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# The Transverse Crack Tension test revisited: an experimental and numerical study

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## Abstract

Several problems arise when measuring the mode II interlaminar fracture toughness using a Transverse Crack Tension specimen; in particular, the fracture toughness depends on the geometry of the specimen and cannot be considered a material parameter. A preliminary experimental campaign was conducted on TCTs of different sizes but no fracture toughness was measured because the TCTs failed in an unacceptable way, invalidating the tests. A comprehensive numerical and experimental investigation is conducted to identify the main causes of this behaviour and a modification of the geometry of the specimen is proposed. It is believed that the obtained results represent a significant contribution in the understanding of the TCT test as a mode II characterization procedure and, at the same time, provide new guidelines to characterize the mode II crack propagation under tensile loads.

*Key words:* Delamination, Fracture Toughness, Numerical analysis, Experimental methods

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## 1 Introduction

2 Interlaminar fracture toughness is a key parameter used not only for the ma-  
3 terial screening and qualification of composite material systems, but also as  
4 an input parameter for delamination in progressive failure analysis. Delamina-  
5 tion is, without any doubt, the most characteristic failure mode of composite  
6 laminates. Interlaminar cracks emanate from free edges, holes, open cutouts;  
7 sometimes they are originated by manufacturing defects or voids at the in-  
8 terface between two adjacent plies. When an interlaminar crack propagates,  
9 due to static or fatigue loads, the laminate loses its structural integrity; in  
10 the case of aeronautic structures this represents a serious air safety concern.  
11 Delamination issues are currently faced during the design of aircrafts and they  
12 have been taken on also in the Boeing 787 and in the Airbus A350 programs.

13 Even though the problem of delamination has been widely investigated, pre-  
14 venting the onset and propagation of interlaminar cracks in aeronautic struc-  
15 tures still remains a challenging question. Indeed, although several advanced  
16 strength analysis methods for delamination have been proposed [1–5], there is  
17 still a lack of confidence concerning their numerical predictions.

18 One source of error is certainly given by the experimental properties used as  
19 input for the failure analysis models, and especially, the interlaminar fracture  
20 toughness. Numerous experimental procedures have been proposed to mea-  
21 sure the interlaminar fracture toughness; the most popular are: i) the Double  
22 Cantilever Beam (DCB) [6] test method for mode I propagation, ii) the End  
23 Notched Flexural (ENF) [7], the Calibrated End-Loaded Split (C-ELS) [8],  
24 and the Transverse Crack Tension (TCT) test methods for mode II propa-  
25 gation, and iii) the Mixed Mode Bending (MMB) [9] test method for mixed  
26 mode propagation.

27 It should be observed that those experimental procedures have been developed  
28 during the last forty years and they have had all different histories. The first  
29 to be adopted by the American Society for Testing and Materials (ASTM) was  
30 the DCB test procedure [6], early in the 1994. This standard was revised and  
31 improved throughout the years and its last version is dated from 2013. More  
32 recently, in 2001, the MMB test procedure [10], was included in the ASTM  
33 standard [9]; its last revision dates from 2013. The ENF test procedure has  
34 been surrounded with more controversy; proposed since the mid 80's, when  
35 first round robin was performed, it was finally adopted only in 2014 after a  
36 long development [11–14]. The ELS End-Loaded Split (ELS) specimen too  
37 was standardized after the extensive work done by the ESIS TC4 committee.

38 [... PARAGRAPH REMOVED IN THE REVISED MANUSCRIPT ...]

39 [... PARAGRAPH REMOVED IN THE REVISED MANUSCRIPT ...]

40 On the other hand, the TCT test, despite its simplicity, has not been stan-  
41 dardized because of the several questions still open that limite its use.

42 First of all, the measurement of the interlaminar fracture toughness in mode  
43 II,  $\mathcal{G}_{IIc}$ , is strongly sensitive to the test method employed. The TCT test tends  
44 to overestimate the interlaminar fracture toughness with respect to the ENF.  
45 This phenomenon was observed by several authors [15–17] and it is still not  
46 fully understood.

47 Moreover, the fracture toughness measured by the TCT depends on the geom-  
48 etry of the specimen. As pointed out by Wisnom [18] and Cui et al. [19], the  
49 measured fracture toughness depends on the total thickness of the specimen.  
50 Observing that the values of fracture toughness and of the crack propagation  
51 stability are affected by the geometry of the specimen, they suggested not to  
52 consider the fracture toughness a material property because it strongly de-  
53 pends on the geometry of the specimen. They concluded that *caution needs to*  
54 *be exercised in using values of fracture energy in situations different from the*  
55 *ones under which they were measured* [18]. The cause for the size effect has  
56 been investigated numerically by Van der Meer and Sluys [20].

57 However, the TCT is an attractive method for the aeronautic industry be-  
58 cause it is as simple to perform as a tensile test while ASTM D7905 [7] re-  
59 quires several repetitions of three point bending loadings at different crack  
60 lengths for calibration purposes. Moreover, the TCT test provides a measure-  
61 ment of delamination fracture toughness in laminates loaded in tension. There  
62 are different realistic scenarios in which mode II delamination takes place in  
63 a laminate loaded in tension, such as around bolted joints, near ply termina-  
64 tions and near matrix cracks. The stress state in the TCT specimen closely  
65 resembles the stress state around the growing delamination crack in these  
66 scenarios. The differences in  $\mathcal{G}_{IIc}$  measurements between the ENF and the  
67 TCT are therefore relevant for accurate prediction of mode II delamination in  
68 laminates loaded in tension. In this paper, the TCT specimen is investigated  
69 experimentally and numerically with the aim of understanding the nature  
70 and sequence of the different dissipative phenomena that take place during  
71 the interlaminar crack propagation. Those collateral dissipative phenomena  
72 interact with the interlaminar crack propagation, and, if not properly taken  
73 into account, may conduct to a misleading interpretation of the actual failure  
74 mechanisms involved, with the consequence of invalidating the experimental  
75 procedure itself.

76 To the best of our knowledge, a lack in the direct experimental observation  
77 of the fracture onset and propagation in a TCT specimen exists in literature.  
78 With the aim of assessing the validity and robustness of the TCT test, several  
79 experimental techniques are used in this work. Two different non-contact full  
80 field methods, the Digital Image Correlation (DIC) and the Thermoelastic

81 Stress Analysis (TSA), are used to investigate respectively the strain and stress  
82 fields in the close-to-crack area. In addition to this, a detailed description of  
83 the morphology of the sample is reported with the support of macrograph  
84 and Micro Computed Tomography (Micro-CT) images. The analysis of the  
85 fracture surfaces is done through Scanning Electron Microscopy (SEM).

86 It is concluded that several parameters play an important role and may inval-  
87 idate the experimental procedure. To mitigate these sources of error, a slight  
88 change in the geometry of the specimen is proposed and investigated. It is  
89 demonstrated that the proposed modification heavily reduces the collateral  
90 phenomena that accompany the interlaminar crack propagation in the classi-  
91 cal TCT specimen.

92 It is believed that the obtained results represent a significant contribution in  
93 the understanding of the TCT test as a mode II characterization procedure  
94 and, at the same time, provide new guidelines to characterize the mode II  
95 crack propagation under tensile loads, an issue scarcely investigated.

## 96 2 Materials and methods

### 97 2.1 Materials

98 Samples were manufactured using unidirectional Hexcel IM7-8552 prepregs  
99 with a nominal ply thickness (after curing) of 0.125 mm. The mechanical  
100 properties of the unidirectional lamina are reported in Table 1.

101 [Table 1 about here.]

102 Unidirectional plates with in plane dimensions of  $300 \times 300$  mm<sup>2</sup> were man-  
103 ufactured with the layup,  $[0_n/\tilde{0}_{2n}/0_n]$ , where the tilde denotes the cut plies.  
104  $n = 3, 6, 8, 9$  was used corresponding to laminate nominal thickness of 1.5 mm,  
105 3.0 mm, 4.0 mm, and 4.5 mm, respectively. Prepregs were cut using a rotary  
106 cutter and placed on top of another to obtain the desired layup. The mate-  
107 rial was cured in hot press according to the suppliers specification [21] and  
108 specimens were cut, using a water-cooled diamond blade saw, to their nomi-  
109 nal dimensions of  $20 \times 200$  mm<sup>2</sup>. The nominal geometry of the TCT sample is  
110 reported in Figure 1.

## 111 2.2 Specimens morphology and Scanning Electron Microscopy

112 The pristine specimens were macroscopically analysed through digital image  
113 macro observation using a 24.1 MPixel single-lens digital reflex camera with a  
114 60 mm macro lens. Micro computed tomography (CT) was performed to evalu-  
115 ate the morphology of the region of interest (i.e. close-to-crack area). The X  
116 ray scanning was executed through the High-resolution micro-CT, SKYSCAN  
117 1272 by Bruker (United States) setting a rotation angle of  $180^\circ$  with a rotation  
118 step of  $0.4^\circ$ . The voltage was set to 60 kV with a 0.25 mm aluminium filter.  
119 The acquired scans were post processed to obtain a 3D image.

120 Scanning electron microscope observations on fracture planes were done on  
121 the failed specimens to analyze the morphology of the surfaces after propa-  
122 gation of the crack. In particular, the close-to-crack area was mechanically  
123 extracted from the tested samples and Scanning Electron Microscopy (SEM)  
124 was performed using SEM Phenom World model Phenom Pro X. In the case of  
125 CFRP, gold coating was not necessary to obtain a good image quality because  
126 of the electroconductivity of the carbon fibres.

## 127 2.3 Digital Image Correlation

128 A 2D-DIC analysis was performed using an in house system coupled with  
129 both a Matlab-based software (i.e. Ncorr [22]) and an open source tethering  
130 software for the camera triggering control. Table 2 shows the parameters and  
131 the main technical data of the hardware used.

132 [Table 2 about here.]

133 DIC analysis was carried out during quasi-static tensile tests, loading the  
134 sample in a MTS 810 servo-hydraulic testing machine. The cross-head speed  
135 was set to 2 mm/min and the load vs. displacement curve was recorded. Prior  
136 to testing the specimen were painted with a matt white paint on top of which  
137 the speckle was made using a matt black paint [23]. The proven ability of  
138 the DIC in dealing with crack propagation in fibre reinforced composites was  
139 demonstrated in [24–26].

## 140 2.4 Thermoelastic Stress Analysis

141 A TSA setup is implemented to acquire the thermoelastic signal over the thick-  
142 ness face of TCT samples [27]. This technique is here chosen for a number of  
143 potential outcomes of particular interest for the evaluation of a TCT configura-

144 tion. These comprise: the experimental evaluation of a full field stress function  
 145 that develops peculiar values when a pure shear mode or a stress component in  
 146 the fibres transverse direction are developed, the possibility to use the same  
 147 stress function to evaluate the ability of a manufactured (and hence defect  
 148 prone) TCT sample in reproducing the expected stress distribution, the possi-  
 149 bility to detect mechanical dissipation energy effects and the sites where this  
 150 may arise. Samples for TSA have been tested under sinusoidal load cycling in  
 151 a MTS 810 servo-hydraulic testing machine. The temperature during cycling  
 152 was measured by a FLIR X6540sc IR camera. This thermographic camera is  
 153 equipped with a cooled InSb focal plane array sensor of  $640 \times 512$  pixels, capa-  
 154 ble of a thermal resolution (Noise Equivalent Temperature Difference) of 18  
 155 mK. The optical setup of the IR camera comprises a 50 mm  $f/2$  lens and a 12  
 156 mm extension ring. This combination allowed to achieve a maximum spatial  
 157 resolution (IFOV) of about  $70 \mu\text{m}/\text{pixel}$ .

158 The temperature variation  $\Delta T$  at the loading frequency is referred to as the  
 159 thermoelastic signal [28,29]. For a generic orthotropic material, with principal  
 160 material directions indicated by subscripts 1 and 3, it is described by the  
 161 following linear stress function [30,31]:

$$\Delta T = -\frac{T_0}{\rho C_p} (\alpha_1 \Delta \sigma_1 + \alpha_3 \Delta \sigma_3) \quad (1)$$

162 where  $\Delta T$  is the thermoelastic effect induced temperature variation,  $T_0$  is the  
 163 absolute sample temperature,  $\rho$  and  $C_p$  are the homogenized bulk material  
 164 density and specific heat,  $\alpha_{1,3}$  are the principal material coefficients of thermal  
 165 expansion (CTE) in longitudinal and thickness direction, and  $\sigma_{1,3}$  are the  
 166 corresponding stress components.

167 In this paper the thermoelastic signal is obtained by two equivalent off-line  
 168 Lock-In procedures: i) the commercial software THESA by Flir, which uses  
 169 a physical reference signal representative of the loading frequency, and ii) a  
 170 custom Fourier Transform based Matlab routine written by the authors [32],  
 171 which uses a reconstructed reference signal. Both analyses were performed  
 172 in parallel allowing to cross-check the uniqueness and reliability of the de-  
 173 termined thermoelastic signal. The thermogram sequences processed by the  
 174 lock-in procedures were acquired over a time window of 32 s with a sampling  
 175 frame rate of 64 Hz. The only sample preparation consisted in painting the  
 176 sample thickness side with three passes of a RS matt black paint.

177 Some preliminary considerations are given about the expected output of the  
 178 TSA analysis. The Lock-In analysis is able to provide both the amplitude  
 179 and phase of the thermoelastic signal, being this the harmonic of the temper-  
 180 ature/time signal at the loading frequency [24,32]. Hence the thermoelastic  
 181 signal can be represented as a trigonometric function as follows:



$$S = A (\cos \omega t + \varphi) \quad (2)$$

with  $A = \Delta T$  and

$$\varphi = \begin{cases} \alpha + 0^\circ & \text{if } \alpha_1 \Delta \sigma_1 + \alpha_3 \Delta \sigma_3 < 0 \\ \alpha + 180^\circ & \text{if } \alpha_1 \Delta \sigma_1 + \alpha_3 \Delta \sigma_3 > 0 \end{cases} \quad (3)$$

182 where  $\alpha$  is a generic shift angle between the sinusoidal loading and the trigger-  
183 ing time of the temperature sampling. In the case of adiabatic conditions,  $\varphi$   
184 can assume two different values that differ by  $180^\circ$  corresponding to a different  
185 sign of the stress function  $\alpha_1 \Delta \sigma_1 + \alpha_3 \Delta \sigma_3$ .

186 In the case of a CFRP TCT sample, two main stress field scenarios are ex-  
187 pected. The zones far from the transverse crack should experience a prevalent  
188 uniaxial stress field with  $\sigma_1 \neq 0$  and  $\sigma_3 = \tau_{13} = 0$ . The zones near the  
189 transverse crack tips are expected to develop a pure shear stress mode, with  
190  $\sigma_1 = \sigma_3 = 0$  and  $\tau_{13} = \tau_{max}$  (notice that in this notation 1,2,3 represent  
191 the principal material and not the principal stress directions). In the second  
192 case the thermoelastic signal should be null, while in the first case a very  
193 low thermoelastic signal is expected, due to the typically low values of  $\alpha_1$  for  
194 CFRPs [30]. Table 1 reports values of the CTEs for the analysed material,  
195 confirming that  $\alpha_3$  is almost an order of magnitude bigger than  $\alpha_1$ . It is also  
196 observed that  $\alpha_1$  is negative for the specific CFRP studied, so zones under  
197 prevalent uniaxial stress should develop a temperature variation  $\Delta T$  in phase  
198 with the load, i.e.  $\Delta T$  increases when the load increases. One potential per-  
199 spective of the present technique is that any departures from a pure shear or  
200 uniaxial stress state should be highlighted by a significant enhancement of the  
201 thermoelastic signal. In fact, such departures both imply that a  $\sigma_3$  compo-  
202 nent arises. Since  $\sigma_3$  is naturally amplified by the coefficient  $\alpha_3 \gg |\alpha_1|$ , its  
203 presence should enhance the thermoelastic signal. Furthermore if a positive  $\sigma_3$   
204 component arises such that  $\alpha_3 \Delta \sigma_3 \geq |\alpha_1 \Delta \sigma_1|$ , a  $180^\circ$  change in phase should  
205 also be observed in the thermoelastic signal.

206 In this work the lock-in filtering is also performed at twice the loading fre-  
207 quency. The such obtained amplitude map is here called Second Harmonic  
208 signal. This information can be correlated with the presence of energy dissi-  
209 pation as proposed in [33] and exploited by some authors [34,35].

## 210 2.5 Numerical analysis

211 The Energy Release Rate (ERR) of a TCT specimen (see Figure 1) is com-  
212 puted using a simple analytical model based on energetic balance as:

$$\mathcal{G}_{II} = \sigma^2 \frac{H}{2E_1} \left( \frac{1}{\eta} - 1 \right) \quad (4)$$

213 where  $\sigma$  is the remote stress,  $2H$  is the thickness of the specimen,  $E_1$  the  
 214 Young's modulus in the longitudinal direction of the specimen, and  $\eta$  is the  
 215 cut factor,  $\eta = \hat{H}/H$ , defined as the ratio between the thickness of the uncut  
 216 plies,  $2\hat{H}$ , and the thickness of the specimen,  $2H$  [17].

217 [Fig. 1 about here.]

218 Equation (4) is derived with the assumption that the delamination crack  
 219 length is sufficiently large for a cracked region with uniform stress distribu-  
 220 tion to exist. In that case, the energy release rate can be computed from  
 221 the difference in elastic energy in cracked and uncracked regions. The solu-  
 222 tion is independent of the crack length and of the orthotropy of the material.  
 223 Alternatively, the Energy Release Rate (ERR) of a crack propagating in an  
 224 orthotropic body, in plane strain, can be obtained using the orthotropy rescal-  
 225 ing technique [36,37]. This approach, based on the stress intensity factors at  
 226 the crack tip, is also valid for short cracks. Let  $x_1, x_2$  and  $x_3$  be the coordinate  
 227 system associated with the specimen. If  $x_1$  and  $x_2$  are also the natural axes  
 228 of the material, assuming that the crack propagates in the  $x_1$  direction, the  
 229 ERR reads:

$$\mathcal{G}_{II} = \left( b_{11} b_{33} \frac{1 + \rho}{2} \right)^{1/2} \lambda^{1/4} \mathcal{K}_{II}^2 \quad (5)$$

230 where the coefficients  $b_{ij}$  are written as function of the compliances,  $s_{ij}$ , as:

$$b_{ij} = s_{ij} - s_{i2}s_{j2}/s_{22} \quad (6)$$

231 and the two dimensionless parameters,  $\lambda$  and  $\rho$ , are defined as:

$$\lambda = b_{11}/b_{33}, \quad \rho = \frac{2b_{13} + b_{55}}{2\sqrt{b_{11}b_{33}}} \quad (7)$$

232 The Stress Intensity Factor (SIF) of Equation (5) reads:

$$\mathcal{K}_{II} = \sigma \sqrt{H} \kappa \quad (8)$$

233 being  $\kappa = \kappa(\alpha, \eta, \rho, \lambda, L)$  a dimensionless correction factor that takes into  
 234 account the geometry of the specimen and the orthotropy of the material.  $\alpha$

235 is the normalized crack length and it is defined as  $\alpha = a/H$  where  $a$  is the  
 236 crack length, and  $2L$  is the length of the specimen.

237 Substituting the SIF of Equation (8) in Equation (5) the energy release rate  
 238 reads:

$$\mathcal{G}_{II} = \left( b_{11} b_{33} \frac{1 + \rho}{2} \right)^{1/2} \lambda^{1/4} \sigma^2 H \kappa^2 \quad (9)$$

239 The correction factor can be found using the Finite Element Method (FEM).  
 240 Finite Element Analyses (FEAs) were carried out in Abaqus commercial soft-  
 241 ware. The two-dimensional model uses the 4-node quadratic, reduced inte-  
 242 gration element, CPE4R. The Virtual Crack Closure Technique (VCCT) [38]  
 243 (implemented in a Python script) and the domain integration method [39]  
 244 Abaqus built-in procedure were both used to estimate the Energy Release  
 245 Rate. The VCCT allows to obtain  $\mathcal{G}_I$  and  $\mathcal{G}_{II}$ , while the domain integral  
 246 method only the total ERR,  $\mathcal{G}$ . The redundant information obtained from  
 247 the domain integration method was used to double check the implemented  
 248 algorithm.

249 In this paper, the ratio between thickness of the uncut plies and the total  
 250 thickness of the laminate is kept constant. Moreover, under the reasonable  
 251 assumption that the length of the specimen is much larger than both the  
 252 thickness of the specimen and the crack length at the unstable crack propa-  
 253 gation ( $L \gg a, H$ ), the length of the specimen,  $L$  does not play a role in the  
 254 determination of the ERR. Therefore,  $\eta$  and  $L$  can be both eliminated from  
 255 the numerical calibration and the only geometric parameter that plays a role  
 256 is the crack length ( $a$  or  $\alpha$ ).

257 Figures 2a and 2b report respectively the mode mixity,  $\psi$ , and the correction  
 258 factor  $\kappa$ , both as a function of the normalized crack length  $\alpha = a/H$  being  $a$   
 259 the crack length. The mode mixity is defined as  $\psi = \mathcal{G}_{II}/\mathcal{G}$  being  $\mathcal{G}$  the total  
 260 energy release rate ( $\mathcal{G} = \mathcal{G}_I + \mathcal{G}_{II}$ ). Of course,  $\psi = 0$  and  $\psi = 1$  for mode I  
 261 and mode II, respectively.

262 [Fig. 2 about here.]

263 Figure 2a reveals that the cracks do not propagate at pure mode II at the  
 264 beginning of the crack propagation and that the condition of  $\psi = 1$  (pure  
 265 mode II) is reached only when  $\alpha > 0.25$  (i.e.  $a > 0.25H$ ). That means that  
 266 care is required when testing thick specimens. Indeed the crack propagation  
 267 in a TCT is unstable and, therefore, the peak load is reached when the crack  
 268 propagation is smaller than the length of fracture process zone,  $l_{fpz}$ . Therefore,  
 269 in a big specimen the unstable crack propagation could occur at mixed mode  
 270 and not at pure mode II as required.

271 Figure 2b shows the correction factor  $\kappa$  as a function of  $\alpha$  for different values  
 272 of  $\rho$  and  $\lambda$ . The correction factor stabilizes only when the normalized crack  
 273 length is larger than a threshold value,  $\alpha > \alpha_t$ , being  $\alpha_t \approx 3$ . This means that  
 274 a correct determination of the fracture toughness in a TCT would require  
 275 also the knowledge of the crack length when the unstable crack propagation  
 276 is reached.

277 The steady-state value of the correction factor,  $\hat{\kappa}$  can be found for  $\alpha \rightarrow \infty$ ; as  
 278 a consequence, its dependence on  $\alpha$  can be eliminated ( $\hat{\kappa} = \hat{\kappa}(\rho, \lambda)$ ). Figure 3  
 279 shows the values of  $\hat{\kappa}$  found numerically and their fitting.

280 [Fig. 3 about here.]

The polynomial fitting surface employed reads:

$$\hat{\kappa} = \sum P_{ij} \rho^{i+1} \lambda^{j+1} \quad (10)$$

281 where  $P_{ij}$  is the element of the matrix  $\mathbf{P}$  of indexes  $i$  and  $j$ . The matrix  $\mathbf{P}$  is  
 282 defined as:

$$\mathbf{P} = \begin{bmatrix} 0.4331 & 4.6730 & -45.68 & 1.835 \\ -0.09148 & -0.3427 & 1.102 & 0 \\ 0.02157 & 0.02272 & 0 & 0 \\ -0.001955 & 0 & 0 & 0 \end{bmatrix} \quad (11)$$

283 It is worth noticing that the TCT is not characterized by a *positive geome-*  
 284 *try* [40] and therefore the use of the size effect method, as already done for  
 285 fibre reinforced composites [41–43], is prevented.

### 286 3 Experiments on the TCT specimen

#### 287 3.1 Preliminary tests

288 Three lay-ups, with  $n=3,6$ , and 9 (see Section 2.1), were tested in the prelimi-  
 289 nary test campaign. Five samples per lay-up were tested at a cross-head speed  
 290 of 2 mm/min and photograms of the samples were acquired. Experimental  
 291 results are reported in Table 3.

292 [Table 3 about here.]

293 For the thinnest samples (i.e. 1.5 mm) net tension failure was observed be-  
294 fore the onset of the crack propagation. For the other specimen asymmetrical  
295 cracks developed invalidating the test see Figure 4. In only one specimen a  
296 symmetrical propagation of the crack was observed. However, it is not possi-  
297 ble to say if the cracks propagated symmetrically throughout the duration the  
298 test or if this condition of symmetry was only reached at the unstable crack  
299 propagation.

300 [Fig. 4 about here.]

301 As the specimens failed with an unacceptable failure mode, the peak loads  
302 reported, for the sake of completeness, in Table 3 cannot be used for the  
303 estimation of the interlaminar fracture toughness. It is worth noticing that  
304 the TCT test exhibit a size effect as different failure modes are observed with  
305 the change of the size of the specimen.

### 306 3.2 Specimens morphology and Micro-CT

307 The results obtained in the previous section shows also that a certain asym-  
308 metry arise within the specimen and this could be related with the presence  
309 of manufacturing defects in the region close to the cut.

310 To highlight the actual geometry of the specimens, the direct observation of  
311 the area around the cut was performed. Even if the manufacturing technique  
312 allows to obtain good quality composites, asymmetries and defects are not  
313 avoidable and represent an intrinsic characteristic of composite material sys-  
314 tems. As shown in Figure 5a, the TCT-specimens geometry does not perfectly  
315 reproduce the theoretical model and a lack in symmetry is observed. In partic-  
316 ular, during the curing time, the plies tend to slide one on the other under the  
317 action of the hot press causing the misalignment between the different layers  
318 leading to the formation of voids and resin pocket enclaves. In Figure 5b the  
319 defects at the crack tip are shown.

320 [Fig. 5 about here.]

321 Moreover, the pressure gradient in the thickness direction may induce a vari-  
322 ation in the cured ply thickness resulting in differences between the two outer  
323 parts of the samples. Such irregularities may have more influence for thinner  
324 samples. Figure 6 show the experimental results of the Micro-CT analysis.  
325 The presence of resin pocket enclaves is revealed in Figure 6a (lighter zones  
326 indicated by the arrows) where the whole volume around the area is reported.

327 [Fig. 6 about here.]

328 Figure 6b reveals the presence of spherical and elongated voids. It is worth  
329 noticing that the distribution, shape and dimension of the defects is random  
330 and this may leads to scatter in the results of the mechanical analysis. Fur-  
331 thermore, voids and defects may affect the crack onset and propagation.

### 332 3.3 Static tests and DIC analysis

333 In total, 7 samples (4 mm thickness) were tested up to failure. The DIC was  
334 used to monitor the strain field and obtain important information on the crack  
335 onset and propagation.

336 Figure 7 reports a typical load vs. displacement curve and the apparent stiff-  
337 ness. It is possible to notice that the curves present a quite linear trend with a  
338 slight variation in slope (at about 14.9 kN). This variation may be attributed  
339 to the first crack propagation. However, the right load value is very difficult  
340 to be unequivocally determined because, at the unstable crack propagation, a  
341 drop in the load is not noticed; this is contrast with what reported in [17]. On  
342 the other hand, DIC analysis revealed that, the first propagation is usually  
343 not symmetrical so that it is not possible to evaluate the mode II fracture  
344 toughness using Equations (4) or (9).

345 [Fig. 7 about here.]

346 Figure 8 shows the speckled reference image (see Figure 8a) and the contour  
347 plot of the strain field  $\varepsilon_3$  (the specimen coordinate system is reported in Sec-  
348 tion 2.5) at different loads. Asymmetries in the strain field are observed prior  
349 to the unstable crack propagation (see Figure 8b) suggesting that a stable  
350 crack propagation has already occurred. This stable crack propagation occurs  
351 at low values of load if compared to the final load drop (see Figure 8c).

352 [Fig. 8 about here.]

353 Moreover, Figure 8c shows that the crack emanates toward a single direction  
354 from a single crack tip, invalidating the test procedure. At higher load level  
355 (i.e.  $\approx 30$  kN), further non-simultaneous crack onset and propagation were  
356 observed.

357 Because of the asymmetry noticed in the cracks propagation, Equations (4)  
358 or (9) cannot be used to estimate the fracture toughness and their use would  
359 induce to an overestimation of the actual value of the interlaminar fracture  
360 toughness.

### 361 3.4 Scanning electron microscopy and fractography

362 The observation and the analysis of the close-to-crack fracture surfaces was  
363 performed on failed specimens through scanning electron microscopy. Figure 9  
364 reports an overview of the fracture surfaces using a relatively low magnifica-  
365 tion.

366 Figure 9 shows an heterogeneous distribution of hackles (see Figure 9a) and  
367 regions where a thin layer of resin tends to persist after the crack onset and  
368 propagation (Figure 9b). The first ones are, usually, associated with mode II  
369 while the second one with cohesive fracture during mode I crack propagation.  
370 In particular, the predominant presence of hackles suggests a dominant mode  
371 II propagation [44,45].

372 Figure 9c and Figure 9d show two different areas where peeling phenomena  
373 of the layers close to the crack plane seem to occur. In Figure 9c, the high-  
374 lighted pulled fibre suggests a localized fibres bridging event. Moreover, a large  
375 number of smooth surfaces corresponding to the imprints of debonded fibres is  
376 observed. Figure 9d shows out-of-plane deformations and a partially debonded  
377 fibre associated to a large area affected by cohesive failure.

378 Figure 9e and Figure 9f show higher magnification SEM images. In particular,  
379 in Figure 9e a portion of debonded fibre is highlighted suggesting that fibre  
380 bridging phenomena may occur. In Figure 9f, the presence of debonded fibres  
381 associated to smooth surfaces (i.e. fibre imprints) and hackles suggests a mixed  
382 mode crack propagation.

383 [Fig. 9 about here.]

384 In conclusion, SEM fractographies indicate that crack growth does not take  
385 place under pure mode II.

### 386 3.5 Thermoelastic Stress Analysis

387 Two nominally identical samples have been analysed with TSA, and will here-  
388 inafter be identified as  $\tau_{ct1}$  and  $\tau_{ct2}$ . Three different loading cycles have been  
389 applied: 1-9 KN, 1-11 KN and 1-17 KN, each at three different frequencies: 2,  
390 4, 6 Hz. Figure 10 shows the amplitude of the thermoelastic signal in temper-  
391 ature units for two samples. The area reported in these maps is cropped upon  
392 the sample thickness, and is then 4 mm wide per 15.6 mm long, centred on  
393 the transverse cut area.

394 [Fig. 10 about here.]

395 It is first of all reported that the transverse cut in the undamaged samples  
396 is filled by cured resin, which then guarantees material continuity, although  
397 a different stiffness should characterize the central cut area from the lateral  
398 ligaments where the plies are continuous. The maps in Figure 10 refer to a  
399 condition where the central resin pocket is not broken, with the only exception  
400 of sample  $\tau\text{ct}2$  tested at 1-17 kN, where such resin pocket was broken due to  
401 the high loads.

402 One common feature of both  $\tau\text{ct}1$  and  $\tau\text{ct}2$  is the very low and uniform  
403 thermoelastic signal present in most of the analysed area, both near and far  
404 from the transverse cut. This can be seen as a confirmation that a general low  
405 signal is expected due to the prevalent  $\sigma_1$  dominated unidirectional stress field.  
406 Near the transverse cut tips both  $\tau\text{ct}1$  and  $\tau\text{ct}2$  present some local spots of  
407 high thermoelastic signal. As discussed in Section 2.4, such a high surge of  
408 thermoelastic signal can be justified by the rise of a  $\sigma_3$  stress component in  
409 the transverse direction, or by a steep rise of  $\sigma_1$ . This last might be due to  
410 stress concentration effects induced by the transverse cut discontinuity, or  
411 to a change of the thermoelastic constant in correspondence to local resin  
412 rich pockets. Whatever the case, all above events indicate a departure from  
413 the pure shear stress field which should eventually activate a pure mode II  
414 delamination failure. Another feature of such high thermoelastic signal spots  
415 is their non-uniform distribution.

416 [Fig. 11 about here.]

417 A rather drastic increase of thermoelastic signal on the area above and below  
418 the transverse cut is observed in  $\tau\text{ct}2$  when the loading amplitude is set to 1-17  
419 KN. Figure 11 shows how such change is already observed at 2 Hz cycling, and  
420 increases in severity by moving to 4 and 6 Hz. The main reason of such change,  
421 verified by direct observation, is the onset of the transverse crack in the resin-  
422 rich pocket separating the cut plies. The formation of such crack under 1-17  
423 kN loading occurred only in sample  $\tau\text{ct}2$ , probably activated by some local  
424 weaknesses and some slight dimensional variations that differentiate sample  
425  $\tau\text{ct}2$  from  $\tau\text{ct}1$ . The formation of such transverse crack was not accompanied  
426 by interlaminar fracture at the cut tips. This last failure is in fact activated  
427 by higher loads as verified by quasi-static monotonic tests (see Section 3.3).  
428 Once material continuity is lost due to the onset of the transverse cut, a surge  
429 of transverse  $\sigma_3$  compressive stresses is expected to occur above and below the  
430 crack (this is typically the case in samples with centered cracks under mode  
431 I loading). The presence of such stress components is likely the reason for  
432 the steep increase of thermoelastic signal above and below the central crack.  
433 During the time window of signal sampling the high amplitude load cycle  
434 will likely introduce some further fatigue damage, but this was never seen  
435 to involve the formation of interlaminar delamination. This local progressive  
436 damage, together with dissipative heating effects, is believed to be the main



437 reason for the different thermoelastic signal acquired in the transverse cut area  
438 with increasing loading frequency (see Figure11).

439 Figures 12 and 13 report the amplitude maps of the Second Harmonic Signal  
440 for sample  $tct2$ . Figure 12 in particular compares the second harmonic signal  
441 between the three load amplitudes: 1-9 kN, 1-11 kN and 1-17 kN at 6 Hz. It  
442 is interesting to observe that for the two lower amplitude cycles the second  
443 harmonic signal is practically null. In the case of the bigger load amplitude,  
444 i.e. the one which determined the transverse crack, it is now observed a second  
445 harmonic signal confined in the zone around the crack.

446 The second harmonic signal was detected also when cycling at 2 Hz and 4 Hz  
447 as shown in Figure 13. Most interestingly the second harmonic signal seems  
448 to increase with the frequency. If the second harmonic component is to be  
449 correlated to dissipative phenomena, it was observed that a big component  
450 of such dissipative effects is related to friction between single plies, with each  
451 lamina termination of the cut plies sliding upon other opposite plies during  
452 the cyclic loading. In fact, it has already been shown that the transverse cut is  
453 not straight and single plies are kind of zig-zagging and occasionally touching  
454 each other (Figure 5).

455 [Fig. 12 about here.]

456 [Fig. 13 about here.]

### 457 3.6 Concluding remarks on the TCT specimen

458 The TCT test procedure suffers from some important limitations.

459 First of all, the actual morphology and geometry of a TCT do not reproduce  
460 the theoretical model without a certain degree of uncertainty and asymme-  
461 tries that, depending on their magnitude, may lead to an invalidation of the  
462 procedure itself. As observed through the DIC analysis, defects and lack of  
463 symmetry, may cause a premature crack nucleation and propagation. In such  
464 case, the analytical model can not be applied for the calculation of the critical  
465 mode II ERR.

466 In that regard, both the TSA and DIC analysis showed a complex triaxial  
467 stress field in the close to crack area and the not negligible presence of local  
468 transverse stresses that are not taken into account in the analytical model.  
469 The shape of the resin pocket also plays a role and this should be taken into  
470 account. Those conclusions are supported by the SEM analysis that showed  
471 the presence of some characteristic features not associated with the pure mode  
472 II crack propagation.

473 It should be emphasized that even if the specimen were perfect and without  
 474 defects, the test could have been invalid. As showed in the numerical analysis  
 475 conducted in Section 2.5, the mixed mode ratio,  $\psi$ , tends to 1 (i.e. pure mode  
 476 II) only when the crack has grown substantially. Therefore the unstable crack  
 477 propagation may occur at mixed mode.

478 Taking into account all these findings, an alternative geometry is proposed in  
 479 the following.

#### 480 4 A modified geometry

481 A new geometry, showed in Figure 14, is proposed. The idea is simple but  
 482 very effective. Two release films are inserted between the cut and uncut plies  
 483 creating two initials precracks. These precracks distance the crack tip from  
 484 the resin pocket and remove the influence that this has on the crack tip.  
 485 Moreover, having two precracks ensures (if those precracks are sufficiently  
 486 long) a pure mode II crack propagation enabling the use of Equation 9 for  
 487 the calculation of the ERR. Here the precracks are manufactured using a  
 488 teflon film with a thickness of 0.05 mm. The thickness of the release film,  
 489  $t_{rf}$ , should not play a role for this configuration. In fact, as explained in the  
 490 following, it is likely that the unstable crack propagation occur at a critical  
 491 value,  $\Delta a_{crit}$ , that is comparable with the length of fracture process zone,  $l_{fpz}$   
 492 ( $\Delta a_{crit} \approx l_{fpz}$ ). Since the length of the fracture process zone is much larger  
 493 than the thickness of the release film,  $l_{fpz} \gg t_{rf}$ , the crack at unstable crack  
 494 propagation may be considered sharp and Linear Elastic Fracture Mechanics  
 495 (LEFM) applies [46]. Furthermore, as will be shown in Section 4.2, the driving  
 496 force curve for the mTCT sample, whose shape is given by Equation (9) and  
 497 Figure 2(b), can reach and become tangent to the material R-curve only after  
 498 the full development of the length of fracture process zone, i.e. when the R-  
 499 curve is fully horizontal. From this observation it is possible to predict that the  
 500 critical ERR measured from a mTCT is the steady state value of the R-curve.

501 [Fig. 14 about here.]

#### 502 4.1 Specimens morphology and Micro-CT

503 Figure 15 reports the macrography of the modified geometry. Even if the  
 504 transverse cut shape still remain irregular, the actual crack tips lie on a much  
 505 more regular area (Figure 15a).

506 [Fig. 15 about here.]

507 Since delamination crack tips are far away from the transverse cut (Fig-  
508 ure 15b), it is believed that the defects near the transverse cut do not influence  
509 the crack propagation.

510 Moreover, the CT scan reveals lower amount of defects. In particular, Figure 16  
511 reports the area close to the crack tips. In this case, elongated defects are  
512 observed in correspondence of the release film surfaces due to the presence of  
513 the discontinuity. Moreover, no bubble shaped voids were detected and this  
514 zone results to be not disturbed by irregularities. If compared with Figure 6b,  
515 it is possible to state that the composite quality in the area around the crack  
516 tip was significantly improved, as well as the symmetry of the sample.

517 [Fig. 16 about here.]

#### 518 4.2 Static tests and DIC analysis

519 Experimental tensile tests were performed on 4 samples at a load rate equal  
520 to 10 kN/min. Figure 17 reports a typical load vs. displacement curve. In the  
521 case of the new proposed configuration, no premature failure and crack onsets  
522 were detected so that the peak load can be considered as the critical load (i.e.  
523 33.88 kN).

524 [Fig. 17 about here.]

525 DIC analysis results are reported in Figure 18. In particular, Figure 18a show  
526 the speckled reference image for the cracked zone (i.e. transverse crack and  
527 release film area). Figure 18a,b,c report the  $\varepsilon_3$  maps at different load level. For  
528 all the cases, the release films and the transverse crack are well highlighted  
529 since they correspond to the most compliant zones. Moreover, even if the  
530 transverse crack area results to be characterized by a complex and irregular  
531 geometry, the area of interest (i.e. close to the crack tips) is homogeneous and  
532 the values of the transverse deformations  $\varepsilon_3$  can be considered negligible until  
533 the ultimate failure. In addition to this, no premature failures were observed  
534 and four simultaneous and symmetric unstable cracks were detected.

535 [Fig. 18 about here.]

536 Considering these results, Equations (4) and (9) can be used to evaluate the  
537 interlaminar fracture toughness. Table 4 reports the mean of critical values of  
538 the energy release rate for the considered material (1.59 N/mm). It is worth  
539 noticing that using Equation (4) or (9) is indifferent and this because the crack  
540 propagates at pure mode II (outside the transition region where mixed mode  
541 occurs).

542

[Table 4 about here.]

543 It is worth comparing the value of the fracture toughness obtained in this  
 544 experimental campaign, with the values reported elsewhere using the ASTM  
 545 ENF procedure. In particular, experiments on the same material system were  
 546 performed in [47,48]. The values reported were of 0.74 N/mm and 0.79 N/mm,  
 547 in [47] and [48], respectively, when using a teflon film to create the precrack.  
 548 In [47] the test was also performed on specimens where the precrack was  
 549 propagated by fatigue (before testing), and the corresponding value of the  
 550 fracture toughness was reported to be 1.13 N/mm. If compared with the value  
 551 of the fracture toughness obtained in this work, the values obtained using the  
 552 ENF are smaller especially when the precrack is created only using a release  
 553 film. It is common knowledge that the unstable crack propagation occurs at  
 554 the tangent point of the crack driving force curve and the R-curve,  $\mathcal{G}_{IIc}(\Delta a)$ ;  
 555 indeed, the following two conditions must be satisfied:  $\mathcal{G}_{II}(\Delta a) = \mathcal{G}_{IIc}(\Delta a)$   
 556 and  $\frac{\mathcal{G}_{II}(\Delta a)}{\partial \Delta a} = \frac{\mathcal{G}_{IIc}(\Delta a)}{\partial \Delta a}$ . These conditions, for the TCT specimens imply that  
 557 the fracture toughness estimated is the steady-state value of the R-curve,  $\mathcal{G}_{IIc}^{ss}$ .  
 558 Indeed, the crack driving force curve of the TCT of Equation (9) is a horizontal  
 559 line for  $\alpha > \alpha_t$  (see Figure 2), and the only tangent point is at  $\Delta a = l_{fpz}$  and  
 560  $\mathcal{G}_{II} = \mathcal{G}_{IIc}^{ss}$ , where  $l_{fpz}$  is the length of the fracture process zone. For the ENF,  
 561 the ERR is proportional to  $P^2 a^2$  and the tangent point is expected to be  
 562 at  $\Delta a < l_{fpz}$  and  $\mathcal{G}_{II} < \mathcal{G}_{IIc}^{ss}$ , leading to a smaller value of the interlaminar  
 563 fracture toughness.

#### 564 4.3 Scanning electron microscopy and fractography

565 The direct observation of the fracture surface close to the crack tips, was done  
 566 through the scanning electron microscope. Figure 19 shows two images at rela-  
 567 tively low magnification. In Figure 19a it is possible to notice two different  
 568 areas, one corresponding to the zone of the release film and the other cor-  
 569 responding to the fractured surface. Figure 19b shows a surface completely  
 570 created by failure processes. From this last, it was assessed the presence of a  
 571 homogeneous and dense distribution of hackles. The presented images confirm  
 572 that the new proposed setup leads to pure mode II fracture.

573

[Fig. 19 about here.]

#### 574 4.4 Thermoelastic stress analysis

575 The thermographic signal on modified TCT specimens (hereinafter referred to  
 576 as mTCT), was acquired during both monotonic and cyclic loading. In particu-  
 577 lar, three thermograms from the monotonic loading are shown in Figure 20a.

578 The first thermogram was acquired at a time  $t^*$  immediately before the onset  
579 of interlaminar delamination, the second thermogram shown is immediately  
580 successive to  $t^*$ , i.e. after 0.1 s (being the sampling frequency adopted of 10  
581 Hz), and the third after 1 sec from  $t^*$ .

582 [Fig. 20 about here.]

583 In Figure 20 the two vertical arrows indicate the terminations of the two  
584 delamination films, while the horizontal arrows point the loading direction.  
585 The thermogram at  $t^*+0.1s$  is the first acquired after the onset of delamination  
586 which occurs at the circled point of the stress/displacement curve as reported  
587 in Figure 20b. It is noteworthy to observe that the temperature of the newly  
588 delaminated area has a sudden increase on the side of the outward laminae.  
589 In fact, the extension of delamination has unloaded the central plies, suddenly  
590 transferring the whole load through the external material. The thermoelastic  
591 temperature change associated to such  $\Delta\sigma_1$  jump in the external material is  
592 positive. Actually, this can be considered as an indirect proof that the  $\alpha_1$  of the  
593 analysed material is negative. The thermoelastic effect induced temperature  
594 change is then gradually faded due to the monotonic loading not providing  
595 adiabatic conditions. Thus the image after 1 sec already shows a homogeneous  
596 temperature distribution between inner and outer laminae. The temperature  
597 monitored during the monotonic loading has then highlighted very clearly the  
598 instant of delamination, demonstrating that the delamination itself is able to  
599 onset at a specific critical load, well identified in the load/displacement curve.  
600 Temperature mapping has also allowed to show the perfect symmetric onset  
601 of delamination failure, with four fronts of interlaminar delamination starting  
602 instantly from the four tips of the two delamination films. Additionally, as  
603 shown in Video 1, it can be seen that the failure is sudden, symmetric and  
604 with no indications of particular differences at the four crack tip sites.

605 The Thermoelastic and Second Harmonic Signals have been determined on an  
606 mTCT sample cycling between 4-21 KN, repeating the analysis at frequencies of  
607 2,4,6 Hz. No influence of frequency was observed on the thermoelastic signal,  
608 which is shown in Fig. 16 for the 4 Hz run. By synchronizing the deformation  
609 cycle with the temperature cycle and focusing on zones of the sample under  
610 pure tensile loading (e.g. the far field or the outer laminae in the artificially  
611 delaminated zone), it was possible once again to verify that  $\Delta T$  increases with  
612  $\Delta\sigma_1$ , i.e. that  $\alpha_1$  is indeed negative.

613 [Fig. 21 about here.]

614 The amplitude map in Figure 21 shows that the outer laminae within the artifi-  
615 cial delamination carry the whole  $\sigma_1$  stress, and hence the thermoelastic signal  
616 here is higher than in the far ends of the sample, where the unidirectional stress  
617 is distributed over the whole thickness. The inner laminae (ending with the

618 transverse cut) have a near zero thermoelastic signal. The phase signal around  
619 the transverse cut is very noisy, also due to the very low stresses. The Second  
620 Harmonic signal is almost null all over the surface, but rather interestingly, it  
621 increases along the artificial delamination, especially near the ends, probably  
622 due to some residual friction. Such trace of high Second Harmonic signal is  
623 particularly useful in revealing where the delamination films end within the  
624 sample. Some rather peculiar features of the Thermoelastic signal are observed  
625 in the zones near the artificial delamination ends. Figure 21 shows that the  
626 behavior is rather symmetrical, with a very similar signal distribution in the  
627 upper and lower delamination tips, a closer look at these zones is provided in  
628 Figure 22, focusing on one side only of the embedded delamination ends.

629 [Fig. 22 about here.]

630 Two zones of high thermoelastic signal are observed, both localized on the  
631 centre thickness area. One is found within the artificial delamination (be-  
632 tween 5 and 7 mm from the top in Figure 22) , and one in the zone ahead  
633 of the delamination (between 9 and 13 mm from the top in Figure 22). Both  
634 are characterized by arising very near the delamination ends (which falls at  
635 about 8 mm from the top), and rapidly fading when moving away from the  
636 delamination ends. The only plausible explanation for such increase of the  
637 thermoelastic signal is the rise of a transverse  $\sigma_3$  component. The zone ahead  
638 of the delamination ends is also characterized by having a  $180^\circ$  shift in phase  
639 compared to the pure  $\sigma_1$  field zones. Therefore, it is possible to state that the  
640 zone within the delamination develops a negative  $\sigma_3$ , and the zone ahead of the  
641 delamination ends develops a positive  $\sigma_3$ . A qualitative explanation could be  
642 attempted by observing that the lateral Poisson contraction of the outer mate-  
643 rial is higher than the inner material, due to the  $\sigma_1$  component concentrating  
644 towards the outer path, and this might develop some transverse stresses in the  
645 inner central zones of material where  $\sigma_1$  is very low. [...] A rather peculiar and  
646 interesting feature is that the thermoelastic signal decreases to very low values  
647 right where the delamination tips are supposed to fall. This could well be due  
648 to a prevalent pure mode II stress field near the fracture process zone. Further-  
649 more, the second harmonic signal, which could be related to friction energy  
650 dissipation, is remarkably low in amplitude, and mainly concentrated on the  
651 delamination line. It is useful to recall that the thermoelastic signal is acquired  
652 under cyclic loading between 4 and 21 kN. This is a quite intense peak-to-peak  
653 load, causing the external ligaments to stretch back and forward, while the  
654 inner sub-laminate is not deforming. It is then normal that some friction is  
655 developed between the stressed and unstressed flanks, but even so, it is very  
656 low. Considering that the fracture test is performed under slow monotonic  
657 loading, the above postulated frictional effects should be even more negligible.  
658 Furthermore, the presence of a  $\sigma_{33}$  compressive component closing the flanks  
659 would have induced a much higher friction and a more widespread and higher  
660 second harmonic signal. Therefore, in light of the above considerations, the

661 thermoelastic maps provide some important hints that  $\sigma_{33}$  plays a marginal  
 662 role in the mTCT, both in terms of crack flanks mutual compression, and in  
 663 terms of a possible mixing mode arising in the fracture process zone.

## 664 5 Numerical modelling and validation

665 With the aim of assessing the trustworthiness of the parameter obtained us-  
 666 ing the modified TCT specimen, a numerical model was used to reproduce the  
 667 experimental results. A Finite Element (FE) model of the modified TCT spec-  
 668 imen was implemented in Abaqus [39]. Only one eighth of the specimen was  
 669 modelled, taking advantage of the symmetry to reduce the computational ef-  
 670 fort. The outer and inner laminae were modelled using C3D8R brick elements  
 671 with a dimension of  $0.5 \times 0.5 \times 0.5 \text{ mm}^3$  while the interface was modelled using  
 672 Abaqus built-in cohesive elements. Both zero-thickness and finite-thickness  
 673 cohesive elements were used leading to virtually the same numerical results.  
 674 In the finite-thickness elements a thickness of 0.01 mm was used following  
 675 the guidelines of the Abaqus Documentation [39]. A detailed definition of the  
 676 cohesive damage model may be found in [39,3] and it is not reported here for  
 677 the sake of conciseness. In the following, only a description of the constitutive  
 678 parameters (see Table 5) necessary for the progressive delamination model is  
 679 reported.

680 [Table 5 about here.]

The strength in pure mode I is calculated as [4]:

$$\bar{\tau}_N = \sqrt{\frac{9\pi E \mathcal{G}_{Ic}}{32 N_e l_e}} \quad (12)$$

where  $E$  is the Young's modulus,  $l_e$  the size of the element along the direction  
 of the crack propagation (0.5 mm), and  $N_e$  is the number of elements within  
 the cohesive zone. Following [4] the number of the elements in the cohesive  
 zone should be higher or equal to 3.  $N_e = 5$  was used. Using Equation (12),  
 the effective strength in pure mode I,  $\tau_N$ , is calculated as [4]:

$$\tau_N = \min(\bar{\tau}_N, Y_T^{ud}) \quad (13)$$

where  $Y_T^{ud}$  is the transverse tensile strength for the unidirectional laminate  
 ( $Y_T^{ud} = 62.3 \text{ MPa}$  as reported in [49]). The effective shear strength, not being  
 a fully independent material property, is calculated as [5]:

$$\tau_{sh} = \tau_N \sqrt{\mathcal{G}_{IIc} / \mathcal{G}_{Ic}} \quad (14)$$

681 Four different values of the fracture toughness were used here to assess the  
 682 statistical quality of the analysis, and in particular:

- 683 •  $\mathcal{G}_{IIc}^{ENF} = 0.79$  N/mm, corresponding to the fracture toughness obtained  
 684 using the ENF test procedure by other researchers [47,48];
- 685 •  $\mathcal{G}_{IIc} = 1.59$  N/mm, the value obtained in this work (see Table 4);
- 686 •  $\mathcal{G}_{IIc}^- = 1.41$  N/mm and  $\mathcal{G}_{IIc}^+ = 1.76$ , corresponding to the boundaries of the  
 687 Interval of Confidence (IC) at 95% for the values of the fracture toughness  
 688 reported in Table 4.

689 Numerical results are reported in Figure 23. In particular, Figure 23(a) re-  
 690 ports the contour plot of the  $\sigma_{11}$  stress (1 is both the fibre direction and the  
 691 longitudinal direction of the specimen) at the unstable crack propagation (at  
 692 the first peak load) while Figure 23(b) reports the curve remote stress vs.  
 693 displacement obtained. As observed the results reproduce the same behaviour  
 694 obtained experimentally (see Figure 22). It should be noticed that the crack  
 695 propagation is unstable at the first peak. The load does not go to zero, but  
 696 increases after complete crack propagation, which is because of the constrain-  
 697 ing effect of the grips that keep together outer and inner laminae. This was  
 698 modelled in Abaqus using TIE constraints, between the outer and the inner  
 699 laminae, at the side of the specimen where the load is applied.

700 In Figure 23(b) is also reported, in light red, the 95% IC range of the peak  
 701 stress. Since the error in predicting the peak load is lower than 3% we can  
 702 conclude that numerical results are in excellent agreement with experiments.

703 [Fig. 23 about here.]

## 704 6 Conclusions

705 The main conclusions of this work can be summarized in the following points.

- 706 i) The crack propagation in a TCT specimen propagates under mode II ex-  
 707 cept in a transition region located at the centre of the specimen with length  
 708 proportional to the thickness of the specimen. Therefore care is required when  
 709 using thick specimen to evaluate the fracture toughness.
- 710 ii) Other causes that prevent a pure mode II propagation are the defects  
 711 near the transverse cut. Micro-CT was able to reveal these defects, and to  
 712 characterise their shape and entity. The asymmetries found in the materials  
 713 originate asymmetric crack propagation at the different crack tips and prevent  
 714 the use of the TCT as a standard test method for the measurement of the  
 715 interlaminar fracture toughness.



716 iii) A new geometry is proposed and validated. This new geometry represents  
717 an improvement on the classical TCT specimens because it limits all the main  
718 causes that prevent a pure mode II propagation.

719 iv) A difference is found when comparing the values of fracture toughness  
720 measured using both the TCT and the ENF specimens. Even though the frac-  
721 ture toughness is a material parameter it is common knowledge that it may  
722 depend on the size and on the shape of the specimen. If the dependence on the  
723 size may be eliminated, or at least reduced, using the size effect method, the  
724 dependence on the shape of the specimen is harder to eliminate and still ob-  
725 ject of research. It has been postulated here that the difference in the fracture  
726 toughness is due to the fact that the TCT tends to measure the steady state  
727 value of the R-curve (the fracture toughness in the strict sense of the word)  
728 while the ENF derives a value of the fracture toughness that correspond to a  
729 point in the rising part of the R-curve. In the authors' opinion, it would also  
730 be worth investigating the crack propagation using computational microme-  
731 chanics. Taking into account the micro-structure of the material could be the  
732 key to explain the diverging values of the fracture toughness obtained using  
733 the ENF or the TCT.

734 v) Two experimental techniques, DIC and TSA, have been successfully im-  
735 plemented to evaluate the full field strain/stress distribution in the thickness  
736 face around the transverse cut. DIC in particular was useful to reveal the lo-  
737 cations and instants of delamination onsets, allowing to observe that the TCT  
738 has a tendency to develop unsymmetrical delamination fronts which hamper  
739 the derivation of the fracture energy at the critical load. DIC and TSA under  
740 quasi-static monotonic loading both showed that the modified TCT geometry  
741 has instead a tendency to develop four symmetrical and simultaneous delami-  
742 nation fronts as required by the test. TSA was particularly useful to evidence  
743 the tendency of the TCT geometry to develop local randomly distributed stress  
744 concentrations near the cut tips, as well as developing dissipation effects prob-  
745 ably due to a frictional sliding between plies at the transverse crack. On the  
746 contrary, the modified TCT geometry showed a good symmetry of stress dis-  
747 tribution, the presence of weak frictional effects near the delamination ends  
748 and a thermoelastic signal compatible with a pure mode II near the delami-  
749 nation tips. These results were confirmed by the SEM analyses performed on  
750 the fracture surfaces.

751 vi) The obtained results represent a significant contribution in the understand-  
752 ing of the TCT test as a mode II characterization procedure and provide new  
753 guidelines to characterize the mode II crack propagation under tensile loads.

754 **Acknowledgement**

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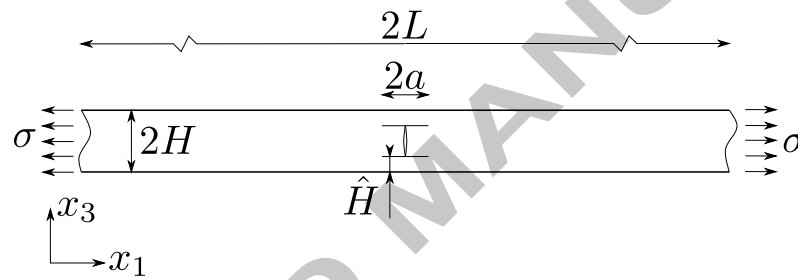
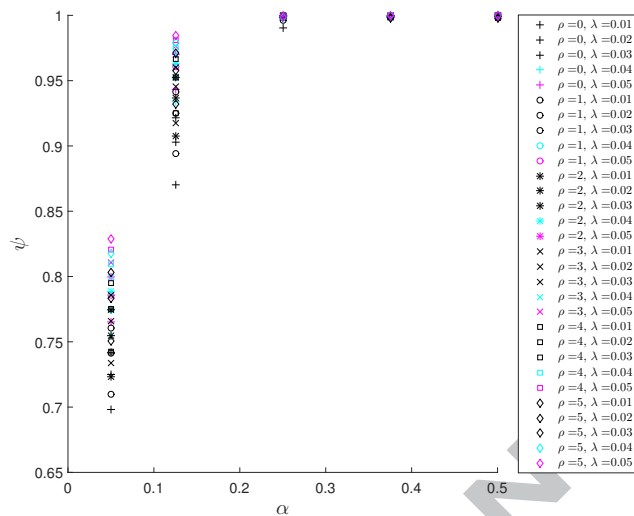
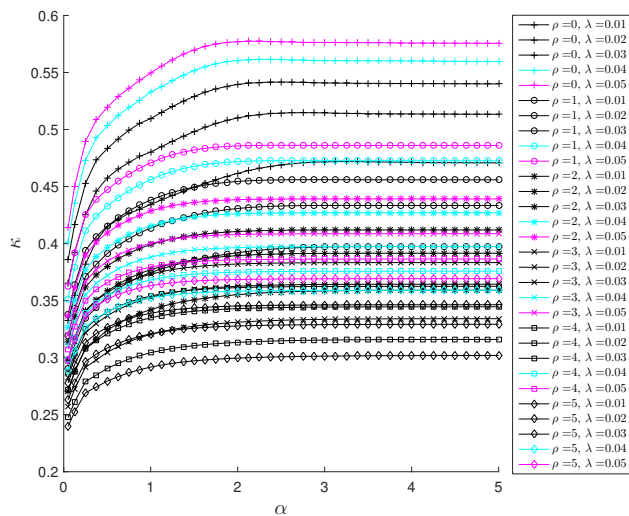


Fig. 1. TCT specimen: geometrical parameters and coordinate system.



(a)  $\psi$  vs.  $\alpha$ (b)  $\kappa$  vs.  $\alpha$ Fig. 2. Mode mixity  $\psi$  and correction factor  $\kappa$  as a function of  $\alpha$ .

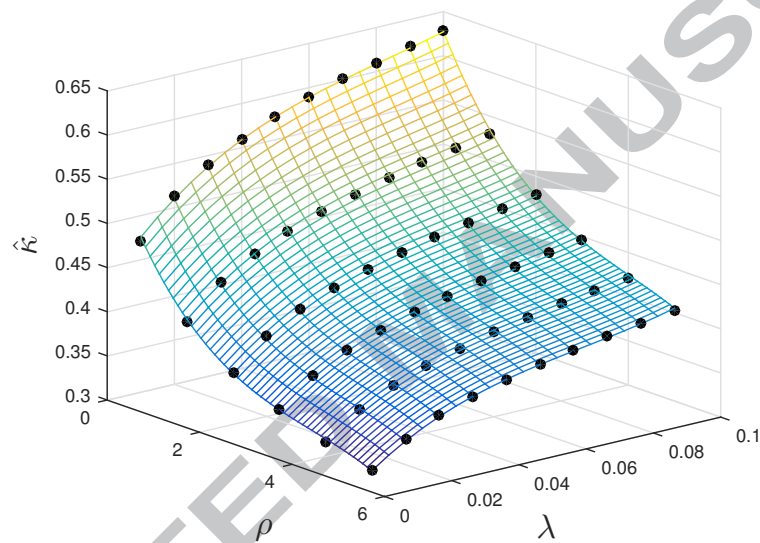


Fig. 3.  $\hat{\kappa}$  as a function of  $\lambda$  and  $\rho$ : numerical results (red dots) and polynomial fitting.

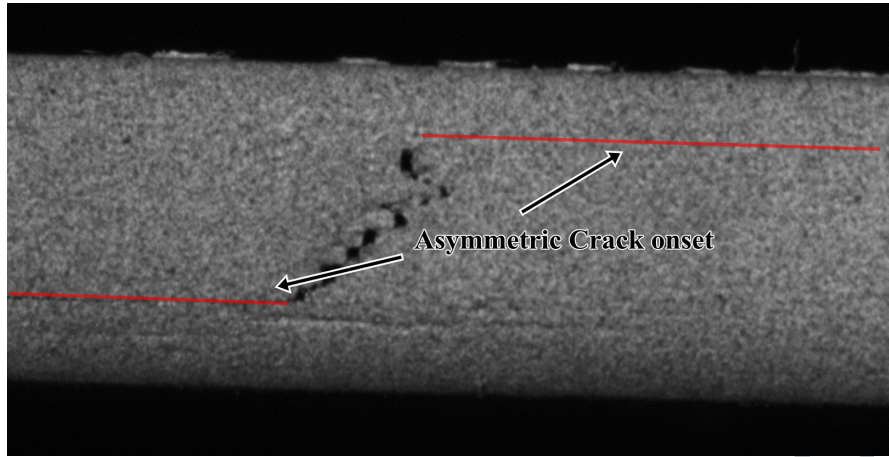


Fig. 4. Asymmetrical crack onset.

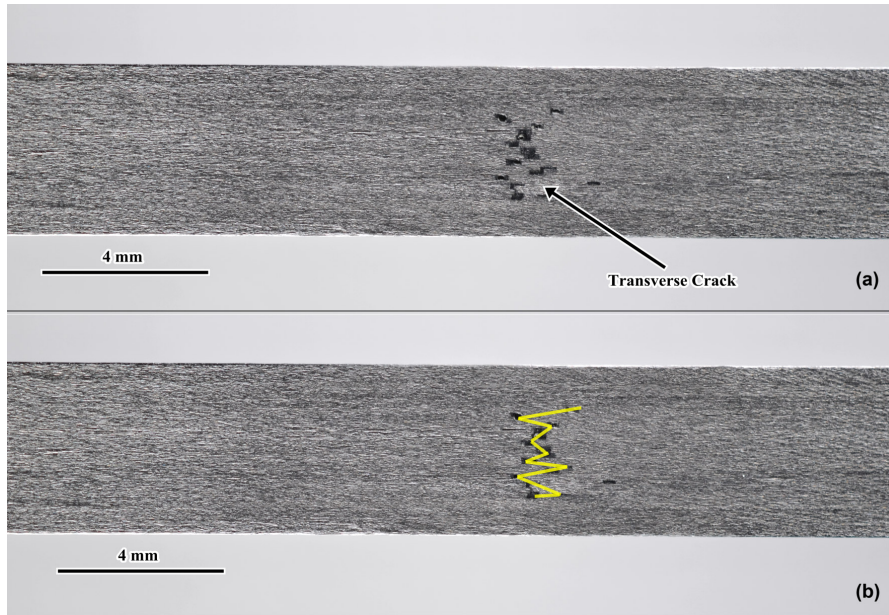


Fig. 5. crack macrography: (a) real picture; (b) crack morphology

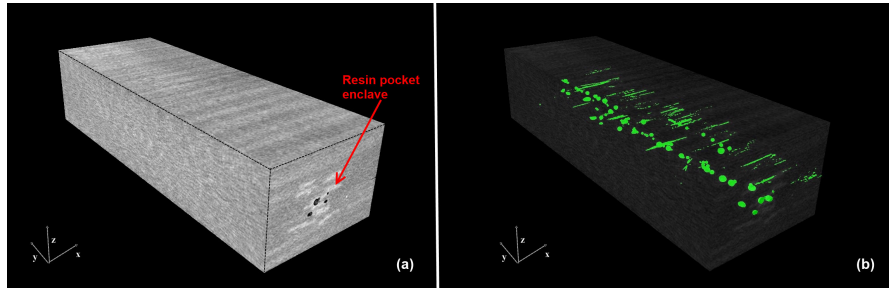


Fig. 6. Micro-CT: (a) 3D reconstruction; (b) Defects distribution

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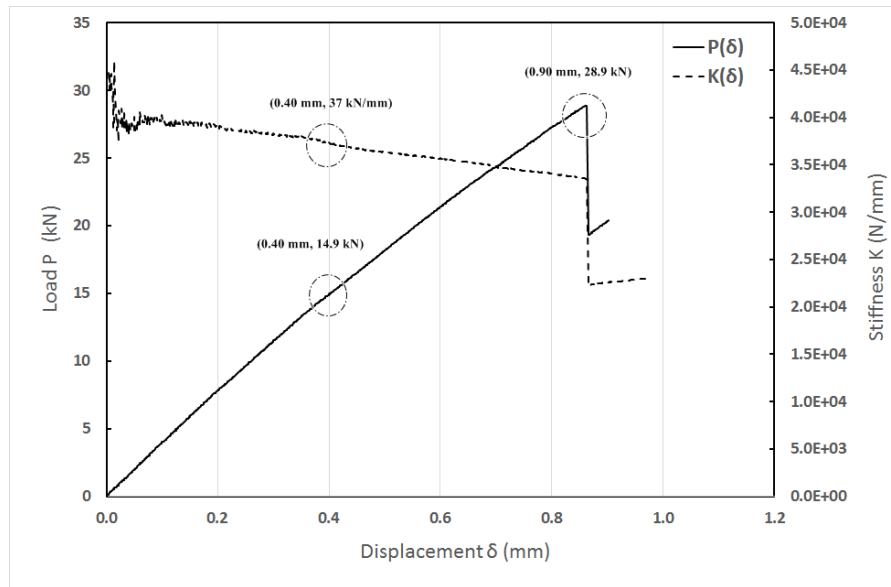


Fig. 7. Typical load vs. displacement curve and stiffness vs. displacement curve obtained in a TCT test

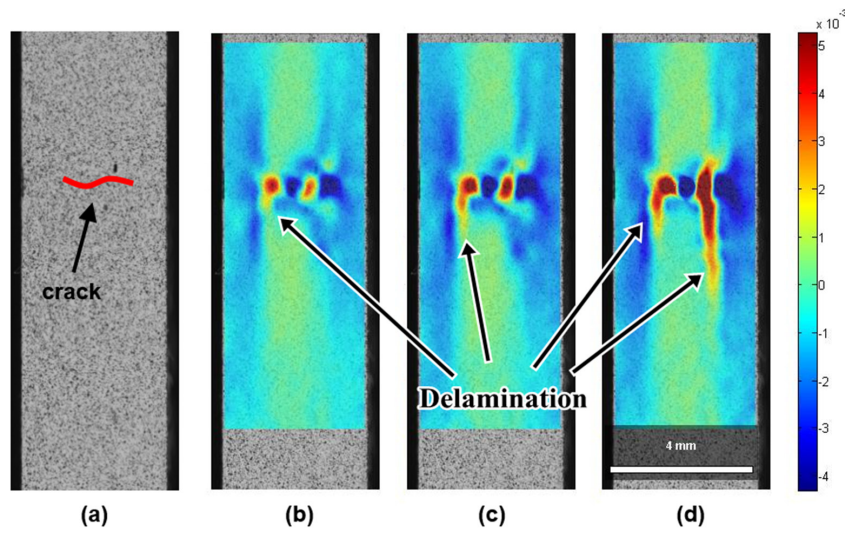


Fig. 8. DIC Results at different loads: (a) Reference image; (b) 22.4 kN; (c) 30kN; (d) 31 kN

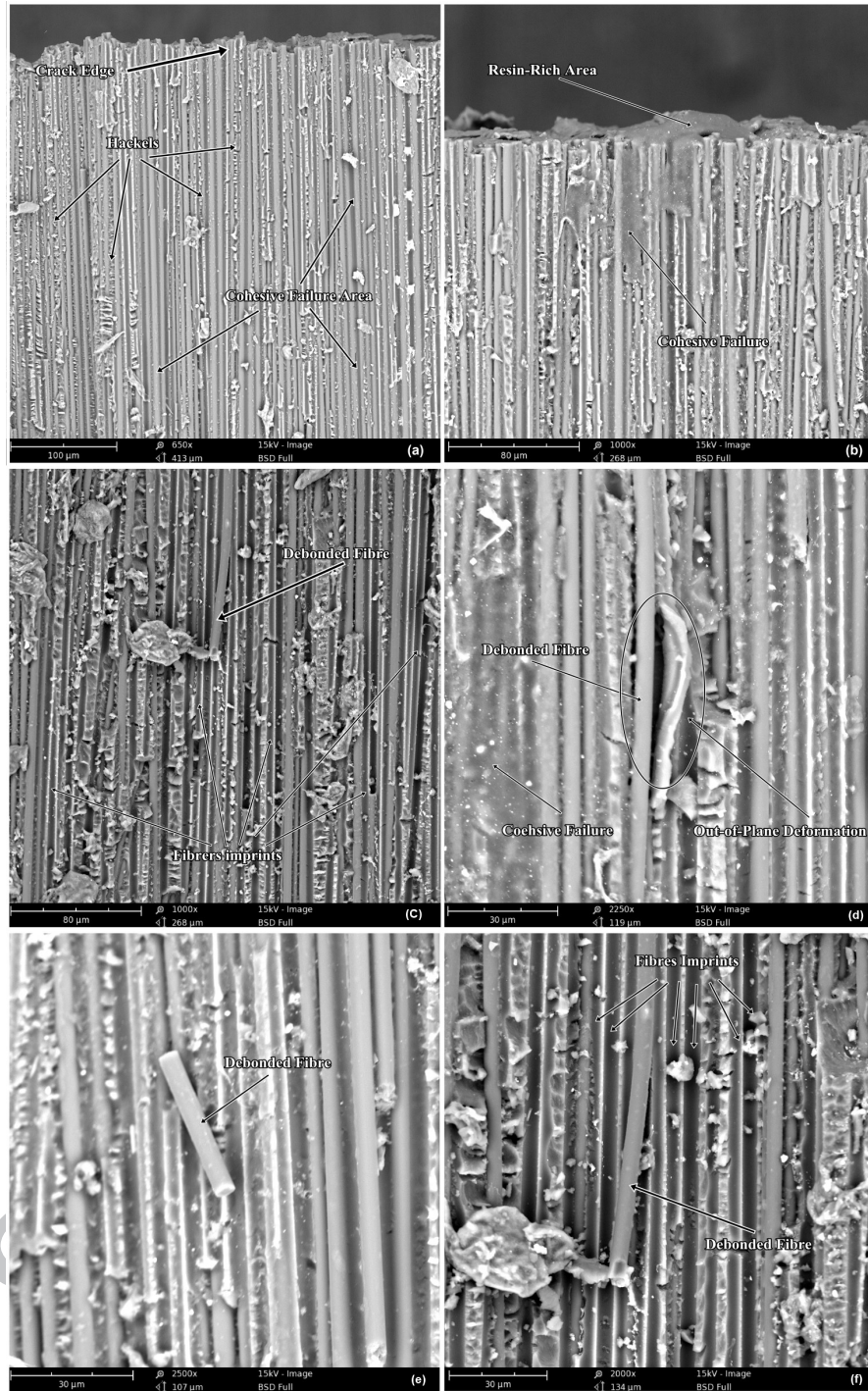


Fig. 9. SEM: (a) close-to-crack overviews; (b) Resin Rich Area; (c) (d) (e) (f) Debonded fibre and fibre imprints.



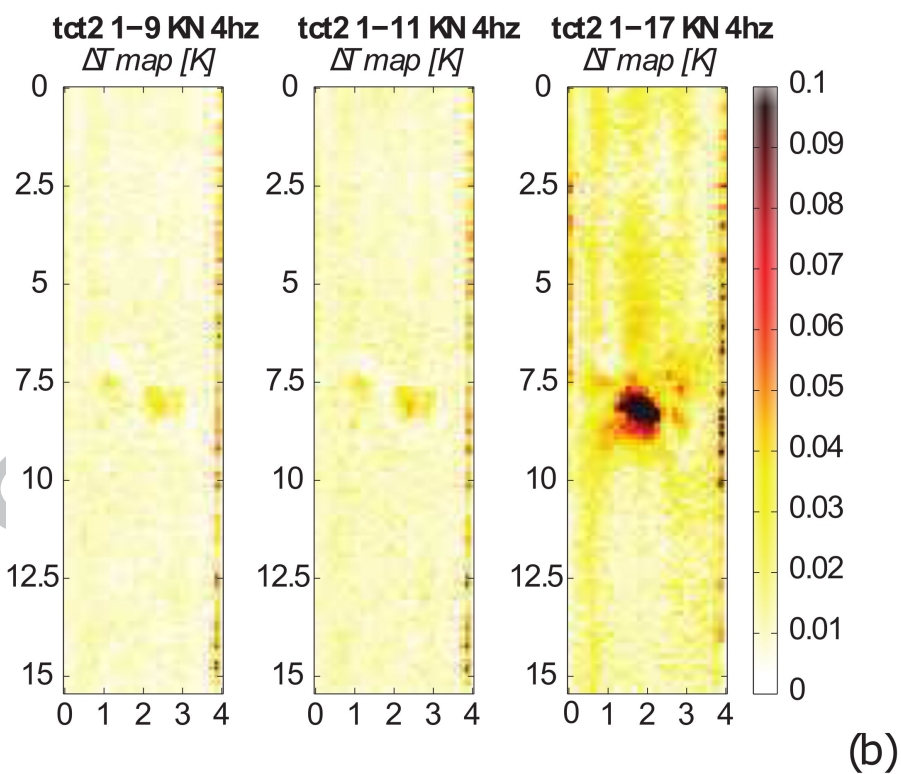
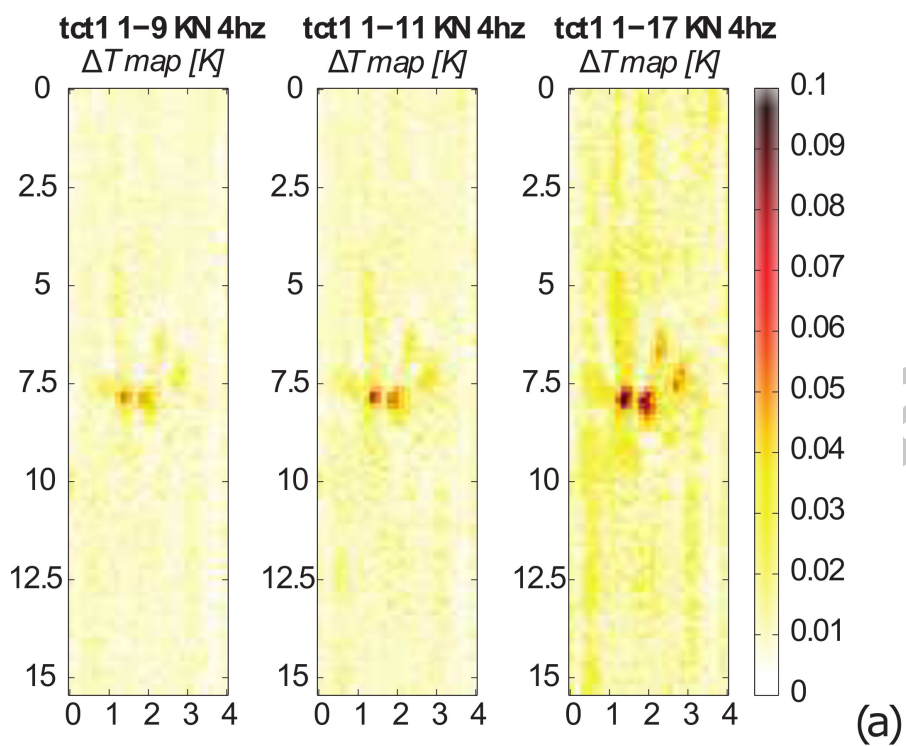


Fig. 10. TSA: (a) Thermoelastic signal amplitude at varying the load amplitude for the sample *tct1*; (b) Thermoelastic signal amplitude at varying the load amplitude for the sample *tct2*.

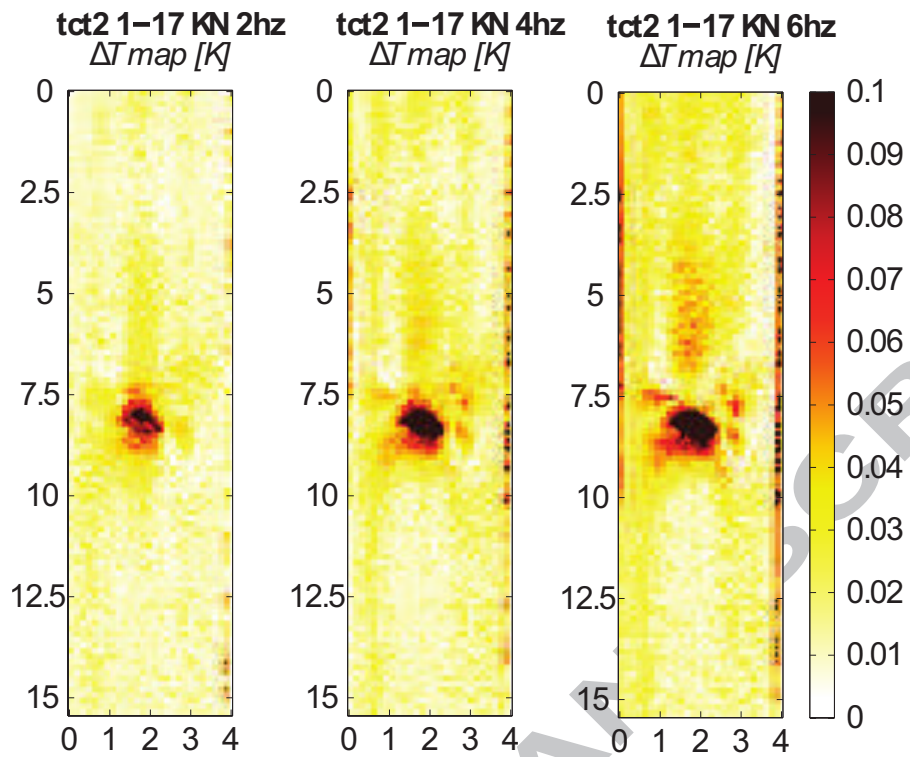


Fig. 11. TSA: Thermoelastic signal amplitude at varying the load frequency for the sample tct2

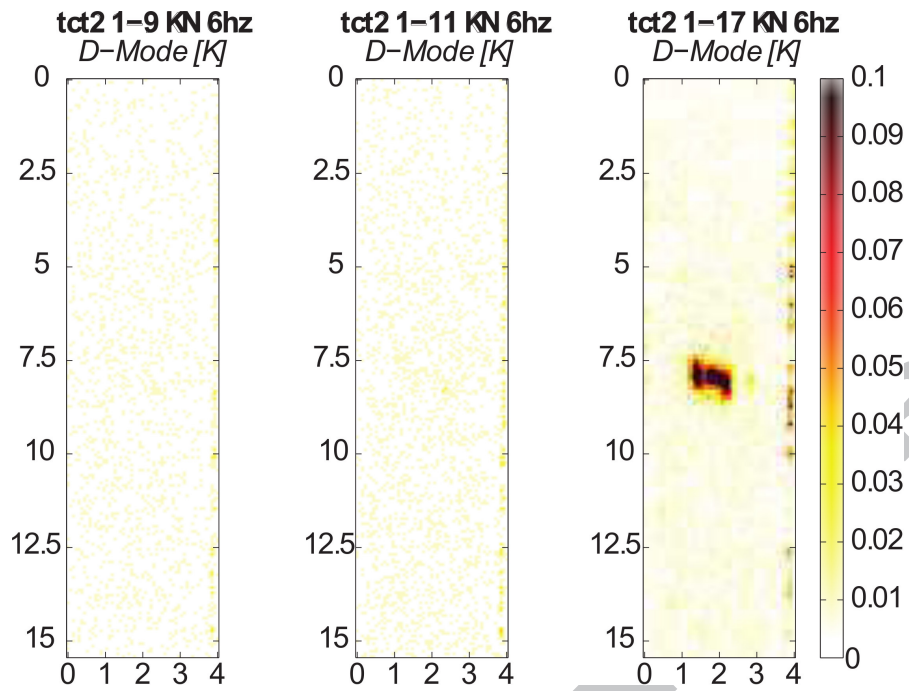


Fig. 12. TSA: Dissipation maps at varying the load amplitude

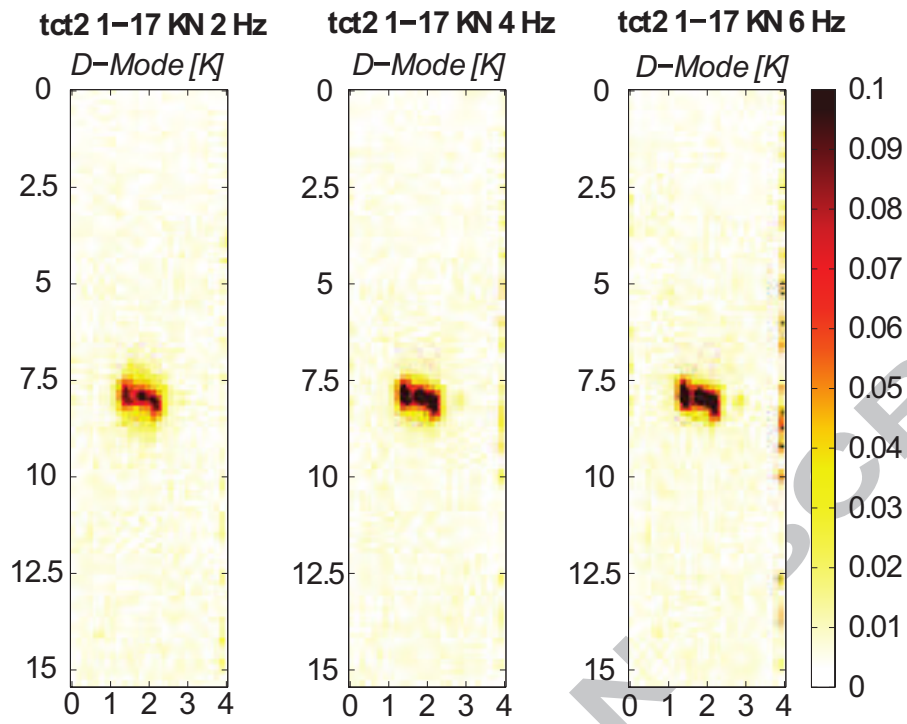


Fig. 13. TSA: Dissipation maps at varying the load frequency

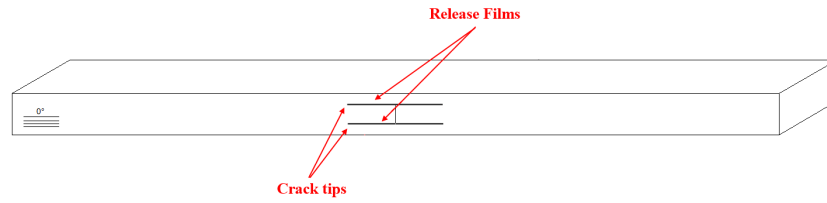


Fig. 14. A new configuration – proposed geometry

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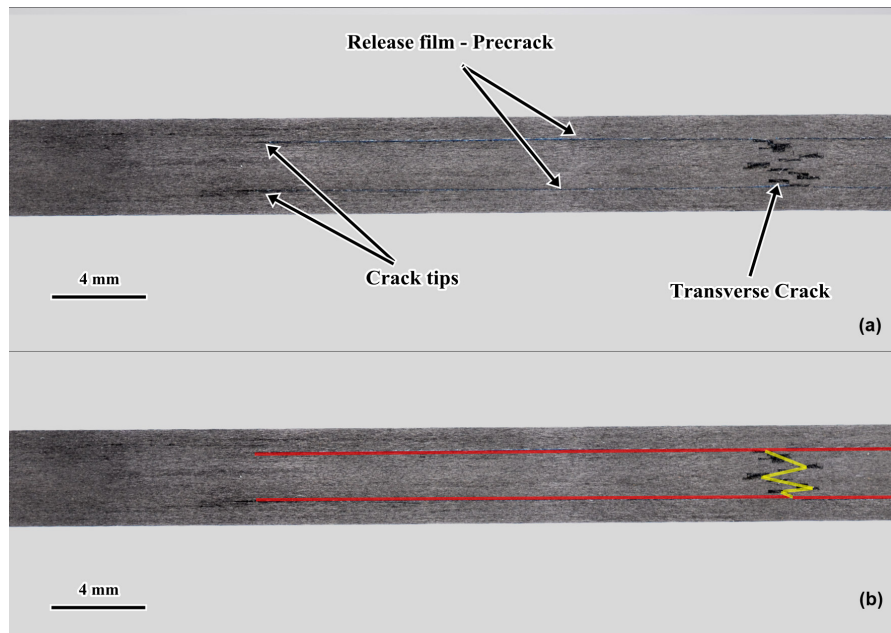


Fig. 15. A new configuration – (a) macrography; (b) crack geometry.

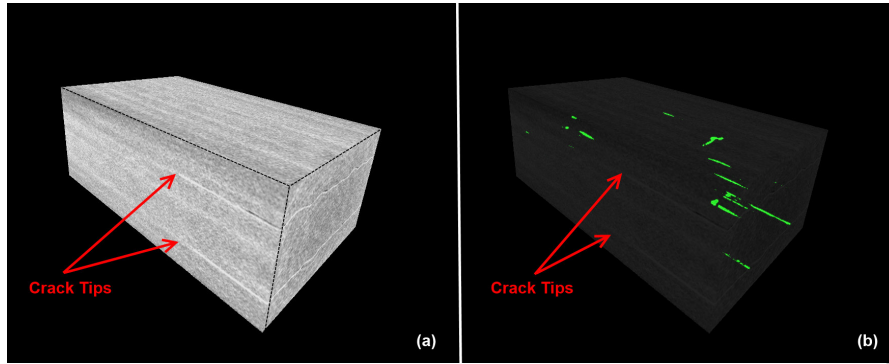


Fig. 16. A new configuration – Micro-CT: (a) 3D reconstruction; (b) Defects distribution

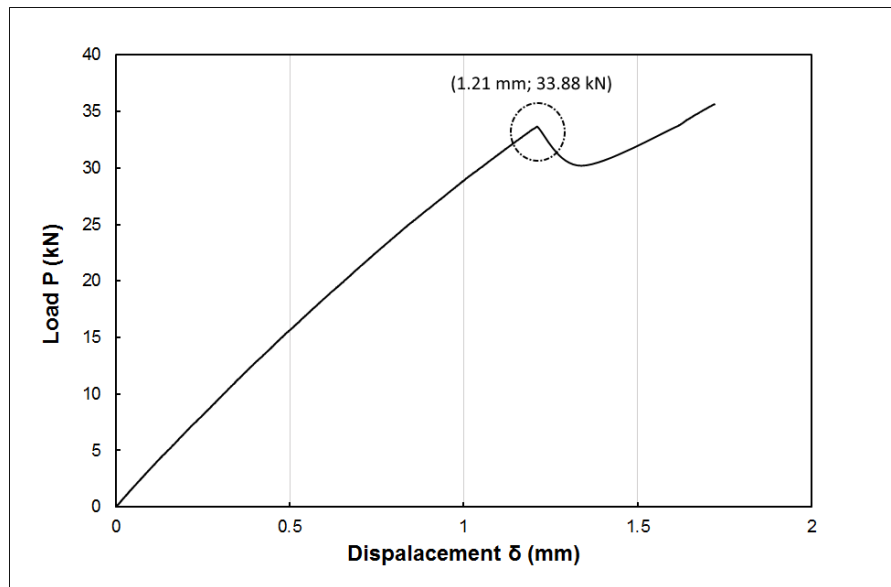


Fig. 17. A new configuration – Typical load vs. displacement curve and stiffness vs. displacement curve



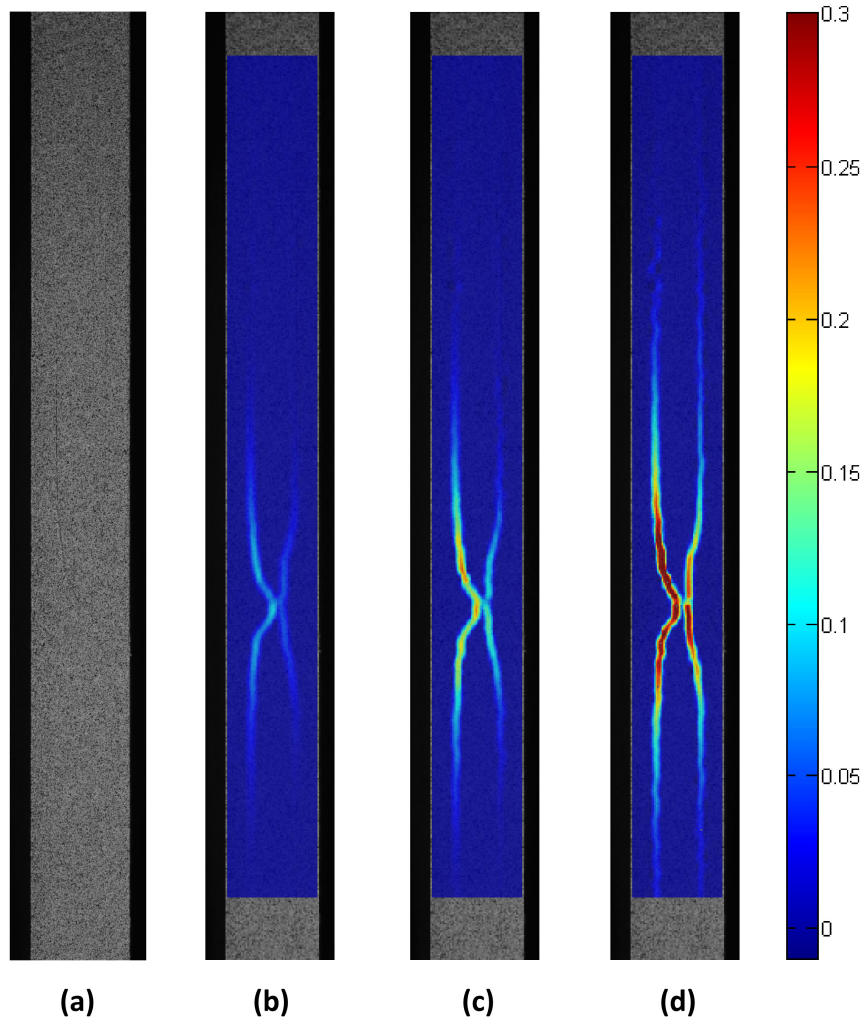


Fig. 18. A new configuration - DIC Results at different load level: (a) Reference Image; (b) 7.5 kN; (c) 15.8 kN; (d) 33.2 kN

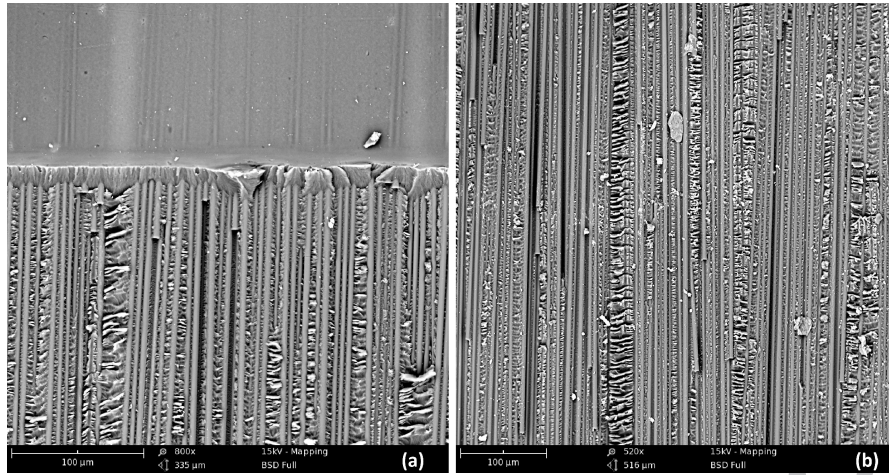


Fig. 19. A new configuration SEM: (a) Crack tip; (b) Crack surface overview

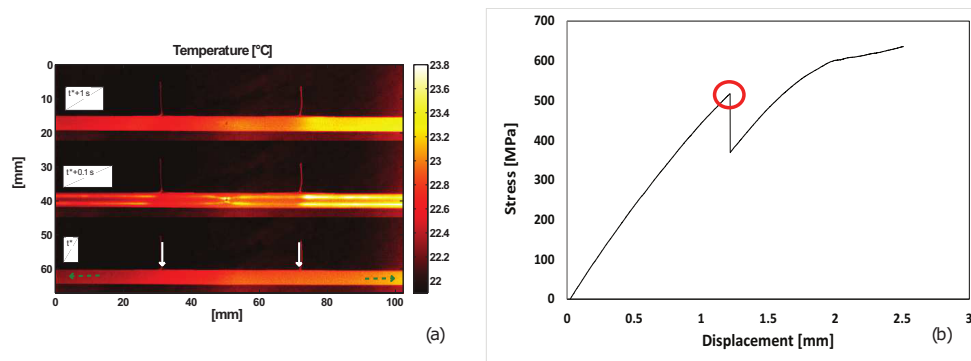


Fig. 20. A new configuration – Monotonic Loading: (a) thermograms sequence during the failure (b) typical stress vs. displacement curve

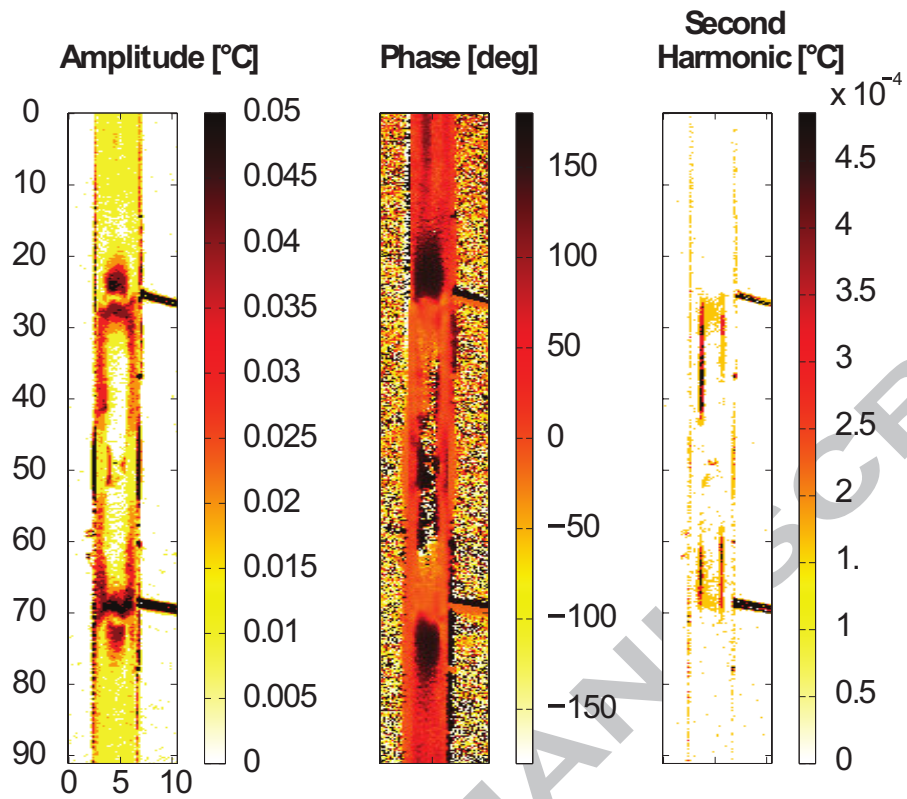


Fig. 21. A new configuration – Thermoelastic amplitude, phase and dissipation mode for 4-21 kN/4 Hz loaded sample

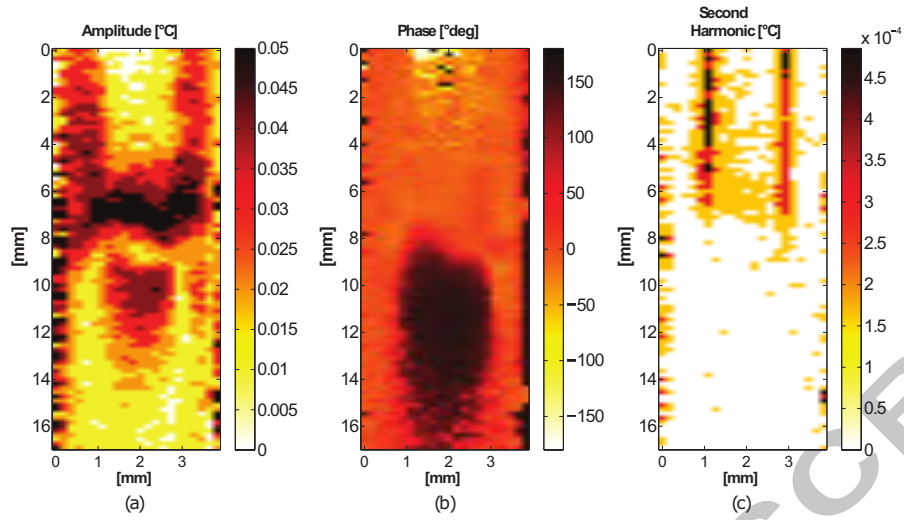
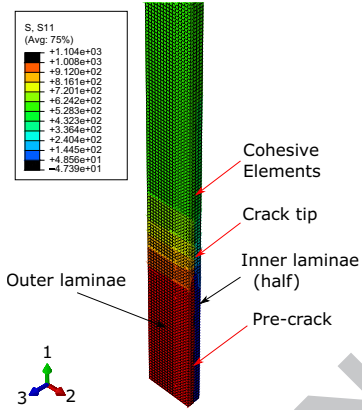
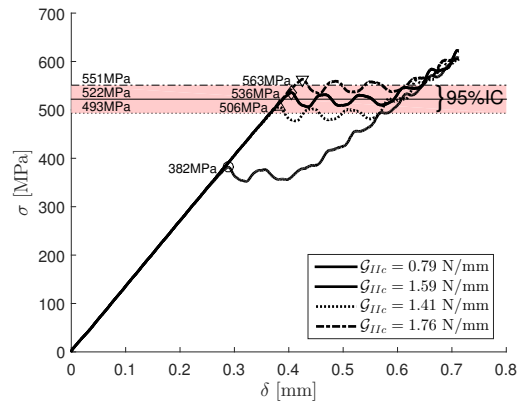


Fig. 22. A new configuration – Thermoelastic amplitude, phase and dissipation mode for a 4-21 kN/4 Hz loaded sample: a close up on the crack tips



(a) FE model of the mTCT specimen (one eighth).



(b) Remote stress,  $\sigma$ , vs. displacement,  $\delta$ , and comparison with experiments.

Fig. 23. FE model results.

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Table 1  
Properties of the cured Hexcel IM7-8552 unidirectional lamina

$E_1$ [MPa]	171420
$E_2$ [MPa]	9080
$G_{12}$ [MPa]	5290
$\nu_{12}$ [-]	0.32
$\alpha_{11}$ [1/K]	$-5.5 \times 10^{-6}$
$\alpha_{22}$ [1/K]	$25.8 \times 10^{-6}$



Table 2  
Photomechanic setup

Camera type	Single-lens digital reflex
Image sensor	23.5×15.6 mm CMOS
Effective Pixel	24.1 MPixel
Focal Lengh	60 mm - macro
Sampling Rate	0.5 Hz
Resultant resolution	20 $\mu\text{m}/\text{mm}$
Subset Radius	20 pixel
Subset Overlapping	5 pixel
Displacement rate	2 mm/sec

Table 3  
Failure mode of the TCTs specimens tested

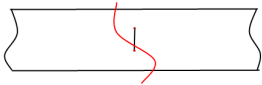

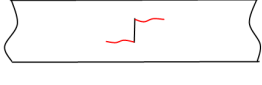

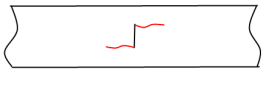
Sample ID	H [mm]	h [mm]	$P_u$ [kN]	Failure mode
TCT-1-1	1.5	0.75	17.5	
TCT-1-2	1.5	0.75	17.2	
TCT-1-3	1.5	0.75	17.4	
TCT-1-4	1.5	0.75	17.3	
TCT-2-1	3.0	1.5	24.2	
TCT-2-2	3.0	1.5	25.3	
TCT-2-3	3.0	1.5	26.2	
TCT-2-4	3.0	1.5	24.5	
TCT-3-1	4.5	2.25	27.7	
TCT-3-2	4.5	2.25	27.8	
TCT-3-3	4.5	2.25	27.0	
TCT-3-4	4.5	2.25	27.2	

Table 4  
Mode II Fracture Toughness

	1	2	3	4	Mean	St.Dev.
$\delta_c$ [mm]	1.22	0.96	1.17	1.21	1.14	0.11
$\sigma_c$ [MPa]	517	498	538	535	522	18
$\mathcal{G}_{IIc}$ [N/mm] (Eq. (4) )	1.56	1.44	1.68	1.66	1.59	0.11
$\mathcal{G}_{IIc}$ [N/mm] (Eq. (9))	1.57	1.46	1.70	1.68	1.60	0.11

Table 5  
Interlaminar material properties

	Material property	Value or calculation method	Ref.
$K$ [N/mm <sup>3</sup> ]	Penalty stiffness	$10^6$	[2]
$\tau_N$ [MPa]	Effective strength in pure mode I	Eq. (13)	[4]
$\tau_{sh}$ [MPa]	Effective strength in pure mode II	Eq. (14)	[5]
$\mathcal{G}_{Ic}$ [N/mm]	Mode I fracture toughness	0.28	[48]
$\mathcal{G}_{IIc}$ [N/mm]	Mode II fracture toughness	0.79, 1.59, 1.41, 1.76	[48]