proceedings

Abstract

Full-field imaging for evaluating mode-II fracture toughness in CFRP laminates†

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† Presented at the Advanced Infrared Technology and Applications (AITA) conference, Kobe, Japan, 15-19 September 2025 .

Abstract: To replicate delaminations at the coupon and substructural scales, simulated defects are often introduced into test specimens; therefore, understanding their behaviour within the laminate is essential. Full-field imaging is employed to investigate the effects of artificial defects in Carbon Fibre Reinforced Polymer (CFRP) composites. Centre Crack Ply (CCP) specimens are used to evaluate the Mode II fracture toughness of laminated composites from a simple tensile test. Two batches of specimens are manufactured using IM7/8552. Artificial defects are introduced using a steel film insert of 5 μm thickness. For the first type of samples, the inserts were coated with Frekote release agent, while for the second type, the steel inserts were incorporated into the laminate without coating. Additionally, a third batch of specimens with a $[0_4, \underline{90}]$s lay-up is manufactured. Thermoelastic Stress Analysis (TSA) and Digital Image Correlation (DIC) are employed to obtain full-field temperature and displacement data from the tested samples. The inclusion of 90-degree plies enhances thermal contrast exploiting their anisotropic mechanical and thermal properties. First, the specimens are tested under monotonic loading to failure, with DIC used to capture strain distributions at damage initiation and failure. In addition, acoustic Emission is employed to evaluate damage initiation. Load drops provide an indirect evaluation of fracture toughness. Results show that full-field imaging is capable of establishing how the release agent and the lay-up configuration influence damage initiation and propagation. The non-adiabatic thermoelastic response is shown to be effective in observing subsurface damage. Finally, a novel approach to evaluate fracture toughness from the temperature increase at the failure event is proposed.

Keywords: Thermoelastic Stress Analysis; Delamination; Composite Materials; Full-Field Imaging, Fracture Mechanics

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

1. Introduction

To simulate delamination in composite laminates, artificial defects are usually introduced into test specimens. The reliability of the measured fracture parameters depends on how accurately these defects can replicate real failure mechanisms. Therefore, a realistic representation of such defects is essential. One widely adopted configuration for investigating mode II fracture [1] behaviour is the Centre Crack Ply (CCP) specimen, originally introduced in the early 1990s [2]. The CCP specimen is a unidirectional laminate in which a number of plies are transversely cut, creating an artificial crack. This cut induces a localised stress concentration that initiates four interlaminar matrix cracks, which then propagate in an unstable manner under tensile loading. Mode II fracture toughness [1], G_{II}, is calculated via an energy-based formulation that depends on parameters such as specimen width W and thickness t, Young's modulus E, the ratio of cut plies x, and the critical load P at which unstable crack propagation is triggered [2]:

$$G_{II} = \frac{P^2}{4W^2Et}\left(\frac{x}{1-x}\right) \quad (1)$$

Early implementations of this test did not always present a good repeatability, due to asymmetric and irregular crack propagations. These issues stemmed primarily from the method of damage initiation, which involved only a transverse ply cut. Subsequent research introduced a modified version of the specimen, including two artificial delaminations at the pre-crack location. The use of inserts serves two principal functions: (i) to stabilise crack propagation by promoting symmetry about the laminate mid-plane, and (ii) to minimise the presence of mixed-mode effects. Le Cahain et al. [3] conducted a comparative study on the effects of various insert materials on fracture toughness measurements. Their results demonstrated that steel inserts offered the closest agreement with insert-free behaviour values. Experimental and numerical studies by Scalici et al. [4], further analysed the effect of the artificial delamination, identifying a minimum crack length at which the mode I/II mixity is eliminated. Beyond static fracture characterisation, the CCP sample has also been employed for fatigue testing [5]. Clip extensometers are used to monitor delamination growth rates, enabling the formulation of semi-empirical crack-growth. Fatigue loading allows the use of Thermoelastic Stress Analysis (TSA), which requires cyclic stress states to exploit the reversible relationship between stress and temperature. For orthotropic plies, the temperature variation is dependent on the applied stress amplitude in the principal material directions ($\Delta\sigma_1,\ \Delta\sigma_2$) and on material properties, such as the coefficients of thermal expansion ($\alpha_1,\ \alpha_2$) density (ϱ) and specific heat capacity at constant pressure (C_p) [6]:

$$\Delta T = -\frac{T_o}{\rho C_p}(\alpha_1\Delta\sigma_1 + \alpha_2\Delta\sigma_2) \quad (2)$$

Few studies have applied full-field techniques in the assessment of CCP specimens [6], employing TSA to analyse crack propagation in carbon and glass fibre laminates. The present work aims at improving the understanding of CCP specimen behaviour by employing Digital Image Correlation (DIC) and TSA. The main objectives include (i) exploit the non-adiabatic thermoelastic response [6], [8], [9] to monitor damage progression without having a direct view of the delamination crack fronts, (ii) gain a deeper understanding of the effects of artificial delaminations in test environments fusing full-field stress and strain data, and (iii) evaluate the fracture toughness by means of full field data, through the direct evaluation of the energy released during the fracture process.

2. Materials and Methods

Three sets of specimens were manufactured using the IM7/8552 carbon fibre/epoxy prepreg. A steel insert 20 mm in length and 5 μm in thickness was employed as the artificial delamination [3]. The primary aim is to investigate the effect of the application of Frekote® release agent on the behaviour of artificial delaminations; in addition, small modifications in the layup are introduced to assess their influence on the full-field behaviour. Three specimen configurations were manufactured, where the numbers between square brackets indicate ply orientation: (1) [0_4, $\underline{0}$]s: steel insert coated with Frekote®; (2) [0_4, $\underline{0}$]s: steel insert consolidated without Frekote®; (3) [0_4, $\underline{90}$]s: steel insert coated with Frekote®. Here, underlined indicates the transversely cut plies. Strips with dimensions 200 mm (length) × 10 mm (width), were cut from the manufactured plates, consistent with the geometry employed in [3], enabling direct comparison with reported fracture toughness values. Specimen preparation for full-field measurements consisted in applying a thin coat of matt black paint for infrared thermal imaging, followed by a fine white speckle pattern applied via spray painting for DIC, allowing the simultaneous acquisition of surface strain and temperature fields. Additionally, each specimen was instrumented with two acoustic emission sensors. The imaging setup comprised a stereo DIC (2 x 12 megapixel FLIR Blackfly white light cameras fitted with 25 mm lenses), alongside a Telops Fast M3K infrared camera – equipped with a 50 mm lens for thermal data acquisition. DIC images were processed using the commercial software MatchID, while TSA data were analysed using a custom in-house algorithm, that applies temporal filtering at the selected loading frequency allowing the extraction of the thermoelastic signal. Mechanical testing involved (i) a monotonic tensile test at a displacement rate of 0.5 mm/min to failure, to evaluate G_{II} and (ii) cyclic loading of 3.5 ± 3 kN, across a range of frequencies from 0.5 to 30 Hz, to capture the influence of artificial delaminations.

3. Results and Discussion

Figure 1 shows results from monotonic tests on unidirectional samples. Six specimens (three with coated, three uncoated inserts) were tested. The load-strain curves from DIC consistently report a load drop, corresponding to the onset of unstable crack propagation (Fig, 1, a), demonstrating the capability of DIC to identify damage initiation and proopagation. IR thermography revealed localized temperature increases (Fig. 1, b), corresponding to energy release during crack propagation. Acoustic emission results (Fig. 1, c) also show a marked increase in acoustic energy concurrent with peak load drops.

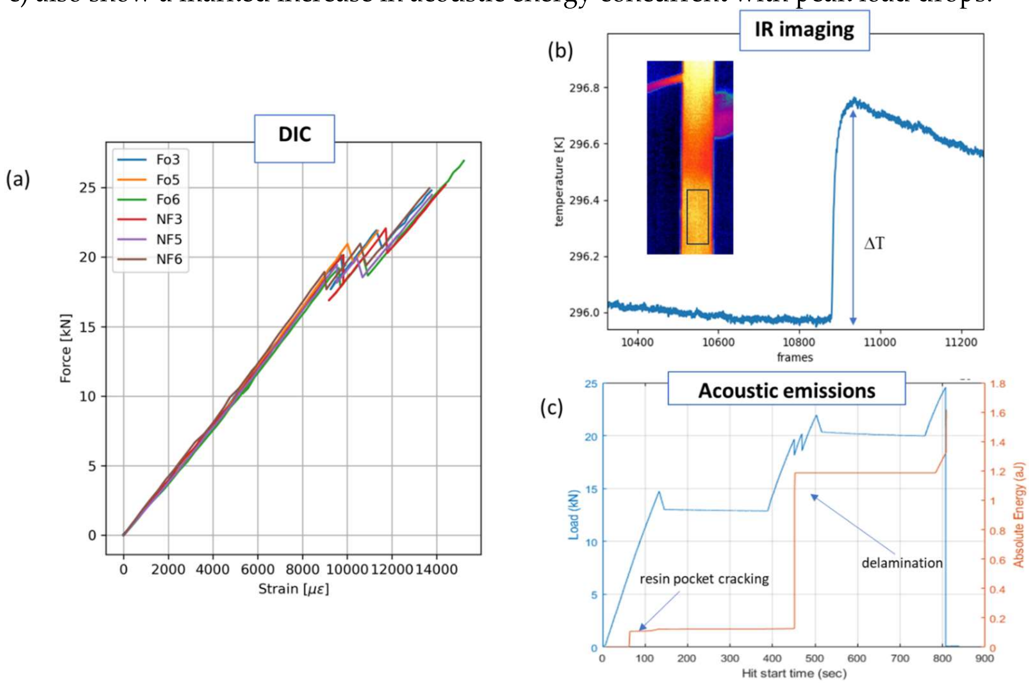

Figure 1. (a) Load-strain Curve; (b) Thermal energy released at damage propagation; (c) total acoustic energy throughout the test.

The mode II fracture toughness calculated from Eq. (1) and averaged over the three specimen per type were 1271 J/m² for the Frekote-coated inserts and 1224 J/m² for the uncoated inserts respectively. These results show close agreement with 1203 J/m² from [2]. The values suggest no significant difference, even though a marginal increase is observed with coated inserts. In addition to the well-established load-drop method Eq. (1), a novel procedure for the evaluation of the energy release rate is introduced. The procedure is based on the localised temperature increase in the area of the delamination (Fig. 1, b). Under the assumption that the crack propagation happens symmetrically through the thickness, the crack fronts propagate instantly and advance in a uniform manner, and assuming that all the fracture energy is dissipated as heat, the G_{II} can be expressed as:

$$G_{II} = \rho C_p \Delta T t \quad (3)$$

The fracture toughness evaluated following this procedure are in excellent agreement with the results obtained employing Eq. (1), with an average value of 1282 J/m² and 1222 J/m² for the coated and uncoated inserts respectively.

Full-field ΔT/To results from TSA at 0.5 Hz are reported in Fig. 2 for the unidirectional specimens with (a) and without (b) Frekote and with the inclusion of the 90-degree plies in the layup (c). TSA is always able to clearly determine the area where the artificial defect has been introduced, that appears as an area with a lower thermoelastic response.

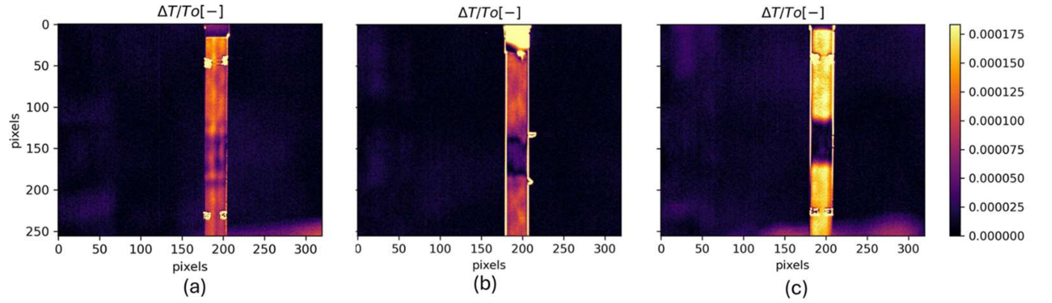

Figure 2. comparison of TSA ΔT/To maps at 0.5 Hz for the (a) $[0_4, \underline{0}]_s$ layup (with Frekote) (b) $[0_4, \underline{0}]_s$ layup (without Frekote) (c) $[0_4, 9\underline{0}]_s$ layup (with Frekote).

Due to the mismatch in the coefficients of thermal expansion (CTE) in the longitudinal and transverse direction for the chosen carbon fibre – the CTE is two orders of magnitude greater in the transverse direction –, the inclusion of 90-degree plies in the centre of the laminate significantly enhances thermal contrast. The 90 degree plies generate a higher thermoelastic response and act like an embedded heat source, thus improving damage detection, tracking and visualisation using TSA.

4. Conclusions

The effects of artificial delaminations on mode II fracture toughness and full-field responses in CFRP laminates using CCP specimens were investigated. The application of Frekote® had minimal impact on the evaluated fracture toughness, when using a 5-µm steel insert. The capability of DIC and IR-Thermography to detect onset of unstable damage propagation has been demonstrated. A novel method for evaluating the fracture toughness through the temperature increase at the event of failure has been introduced, showing remarkable agreement with the well-established method based on the load drop. When performing TSA on carbon fibre samples, the introduction of 90-degrees enhanced thermal contrast, thereby improving the detectability of subsurface delaminations.

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Funding: The research was supported by the EPSRC Programme Grant 'Certification for Design – Reshaping the Testing Pyramid' (CerTest, EP/S017038/1).
Data availability statement: Data will be made available upon request.