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Mixed-mode fracture toughness of co-cured and secondary bonded composite joints

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ABSTRACT

In the present study, the mixed-mode fracture toughness of three composite joint systems (2 secondary bonded and 1 co-cured) was investigated. The two secondary bonded systems predominantly resulted in cohesive failure with occasional interlaminar failure during mixed-mode loading while the co-cured system failed adhesively. This was attributed to moisture stored in the prepreg being released during the co-cure process.

The mode II toughness was consistently 5–6 times that of the corresponding mode I case for each system. The increased toughness was due to a combination of an increased fracture surface area and a larger damage zone.

1. Introduction

Fibre reinforced polymers (FRP) have been replacing traditional materials, such as steel and aluminium, in critical load bearing applications in a wide range of industries including aerospace, automotive and renewable energy generation. In many of these applications, composite assemblies are typically drilled and bolted together. This process damages the fibre reinforcement and introduces stress concentrations. A superior method of joining composite parts is to use a structural adhesive, as this results in an improved stress distribution across the entire joint [1].

Composite joints can either be secondary bonded, which involves adhesive bonding of two precured laminates, or co-cured, in which the laminate and adhesive are cured in a single processing operation. Prior to the use of these materials in critical load bearing components, a greater understanding of the fracture behaviour of these composite joint systems is required. Co-cured joints, for example, can suffer from problems associated with trapped water, both free and bound, being released during the co-curing process and adversely affecting the quality of the adhesive joint. These joint systems are often evaluated using lap-shear type tests [2], which can mask the problems associated with co-cured joints.

While it is important to examine the pure modes I and II fracture of adhesive joint systems, it is unlikely that a joint will be loaded in a single mode. The joint may experience mixed-mode I/II loading during in-service conditions. The mixed-mode fracture toughness, $G_{I/IIC}$, of adhesively bonded composite joints can behave in a number of ways. Some researchers have reported joints where the fracture toughness increases as the percentage mode II is increased [3,4], while others have shown that a slight decrease can also occur [5]. It has been shown that the fracture toughness of some adhesively bonded systems is independent of mode-mixity [6]. It may also be the case that an increase in the mode I component of the mixed-mode fracture toughness can occur as percentage mode II increases, particularly during interlaminar fracture [7,8].

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Nomenclature

a	crack length
A_U	area ratio of upper beam arm
A_L	area ratio of lower beam arm
A_R	average area ratio of upper and lower beam arms
B	width of the specimen
E_f	flexural modulus
F	large displacement correction factor
G_I	mode I strain energy release rate
G_{II}	mode II strain energy release rate
$G_{I/II}$	mixed-mode strain energy release rate
G_C	total critical fracture toughness
G_{IC}	mode I critical fracture toughness
G_{IIC}	mode II critical fracture toughness
$G_{I/IIC}$	mixed-mode critical fracture toughness
h	thickness of the substrate (for DCB and ELS specimens)
h_1	thickness of the lower beam (for ADCB specimen)
h_2	thickness of the upper beam (for ADCB specimen)
L_U	length of the upper crack path
L_L	length of the lower crack path
L_0	length of perfectly flat crack path
N	load block correction factor
P	force
α	fitting constant for Benzeggagh failure criterion
δ	crosshead displacement
Δ_I	mode I crack length correction factor
Δ_{II}	mode II crack length correction factor
κ	1st fitting parameter for Hashemi failure criterion
φ	2nd fitting parameter for Hashemi failure criterion

The scrim cloth used in numerous film adhesives (e.g. FM300-2M) can play an important role in the mixed-mode fracture behaviour of bonded systems. Parvatareddy and Dillard [5] noted that the mode I fracture toughness was higher than the mode II toughness of a titanium alloy (Ti–6Al–4V)/film adhesive (FM-4) joint system. During mode I fracture the crack propagated in the centre of the adhesive layer, along the scrim cloth. However, during mixed-mode and mode II fracture, the crack propagated along the adhesive–substrate interface, away from the scrim cloth. The author proposed that the scrim cloth played an important role in energy dissipation by providing weakened sites where fracture can initiate.

The present study aims to investigate the mixed-mode fracture toughness of a single co-cured and two secondary bonded composite joint systems using a variety of linear elastic fracture mechanics (LEFM) based tests, the aim being to link the experimentally measured fracture toughness with the observed damaged mechanisms in the joint systems.

2. Materials & manufacture of joints

Two aerospace grade materials were used in the present study; a 180 °C cure unidirectional carbon-fibre/epoxy prepreg (CYCOM 977-2/HTS) and a dual 120/180 °C cure epoxy film adhesive (FM300-2M). The film adhesive contains a polyester scrim cloth with random fibre orientation that aids in handling and also in controlling the bondline thickness. Both materials were manufactured and supplied by Cytec Engineered Materials (CEM).

The composite laminates and adhesive joints were produced in-house at UCD using a vacuum bagging layup procedure similar to that used in industry. Secondary bonded joints were produced by curing a single sheet of FM300-2M adhesive at either 120 °C or 180 °C between two pre-cured laminates. As the adhesive was supplied in the form of a flexible film, no additional preparation was required. Each laminate consisted of 10 plies of 977-2/HTS. Prior to bonding, the laminates were grit-blasted to remove any release agent residue and also to roughen the surface which aids in adhesive bonding [9]. The laminates were cleaned with a methanol solvent wipe after grit-blasting to remove any grit. A 12 μm thick PTFE sheet was placed between the laminate and adhesive on one side of the layup to act as a crack initiator. Co-cured joints were produced in a similar fashion by curing the prepreg and the adhesive at the same time in a single process operation at 180 °C.

The following designations will be used to refer to each of the three joint systems:

- CC180 – co-cured composite joint manufactured by curing the prepreg and adhesive together in a single operation at 180 °C.