p da(\epsilon_c - \epsilon_{rc}) \\ &= (F_p - F_a)da + \frac{F_p^2}{bh_cE_c}da - \frac{F_p\sigma_{rc}}{E_c}da \end{aligned} \tag{2}$$

in which E_c and h_c are the Young's modulus and thickness of the peel arm, respectively. ε_c represents the elastic strain in the composite tape peel arm during peeling, while ε_{rc} is the pre-strain in the composite tape peel arm caused by the residual stress σ_{rc} during the bonding.

The energy dissipation during the test includes the plastic deformation of the peel arm and the friction of the test setup. The