Interlaminar Fracture Behaviour Of Emerging Laminated-Pultruded Cfrp Plates For Wind Turbine Blades Under Different Loading Modes

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CONTENTS

INTERLAMINAR FRACTURE BEHAVIOUR OF EMERGING LAMINATED-PULTRUDED CFRP PLATES FOR WIND TURBINE BLADES UNDER DIFFERENT LOADING MODES

X. Li[1*], F. Monticeli[1], J.A. Pascoe[1] and Y. Mosleh[2]

[1]Department of Aerospace Structures and Materials, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands
Email: lixinwpu@foxmail.com, F.M.Monticeli@tudelft.nl, J.A.Pascoe@tudelft.nl
[2]Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
Email: Y.Mosleh@tudelft.nl

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Abstract

Driven by the energy transition and the reduction of carbon emissions, pultruded CFRP plates have emerged as an affordable high performance material for designing wind turbines with larger rotors. To enable the creation of thicker laminates, pre-cured plates are bonded together using an epoxy resin. The present study focuses on characterizing the fracture behaviours of these laminated bonded plates under different modes, and to generate fracture criteria for numerical simulations establishing design allowables and service life. Double cantilever beam tests, end-loaded split tests, and mixed-mode bending tests were conducted under quasi static loading for such plates. Mode I crack propagation showed brittle failure while mode II fracture tests on the other hand, presented a more stable crack growth. Finally, power law and Benzeggagh-Kenane law criteria were established to numerically describe the fracture behaviours. Overall, the results show that the available standards for fracture toughness testing are also suitable for these laminated-pultruded composite plate structures, enabling the material characterization needed for design.

1. Introduction

Larger and larger rotors have been designed for wind turbine blades to enable more energy capture, resulting in ever increasing structural loading. Carbon fibre reinforced polymer (CFRP) composites, due to their outstanding mechanical performance, have been utilized in spar caps of wind turbine rotors to carry and transfer increased loads in the flap direction. Among them, pultruded CFRP plates have emerged as an affordable high performance material for wind turbine design [1, 2]. To enable the creation of thicker laminates, pre-cured plates are bonded together using an epoxy resin. Considering the dominant role of such CFRP composites in load-bearing structures of wind turbine blades, it is necessary to characterize the fracture behaviours of these novel laminates under different modes, and to further generate fracture criteria for numerical simulations establishing design allowables and service life.

One question which may rise first is should these laminated pultruded plates be treated as composite laminates or adhesive joints? Considering the standardized tests are mainly proposed for composite laminates with a thickness of 2 mm to 5 mm, it is not clear whether the characterization of fracture behaviours of such bonded pultruded plates can follow these existing test standards or not. So far, some researches have been conducted to consider the modification of standard specimen dimensions for pultruded composites. Burda et al. [3] recommended that the length of double cantilever beam specimens should be at least 250 mm to characterise the pure mode I fracture behaviour of pultruded glass fibre-reinforced epoxy rods and to provide a suitable R-curve. Yan et al. [4] found that mode II crack propagation using the end-notched flexure test configuration becomes more stable when increasing pre-crack length for pultruded carbon fibre-epoxy composites. Zhang et al. [5] increased the length of specimens for end-loaded split tests to investigate the mode-II fracture properties for an adhesive layer of 2 mm thickness. However, a systematic inversitiagtion into the applicability of different test standards on the laminated pultruded composite plates is needed, covering different loading modes (i.e. mixed mode ratio). Besides, it will also be interesting to understand how the the development of the fracture pattern is affected by different loading modes for such plates, which is rarely reported in literature.

Therefore, the present study aims at provide a comprehensive insight on quasi-static behaviours of laminated pultruded composite plates under four types of loading modes. Both the applicability of the existing test standards and effect of loading modes on the fracture pattern of such plates will be explored further.

2. Experimental setups

2.1. Materials and specimens

Zoltek^{TM} PX35 pultruded plate bonded with SWANCOR 2511-1AL/BL epoxy resin was studied in the present work, and the overall thickness of such laminated pultruded plates is about 6.1 mm. At the interfaces between the top and the bottom pultruded plate, a glass fibre veil (M524-ECR30A) with an areal weight of 30 g/m^2 was placed during the resin infusion process, to improve the fracture toughness. The curing process consists of 24-hour curing at room temperature, followed by 3-hour curing at 65°C and 4-hour curing at 80°C. According to ASTM D5528, ISO 15114 and ASTM D6671 [6,7,8], specimens were cut in different dimensions for each type of loading mode, as summarized in Table 1. The initial crack length is measured from the loading line to the crack front. Aluminum loading blocks were bonded on the specimens using LOCTITE EA 3430 and cured at room temperature for at least 24 hours.

Table 1. Geometry dimensions of different types of specimens.

Specimen Type	Loading mode	Length (mm)	Width (mm)	Initial crack length (mm)
DCB	Mode I	200	25	80
ELS	Mode II	180	20	66
MMB	Mixed mode I/II	170	25	32

2.2. Experimental procedures

For most of specimens, mode-I pre-cracking with a length of 2 mm to 10 mm was created. Afterwards, double cantilever beam tests (DCB), end-loaded split tests (ELS), and mixed-mode bending (MMB) tests were conducted under quasi static loading at a rate of 0.5 mm/min or 1 mm/min, as shown in Figure 1. For ELS specimens, the free delamination length is 110 mm and the clamping region is 60 mm. For MMB specimens, the distance from the loading line to the mid supporter is 70 mm. Eventually, four mixed-mode ratios (MMRs), calculated as the ratio of mode II strain energy release rate to the total strain energy release rate, were covered in the present study, i.e. 0, 0.33, 0.67, 1. During the tests, the crack propagation was monitored by an OPTOMOTIVE camera with a resolution of 2048 × 2048 pixels, and image acquisition was performed every 1-5 second(s). For DCB tests, the test was stopped when the crack propagated along the entire interface. For ELS tests, the test was stopped when the crack propagated close to the clamping region where the force start to increase. For MMB tests, the test was stopped at either the crack propagating to the middle support or unstable crack propagation along with a sudden drop of force. Three to four tests were repeated for each mixed mode ratio. Regarding the data reduction methods for determining mode I and mode II crack intiation toughness, the Compliance Calibration method [6] and the Corrected Beam Theory using Effective crack length [7] were used for mode I and mode II, respectively.

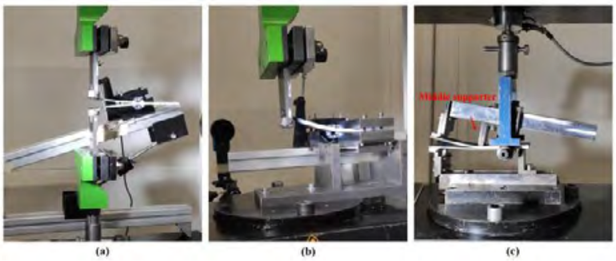

Figure 1. Test setups: (a) DCB tests, (b) ELS tests, (c) MMB tests.

3. Results and discussions

FigureFigure ***2*** shows the force-displacement curves and the crack length history under different loading modes. Overall, a sudden drop of force occurred more frequently for mode I dominant fracture tests (i.e. MMR = 0 and 0.33) accompanying unstable or fast crack propagation, while the post-peak section of force-displacement curves were smoother along with stable and slow crack propagation for mode II dominant fracture tests (i.e. MMR = 0.67 and 1). For the mode I dominant fracture tests, adhesive and substrate failure accompanied cohesive failure. In contrast, mode II dominated fracture tests only showed cohesive failure of the epoxy resin at the interfaces.

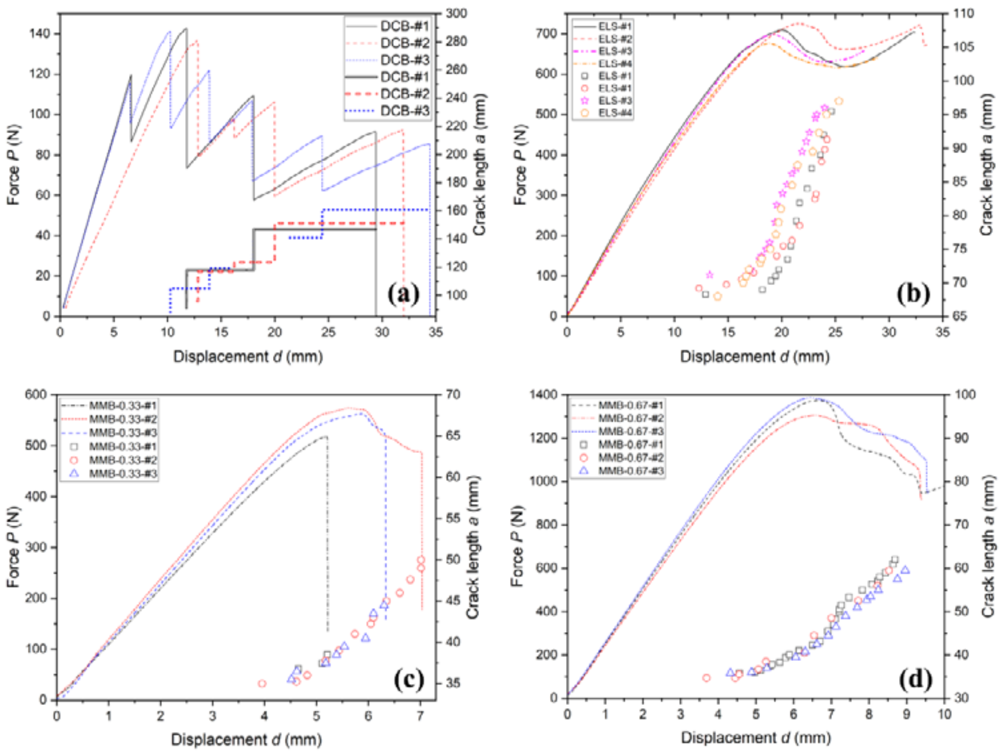

Figure 2. Force-displacement curves and crack length-displacement curves obtained from DCB tests (a), ELS tests (b), MMB tests at a mix-mode ratio of 0.33 (c) and MMB tests at a mix-mode ratio of 0.67 (d).

A plateau of the SERR-crack length curves was not clearly presented for all loading modes, as shown in FigureFigure ***3***. This phenomenon indicates either the crack propagation of such laminated-pultruded plates is relatively less stable in general or suggests a redesign of specimen dimensions to allow sufficient crack growth.

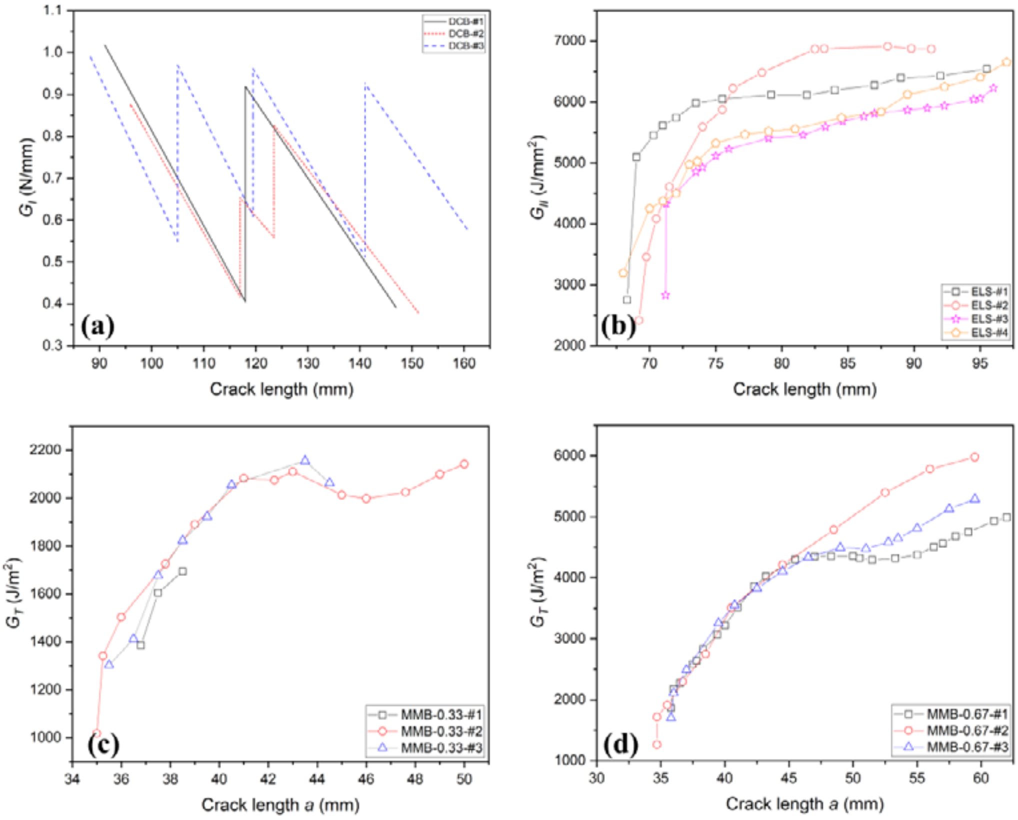

Figure 3. R-curves obtained from DCB tests (a), ELS tests (b), MMB tests at a mix-mode ratio of 0.33 (c) and MMB tests at a mix-mode ratio of 0.67 (d).

To establish the mixed mode I/II failure envelope, both power law and Benzeggagh-Kenane (B-K) law were selected. In the present study, the crack initiation toughness was considered for fitting the failure envelope while the crack propagation toughness could not be determined as no clear plateau of the SERR - crack length curves can be recognized from the DCB, ELS and MMB tests. The crack initiation was identified visually, rather than using the criteria based on the change of compliance of force-displacement curves which could produce over-conservative measurements. Although the determination of crack initiation using the visual observation is highly affected by the image resolution and may create manual deviations, it is less conservative. As shown in Figure Figure ***4***, a high coefficient of determination (R^2) is presented whether using the power law or B-K law. Among the three different fits by applying the power law, the one with fitting parameters equal to 1.0 (Fitted 3 in Figure Figure ***4*** (a)) indicates the possibility of a linear relation between the mixed mode I/II fracture toughness components.

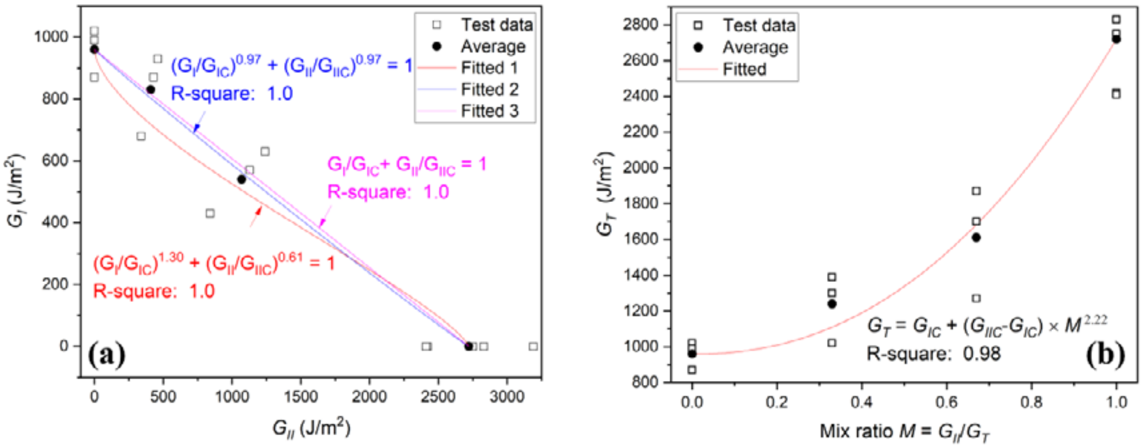

Figure 4. Mixed mode I/II failure envelope based on power law (a) and B-K law (b).

By following specimen design and test configurations introduced in the test standards [6,7,8] , the pure mode I mode I, pure mode II and mixed mode I/II interlaminar fracture behaviour of laminated pultruded composite plates can be obtained properly. However, considering the specimen thickness in the present work is close to the recommend values, whether these test standards are applicable for very thick laminated pultruded composite plates should be investigated further.

4. Conclusions

The interlaminar fracture behaviours of laminated pultruded CFRP plates was characterized at four mode mix ratios by conducting DCB, ELS and MMB tests. Then both power and B-K laws were selected to create the mixed mode I/II failure envelope. The main conclusions are listed hereafter:

1) Mode I dominant fracture tests presented frequent sudden drop of force accompanying unstable or fast crack propagation. As for mode II dominant fracture tests, the post-peak section of force-displacement curves were smoother along with stable and slow crack propagation.
2) Both the power law and B-K law are capable to describe the mixed mode I/II failure envelope. A linear relation between the mode I SERR component and the mode II SERR component may exist for such plates according to the fits using the power law.
3) The existing test standards are applicable for such laminated pultruded CFRP plates with a thickness slightly over the recommend limit. However, more investigations should be continued to verify their capabilities for very thick laminated pultruded composite plates.

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