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Mode-I, mode-II and mixed-mode I+II fracture behavior of composite bonded joints: Experimental characterization and numerical simulation

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The fracture behavior of composite bonded joints subjected to mode-I, mode-II and mixed-mode I + II loading conditions was characterized by mechanical testing and numerical simulation. The composite adherents were bonded using two different epoxy adhesives; namely, the EA 9695 film adhesive and the mixed EA 9395-EA 9396 paste adhesive. The fracture toughness of the joints was evaluated in terms of the critical energy release rate. Mode-I tests were conducted using the double-cantilever beam specimen, mode-II tests using the end-notch flexure specimen and mixed-mode tests (three mixity ratios) using a combination of the two aforementioned specimens. The fracture behavior of the bonded joints was also simulated using the cohesive zone modeling method aiming to evaluate the method and point out its strengths and weaknesses. The simulations were performed using the explicit FE code LS-DYNA. The experimental results show a considerable scatter which is common for fracture toughness tests. The joints attained with the film adhesive have much larger fracture toughness (by 30–60%) than the joints with the paste adhesive, which exhibited a rather brittle behavior. The simulation results revealed that the cohesive zone modeling method performs well for mode-I load-cases while for mode-II and mixed-mode load-cases, modifications of the input parameters and the traction-separation law are needed in order for the method to effectively simulate the fracture behavior of the joints.

1. Introduction

In recent years, adhesive bonding finds an increasing use in aircraft structures both for assembling structural parts and applying composite patch repairs due to its specific advantages over mechanical fastening [1–3]. Nonetheless, joining and patch-repairing of large primary composite structural parts by adhesive bonding is for the moment not feasible due to several reasons such as the sensitivity of the bondline to bonding quality reduction scenarios [4–6], the inability of existing non-destructive testing techniques to detect weak bonds [4–6] and mainly, the failure of existing designs to comply with certification rules [7]. As mechanical fastening mitigate the massive introduction of composites in aircrafts and the number of in-service patch repairs is increasing rapidly, due to the increasing number of in-service ageing aircrafts, there is a need to overcome the previously mentioned hindrances and enable the use of (boltless) adhesive bonding in primary large aircraft structures.

In general, strength of bonded joints is measured in terms of fracture toughness. Thus, both mechanical tests and numerical models aim at the development of functions between the applied force and crack growth in the adhesive.

Until today the mechanical tests used to measure the fracture toughness of bonded joints usually followed standards developed for characterizing interlaminar fracture toughness of composite laminates as only recently standards were published for bonded joints (ISO 25217 standard for mode-I testing). Despite the similarities between the two failure mechanisms, the debonding process is a far more complicated phenomenon than delamination as it takes place in a three-material system (adherent, adhesive and adherent/adhesive interface) compared to delamination which takes place in a two-material system (layers and interface between them). Thus, the standards often fail to accurately describe the fracture behavior of composites bonded joints.

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In the literature, there have been reported several experimental works on fracture behavior of composite bonded joints e.g. Refs. [8–12]. The majority of them have focused on the mode-I loading as it is considered to be the most critical. However, this is not the case as during operation mixed-mode I + II loads of varying mixity are usually applied to composite bonded joints. It is therefore very important to characterize also the mode-II and mixed-mode I + II fracture behaviors of each composite adherent/adhesive system. To the author's knowledge, there have been reported very few works in which a complete characterization of the fracture behavior (mode-I, mode-II and mixed-mode I + II) of a composite adherent/adhesive system to have been performed e.g. Ref. [13].

Two fracture mechanics-based numerical approaches have been mainly used for simulating fracture behavior of composite bonded joints: the Cohesive Zone Modeling (CZM) method and the Virtual Crack Closure Technique (VCCT). Both approaches have strengths and weaknesses. The strengths of CZM are the capability of predicting initiation and growth of debonding without prior assumptions about location and direction and its applicability to complex structures subjected to complex loads. Its weaknesses are the difficulties to characterize the required input data and the mesh dependency. On the other hand, the strengths of the VCCT are the maturity, which comes from the numerous applications of the method in metals, and the direct crack growth prediction using the energy release rate G. Its weaknesses are the assumptions that need to be made for the cracks (number, location, size) and the difficulty in the application to complex structures subjected to complex loads. Additional advantages of the CZM method with respect to the VCCT method, related primarily to the evolution of the method through research and not to its theoretical framework, is the capability of considering moisture absorption through the use of moisture-dependent cohesive zone parameters [14], the capacity of considering different interface failure criteria [15] and rate-dependency effects [16], and the existence of closed form formulae for deriving the failure load and the optimal bonding length [17]. Although numerous works have been reported in the literature on the use of the CZM method e.g. Refs. [14–23] and the VCCT e.g. Refs. [24–27] for simulating crack growth in composite bonded joints, a complete assessment of the approaches is not feasible since the simulations have been performed for a single loading-mode, which in most cases is mode-I.

The aim of the present work is to fully characterize the fracture behavior of two different adhesive/composite adherent systems, that are widely used in aeronautic applications, by conducting mode-I, mode-II and mixed-mode I + II mechanical tests and to evaluate the CZM method through its critical application in the three loading modes.

2. Experimental

2.1. Materials and manufacturing

All CFRP plates consisted of 16 unidirectional plies of the 8552/IM7 Hexply prepreg material. A quasi-isotropic stacking sequence of $[0/+45/90/-45/0/+45/90/-45]_s$ with 0° surface plies was chosen to minimize the undesired delamination failure close to the bondline while testing. The autoclave curing cycle was performed in accordance with the material data sheet specifications leading to an overall plate thickness of 2 mm. A PTFE release film between the plate's surface and the steel tooling ensured a constant overall surface finish.

After cleaning with acetone and isopropanol, atmospheric plasma was used for surface treatment of the bonding surface (Plasmatreat generator FG5001) with the following parameters: plasma frequency 17 kHz, rotating nozzle (RD1004), velocity of 100 mm/s and a surface distance of 10 mm. For intermediate storage, activated surfaces were protected with aluminum foil.

A release film of 60 mm length was inserted at one site of all plates prior bonding to obtain an initial delamination for fracture toughness tests.

Two types of adhesive were used for bonding: a one-component epoxy film adhesive of high curing temperature (130 °C) with an average thickness of 0.15 mm (Hysol EA 9695 0.05 PSF K), which was cured in an autoclave cycle with a pressure of 4.5 bar and a temperature of 130 °C applied for 2 h, and a mixture of two paste adhesive systems (80% Loctite EA9395 and 20% Loctite EA 9396). The latter is the unfilled version of the first adhesive; thus, chemical miscibility was ensured. By mixing the paste adhesives, an optimized viscosity for the specific application was attained. A high speed centrifugal mixer was used to obtain a homogenous mixture free of pores. The adhesive was applied by use of a cartridge. Metallic distances were implemented at the edges (trim area) of the plates to set the bondline thickness to its desired value of 0.3 mm. Subsequently, joining and curing of the mixed adhesive was performed in a heated press by applying a pressure of 3 bar and a temperature of 100 °C for 2 h.

All bonded plates were checked for porosities by ultrasonic C-scans. Afterwards, the plates were trimmed and cut to the final specimen dimensions specified by the standards of the tests.

2.2. Mechanical testing

Mode-I, mode-II and mixed-mode I + II tests of three mixity ratios were conducted to fully characterize the fracture toughness of the CFRP bonded joints in terms of critical energy release rate G. Mode-I and mixed-mode tests were conducted using a Tinius Olsen H5K–S UTM tensile machine with a load cell of 500 N while mode-II tests using an MTS universal testing machine with a load capacity of 100 kN.

2.2.1. Mode-I tests

Mode-I tests were conducted according to the ASTM 5528-01 standard [28] using the double cantilever beam (DCB) specimen schematically shown in Fig. 1. The tests were conducted under the displacement rate of 1 mm/min Fig. 2 illustrates a specimen mounted on the tensile machine during a mode-I test. Crack growth was monitored at one side of the specimen since observations

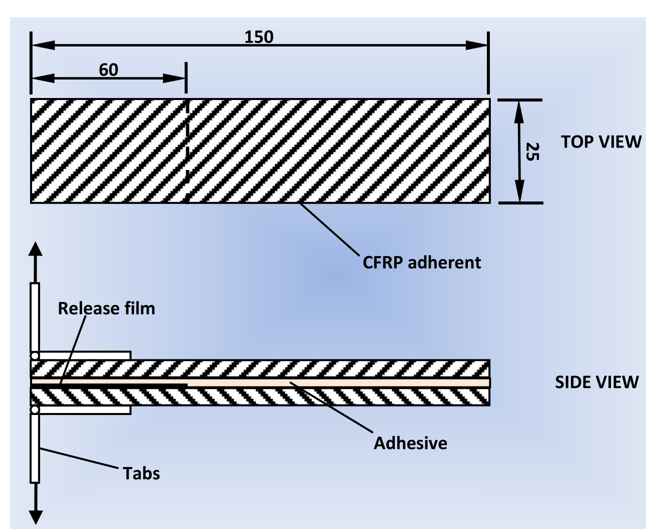

Fig. 1. Schematic representation and dimensions of the DCB specimen.