Experimental characterisation of macro-crack propagation in 3D woven composites, size effect and associated damage gradient models

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EXPERIMENTAL CHARACTERISATION OF MACRO-CRACK PROPAGATION IN 3D WOVEN COMPOSITES, SIZE EFFECT AND ASSOCIATED DAMAGE GRADIENT MODELS

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Abstract

The critical energy release rate G_C was identified on 3D woven carbon/epoxy composites, using CT and SENB specimens. The analysis relied on multiple instrumentation methods to monitor the crack growth and compared several methods for the crack detection and G_C estimation in order to obtain a robust process. Variation of G_C with the specimen size and shape was highlighted. A non-linear framework was then proposed to describe fracture propagation in the material, relying on the existence of an internal length. The use of at least two material parameters G_f, an asymptotic fracture release rate, and c_f, a characteristic internal length, is necessary to completely describes the variation of the apparent G_c with the specimen shape and scale. The use of non-linear models introducing internal lengths and controlling the dissipated energy is then investigated to transcribe the experimental results.

1. Introduction

The constant rise of 3D woven composite materials use in aeronautics implies a good understanding of their fracture properties, a clear identification of the related parameters and a robust transfer to numerical simulations. These materials exhibit a high level of complexity (heterogeneity, high anisotropy, influence of the local structure) and the methods used to characterize their mechanical behavior must be subjected to a special care.

The characterization of a macro-crack propagation in 3D woven composites with polymeric matrix is a key asset for the future design of aircraft parts. It is usually done through the identification of the critical energy release rate G_C, which represents the energy released by the structure during the crack propagation divided by the surface area created.

In this work, an experimental study will be performed on both Compact Tension (CT) and Single Edge Notched Beam (SENB) specimens, on a highly unbalanced 3D woven composite (section 2). The special care put on the data analysis will be presented, especially the crack-tracking using several measurement techniques, in order to improve the measurement's reliability (section 2.2). Several methods will be applied to the tests data in order to estimate G_C, under condition that they don't imply the validity of Linear Elastic Fracture Mechanic (LEFM) or any other spurious assumption (section 0).

In this paper we will study, for this material, the potential variations of the estimated G_C value depending on the test geometry and size. The influence of the size effect will be investigated by scaling the specimen with in-plane homothetic size factors from 0.75 to 2.5 with respect to the

standard. The difference with the LEFM will be pointed out, which can be explained by the presence within the material of a characteristic length affecting crack propagation [1] and justifies a non-linear framework for the analysis (section 3.1). G_C thus becomes an apparent value that cannot, by itself, characterise the macro-crack propagation. At least 2 parameters are necessary: c_f an internal length and G_f an asymptotic value of G_C when the size of the specimen is large compared to the internal length of the material.

For further details on the mechanisms responsible for the introduction of an internal length, CT tests carried out in a X-ray tomograph and post-fracture SEM images will be set-up (section 3.2). Two internal lengths characterizing the crack process and induced by the micro-structure of the material will then be introduced and an adapted non-linear model will be presented. The identification of the parameters c_f and G_f will accurately describe the experimental results (section 0).

Finally, we will discuss the application of those results into numerical simulations using models introducing internal lengths in order to transcribe the geometry and size effect (section 4).

2. Experimental G_C estimation using stress-gradient specimens

2.1. Experimental Setup

The tests were carried on a highly unbalanced 3D woven composite provided by Safran Aircraft Engines. The specific characteristics fall under industrial condentiality, therefore all the results of this study are normalized. This material is manufactured using an epoxy matrix and carbon fibers. The crack will propagate along the warp direction, characterizing the failure of the weft yarns: this facilitates the good execution of the test and especially allows a straight crack path strongly guided by the warp yarns.

The estimation of the critical energy release rate G_C is performed using stress-gradient specimens exhibiting a stable crack propagation [2]. The compact Tension (CT) and Single Edge Notched Beam (SENB) are used and the configurations for size T1, defined from metallic or ceramic ASTM standards [2], as reported in Figure 1.

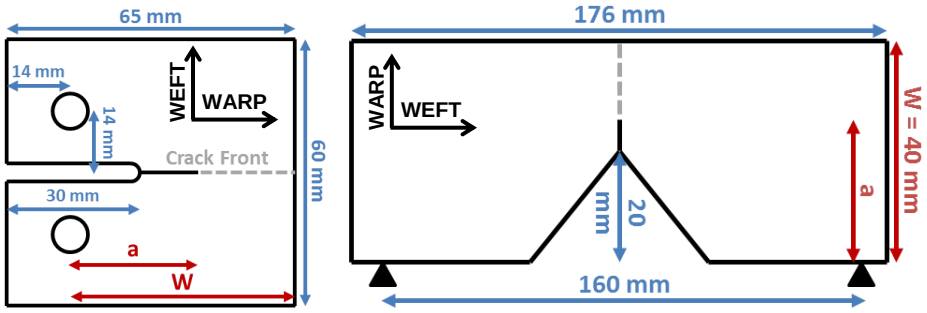

Figure 1. CT and SENB standard specimens (Size 1)

Careful consideration should be given regarding the specimen design in order to avoid undesired failure mode:

- The propagation must occur in a quasi-static manner in order to obtain multiple propagation points and thus a sufficient confidence in the experimental results. For this, the pre-crack should be long enough so that $\partial G/\partial a \leq 0$, where G is the energy release rate for a given loading condition and a the crack length. This condition leads to different pre-crack lengths for the various configurations, presented in the Table 1.
- Undesired compression failure at the back of the specimen [4] should be avoided by using a specimen with large enough dimensions. Indeed, if the crack propagates under a constant value G_C, the compressive stress at the back of the specimen evolves as $1/\sqrt{W}$ where W is the characteristic size of the specimen [5]: the bigger the specimen, the later compressive damage may occur.

- On the other hand, the thickness t of the specimen should be sufficient compared to the W in order to avoid failure by buckling during the CT tests, with is prevented here by the use of specimens with a thickness t equals to 8mm.

Following those requirements, the various configurations of CT and SENB specimens tested are presented in Table 1.

Table 1. Summary of the stress-gradient specimens tested and associated instrumentation

Specimen Type	Size	W [mm]	Pre-crack [mm]	Quantity	DIC	OT	IRT	μ-T
CT	T0.75	38.2mm	4mm	2	x	x		IS
	T1	51mm	5mm	2	x	x		PT
	T1.5	76.5mm	6mm	2	x	x	x	PT
	T2	102mm	8mm	2	x	x	x	PT
	T2.5	127.5mm	10mm	3	x	x		PT
SENB	T1	40mm	7mm	3	x	x		PT

2.2. Crack Length Measurement

Several instrumentation methods were used to follow the crack tip position a, as this value is a key parameter for the estimation of the energy release rate. The tests are instrumented using Digital Images Correlation (DIC), Optical Tracking (OT), passive Infra-Red Thermography (IRT) and X-ray tomography (μ-T), either Post-Test (PT) or In Situ (IS). The data from those instrumentations are compared in order to avoid any dependency to a specific method and consolidate the results, as they each rely on a specific kind of information : visible macro-crack at the surface (OT) or inside the specimen (μ-T), mechanical displacement fields (DIC) or thermal heating at the propagation points (IRT).

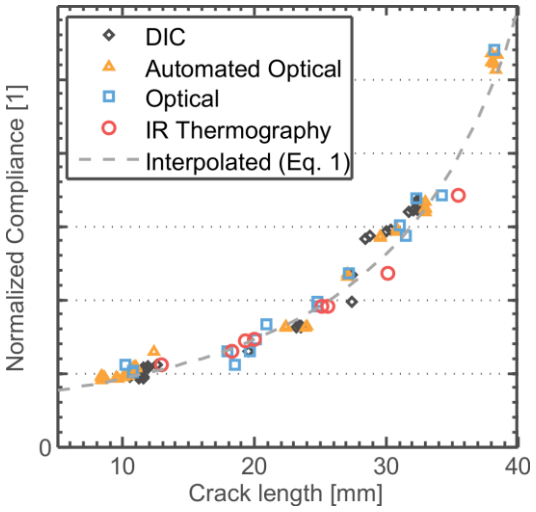

Figure 2. Comparison of the crack length measurement

The several instrumentation analysis methods have been automated and the results are presented in Figure 2. The deviation observed between the methods is of the same order of magnitude than differences observed on each side of the specimen and remains small in comparison to the total length propagation. More importantly, as only the crack length variation is used for the G_C estimation methods later presented (see section 0), no impact is subsequently observed on the resulting energy release rate estimation. For the present study, fast automated methods available at any time, i.e. the automatic optical tracking and DIC tracking, have been used and confronted on each side to obtain a reliable measurement.

2.3. G_C estimation

The characterization of fracture propagation is usually done via an energetic approach, which tries to estimate the critical energy release rate G_C. In the general framework of LEFM, G_C does not depend on the geometry or the crack length and is assumed to be a material property. The variation of G_C with the geometry and size is here investigated through the analysis of the different tested configurations, especially the in-plane homothetic sizing of the CT specimens.

Several methods for estimating the critical energy release rate are available in the literature [2], [3]. Two methods are selected here based on the fact that they don't rely on any unfounded assumption in the context of 3D woven composite testing.

Area Method: It consists in a direct estimation of the elastic energy variation between two propagation points over the crack surface created.

$$G_C = \frac{P_1 d_2 - P_2 d_1}{2\, t\, \Delta a} \tag{1}$$

with P_i and d_i the load and displacement at a propagation time i, t the thickness and a the crack length.

Modified Compliance Method (MCM): The energy change can also be obtained in a continuous manner by using the change in the compliance with the crack length evolution:

$$G_C = \frac{P_C^2}{2t}\frac{dC}{da} = \frac{P_C^2}{2tW}\frac{dC}{dx} \tag{2}$$

with $C = d/P$ the compliance and $x = a/W$ the normalized crack position. It requires interpolating the compliance at each measured crack length in order to compute the derivate. The interpolating function is chosen as:

$$C(x) = \frac{C_0}{(x_m - x)^p} \tag{3}$$

which is based on by the evolution of the compliance under LEFM assumptions [6], so that parameters are expected to be $x_m \approx 1$ and $p \approx 2$. Those two methods are in good agreement and don't introduce any bias in the results. On the contrary, the VCCT method or methods using interpolation of the stress intensity factors were excluded. These methods are in fact conducted under LEFM assumptions: they use numerical simulations assuming that the material behavior stays elastic around the crack.

A variation with the size and geometry of the estimated G_C value is highlighted in Figure 3. It invalidates the use of the general LEFM framework for describing the crack propagation in 3D woven composite, although this phenomenon isn't usually exhibited in laminated composites. An adapted framework describing the evolution of the apparent G_C value with the shape and size of the specimen is thus needed, as G_C can no longer be considered as a material property.

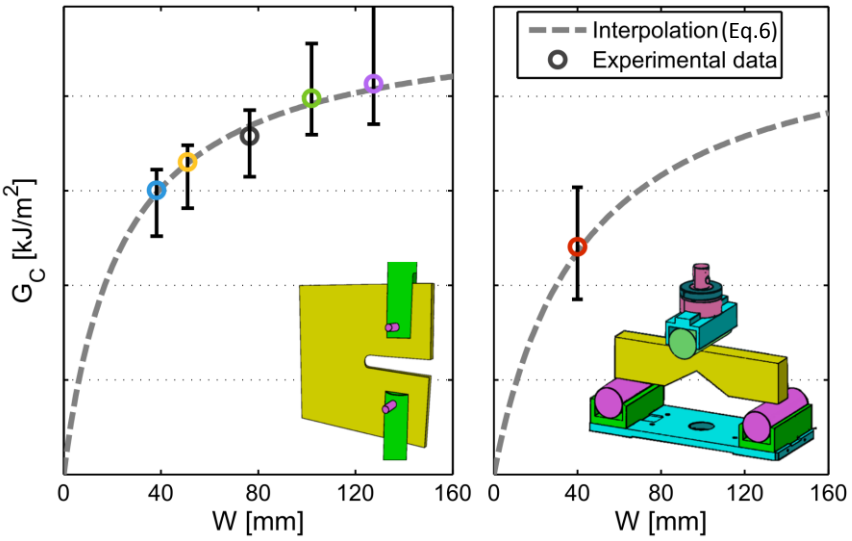

Figure 3. Experimental results of the G_C estimations obtained from CT and SENB specimens

3. Non-linear framework for crack propagation

3.1. Apparent G_C value in presence of size and geometry effect

The size effect in fracture has already been studied by Bazant, especially in the case of concrete [1]. The scaling laws when studying homothetic specimens can in the general case, in presence of material internal lengths guided by the meso-structure and affecting the crack propagation, be expressed through energetic considerations as [1] :

$$G_C = \frac{G_f}{1 + W_0/W} \tag{4}$$

where G_f is the asymptotic value of G_C : when the specimen size is large enough it identifies as the LEFM value. W_0 is a transition size of the specimen from a crack propagation driven by local mechanisms to a propagation under brittle conditions and described by the LEFM theory. W_0 depends on an internal length c_f, considered as a material value. The mechanisms responsible for this behavior must be exhibited in order to explicit the dependency of G_C to c_f and to compare the values obtained on specimens with different geometrical singularities.

3.2. Investigation of the crack mechanisms

For this purpose, complementary tests are performed on the same 3D woven material:

- Scanning Electron Microscope (SEM) views of the crack profile are obtained from fractured specimens to investigate the distribution of the pull-out length of the yarns on both sides of the average crack surface. This distribution does not seem to vary with the geometry or the size of the specimen and happens over a characteristic length of a few millimeters (see Figure 5.). This introduces a notion of crack width, which is a compatible mechanism for the evolution of the apparent G_C value.
- In-situ X-ray tomographic tests are also performed on CT specimens using a special assembly designed to carry out the CT tests inside the tomograph chamber without interfering with the X-rays. The progressive failure of the fiber inside the yarn can be observed, occurring over the range of two columns of waft yarns: as showed in Figure 4. A sectional cut through the yarn column currently transmitting loads shows that some of the yarns in that column are already cracked while others appear to be intact. This introduces, along with the numerous transverse cracks and inter-yarn debounding observed, a notion of process zone along which failure happens in a progressive manner. The characteristic size of this process zone is of the same order of magnitude as the length between two weaving columns.

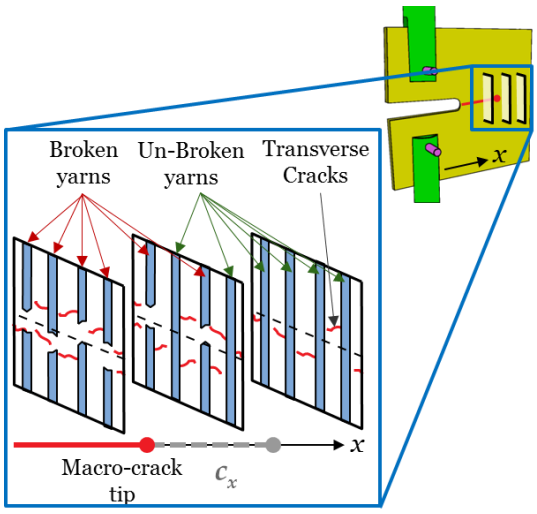

Figure 4. Diagram of the crack built-up obtained from in-situ X-ray tomography

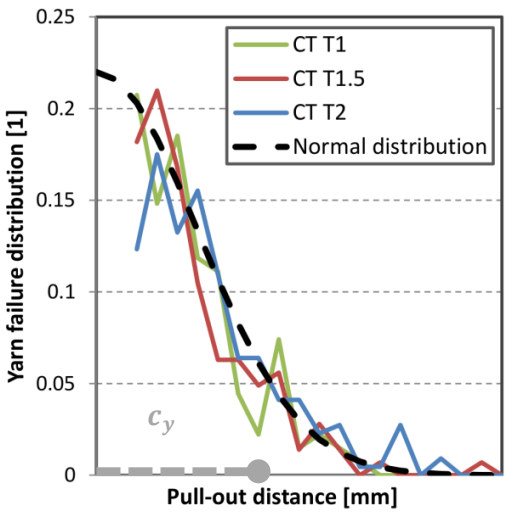

Figure 5. Distribution of the yarn pull-out distance for different CT specimens

The identification of those mechanisms can explain the evolution of G_C with the geometry and size of the specimen and calls for an adapted fracture framework which introduces two internal length: c_x, a process-zone length introduced along the crack path and c_y, a crack width perpendicular to the crack surface.

3.3. Equivalent configuration using two internal lengths

Such a framework can be introduced by considering equivalent linear elastic (LE) configurations (see Figure 6.). In this approach, the real configuration of the crack, which presents a non-linear area around the macroscopically observed crack, is approximated by an equivalent elastic configuration that leads to identical mechanical fields away from the crack and identical load/displacement curves. This configuration is obtained by introducing a shift c_x between the observed macro-crack and the equivalent crack and by giving a width c_y to the crack. Both c_x and c_y are assumed to be material properties which do not vary with the crack propagation or the geometry.

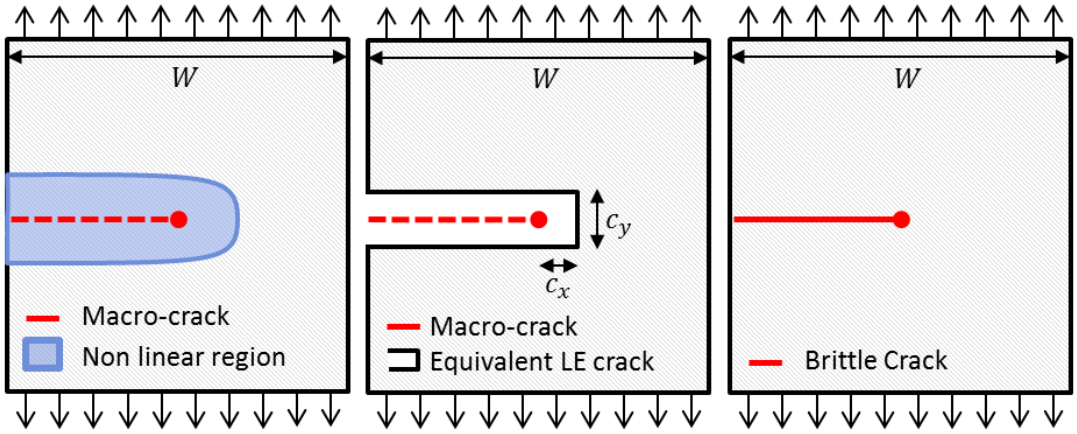

Figure 6. Real configuration, Equivalent Elastic configuration and Brittle configuration

For brittle cracks, the energy release rate can be generally expressed in the form of [1] :

$$\text{Brittle configuration :} \qquad G_C = \frac{P_C^2}{WE'} g(x) = \frac{P_C^2}{WE'} g(x, 0, 0, \dots) \tag{5}$$

where E' is an equivalent modulus of the material and g a dimensionless function that only depends on the shape of the stress fields around the crack tip through the normalized position x of the crack. This configuration only takes into account the macro-crack surface and neglects the presence of non-linearities around the crack tip. It fits the usual definition of G_C defined by the dissipated energy over the created crack surface and applied in section 2.

The brittle configuration can be considered as a particular case of a general framework with the others non-linear parameters taken equal to zero (Eq. 5). The equivalent LE configuration allows a more accurate description of the real fracture process and can introduce the internal lengths c_x and c_y through dimensionless arguments:

$$\text{Equivalent LE configuration :} \qquad G_f = \frac{P_C^2}{WE'} g\left(x, \frac{c_x}{W}, \frac{c_y}{W}\right) = \frac{P_C^2}{WE'} g\left(x + \frac{c_x}{W}, \frac{c_y}{W}\right) \tag{6}$$

Here, g takes two parameters: c_x is introduced via a shifting of the crack tip position x. The fracture energy release rate G_f thus defined takes into account all the failure phenomena and can be taken as a material property. The evolution of the apparent energy release rate G_C is then obtained by:

$$G_C = \frac{G_f g(x, 0)}{g\left(x + \frac{c_x}{W}, \frac{c_y}{W}\right)} \cong \frac{G_f}{1 + \frac{\partial_{cx} g(x)}{g(x)} \frac{c_x}{W} + \frac{\partial_{cy} g(x)}{g(x)} \frac{c_y}{W}} \tag{7}$$

which is similar to the Eq. 4 for $W_0(c_x, c_y) = \partial_{cx} g(x)/g(x) c_x + \partial_{cy} g(x)/g(x) c_y$. The function g and its derivatives over the internal lengths can be obtained from linear elastic simulations, by varying the position and width of the crack inside a given structure (see Figure 7.), and can be compared to the values given in crack hand books [6] for the derivative along the x value.

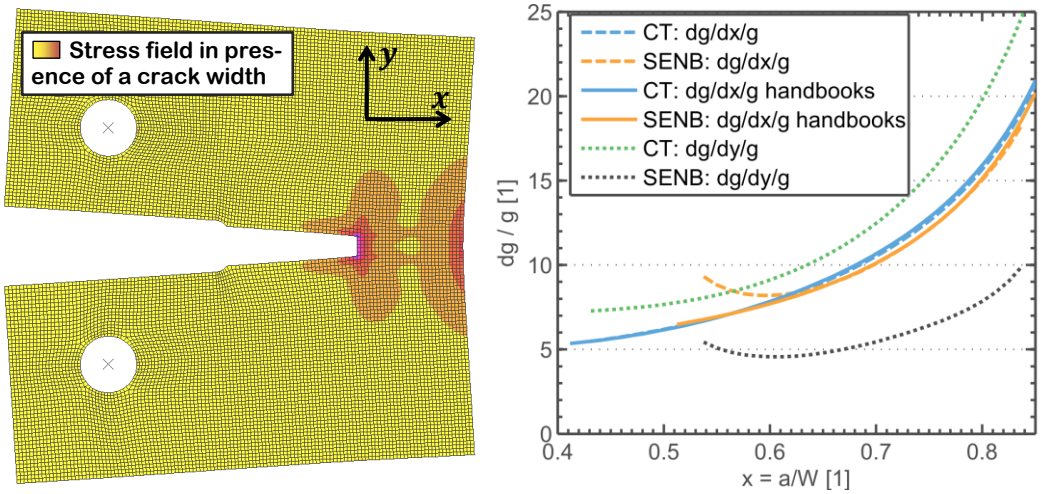

Figure 7. Numerical determination of the g function for CT and SENB specimens

Once the g functions have been determined for CT and SENB specimens, the identification of the material parameters G_f, c_x and c_y accurately describes the evolution of the apparent G_C estimated during the experimental campaign (see the dashed line on Figure 3.). It explains the increasing value of G_C with the specimen size and the differences between CT and SENB specimens. The values of c_x and c_y are in good agreement with the order of magnitude of the phenomena observed in section 3.2.

In equation 7, the evolution of G_C is determined by:

- Parameters specific to the studied configuration, which need to be modified for every test: $W, x, g(x)$ and its derivatives;
- Parameters specific to the material, which are identified once for all: G_f, c_x and c_y.

This framework can be used to predict the G_C value for any given structure once the g function has been determined through linear elastic simulation. Note that this model can also be extended to any number of internal lengths as long as their influence on the equivalent elastic configuration is explained.

4. Use in numerical simulations

When trying to transcribe the crack propagation in 3D woven composites, the experimental results lead to the use of fracture models introducing internal lengths and in which the energy can be controlled in order to obtain the same size and geometry effects.

Numerical simulations of the behavior of composites are usually performed using continuous damage models [7]. Those models introduce internal variables transcribing the progressive failure of the fiber and offer an adapted framework for describing the transition from diffuse damage mechanisms to the apparition of a macro-crack, without having to pre-determine the crack path.

However, it has been demonstrated that the stress-strain softening introduced to account for the fiber failure variables leads to ill-defined problems which compromise the simulations [8]. Moreover, those models don't introduce internal lengths and don't exhibit the size effect observed during the tests.

Thus, the focus should be put on gradient or non-local damage models, which both make up for the ill-posed problem and introduce internal lengths characterizing the fiber yarns failure. Several approaches can be found in the literature (integral non-local [9], gradient non-local [10], phase field [11]). The practical choice should be guided by the fact that the model leads to an evolution of the apparent critical release rate G_C with the specimen size and geometry which match the one met in the

experimental campaign.

5. Conclusions

An experimental characterization of the crack propagation was performed on 3D woven composites, using CT and SENB specimens. A special care was put on the crack length measurement and critical energy release rate G_C estimation in order to assure a robust methodology. Several configurations were tested in order to determine a potential effect of the specimen size and geometry. The results show a strong evolution of the apparent measured G_C, which in particular increases with the size of a specimen until G_C reaches an asymptotic value, when the effects of the micro-structure is of a small enough scale compared to the mechanical fields.

This result compromises the use of the Linear Elastic Fracture Mechanic to describe the crack propagation in 3D woven composites and necessitates the introduction of internal lengths influencing the crack formation. The investigation of the cracking process highlighted the presence of two characteristic material length linked to the micro-structure: a shifting c_x along the crack axis due to a process-zone ahead of the macro-crack tip and a crack width c_y transcribed by a yarn failure and pull-out distributed across the main crack surface.

A non-linear fracture model was then proposed taking into account the influence of those two mechanisms on the apparent G_C value at the macroscopic scale. The identification of the internal lengths c_x and c_y are consistent with the characteristic size of the phenomena observed in the tests.

Those results guide the choice of numerical models to describe the crack propagation in 3D woven composite: internal lengths should be introduced in those models and the dissipated energy must be controlled in order to exhibit the same size and geometry effects than have been highlighted in the experimental campaign. Non-local continuous damage models could be used.

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