Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 5 (2017) 40–47

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

# Mixed-mode fracture characteristics of metal-to-metal adhesively bonded joints: experimental and simulation methods

M G Droubi*, J Mcafee, R C Horne, S Walker, C Klaassen, A Crawford, A K Prathuru and N H Faisal*

*School of Engineering, Robert Gordon University, Garthdee Road, Aberdeen, AB10 7GJ, UK*

**Abstract**

Fracture behavior of adhesively bonded joints subjected to mixed-mode (i.e. mode I+II) loading conditions is of importance in many industrial applications. This research therefore aims to characterise the failure behaviour of metal-to-metal (i.e. both aluminium adherends) adhesive joints using the mixed mode bending test (MMB), adapted from ASTM D6671/D6671M standard, along with instrumentation using acoustic emission (AE) sensor. Twenty-four adhesively bonded specimens were prepared using two types of adhesive bond materials (acrylic, cyanoacrylate) with two different bonded area 65% and 100%. To understand the effect of mixed-mode loading conditions on the failure behavior, two different mixity ratios were achieved through the design of the MMB test fixture and tested for each bonded joint. The AE results during mechanical testing shows that the time domain signals were spread over the loading phase with distinct features for different mixity ratios. They successfully identified the moment of adhesive fracture during every test. Also, the fracture behavior of the bonded joints was simulated using virtual crack closure technique (VCCT) method using finite element method to understand the loading dynamics in specimen when considering a combination of various design parameters. In addition, an analytical method (e.g. corrected beam theory or CBT) was used to determine strain energy release rates of each specimen. The results show that both the brittle and ductile specimens exhibited higher energy release rates when mode II proportion of loading was increased during the crack initiation phase. The proposed measurement can be useful to assess the overall structural health of bonded systems.


Peer-review under responsibility of the Scientific Committee of ICSI 2017

*Keywords:* mixed-mode fracture; adhesively bonded joints; acoustic Emission

* Corresponding author. Tel.: +44(0)1224-26-2336.
*E-mail address:* m.g.droubi@rgu.ac.uk; n.h.faisal@rgu.ac.uk;

2452-3216 
Peer-review under responsibility of the Scientific Committee of ICSI 2017
10.1016/j.prostr.2017.07.059

## 1. Introduction

The joining of two or more components is the main objective of fabrication and has been historically present throughout several engineering applications such as marine, automobile, aerospace and construction. This allows for structures or physical systems to perform to their operational requirements, transferring forces from one surface to another, whilst exchanging overall attributes such as weight, size and strength specific to their purpose. The adoption of adhesive bonding is mainly due to the advantages that it provides over mechanical fixing techniques (i.e., welding, screws and bolts) including but not limited to: reductions in weight, the variety of materials that can be bonded, a uniform stress distribution on the load, strong cohesive properties and a resistance to corrosion. From literature, three main crack types (failure modes) exist: mode I, dictated by normal opening forces, and modes II and III, defined by in-plane and out of plane shear sliding forces respectively (Choupani, 2008).

To further develop the performance and safety of adhesively bonded joints, a greater understanding of their behaviour in relation to these three modes must be acquired. Adhesive bonds are specifically subject (but not limited) to two major types of failure: adhesion, a failure at the bond interface, and cohesion, caused by failure within the adhesive material itself. Although many manufacturers are aware of these behavioral characteristics and their common causes, there is much less of an understanding of the combinational effects. Within the aerospace industry alone, difficulty has been reported in understanding the mechanism of transition, from a strong bond displaying cohesive failure to a weak bond exhibiting adhesion failure (Davis and McGregor, 2010). With many inspection techniques occurring after a major incident, this transition is overlooked, incorrect conclusions are drawn and issues are not addressed. Therefore, it is imperative to investigate this subject thoroughly to avoid potential disaster.

Although many monitoring procedures used to predict failure within adhesive joints, such as eddy current, neutron radiography and infrared spectroscopy, only a small number of these procedures have proven to be effective in predicting failure. Ultrasonic testing is by far the most commonly used method, allowing for sub-millimetre detection of failed or misdirected adhesive. However, the ultrasound must be coupled with water and moved over every area of the component to be tested, which can be time-consuming (especially over large areas) (Vine, 1999). Acoustic emission (AE) technique can be used to detect transient elastic waves emitted by a growing fracture or stress level within the material (Sachse and Kim, 1987). As this is the only non-destructive testing method that utilises energy released from the material under examination, sensors can receive signals originating from various locations, reducing direct contact area and time taken to test. The specific ability to monitor components during the loading lifespan allows for a greater understanding of the initiation and growth of cracks. Because of this, AE can be employed in the identification of failure at extremely early stages, preventing catastrophic structural damage. Dzenis and Saunders (2002) have attempted to characterise AE signals from various fracture mechanisms under mode I, mode II and mixed-mode fracture of adhesively bonded joints, using computational pattern recognition analysis. Using two wideband sensors placed on either side of the crack tip, a clear separation of the pure mode was observed, while mixed-mode signals were found to be like those of mode II.

In this study, the effects of varying adhesive type (ductile or brittle), quality of bond (adhesive contact area) and mode-mixity (i.e. ratio of mode I to mode II failure) of the specimens were investigated. To inflict mixed-mode loading conditions, a purpose built and standardised mixed-mode bending (MMB) test rig was developed. Also, the behaviour of adhesively bonded joints under mixed-mode loading was examined, incorporating finite element (FE) analysis, analytical calculations and an experimental MMB test procedure.

## 2. Experimental procedure

### *2.1. Specimen preparation*

Each specimen comprised of two identical aluminium-alloy 6082 bars (Fig. 1a), to the specified dimension of 200 mm x 25 mm x 6 mm. Two 3.6 mm countersunk holes were drilled through one side of the bars to accommodate two countersunk head M3 screws. Hinges were screwed on to the specimens and connected to the hinge clamps of the MMB fixture. To remove dirt and contaminants, each specimen was wiped down thoroughly with acetone from an applicator bottle; after which, each section was sprayed with Loctite® SF 7063$^{TM}$ aerosol multi-purpose cleaner and wiped down to further remove any impurities. After allowing the specimens to air-dry, Loctite® 7649$^{TM}$ adhesive