Development of a novel compact tension specimen to mitigate premature compression and buckling failure modes within fibre hybrid epoxy composites

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Abstract

A Notched Curved Compact Tension (NCCT) and Extended Notched Curved Compact Tension (ENCCT) specimen geometries are presented for the measurement of translaminar critical strain energy release rates in composite laminates with low compressive to tensile strengths. Premature compressive and buckling failure occurred when a conventional Compact Tension (CT) specimen geometry (similar to ASTM E399 (2013)) was utilised for monolithic Non-Crimp Fabric (NCF) S2-Glass/MTM57 epoxy composite and an interlayer fibre hybrid T700 carbon spread tow/NCF S2-glass epoxy composite. The NCCT and ENCCT specimen design methodology and manufacturing routes are presented where premature compressive failure was mitigated through a curvature at the rear of the file and the introduction of a through-thickness groove that had been pre-cured along the crack growth region. The latter ensured that buckling was eliminated, whilst stable crack growth was achieved. The development involved FE model material validation and optimisation for the novel specimen design. Experimental tests presented both interlayer and intralayer fibre hybrid composites with good repeatability and low scatter within the results.

Keywords: Buckling, Translaminar Mode I Finite element Design Fracture

1. Introduction

The need to characterise materials’ translaminar through-thickness fracture toughness relates directly to FE modelling and component design of industrial components, where loading scenarios such as open hole tension and impact are often involved. Energy-based numerical modelling techniques [2–5] require translaminar fracture toughness properties as well as initiation strengths for composites, particularly favoured during impact situations, where stress-based models would be insufficient in modelling the extent of damage. Recently, researchers [6–9] have characterised the fracture toughness of monolithic CFRP composites using the Compact Tension (CT) specimen design similar to the ASTM E399 [1] test standard. The successful application of a typical CT geometry, however, relies on the relatively similar tensile and compressive strength of the material system, whereby the opening of the arms at the notched end creates compressive forces at the un-notched end leading to premature failure through compression and buckling at the rear of the specimen [6,10,11]. This tends to occur particularly where woven materials are employed using current test methods, summarised succinctly by Blanco et al. [11] and Laffan et al. [12]. Table 1 shows the materials used within this study, all of which were manufactured using Resin Film Infusion (RFI) using MTM57 resin film, vacuum bagged at a ramp rate of 100 °C/h to 125 °C, and held for 1 h before a non-controlled cool down to room temperature. The volume fractions are also presented, from Thermogravimetric Analysis (TGA) burn-off [13].

For the materials tested in this research, premature compressive and buckling failure occurred within the composites containing S2-glass and Vectran, where considerably lower (about 50% for the S2-glass composite and 11% for the Vectran composite) compressive strength relative to tensile strength was observed. It became apparent that the load required to propagate a crack within a CT specimen was proportional to the tensile strength of the material and therefore, a material with a relatively low compressive to tensile strength ratio tended to lead to premature out-of-plane buckling at the rear of the specimen.

Preliminary tests carried out on the monolithic S2-glass composite...
and intralayer fibre hybrid T700 carbon/Vectran composite showed that an array of typical CT specimen geometries failed through modes FM1 and FM6 due to the low compressive strength and modulus of this system. A novel specimen geometry, named the ‘Notched Curved Compact Tension’ (NCCT) specimen (due to its geometrical features, see Section 3), was developed by means of numerical modelling and experimental testing. The NCCT specimen allowed large crack lengths, of up to 20 mm, without premature failure or the need for an anti-buckling device for the monolithic S2-glass material. The specimen geometry was then refined and brought in line with a more repeatable manufacturing process, allowing translaminar fracture toughness testing of the intralayer fibre hybrid T700 carbon/Vectran composite as well as the monolithic S2-glass composite. Named the ‘Extended Notched Curved Compact Tension’ (ENCCT) specimen (Section 3), this new design was an improvement on the NCCT due to extending the specimen length aiding in capturing longer R-curve crack lengths, increasing the in-plane cracking area (for larger unit cell architectures), as well as introducing an inclined through-thickness crack which reduced the stress concentrations around the fractured region.

2. Preliminary standard CT geometry tests

Both experimental and numerical testing were employed across various CT geometries towards gleaning the translaminar fracture toughness of the monolithic and fibre hybrid materials for impact modelling. All numerical models for the various CT specimen geometries were run using Abaqus 6.14 in both implicit linear static to determine the failure strains, and eigenvalue buckling to determine the critical buckling loads at these failure strains.

The numerical FE models were comprised of continuum shell elements (SC8R), cohesive elements (COH3D8), and rigid body elements (R3D4). The continuum shell elements (SC8R) were assigned the composite laminate properties found through standardised material testing, and assigned using the Abaqus composite material property for each ply (where one element through-thickness contained two plies, and each ply had three integration points to allow for bending). The cohesive elements (COH3D8) were assigned the MTM57 resin material properties and were located at three regions spaced 1 mm equally through the thickness of the specimen to capture the interlaminar stresses between neighbouring continuum shell ply stacks. Rigid body elements (R3D4) were used to model the loading pins with frictionless tangential and hard normal penalty contact properties with the specimen. Using a typical CT specimen geometry (Fig. 2), a mesh sensitivity study was employed (Fig. 3) where the total internal energy of the model was tabulated against the mesh size around the notch tip. Six discrete element sizes at the notch tip and up to a 5 mm radius from the notch tip between 2 mm and 0.05 mm were investigated. Elements at the rear of the specimen were set to 1 mm (since the tow size for the S2-glass composite was within this order of magnitude) for each model and the remaining elements were set globally to 2.5 mm in size.

The internal energy within the model was seen to converge where the mesh size around the notch tip was approximately 0.5 mm, quantified as a convergence of 0.03% difference to the trending value at 0.05 mm (note, the strain magnitudes also followed a similar trend to converge at the same mesh density). Therefore, to aid in computational time and efficiency, a mesh size of 0.5 mm was used around the notched region (in tension) and 1 mm at the pins and rear of the specimen (in compression, where high compressive stresses were likely to occur (failure modes FM1 & FM5, Fig. 1)). The CT model ASTM E399 [11] shown in Fig. 2 contained a total of 62,676 nodes and 42,420 elements, comprising of 31,986 SC8R, 3360 R3D4 and 7074 COH3D8 type elements. By running multiple linear static models at discrete crack lengths, an approximate crack length (if at all) could be determined before buckling failure at the rear of the specimen occurred. This was achieved by first conducting linear static analysis on a specimen with a discrete crack length and determining the driving force responsible for a Abaqus maximum strain criterion greater than unity around the notch tip as follows [14]:

Table 1

| Material description | Image | Volume fractions (CV%) |
|----------------------|-------|-----------------------|
| Monolithic S2-glass non-crimp (0°/90°) (312 gsm fibre blanket density) | ![Image](image1.png) | 0.559 (1.47) |
| Monolithic T700 carbon spread tow 12 K plain weave (88 gsm fibre blanket density) | ![Image](image2.png) | 0.532 (3.65) |
| Interlayer fibre hybrid: T700 carbon spread tow 12 K plain weave/ S2-glass non-crimp (0°/90°), alternate carbon (C) and glass (G) ply blocks of [C-G-C-G-C-G-C]. Note, the S2-glass fibre imprint can be seen through the top ply T700 carbon spread tow | ![Image](image3.png) | Carbon: 0.194 (2.34) Glass: 0.365 (2.22) (Total: 0.559) |
| Intralayer fibre hybrid 2 × 2 twill weave: T700 carbon/Vectran (520 gsm fibre blanket density) | ![Image](image4.png) | Carbon: 0.297 (15.94) Vectran: 0.343 (23.33) (Total: 0.640) |

Fig. 1. Diagram of a conventional CT specimen with the locations of possible failure mechanisms [11].
where: $\varepsilon$ is the strain in the given direction and $\gamma$ is the shear strain in the given direction; note that ultimate compressive strains are deemed positive.

This driving force was then employed within an eigenvalue buckling mode analysis to quantify whether buckling would occur for this particular crack length and at this ‘cracking’ driving force. This data is summarised in Table 2 for the monolithic S2-glass composite and intralayer fibre hybrid T700 carbon/Vectran composite properties regarding four 5.6 mm thick CT specimen geometries (thickness as recommended by Blanco et al [11] as a result of their parametric study). It should also be noted that the numerical FE studies were undertaken at 5 mm discrete crack length intervals.

The corresponding load versus displacement graphs for these tests undertaken at a stroke rate of 1 mm/min are shown for the CT (Fig. 4), 2TCT (Fig. 5), and ECT (Fig. 6) type specimens along with post-test x-ray images highlighting the premature failure mode denoted in Fig. 1 [11]. Buckling (FM6) was noticed within the CT and 2TCT specimens as well as compressive failure at the rear end of the specimen (FM1) occurring in both the CT and ECT specimens. This indicated that either a thicker specimen or an anti-buckling device was required to counteract this out-of-plane buckling, both of which have drawbacks. Creating a thicker CT specimen has been seen to affect the fracture toughness of the materials tested, as investigated by Teixeira et al. [7] when using monolithic spread tow carbon, as well as increasing the manufacturing cost. Anti-buckling devices inherently lead to unknown stress variations and concentrations through the specimens being tested, and thus have been disregarded throughout this study.

3. Development of a novel compact tension specimen

3.1. Model development

A ‘Curved Compact Tension’ (CCT) geometry profile (Fig. 7) was developed by introducing a 30 mm radii at the rear of the typical
compact tension specimen, tangential to the connecting horizontal sides so as to eliminate unnecessary stress concentrations at the rear of the specimen. Despite the reduction in compressive stresses at the rear of the specimen, experimental tests showed that buckling lead to compressive failure regardless of the curvature. Crazing was also seen around the notch and a through-thickness crack was barely visible (Fig. 8).

To mitigate this type of buckling failure, the 4 mm curved CT specimen shown in Fig. 8 was modelled numerically at a thickness of 10 mm, whereupon eigenvalue buckling modes analysis was carried out. Similar to the procedure carried out within Table 2, the load required to propagate the crack was below the critical buckling load up to a crack growth of 12 mm. An $R$-curve of $12$ mm crack length was not likely to indicate a propagation fracture toughness, and thus a new design was employed.

It was apparent that the solution to mitigate premature buckling was to reduce the CT geometry’s ‘cracking’ driving force, whilst increasing the force associated with the out-of-plane normal buckling of the specimen. To achieve this, and also capture long crack lengths whilst maintaining a high buckling-to-crack propagating load, the
thickness of the crack growth area was reduced by introducing a 4.7 mm thick rectangular notched section 4 mm × 60 mm either side of the specimen along the crack growth region, located 12 mm from the rear of the specimen (Section 3.2). This reduced the load required to propagate the crack whilst maintaining a high critical buckling load due to a relatively thick rear of the specimen. The specimen was named the ‘Notched Curved Compact Tension’ (NCCT) specimen due to its dimensional features (Fig. 9) and a study to optimise the ratio between the critical buckling load (Fig. 10b), and a linear static model utilising the maximum strain criterion was used to determine the load required for crack propagation (Fig. 10c).

The eigenvalue buckling mode FE model shown in Fig. 10a defines the critical buckling load of the specimen geometry at five linear static FE models containing discrete crack lengths between 21 mm and 41 mm. The critical buckling load taken from the eigenvalue analysis was then scaled by a 50% safety factor and applied directly to the corresponding linear static FE model with the same crack length (Fig. 10b).

From the linear static model, it was clear that at all discrete crack lengths, the critical buckling load (with a 50% safety factor) applied to the linear static model sufficiently superseded the maximum strain criterion around the crack tip, whilst the rest of the model remained undamaged. The maximum strain criterion data at the notch tip is summarised in Table 3.

The materials tested as follows worked as intended when using the NCCT test specimen design:

- Monolithic S2-glass non-crimp (0°/90°);
- Monolithic T700 carbon spread tow 12 K plain weave;
- Interlayer fibre hybrid: T700 carbon spread tow 12 K plain weave/S2-glass non-crimp (0°/90°), alternate carbon (C) and glass (G) ply blocks of [C-G-C-G-C-G].

The intralayer fibre hybrid T700 carbon/Vectran did not however perform as intended due to considerable fibre pull-out from the thickened region of the specimen, leading to erroneous loads and thus the associated fracture energy. The unit cell size of this fibre hybrid is larger than the 4 mm high thinned region height allowed. Because of this, an update to the NCCT was made whereupon the thinned area was increased to accommodate the larger unit cell of the 2 × 2 twill weave (10 mm × 10 mm), as well as extending the specimen length so as to capture a longer crack and hence a more comprehensive R-curve. The thinned region was also chamfered to the thicker region to lower the critical buckling load (Fig. 10b), and a linear static model utilising the maximum strain criterion was used to determine the load required for crack propagation (Fig. 10c).

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stress concentrations around the transition (Section 3.2). The notch tip was reduced from 35 mm to 25 mm from the end of the specimen and the design was named ‘Extended Notched Curved Compact Tension’ (ENCCT) (Fig. 12 and Fig. 13). By comparing the NCCT (Fig. 9) and ENCCT (Fig. 13) type specimens, it can be seen that the maximum crack length is 25 mm for the NCCT and 50 mm for the ENCCT type specimens due to the thinned region and notch tip location, allowing for a longer $R$-curve within the ENCCT specimens.

3.2. Specimen manufacture

The materials used for the NCCT specimen type were laid-up in parallel in panels of dimensions 120 mm × 480 mm, as shown in Fig. 14. PTFE inserts of dimensions 4.7 mm × 4 mm × 60 mm were inserted at cuts made either side of the panel before curing to achieve the thinned cracking region of the NCCT specimen. Care was taken to ensure that the inserts lined up with each other either side. Resin rich regions around the cut could be seen where the fibres, which were cut by hand using a surgical scalpel, slightly exceeded the dimensions of the inserts by about 1 mm (Figs. 15 and 16).

Each specimen had a total nominal thickness of 10 mm, comprising of 4 mm thick sides nominally, and varying thinned crack growth regions with a total of three tests per material type. The ply counts and nominal cured thicknesses are shown in Table 4.

Upon curing, one side of the inserts were removed and the specimen shapes were cut using a waterjet cutter to their desired dimensions. The specimens were then notched using a circular diamond saw with one of the PTFE inserts in place, providing some support for the thinned region during the cutting process. The insert was then removed and the notch tip was run over three times using a surgical scalpel by hand to create a sharp crack tip prior to testing, as recommended by S. Pinho since the notch tip radius has been seen to affect the fracture toughness [15].

The ENCCT specimens were manufactured in the same manner as the NCCT specimens except the PTFE inserts were chamfered using sandpaper to create a sloping transition between the thick sides of the specimen and the thin cracking region. This was employed to minimise stress concentrations occurring at the sharp inside edge of the thinned region, which could affect the crack path. The panel that the specimens were cut from were arranged in a row of three by a column of two to reduce the curvature on the caul plate which had a slight thinning effect on the edges of the NCCT specimens under vacuum of the autoclave cycle. Figs. 17 and 18 show the ENCCT specimen for the intralayer fibre

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**Fig. 8.** Buckled CCT geometry without through-thickness groove: a) profile view b) front view c) back view.

**Fig. 9.** NCCT specimen type.

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**Fig. 10.** NCCT specimen geometry: a) Specimen FE model b) Eigenvalue first buckling mode (the contour shows the normalised out-of-plane displacement) c) Maximum strain criterion at 50% of buckling load (contour other than blue indicates values greater than unity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
hybrid T700 carbon/Vectran before and after the PTFE inserts were removed and scale bar drawn respectively. The ENCCT specimens were C-scanned and X-rayed prior to testing (Fig. 19) to identify any delaminations, discontinuities, and inclusions which could affect the crack driving force and thus lead to erroneous fracture toughness data. The light regions seen in Fig. 19 are where the waterjet cutting has created fibre debris and vacuum bagging had distorted the surface of the specimen.

4. Test set-up

The NCCT and ENCCT testing was carried out at room temperature (20 °C) using an Instron 5969 test machine at a constant stroke of 0.5 mm/min in tension, where the crosshead displacement (mm), load (N) and time (s) was recorded (Fig. 20). Video recording was employed to capture the crosshead displacement (mm) from markers on the specimen surface using an Imetrum optical strain system at 10 Hz and also the crack growth (mm) against the scale bars drawn on each specimen. The Imetrum optical strain and the Instron 5969 sources were correlated automatically via an analogue to digital converter and thus the load from the crosshead and the optical displacement curves could be plotted purely from the pin locations, eliminating the test machine and instrumentation compliance errors. A backlight was used to show clear crack growth through the specimen thickness for the translucent monolithic S2-glass material and for the other opaque materials front lighting sufficed. The crack growth was followed optically and the crack length, denoted as \( a \), was given as the initial crack length \( a_0 + \) crack growth.

5. Data reduction

An area method [16] was used to calculate the critical strain energy release rate at various crack lengths to populate the \( R \)-curve. This method was easily employed due to the thinned region providing clear optical through-thickness crack length measurement. The following formula was used to determine the critical strain energy release rate \( G_{IC} \) (J/m²) of the material:

\[
G_{IC} = \frac{E}{a \cdot t}
\]

where \( E \) is the energy expended propagating the crack (J), \( a \) is the crack length (m), and \( t \) is the specimen thickness at crack (m).

The energy required to propagate the crack was calculated as the integral of the load versus displacement curve, ignoring the elastic...
energy stored within the specimen (Fig. 21). The plastic energy $E'$ was correlated with the crack length taken from the video capture in the test at specific points to determine the critical strain energy release rates along the crack length. The benefits of this approach include its simplicity and independence from compliance calibration curves. The major drawback of the area method is the reliance on the user’s measurement of the crack length, which can be subjective to both parallax and human errors.

As well as the area method, the Modified Compliance Calibration (MCC) method [16] was also used to calculate the critical strain energy release rates for the monolithic S2-glass material, validating the use of the area method as an accurate means of data reduction for the NCCT specimen type. The MCC method involved determining a compliance calibration curve from the range of discrete crack lengths under linear elastic FE modelling. By plotting compliance (mm/N) versus crack length (mm), the compliance calibration curve for the monolithic S2-glass NCCT specimens were fit using the following function:

$$C = (aa + \beta)^x$$

where $a$ is the crack length, and $\alpha$, $\beta$, and $\chi$ were calculated to best fit the experimental data [16].

The critical strain energy release rate was then calculated using the following formula:

$$G_{IC} = \frac{P_c^2 \, \frac{dC}{da}}{2t}$$

where $P_c$ is the critical load prior to crack growth, $t$ is the thickness of cracked region, and $dC/da$ is the differential of the compliance curve.
Similarly to the MCC method, a compliance calibration (CC) method [16] was used to support the area method data reduction for the ENCCT intralayer fibre hybrid T700 carbon/Vectran specimens. The CC procedure followed the same data reduction as MCC except the compliance curve was derived experimentally by cutting to known crack lengths and measuring the initial elastic compliance after each discrete cut.

Fig. 22 shows a typical crack growth made visible through the use of a backlight for the monolithic S2-glass NCCT specimens. The crack in this particular specimen can be seen to have propagated directly along the thinned region and jumped vertically in-plane along a tow to then continue its translaminar development at the boundary at the change of thickness. The monolithic S2-glass material exhibited crazing along the thinned region prior to crack formation and it was important to distinguish the difference between matrix crazing (discolourment and change in translucency) and crack propagation by the slip stick behaviour of the crack growth.

Table 4
NCCT and ENCCT ply counts and nominally cured thicknesses.

| Material, specimen type | Thick side: ply count (nominally cured thickness) | Thin middle: ply count (nominally cured thickness) |
|-------------------------|-----------------------------------------------|-----------------------------------------------|
| Monolithic S2-glass (G), NCCT | [G][G]^20, 4.7 mm | [G]^4, 1.0 mm |
| Monolithic T700 carbon (C), NCCT | [C][C]^20, 4.7 mm | [C]^10, 0.9 mm |
| Interlayer fibre hybrid T700 carbon (C)/S2-glass (G), NCCT | [C-G-C-G-C-G-C]^4, 4.2 mm | [C-G-C-G-C-G-C], 1.0 mm |
| Intralayer fibre hybrid T700 carbon/Vectran (V), ENCCT | [V]^7, 4.2 mm | [V], 0.8 mm |

Fig. 17. Intralayer fibre hybrid Vectran/T700 carbon ENCCT specimen with PTFE insert still intact.

Fig. 18. Intralayer fibre hybrid Vectran/T700 carbon ENCCT specimen with PTFE inserts removed and scale bar labelled for optical crack measurement.

Fig. 19. C-scan and x-ray of ENCCT intralayer fibre hybrid T700 carbon/Vectran specimen prior to testing.

Fig. 20. NCCT and ENCCT test set-up.
6. Results

6.1. Compliance curves

Fig. 23 shows the FE derived compliance calibration curve for the monolithic S2-glass NCCT specimens used in calculating the MCC method critical strain energy release rates. Fig. 24 shows the experimentally derived compliance calibration curve for the intralayer fibre hybrid T700 carbon/Vectran ENCCT specimens used in calculating the CC method critical strain energy release rates. It should be noted that the possible crack length is much larger for the ENCCT compared to that of the NCCT test type.

6.2. Critical strain energy release rates

Fig. 25 shows the critical strain energy release rate calculated using the area method compared with that of the MCC method [16] for the monolithic S2-glass NCCT specimens. The initiation critical strain energy release rate can be seen have been approximately 20 kJ/m². The propagation critical strain energy release rate can be seen to have been on average 156.5 kJ/m² (CV = 8.8%) for the MCC method and 131.6 kJ/m² (CV = 10.8%) for the area method. Propagation values were determined where the $R$-curves tended to plateau towards a constant value, where $\Delta a > 11$ mm.

Fig. 26 shows the critical strain energy release rate calculated using the area method as compared with that of the CC method [16] for the intralayer fibre hybrid T700 carbon/Vectran ENCCT specimens. The initiation critical strain energy release rate can be seen have been approximately 60 kJ/m² for the CC method and 30 kJ/m² for the area method. The propagation critical strain energy release rate can be seen to have been on average 173.2 kJ/m² (CV = 44.9%) for the CC method and 154.7 kJ/m² (CV = 15.4%) for the area method, both measured upon plateauing, where $\Delta a > 15$ mm.

Fig. 27 shows the full $R$-curves for the monolithic S2-glass, monolithic T700 carbon, and interlayer fibre hybrid T700 carbon/S2-glass using the NCCT specimen type. Fig. 27 also displays the intralayer fibre hybrid T700 carbon/Vectran $R$-curve using the ENCCT specimen type.

7. Discussion

The NCCT and ENCCT test specimens showed reasonable and repeatable critical strain energy release rate values despite possible limitations associated with the difficulty of specimen manufacture, namely the alignment of the PTFE inserts and the hand-cutting of fibre plies. Comparing the results to other compact tension tests in the literature, the designs presented exhibited a similar if not lower coefficient of variation across a range of data reduction methods [6,16,17]. The MCC method [16] (which determines a compliance calibration curve through FE models) and CC method [16] (which determines a compliance calibration curve through experimental testing) were compared to the area method in the form of $R$-curves and showed good correlation for the critical strain energy release rates in both initiation and propagation.

Post-test radiography was undertaken to determine any regions of unwanted plastic deformation remote from the crack, which could have led to erroneous results due to plastic energy being dissipated outside of the crack growth region and through failure modes other than trans-laminar fracture. Fig. 28 shows the post-test radiograph of the NCCT specimens, indicating that all of the fracture energy had been dissipated through the crack, as required. Note than the white region within the monolithic T700 carbon specimen occurred at the latter stages of the test and at large crack lengths, whereupon the specimen had fractured invalidly at the corner of the thinned region. Fig. 29 shows the post-test radiography of the ENCCT specimen, where penetrant impregnation can be seen within the thickened region due to fibre fracture. Due to there being no measured presence of delamination or fibre pull-out between the thick and thinned region of the specimens from the radiographs, a realistic fracture toughness value was likely to have been gleaned. It should be noted that the two arms of the ENCCT specimen were drawn apart completely to allow easier inspection, hence the through-thickness fracture separating the specimen into two pieces at the rear of the radiograph (Fig. 29).

Post-test SEM images were taken of the NCCT and ENCCT specimens (Fig. 30 through to Fig. 33). The resulting images were used to glean the reasoning behind both the shape and magnitude of the $R$-curves.
presented in Fig. 27. Firstly, the failed monolithic S2-glass NCCT specimen (Fig. 30) showed uniform and regular fracture of the NCF fibre tows (hence the low scatter), with prominent fibre pull-out (hence the high fracture toughness). Whereas, the monolithic T700 carbon counterpart (Fig. 31) shows very little fibre pull-out (indicative of low fracture toughness), as well as drastic variations in crack path due to sporadic slip-stick crack behaviour (resulting in very few data points to be captured). The fibre hybrids exhibited similar behaviour, with the interlayer T700 carbon/S2-glass NCCT specimen (Fig. 32) showing large S2-glass pull-out, tending to control the crack path and hence reduce the slip-stick carbon spread tow behaviour noticed within the monolithic carbon. The R-curve for the interlayer hybrid can be seen to be midway between its monolithic counterparts, indicating that a ‘rule of mixtures’ approach may be applicable to fibre hybrid fracture toughness, although further work is required to demonstrate this conclusively. The ENCCT specimen intralayer fibre hybrid T700 carbon/
The fracture toughnesses gleaned by utilising these novel Compact Tension specimen geometries present opportunities for energy-based numerical modelling of these fibre-hybrid composites, whereby the composite’s strength is used to initiate damage and the fracture toughness is used to propagate the damage [2–5]. These energy-based numerical modelling approaches allow for advanced optimisation and design of industrial components, such as automotive bodywork, where the extent of damage as well as its initiation is required.

Further testing is required to determine whether the NCCT and ENCCT specimen geometries are suitable for other materials and fibre architectures. However, due to the successful results when using the NCCT specimen with monolithic Vectran composites [18] (which exhibit an extremely low compressive to tensile strength ratio (∼0.11)), it is likely that the ENCCT geometry will suit the vast majority of fibre reinforced composites where buckling is an issue when adopting standard CT specimen types.

The calculation of the critical strain energy release rates were derived using an area method [12] which utilised multiple optical crack length measurements taken during testing. This negated the need for compliance calibration methods [16], which often rely heavily on the accuracy compliances derived from numerical modelling [6,7,17]. Both numerically FE-based and experimental compliance calibration methods have however been used to support and verify the area method critical strain energy release rates, although the ENCCT method did present higher scatter within the results. This may be due to the T700 carbon/Vectran’s highly complex intrawoven fibre hybrid structure, but further work must be carried out with various material architectures to demonstrate this conclusively. Due to an accessible manufacturing approach and clear reduction of buckling and compressive failures, the ENCCT specimen geometry becomes an attractive candidate for researchers facing similar premature compression/buckling failures when utilising the common CT type specimen geometries.

8. Conclusions

The successful application of numerical modelling to optimise the critical buckling load and dispersion of compressive stresses within a typical CT specimen geometry have been presented. The following conclusions can be made from the resulting NCCT and ENCCT specimen geometries and fracture toughness data:

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**Fig. 24.** Intra-layer fibre hybrid T700 carbon/Vectran CC method compliance calibration curve (experimentally derived) for the ENCCT specimen type.

**Fig. 25.** Representative critical strain energy release rate (GIC) versus crack length (a) for the monolithic S2-glass NCCT specimens.

**Fig. 26.** Representative critical strain energy release rate (GIC) versus crack length (a) for the intralayer fibre hybrid T700 carbon/Vectran ENCCT specimens.

Vectran presented sparsely separated Vectran tow pull-out lengths (since a 2 x 2 twill weave was used), leading to large scatter in the fracture toughness having been displayed in the R-curve.
The NCCT and ENCCT specimen geometries have been proven to alleviate unwanted buckling effects commonly associated with typical Compact Tension geometries.

The fibre pull-out lengths were noticed to correlate directly to the translaminar fracture toughness values measured. The fibre architecture (2 × 2 twill) associated with the intralayer fibre hybrid T700 carbon/Vectran composite was seen to increase the scatter in the gleaned fracture toughness.

The interlayer fibre hybrid T700 carbon/S2-glass composite exhibited a fracture toughness between its' two constituent monolithic fibre composites.

The ENCCT design can be improved upon by increasing the notched height to allow for larger unit cell fabrics, and hence more complex fibre hybrid composite translaminar toughness testing.

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Fig. 30. Electron micrograph of NCCT specimen, monolithic S2-glass composite (×9).

Fig. 31. Electron micrograph of NCCT specimen, monolithic T700 carbon composite (×7).

Fig. 32. Electron micrograph of NCCT specimen, interlayer fibre hybrid T700 carbon/S2-glass composite (×9).

Fig. 33. Electron micrograph of ENCCT specimen, intralayer fibre hybrid T700 carbon/Vectran composite (×7).
Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compstruct.2018.06.124.

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