World Academy of Science, Engineering and Technology
International Journal of Aerospace and Mechanical Engineering
Vol:17, No:12, 2023

Determining the Mode II Intra-Ply Energy Release Rate of Composites Made of Prepreg

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***Abstract*—**The distinction between interlaminar and intralaminar fracture toughness is challenging. For loading mode I, the double cantilever beam specimens were often used for the interlaminar fracture toughness and the compact tension specimen for the intralaminar fracture toughness. For the analysis of interlaminar properties regarding energy release under different loading modes, the geometry of the DCB specimen can also be tested under three-point bending for Mode II characteristics. The same specimen can also be tested with defined superimposed loading conditions (mixed mode) using the Mixed Mode Bending test apparatus. However, this approach has not been applicable for intralaminar characteristics, as crack initiation in a single layer for laminates made out of prepreg, has not been feasible. The method presented in this work enables differentiation of interlaminar and intralaminar energy release rates in Mode II loading with nearly identical specimen geometry. With this, a practically identical energy release rate is observed in Mode II for the investigated material IM7/8552.

***Keywords*—**Fibre reinforced plastics, end-notched flexure, energy release rate, fracture toughness, intralaminar, interlaminar.

I. Introduction

COHESIVE zone elements (COH) are frequently used in the simulation of Carbon-fibre-reinforced-plastics (CFRPs) bonded joints, since they can represent damage and associated degradation of material properties in a finite element method simulation. This is done via a so-called traction-separation law (TSL), which is to be determined for the loading modes defined in fracture mechanics. The necessary material parameters are typically determined experimentally. Due to the possibility of determining the necessary characteristic values for a COH element on a single specimen geometry for the different loading modes, the concept has become established for COH elements [1]-[5]. This is used for adhesives as well as for the description of delaminations, i.e. the so-called interlaminar damage [1]-[5]. The fracture mechanics values required for Mode I are determined with the double cantilever beam (DCB) test and those for Mode II with the ENF test. For superimposed loading conditions, the material behaviour for specific superimposed conditions (mixed mode ratio) can be determined using the mixed mode bending (MMB) test. Material models are also available for fibre layers that can describe damage to the fibre layer, but there is no concept that allows the TSL parameters to be determined for intralaminar damage on a geometrically identical specimen for the different loading modes. With the development of Sato et al. [6], a significant advancement has been made in this direction. In contrast to [7], where interlaminar Double Cantilever Beam (DCB) and intralaminar Compact Tension (CT) specimens were used to compare fracture toughness, Sato et al. introduced a modified DCB test method. This modified DCB test allows for the distinction between interlaminar and intralaminar fracture toughness evaluations for dry semi-finished products. Reference [6] also introduced a distinction between intralaminar damage and the type of damage occurring in CT specimens.

Delamination and the associated interlaminar characteristics remain unaffected by the proposed definition and describe the crack growth between two fibre plies in a resin-rich area of a laminate. However, in the case of intralaminar cracks, a distinction is made between intralaminar delamination and splitting, the latter corresponding to the crack growth of the CT specimen. Fig. 1 shows that the material behaviour of a single layer cannot be investigated by splitting. In order to investigate only a single layer, Sato et al. [6] developed an adapted DCB specimen manufacturing procedure that allows the generation of a crack in a single layer. In this method, an additional fibre layer is first partially impregnated, then opened and the insert, which consists of a thin release film, is applied. This creates a crack in the fibre layer itself, and when the specimen is subsequently loaded, the stress is concentrated at the crack tip of the artificially created crack, causing natural crack growth to occur within the cracked single layer. Using this method, a significant difference was found between interlaminar critical energy release rate (CERR) and intralaminar CERR. The major advantage of the method is that an almost identical specimen geometry can be used (see Subsection II *C*) and, due to the identical test setup, the same mathematics can be used to evaluate the test results. A disadvantage of the method is that it cannot be used for prepreg semi-finished products, as these are already fully impregnated at the supplier and the production process described in [6] cannot be used. In order to achieve this, another modified Double Cantilever Beam (mDCB) specimen was developed in [8], which makes the approach of the "Intralaminar Film Insertion Method" by Sato et al. [6] also accessible for prepreg.

With the mDCB specimen [8], a method has been presented which has already achieved a distinction between interlaminar and intralaminar fracture toughness in Mode I for the material 8552. To establish a TSL that can describe any loading condition, it is typical to interpolate between Mode I and Mode

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II using Power-Law or Benzeggagh-Kenane-Law (BK-Law) [1], [4]. However, since the TSL for Mode I & II should be determined first, the distinction between interlaminar and intralaminar fracture toughness under load in Mode II is presented. For this purpose, the modified ENF (mENF) specimen is presented first and the geometry differences to the ENF specimen are discussed. This is followed by a description of the manufacturing process and an adapted test procedure which is necessary to achieve targeted crack growth exclusively within a single fibre layer. Subsequently, test results comparing ENF and mENF specimens are presented.

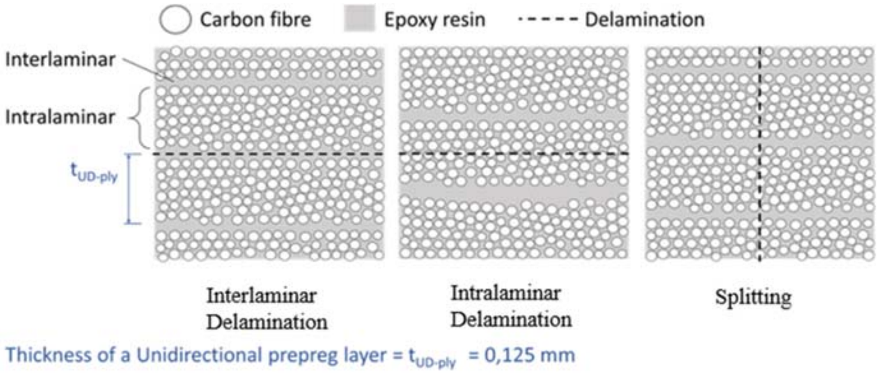


Fig. 1 Definition of interlaminar, intralaminar and splitting [8]

II. Material and Methods

The theoretical basis for this work is explained below. First, the unidirectional (UD) CFRP prepreg used is presented. This is followed by the ENF specimen and the associated three-point bending (3-PB) test to determine the CERR. Finally, the modified ENF specimen developed within the scope of this work is described in terms of geometry, manufacturing process and test procedure.

A. Material

The material investigated is the UD prepreg Hexply 8552-IM7(12K)-134-33% from Hexcel (Hexcel Corporation, Stamford, Connecticut, United States). This prepreg is widely used in research [1], [7]-[10]. Therefore, many publications deal with it so that it can be used as a reference for the determined characteristic values. The matrix resin 8552 is an amine-cured toughened epoxy resin. Therefore, this prepreg shows a comparatively high impact strength.

B. ENF Test

The ENF test is a standardised test, it serves to determine the interlaminar fracture toughness and provides characteristic values for the CERR in loading mode II. The test is defined in ASTM-D7905/D7905M [11], according to the ASTM, a laminate with an even number of layers should be produced with a release film between the middle two fibre layers so that the laminate has an artificial crack after curing. In the test itself, a 3-PB load is then applied to the specimen, as shown in Fig. 2. Due to the differences in geometry and the potential formation of resin pockets between the artificial cracks generated by the manufacturing process and natural crack fronts [7], the determined characteristic values are consequently influenced. Therefore, the standard distinguishes between pre-cracked and non-pre-cracked tests. Since the modified ENF specimen can currently only be tested with a pre-crack (see Subsection II *C* 3), only the corresponding test procedure is described below.

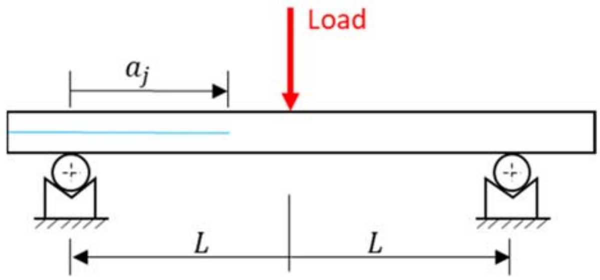


Fig. 2 ENF Test-Setup according to [11]

Precracked Toughness Only

The ASTM [11] describes the test procedure for specimens that already have a precrack prior to the fracture test. Since the shape of the crack front can vary depending on the method used for precrack generation, the ASTM requires that for this test the shape of the crack front can be determined at least 5 measuring points across the specimen width before the test is carried out if the precrack was not generated with a Mode II load.

Regardless of whether precracked or not, the ASTM requires so-called compliance calibration (CC) tests for the subsequent evaluation of the test data. By changing the specimen position in the test fixture, the distance between the left support and the crack tip is varied so that the crack length is 20 mm in one case and 40 mm in the other. The test load, which depends on a_j, is calculated using the formula:

$$P_j = \frac{2B}{3\,a_j}\sqrt{G_{IIc}E_{lf}\,h^3} \quad (1)$$

P_j is 50% of the expected force for crack initiation. B is the specimen width, a_j the respective crack length respectively the distance between the left support and the crack tip. h describes half the specimen thickness, G_{IIc} is an estimated value for the fracture toughness and E_{lf} is the flexural modulus which can be calculated according to the Classical Beam Theory (CBT) using the following formula with the data from the CC tests.

$$E_{lf} = \frac{L^3}{4ABh^3} \tag{2}$$

Here L describes the distance between a support and the load applying plunger. A is the CC coefficient resulting from the CC tests. A linear regression is performed on the force-displacement curve between 90 N and the calculated test load P_j. This describes the compliance as a cubic function of a_j as:

$$C = A + ma^3 \tag{3}$$

where C is the compliance, A the intercept and m the slope of the regression analysis. The fracture toughness G_{IIc} is then determined using:

$$G_Q = \frac{3mP_{max}^2 a_0^2}{2B} \tag{4}$$

Thereby G_Q is the fracture toughness under Mode II load, P_{max} is the maximum force measured during the test. a_0 is the initial crack length which should be 30 mm during the final test. As a validation check, it must then be checked whether the calculated fracture toughness G_Q, for non-mode II cracked specimens, meets the requirement 15 % ≤ $\%G_{Q,j}$ ≤ 60% where $\%G_{Q,j}$ is to be determined for the crack lengths j = 20 mm and 40 mm as follows:

$$\%G_{Q,j} = \frac{100(P_j\, a_j)^2}{(P_{max}\, a_0)^2} \tag{5}$$

If the requirement is met by the determined fracture toughness G_Q, the following applies:

$$G_{IIc} = G_Q \tag{6}$$

C. Modified End-Notched Flexure Specimen

In the following, the modified end-notched flexure (mENF) specimen is presented, first, its geometry is discussed and the differences to the ENF specimen are highlighted. This is followed by a description of the associated manufacturing process and the test procedure adapted for this specimen.

1. Geometry

According to [11], the ENF specimen has a width of 19-26 millimetres with a length of at least 130 millimetres, the length of the artificial crack at the notched end must be at least 45 millimetres and the specimen thickness should be between 3.4 and 4.7 millimetres. Fig. 3 (a) shows a schematic representation of the ENF specimen. In addition, the area in which the insert generates the artificial crack is highlighted in blue. The length from the centre of the left support of the specimen to the end of the insert is the initial crack length a_0. Underneath, the artificial crack tip of the ENF specimen is shown in Fig. 3 (b1) and that of the mENF in Fig. 3 (b2). The special feature of the mENF is the additional fibre layer in the middle of the specimen, which is shortened by the length of the artificial initial crack. In order to avoid ondulation in the area of the initial crack due to the additional fibre layer, an insert corresponding to the nominal layer thickness is placed in the area of the artificial crack, thus ensuring that the fibre layers remain straight. This is shown in Fig. 3 (c2) using a microscope image. The additional fibre layer to the right of the insert is also clearly visible. For comparison, the artificial crack tip of the ENF specimen is shown in Fig. 3 (c1) with the same scale.

2. Manufacturing

The manufacturing of the mENF specimen differs from that of the ENF specimen in only one point. At first, half of all fibre layers are stacked on top of each other for both types of specimen. Then, in the case of the ENF specimen, a release film is inserted in such a way that no connection can form between the fibre layers in an area of at least 60 millimetres (see blue area in Fig. 3). In the case of mENF, a metal foil wrapped with a release foil is inserted first and then the additional fibre layer is applied as close as possible to the end of the insert (see Fig. 4). The thickness of the metal foil is chosen in such a way that the release foil and metal foil together correspond to the thickness of a fibre layer. Subsequently, the second half of the fibre layers is successively applied and finally cured in the autoclave.

3. Test Procedure

For the generation of a precrack, the ASTM also recommends applying a Mode II load, since the crack initiation and the initial crack growth occur instable and it has already been shown in [6] and [8] that the fracture toughness intralaminar is higher than interlaminar at least for Mode I load, the specimens were precracked in Mode I in the context of this investigation, since a method for the targeted crack initiation within the fibre layer has already been developed for Mode I [8]. To ensure that precrack generation by means of Mode I loading does not influence the test results, this method was also used for precrack generation in the ENF specimen.

III. Results and Discussion

In the following, the test results are presented. First, the force-displacement diagrams are considered and some microscope images after completion of the test, the artificial crack tip and the fracture surfaces are illustrated. In addition, the determined fracture toughness for both specimen types is shown. Finally, the data collected are interpreted.

A. Test Results

Fig. 6 shows the force-displacement curves of ENF and mENF specimens. The different shades of blue represent different batches of specimens as the mENF specimens were made from two different plates. The dotted lines indicate that the insert mentioned in Section II *C* 2 is present in the area of the artificial crack during the test.

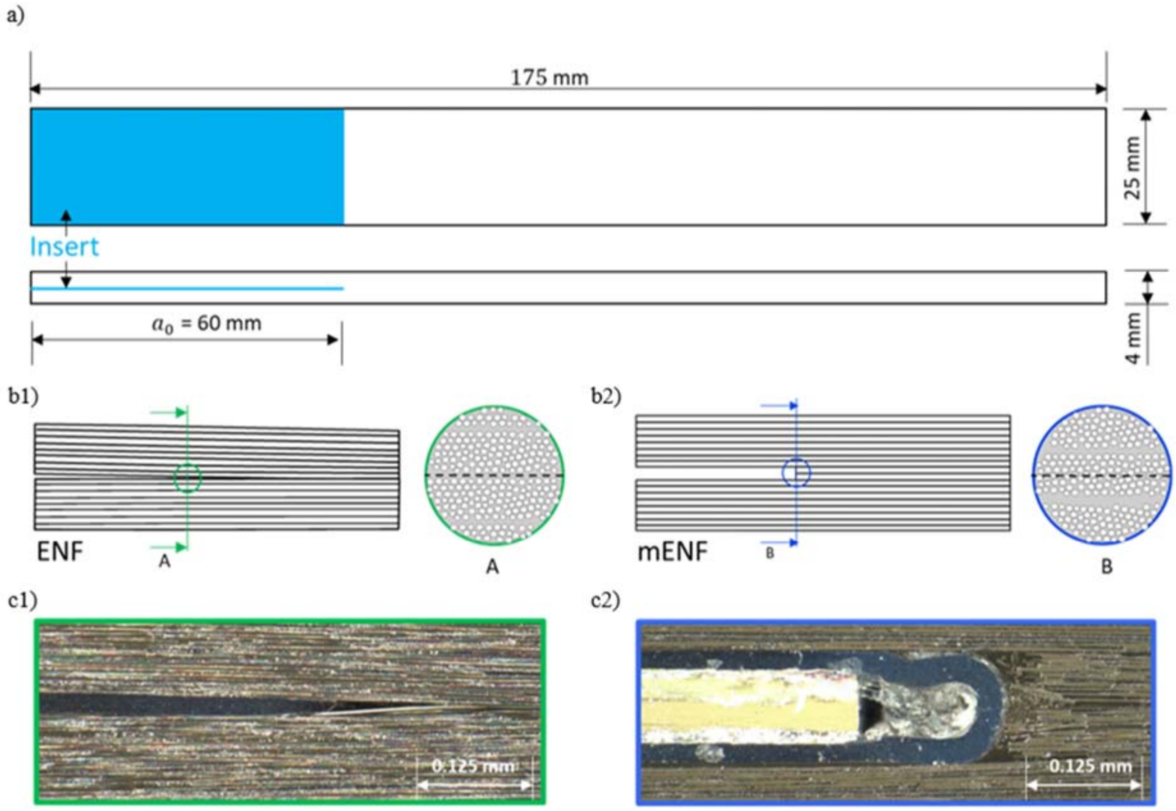


Fig. 3 (a) Sketch of the ENF specimen according to [11]; (b1) sketch of the artificial crack tip at ENF, (b2) sketch of the artificial crack tip mENF; (c1) microscope image ENF cracktip, (c2) microscope image mENF cracktip [8]

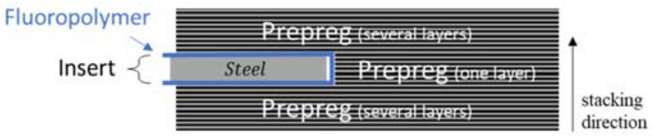


Fig. 4 Sketch of the manufacturing process [8]

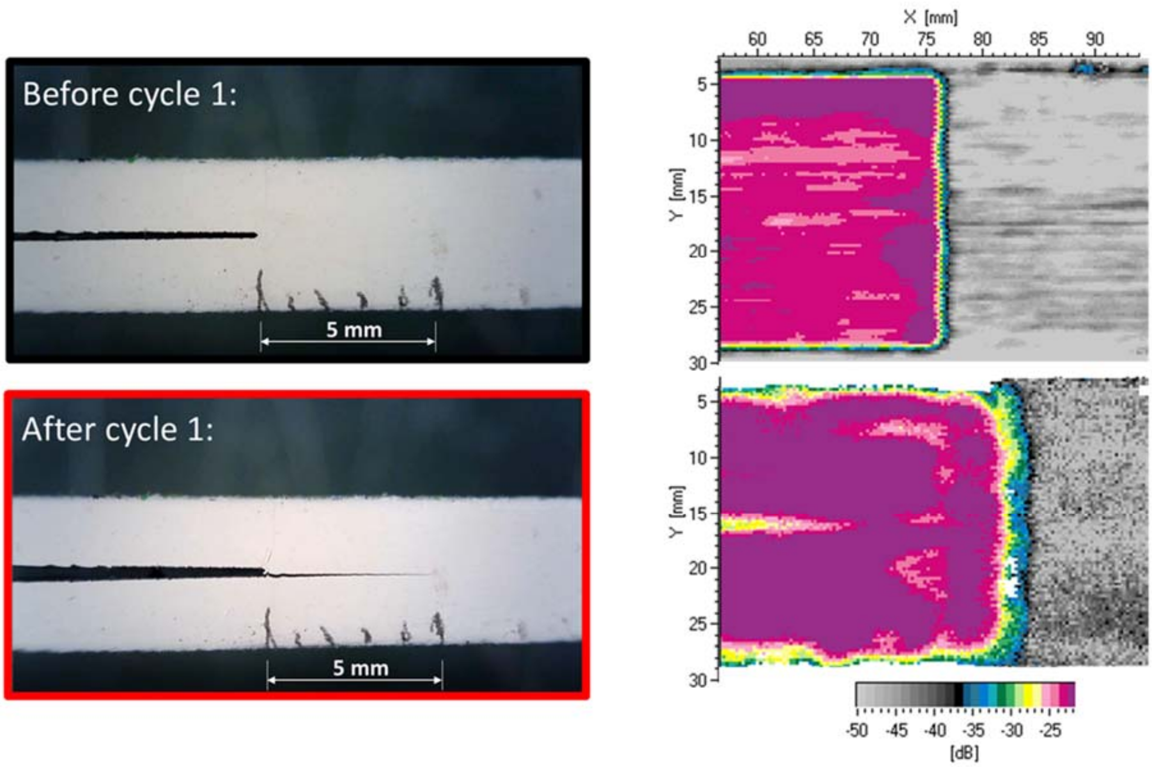
By comparing the curves, only a slightly higher stiffness can be observed for the mENF specimens compared to the ENF. However, this is to be expected due to the additional fibre layer and its influence on the specimen thickness as well as its bending stiffness. Similar observations have also been described by [6]. The force at crack initiation is on average ~957N for both specimen types, with a smaller scatter for ENF with ± 6N than for mENF with ± 40N. Since the gap due to the artificial crack is significantly larger in the mENF specimens than in the ENF specimens, mENF specimens with and without inserted inserts were tested and no uniform trend is detectable with regard to the force at crack initiation. Only the stiffness is minimally higher with the insert inserted, as expected. Table I shows the values determined for the CERR in Mode II, which are determined according to the evaluation method described in Chapter II *B* according to [11]. In addition, Table I shows the results of the same specimens, which were evaluated with the evaluation method specified in DIN EN 6034 [12]. The values for the CERR are 20-25% higher, the difference between interlaminar and intralaminar is 5% greater than in the evaluation according to ASTM.

Microscopic Analysis

Since it is not possible to check the crack path with the human eye due to the thickness of a fibre layer of about 0.125 mm, therefore, provided are microscopic images illustrating the transition between artificial and natural cracking in an mENF specimen.

Fig. 7 (a) shows exemplary the crack path of an mENF specimen, here the additional fibre layer is clearly visible, which was split almost in the middle by the crack and so half of the fibre layer remains on the upper and lower part of the mENF specimen. Fig. 7 (b) shows the same image with the areas of the artificial crack (orange), the additional fibre layer (green) and the crack path (red) highlighted.

The fracture surfaces show slight differences between ENF and mENF. While the mENF specimen is almost perfectly flat in the area of the artificial crack, the ENF specimen shows a waviness in this area, which is also present in the area of the Mode II crack growth. Furthermore, the transitions between the areas marked in Fig. 8 are less clearly distinguishable from each other in ENF. Furthermore, it can be seen that the fracture surface of the mENF specimen has more and also longer fibre fragments compared to the ENF specimen.



(a) (b)

Fig. 5 (a) mENF specimen without natural crack (non-precrack), below with a natural crack (pre-cracked) [8]; (b) corresponding ultrasonic scan of mENF with and without natural crack

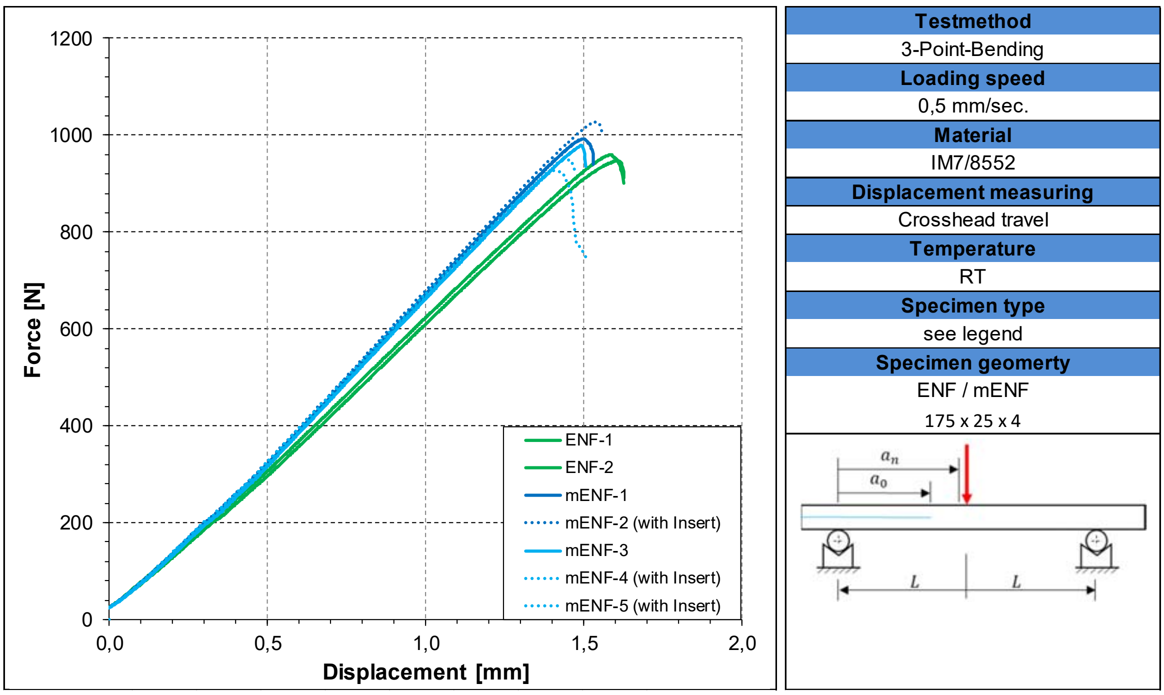


Fig. 6 Force-Displacement-Curves from ENF, mENF with and without Insert in the precracked area

TABLE I
ENERGY RELEASE RATES

	ENF-1	ENF-2	mENF-1	mENF-2	mENF-3	mENF-4	mENF-5	Avg. ENF	Avg. mENF
ASTM	0,69	0,66	0,67	0,68	0,66	0,69	0,65	0,68	0,67
DIN	0,84	0,87	0,83	0,88	0,81	0,78	0,74	0,86	0,81

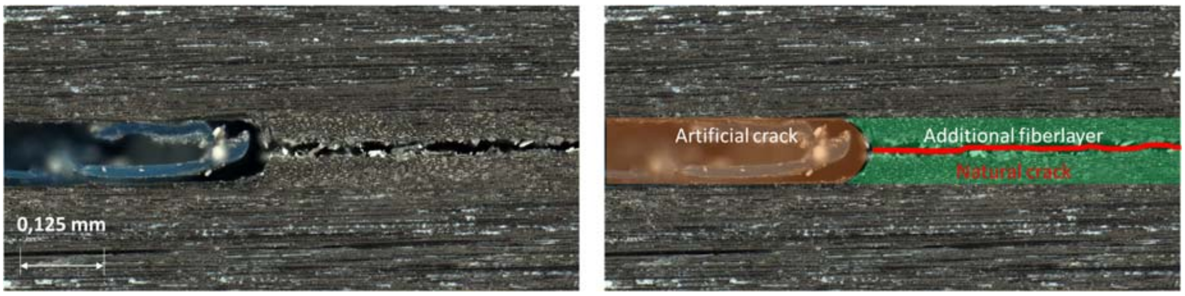
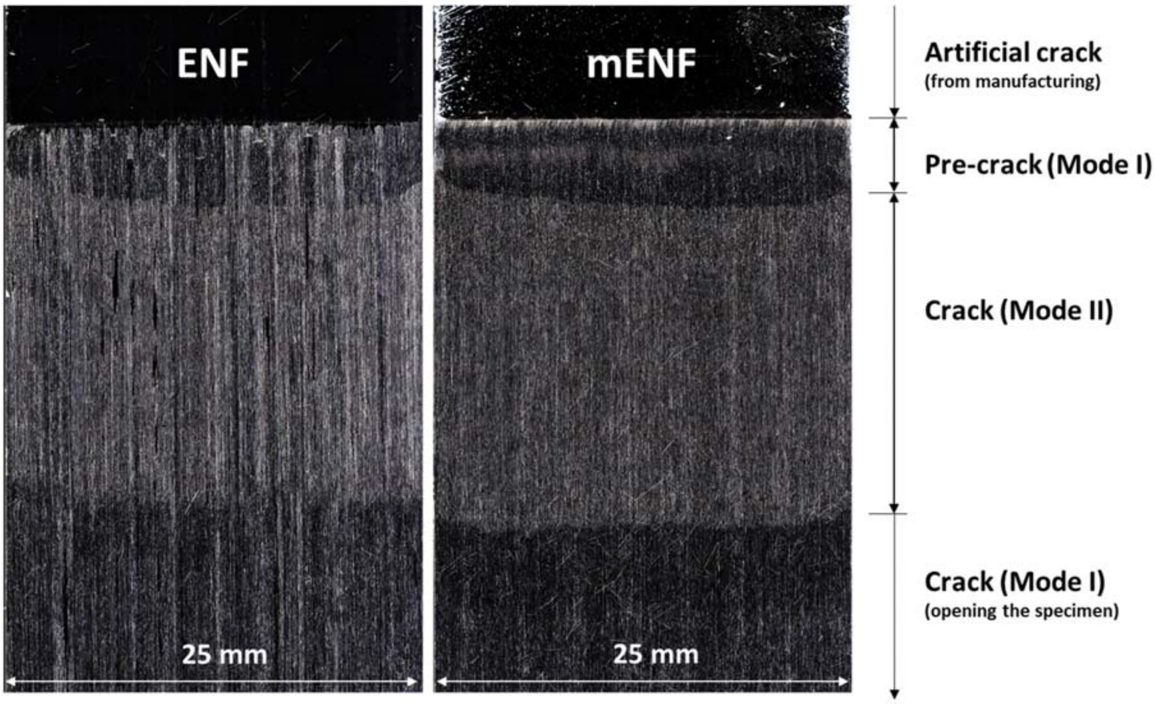


Fig. 7 Microscopic image of mENF crack path



(a) (b)

Fig. 8 Fracture surfaces: (a) ENF, (b) mENF

B. Interpretation

The analysis of the force-displacement diagrams indicates that the geometric modification of the ENF specimen has a minor influence on the stiffness behaviour. However, this may also be caused by inaccuracies in specimen positioning in the test fixture, as demonstrated by the CC-20 and CC-40 force-displacement plots. The force at crack initiation is at a comparable level for both specimen types. It can therefore be assumed that the crack did not propagate through the additional fibre layer. The analysis of the crack tip and the result that the crack in mENF specimens exclusively growths through the additional fibre layer as planned and no difference between the determined characteristic values of ENF (interlaminar) and mENF (intralaminar) could be determined, underlines both the statements of [7] that there is no difference in the CERR between interlaminar and intralaminar for the investigated material IM7/8552. In addition, this supports the statements of [8] that the difference observed in Mode I, when using modified DCB specimens, is due to the influence of so-called fibrebridging.

IV. SUMMARY

It has been shown that the distinction between interlaminar CERR and intralaminar CERR is a highly researched field. There are different definitions of intralaminar crack growth [6], [7]. The definition presented by [6] is followed in the context of this work so that intralaminar crack growth is not associated with the splitting that occurs in a CT specimen. Here, the term intralaminar indicates that the crack propagates exclusively within a single fibre layer. With the method presented by Sato et al. [6], a significant difference between the interlaminar and intralaminar CERR could be observed. This method is limited to dry semi-finished products as the layer in which the crack is foreseen to grow must first be partially impregnated. Since prepregs are already fully impregnated on delivery, a modification of the ENF specimen had to be made to adapt the method according to [6] for laminates made of prepreg. The mENF specimen presented here follows the approach of [6] and allows crack growth to be measured within a single layer. This is achieved by a minimal geometrical adaptation in the form of an additional prepreg layer. This is reduced by the length of the artificial crack. By creating a "starter notch" during the pre-test, it is achieved that in the actual test the natural crack growth takes place exclusively within the additional fibre layer and thus enables the determination of the fracture toughness of a single layer. Thus, a comparison between interlaminar and intralaminar fracture toughness can now be carried out using an almost identical specimen geometry. The test data evaluation also follows the same mathematical assumptions and makes the concept for the determination of the mixed mode TSL based on the DCB, ENF, MMB tests also accessible for intralaminar characteristic values.

FUNDING

This research was supported by the Federal Ministry for Economic Affairs and Climate Action, as part of LuFo – the Federal Aviation Research Programme, in the project: JoinDT [grant number 20W1918F]

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support by Herbert Theilen (Laboratory of Lightweight Design of HAW Hamburg) for the fruitful discussions about manufacturing as well as for the assistance while carrying out the experimental investigations. The financial support by the Federal Ministry for Economic Affairs and Climate Action is very much appreciated by the authors.

APPENDIX

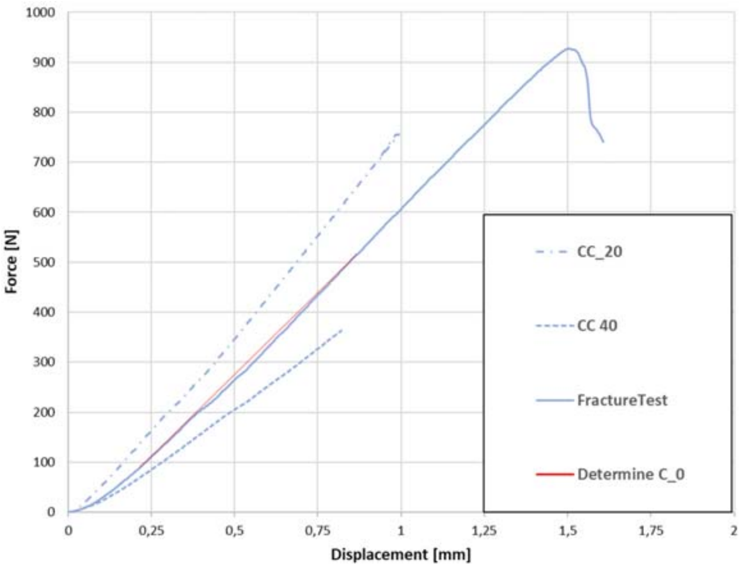


Fig. 9 Force-displacement-curves from mENF 5, including CC-20, CC-40 and linear regression to determine C_0

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