Composites Science and Technology 165 (2018) 66–73

Contents lists available at ScienceDirect

Composites Science and Technology

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

Experimental determination of Through-Thickness Compression (TTC) enhancement factor for Mode II fracture energy

Xiaodong Xu*, Michael R. Wisnom, Xiaoyang Sun, Tamas Rev, Stephen R. Hallett

Bristol Composites Institute (ACCIS), University of Bristol, University Walk, Bristol BS8 1TR, United Kingdom

ARTICLE INFO

Keywords:
B. Delamination
B. Fracture toughness
C. Finite element analysis (FEA)
Bi-axial testing

ABSTRACT

Mode II fracture energy, G_{IIC}, is a critical parameter for determining the propagation of delamination in composite laminates. Its value can be affected by Through-Thickness Compression (TTC) stress acting on the crack tip and here this effect has been studied using IM7/8552 carbon/epoxy laminates with cut central plies. External TTC loads were applied through bi-axial testing. Unidirectional (UD) cut-ply specimens were used to determine the TTC enhancement factor, η_G, for G_{IIC}. A similar enhancement effect was also found in Quasi-isotropic (QI) specimens with 2 extra cut central 0° plies inserted into the layup. The TTC enhancement factor was implemented in a Finite Element Analysis (FEA) framework using cohesive interface elements, showing that the determined η_G can be successfully used to model the effect of TTC on delamination.

1. Introduction

Laminated composite materials have outstanding in-plane properties, but typically low interlaminar properties. This characteristic is due to the fact that fibres lying in the plane of a laminate do not provide reinforcement through the thickness, so the laminate relies on the relatively weak resin to carry loads in between its laminae. Delamination is a major cause of failure in composite laminates, which can cause separation without breaking the fibres. Accurate prediction of delamination initiation and propagation is of considerable importance since it is a critical failure mode for many composite structures. Delamination can occur due to many causes [1], such as through-thickness tensile loading, geometry and discontinuities e.g. at free edges and ply drops.

Composite structures for load carrying applications are often subjected to multi-axial loading conditions, with a significant volume of work having been done on delamination under Through-Thickness Compression (TTC) stresses [2–10]. This is particularly relevant to the design of bolted joints [11] and components prone to impact. Fracture mechanics approaches are usually adopted to predict delamination, based on strain energy release rate analysis. Wisnom et al. [2] demonstrated that for glass/epoxy specimens with cut central plies, Mode II fracture energy is apparently not constant, but increases with specimen thickness, which can be explained through the presence of TTC stresses, according to the current study. Cui et al. [3] described the increase of G_{IIC} due to TTC enhancement, ΔG_{IIC}, empirically:

$$\Delta G_{IIC} = -\eta_G \sigma_{33} G_{IIC} \quad (1)$$

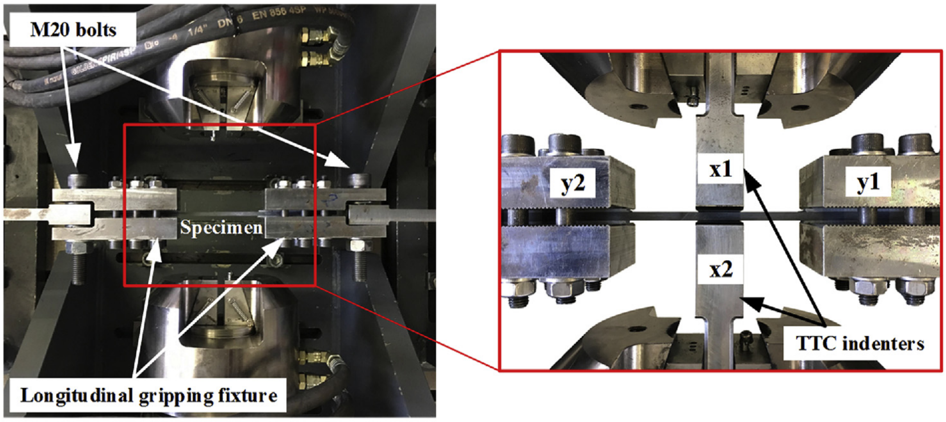
where η_G is the TTC enhancement factor for G_{IIC}, σ_{33} is the TTC stress.

It is difficult to apply and maintain the TTC loads in the standardised Mode II fracture testing configuration, e.g. the End Notched Flexure (ENF) tests following the ASTM D7905 [12]. Therefore, only a few papers are available on the TTC enhancement factor for Mode II fracture energy G_{IIC}. In the existing literature, there are three ways to apply TTC loads. The first method is through the introduction of hydrostatic pressure. Rhee [4] applied hydrostatic pressure to CU125NS non-woven graphite/epoxy filament wound Unidirectional (UD) thick-walled cylindrical pressure vessels. A compliance method was used to calculate the fracture energy, which increased by 35% when the applied hydrostatic pressure was increased from 0.1 MPa to 200 MPa. Cartié et al. [5] conducted 4-point ENF tests under hydrostatic pressure. They demonstrated that G_{IIC} of IM7/977-2 carbon/epoxy laminates increased linearly by up to 25% when hydrostatic pressure increased to 90 MPa. It is extremely hard to apply hydrostatic pressures in a test configuration, hence special test facilities are needed. The main limitation of this method is that the hydrostatic pressure locally creates a complex tri-axial stress state, making it difficult to determine the exact TTC stress applied to the delamination interface. Once the crack is open, the previously applied TTC pressure will be cancelled out by the same hydrostatic pressure acting on the new crack surface in the opposite

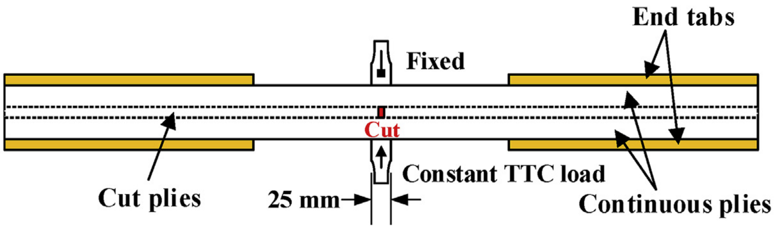
---

* Corresponding author.
E-mail address: xiaodong.xu@bristol.ac.uk (X. Xu).

https://doi.org/10.1016/j.compscitech.2018.06.012
Received 8 March 2018; Received in revised form 11 June 2018; Accepted 12 June 2018
Available online 15 June 2018
0266-3538/



a) Bi-axial test fixtures.



b) Schematic of the specimen with TTC indenters (not to scale).

Fig. 1. Bi-axial test set-up. a) Bi-axial test fixtures. b) Schematic of the specimen with TTC indenters (not to scale).

direction. The second method is through the design of specimen geometry. An early attempt was to use E-glass/913 glass/epoxy and XAS/913 carbon/epoxy central cut-ply and tapered specimens under in-plane tensile loads [3]. Internal TTC stresses are created due to the discontinuity within the specimen, which can enhance G_{IIC}. Another effort was made to apply transverse compressive loads to edge-cracked off-axis specimens to generate local transverse stresses at the crack tip [6]. The transverse compressive stresses were normal to the in-plane matrix crack, and they are equivalent to the internal TTC stresses applied normal to the delamination interface in the cut-ply tests [3], assuming transverse isotropy. G_{IIC} was enhanced up to fourfold for the S2/8552 glass/epoxy laminates [6]. The common issue with these methods is that the TTC stress distribution [3] or the transverse stress distribution [6] is not uniform due to the geometrical discontinuity. The directly applied external TTC load component also increases with the applied resultant load in Ref. [6]. The average local TTC stress [3] or transverse compressive force [6] needs to be determined by a Finite Element Analysis (FEA). The third method is through mechanical clamping, such as the modified transverse crack tensile IM7/8552 specimens tested with a bolted clamping assembly in Ref. [10]. A disadvantage with such mechanical clamping is that the external TTC loads are difficult to measure accurately, the applied TTC stresses have to be determined empirically and the applied TTC stresses cannot be maintained constant throughout the test due to Poisson's effect. In an alternative method to applying the TTC stress, Gan et al. [7] developed a simple bi-axial test in which the external TTC loads can be accurately measured and maintained throughout the tests. They used this to determine the TTC enhancement factor η_f for interlaminar shear strength for IM7/8552 carbon/epoxy laminates, but the TTC enhancement factor or G_{IIC} was not studied.

UD laminates with cut central plies across the full width can be used to study delamination propagation [2,3]. The existing literature [2–6,10] reported to study the TTC enhancement effect on G_{IIC} for delamination propagation are all based on UD laminates. Results for specimens with stacking sequences other than UD are lacking.

In this paper, the TTC enhancement effect on G_{IIC} has been studied by means of bi-axial testing. The TTC enhancement factor for G_{IIC} is determined with UD IM7/8552 carbon/epoxy laminates with cut central plies. A set of Quasi-isotropic (QI) specimens with 2 extra cut central 0° plies across the full width were also tested to investigate the TTC enhancement effect for the same 0°/0° interface within a different layup.

The current study extends the previous work on the TTC enhancement factor on interlaminar shear strength [7] to cover the TTC enhancement factor on G_{IIC}. The characterisation of the two TTC enhancement factors is crucial for the accurate prediction of delamination initiation and propagation. Compared with the existing methods [3–6,10], the current bi-axial test method can maintain constant applied TTC loads throughout the tests. All experimental results fall on the same linear regression line, confirming a consistent and significant TTC enhancement effect on Mode II fracture energy. The determined TTC enhancement factor is implemented in an FEA framework using cohesive interface elements and is able to simulate successfully the experimentally observed behaviour.

2. Experimental configuration

The material used in the current study is Hexcel's Hexply® IM7/8552 carbon/epoxy UD pre-preg, with a nominal ply thickness of 0.125 mm. Two panels with different stacking sequences were made. One was a 40-ply UD $[0]_{40}$ plate, with 8 central plies cut across the full width. The other plate had a layup of $[(45/90/\text{-}45/0)_4(0)]_s$ - a QI stacking sequence with 2 extra 0° plies at the mid-plane that were cut across the full width. The central 0° pre-preg plies were cut with a sharp blade and