Composites: Part A 93 (2017) 153–162

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Influence of loading rate on the mode II fracture toughness of vinyl ester GRP

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ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 14 November 2016
Accepted 21 November 2016
Available online 27 November 2016

Keywords:
A. Glass fibres
B. Fracture toughness
D. Mechanical testing

ABSTRACT

Four point bending end notched flexure (4ENF) tests were used to evaluate the mode II fracture toughness (G_{IIC}) of glass fibre reinforced vinyl-ester (GFRP) specimens in order to expose the sensitivity of G_{IIC} to loading rate. Tests were carried out at load displacement rates ranging from 1 to 6000 mm/min. Finite element models were used to evaluate the correction factors that are required during data reduction in order to compensate for geometrical non-linearity in the test. A high speed video camera was used in conjunction with the digital image correlation technique to measure crack propagation during the tests. It was found that, for short crack lengths, G_{IIC} tended to increase as loading rate was increased.

1. Introduction

Fibre reinforced polymer composite (FRP) materials can provide excellent performance in terms of strength and stiffness versus weight, as a result they have become important for structural applications in a wide range of industries including automotive, energy and marine. However, due to some critical performance limitations that are exhibited by FRP materials, such as limited ductility, it is often necessary to use FRP in conjunction with metallic components. Typically the metallic component is able to provide the combination of strength and ductility that is required in locations that are subjected to high stresses. In such situations it is necessary to form a load bearing joint between the FRP and metallic components. The present study is part of a project that is investigating the performance of perforated double-lap joints between Glass-fibre Reinforced Polymer (GFRP) and steel. Tests on perforated GFRP-to-steel double-lap joints of the type shown in Fig. 1 have demonstrated that the joints exhibit greater tensile strength when tested under impact loading rates than they do under quasi-static loading rates [1]. Finite element (FE) models of the joints indicate that mode II fracture toughness (G_{IIC}) of the GFRP matrix is the material property that dominates the tensile strength of the perforated joints. We therefore speculate that G_{IIC} of the vinyl-ester polymer resin used in the joint specimens is greater at impact loading rates than at quasi-static loading rates.

There is limited data in the literature regarding the effect that changes in loading rate have on the value of G_{IIC} for vinyl-ester composites. Compston et al. [2] investigated loading rate effects on G_{IIC} for unidirectional vinyl-ester GFRP. They generated data for specimens that used five different resins, one un-toughened resin and four toughened resins. They reported that loading rate had no significant effect on G_{IIC}. However, it is worth noting that Compston et al. attributed greater significance to their results for maximum toughness ($G_{IIC-max}$) than they did to their results for crack initiation toughness ($G_{IIC-init}$). Their results suggest that $G_{IIC-init}$ increases as loading rate increases for four of the five resins that they tested, including the un-toughened Derakane 411-45 resin. There is significantly more literature regarding the effect of loading rate on G_{IIC} for epoxy-resin composites, although the majority of this covers carbon-fibre rather than glass-fibre composites. The bulk of this literature suggests that G_{IIC} for carbon-fibre epoxy composites (epoxy CFRP) reduces as loading rate increases [3,4]. An extensive review of the literature was reported by Jacob et al. [5] in 2005, they concluded that there appears to be a lack of consensus regarding the influence of loading rate on fracture toughness properties of composite materials.

A more recent study by Guimard et al. [6] used physical test results for G_{IIC} over a range of loading rates to show that it is not possible for numerical models to replicate their experimental results unless the cohesive interface used in the numerical model incorporates a rate effect. Guimard et al. attribute the apparent increase in G_{IIC} to an increase in microcracks at the crack tip as crack velocity increases.

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http://dx.doi.org/10.1016/j.compositesa.2016.11.023
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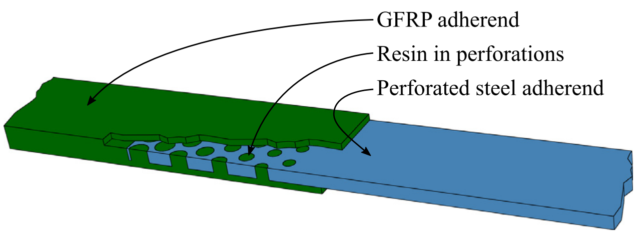

Fig. 1. Cut-away view of a co-bonded perforated steel-GFRP double-lap joint [1].

Verdiere et al. [7] studied un-tufted and tufted epoxy CFRP material at various loading rates up to approximately 7 m/s, this is a significantly higher loading rate than the maximum rate used here. They found that there was a significant rate effect on G_{IIC} for the tufted material while there was little rate effect for the un-tufted material.

Marzi et al. [8] used reinforced double cantilever beam specimens and reinforced end notched flexure specimens to study the loading rate effect on G_{IC} and G_{IIC} respectively for epoxy CFRP material. They found that for G_{IC} (mode I fracture toughness) there was a strong loading rate effect, while for G_{IIC} no rate effect was detected.

The lack of consensus in the literature regarding the effect of loading rate on G_{IIC} prompted us to carry out the experimental study reported here, in which we perform mode II fracture tests at a range of load displacement rates.

2. Materials and specimen fabrication

The resin, reinforcement and reinforcement orientation used in this study were chosen in order to match those used in the hybrid joints being tested as part of the overall project [1]. The polymer matrix was Dow Derakane 510A-40, an epoxy vinyl ester resin designed to offer a high degree of fire retardance combined with good chemical resistance and toughness [9]. The reinforcement consisted of four plies of Owens Corning TTX1330 fabric, this is a stitch bonded non-crimp tri-axial E-CR glass fabric with areal weights of 520 g/m^2 in the 0° direction and 401 g/m^2 in both the +45° and −45° directions.

A 12.7 micron thick Teflon® film was used to generate an initial debonded region in the specimens as is required for the end-notched flexure test. The reinforcement and debond film were layed up by hand and the vacuum assisted resin transfer moulding (VARTM) process was used to fabricate a single sheet of GFRP material which was then cut into individual specimens using a water-jet cutter. The nominal dimensions of the specimens and the reinforcement layup are shown in Fig. 2. The overall length and width of the specimens are as suggested by Hodgkinson [10], the overall thickness is the result of the chosen reinforcement layup, and the length of debond film is in accordance with the DoD Composite Materials Handbook [11]. During fabrication the resin was mixed and cured in accordance with the recommendations of the manufacturer.

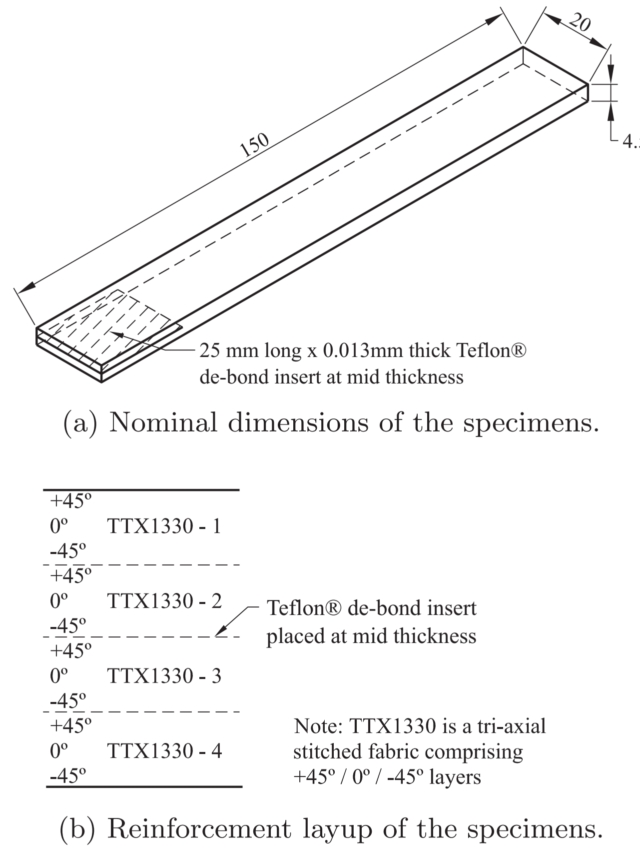

Fig. 2. Details of the test specimens.

3. Physical testing

3.1. Test configuration

A variety of test configurations have been proposed for evaluating G_{IIC} of fibre reinforced composite materials [10]. Experimental comparisons of five of the most commonly used configurations are provided by Davies et al. [12] and Wang et al. [13]. The three point bending end notch flexure (ENF) configuration has the disadvantage of not generating stable crack growth in the specimen [10,12] while the over notched flexure (ONF) configuration was found to suffer from an increase in frictional effects as crack length grows [13]. The stabilised end notched flexure (SENF) configuration relies on the measurement of crack shear displacement during the test, this measurement is used as feedback to the test machine in such a way as to deliver a constant shear displacement rate during the test [12]. Providing this load control feedback while carrying out a test at a relatively high load displacement rate was considered to be a significant added complexity which made the SENF configurations un-attractive.

The four point bending end notched flexure (4ENF) and end loaded split (ELS) test methods have both been shown to deliver repeatable and reliable results [12,13] and do not suffer from the disadvantages described above for the ENF, SENF and ONF configurations. However, a standard Instron 4ENF fixture was available to the author and making the necessary modifications to this fixture was considerably more economical than making an ELS fixture. Therefore the 4ENF test configuration was chosen for the tests carried out here.

The 4ENF test was proposed by Martin and Davidson [14] as an improvement on the standard three point bending end-notched flexure (ENF) test. As the name suggests a four point bending fixture is used, see Figs. 3 and 4. A 4ENF specimen has a mid-thickness starter crack at one end. The specimen is placed in the test fixture in such a way that the tip of the pre-crack is positioned just inside the inner span of the fixture. During the test, flexural stresses are imposed on the specimen. When these stresses are sufficiently large, then mode II fracture occurs at the crack tip and the mid-thickness crack is forced to propagate further into the specimen. The compliance of the specimen increases due to this crack propagation which leads to a reduction in the flexural stresses and thus crack propagation is arrested. In the context of the current