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Evaluation of delamination propagation speed by means of high speed infrared thermography during low velocity impact tests

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Abstract

Delamination is an important damage mechanism for laminated composite materials, particularly when out-of-plane loading is considered. Its experimental characterisation is generally based on standard tests in which a crack propagates within an interface. The mechanical properties obtained can vary according to the crack propagation speed. To the author's knowledge, few studies have evaluated the delamination propagation speed for classical loading cases such as low velocity impacts. Therefore, the present study focuses on the real-time measurement of the delamination area evolution during low velocity / low energy impact tests on T700GC/M21 cross-ply laminates using high-speed infrared thermography. The delamination propagation speeds obtained in this study vary as a function of impact velocity and direction of propagation.

Keywords: Delamination, Layered materials, Time-resolved tracking, Infrared Thermography, low velocity impacts

1. Introduction

Delamination is a key damage mechanism in composite structures, particularly when out-of-plane loadings such as impacts are considered. Various experimental protocols have been proposed to evaluate the material properties associated with this damage mechanism [1, 2, 3]. For example, to characterize the fracture toughness in mode I, DCB tests are performed. For these tests, the delamination crack usually propagates at the interface between two 0° plies. This particular stacking sequence ($[0^\circ]_{16}$) simplifies the experimental set-up and the data reduction. However, when dealing with impact loadings, the fracture toughness rate dependency has to be experimentally considered. A first limitation comes from the fact that there is currently no clear agreement in the literature concerning the evolution of the fracture toughness with the loading rate [4]. Another difficulty comes from the fact that there are currently only a few studies in the literature dealing with the experimental investigation of the delamination crack speed during impact loadings [5, 6, 7]. It is due to the fact that usually, the measurement techniques used in these tests do not have a sufficient temporal resolution to capture this quantity and/or are performing post-mortem analysis of damage extension. Consequently, the crack propagation speeds that have to be targeted in experimental investigations such as DCB tests remain an open question. To the authors' knowledge, the last paper trying to address that question is the one of Minnaar and Zhou [7]. In the introduction of the paper, they do an extensive

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review of the previous studies dealing with time-resolved monitoring of damage progression in layered materials. A specific focus on delamination crack propagation speed is performed here, for more details regarding time-resolved monitoring of other damage type progression in layered materials the reader can refer to Minnaar and Zhou [7]. Two measurement techniques have been successfully used in the literature to evaluate delamination crack propagation speed in composite materials under impact tests: high-speed photography [5] and full-field laser interferometry [6, 7]. In the present work, a high-speed infrared camera is used during low-velocity impact tests in order to evaluate delamination crack propagation speed during the tests. The goal is to evaluate the delamination area growth for different impact velocities/energies. The main interest of this new method is its relative simplicity of installation, as it only requires adding a high-speed infrared camera to the test setup in order to monitor the non-impacted surface of the composite plate.

2. Materials and methods

The experimental setup used in this study has been recently published [8]. A modified Instron Dynatup impact machine allows monitoring of the non-impacted surface of the composite plate with a high-speed infrared camera. A camera configuration close to the one used in the previous study [8] has been used. The details of the optical system used are given in Table 1.

Table 1: Optical setup used in this study

Camera	TELOPS Fast M3K
Lens	Janos ASIO 50 mm F/2.3 MWIR
Images resolutions	128×100 pixels
Frame rate	12 000 Hz
Integration time	$9.96 \mu\text{s}$
Pixel size	0.43 mm
Field of View	$55 \times 43 \text{ mm}^2$

Tests for different energy levels are considered in the sequel: 5.75 J, 9.65 J and 19.55 J. As the same hemispherical impactor of 16 mm diameter and 13.01 kg is used, the energy level variation is obtained by modifying the initial drop height and hence impact velocity. The three considered speeds in this study are 0.94 m.s^{-1} , 1.22 m.s^{-1} and 1.73 m.s^{-1} . The speed of the impactor just before the impact is measured on the testing machine with a photoelectric sensor.

The material considered is the T700GC/M21 which is a carbon/epoxy composite material. The ply weight area is 268 g.m^{-2} . In the previous study [8], a quasi-isotropic stacking sequence has been used to illustrate the ability of this measurement technique to capture damage initiation and growth (matrix cracking and delamination). For this specific work dedicated to delamination crack speed observation, a well-studied cross-ply stacking sequence is used: $[0_3/90_3]_s$. The main interest of this configuration is that only the two interfaces between the 0° and the 90° plies may be subjected to delamination. This greatly simplifies the data reduction. Moreover, based on the results available in the literature, this cross-ply stacking sequence develops a very typical delamination pattern that will allow us to validate the final delamination shape obtained with the infrared images.

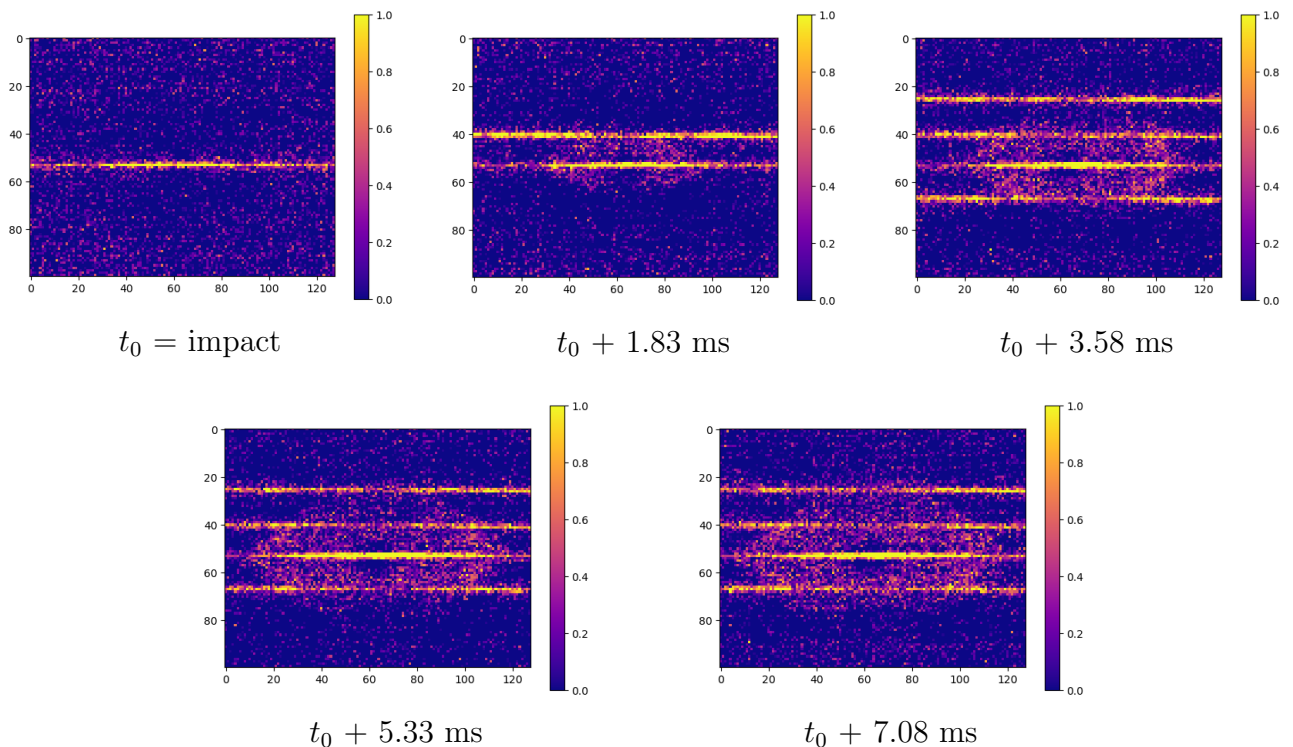


Figure 1: Raw apparent temperature increase maps of the 0.94 m.s^{-1} test at five different times.

3. Results

Figure 1 illustrates the phenomenology of the damage development in the case of the 0.94 m.s^{-1} test. The impact occurs in the middle of the image. There is a very fast appearance of a “horizontal” band, which correspond to the propagation of a matrix crack under the impact point. Then, a characteristic arrow-shaped area for these laminates appears and expands toward the borders of the images in the 0° direction. During this expansion, other “horizontal” lines appear. In the case of the 0.94 m.s^{-1} impact test, the delamination area is fully contained in the field of view. However, for the 1.22 m.s^{-1} and 1.73 m.s^{-1} impact tests, the final delamination area is larger than the field of view of the camera, so only the first stages of the propagation can be studied.

In order to quantify the delamination process that occurs on the back of the composite plates subjected to impact, the apparent temperature maps are computed. To do this, a reference image taken before the start of the test is subtracted from all the images captured by the IR camera. As the apparent increase in temperature due to the delamination process is small, the temperature measured is close to ambient temperature and the integration time used is short, the images recorded are quite noisy. So, before the areas corresponding to the delamination can be determined, the maps need to be filtered. In the present work, the apparent temperature maps are filtered using the following process:

1. a temporal first-order lowpass Butterworth filter with a cutting frequency of 600 Hz is applied to each pixel independently,
2. each pixel values are normalized with respect to the maximum value recorded for that pixel during the test. This processing helps for the visualization near the “horizontal” bands.

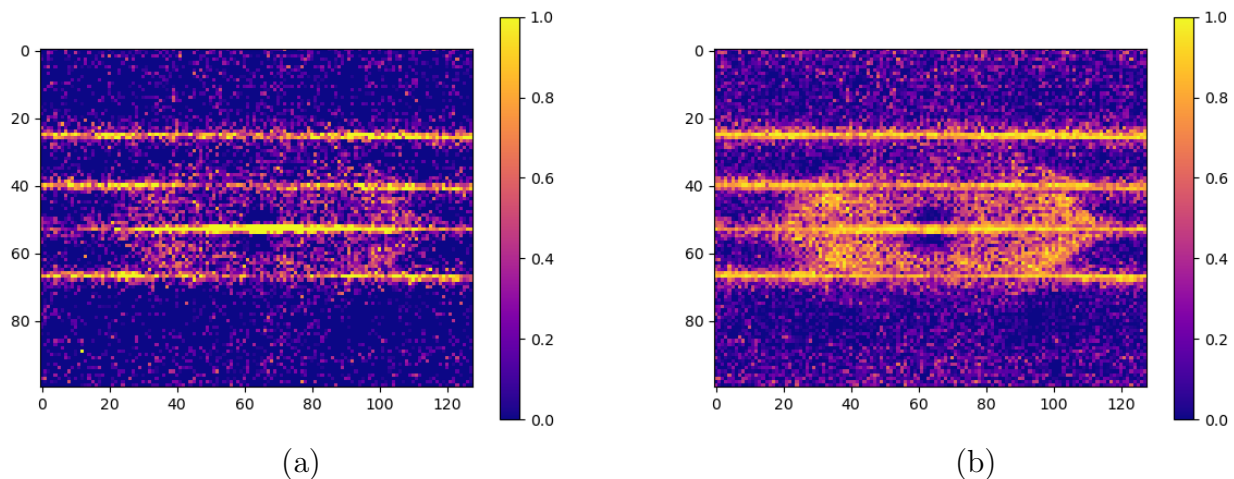


Figure 2: (a) - Raw apparent temperature increase map 4.25 ms after impact in $^{\circ}\text{C}$ - (b) - filtered image after temporal lowpass Butterworth filter and pixel by pixel normalization.

Figure 2 illustrates the effect of the process used to better visualize the damaged area. Once this image processing is done, the damaged area has been manually selected using a lasso tool since selection using a threshold criterion would also select the high-temperature “horizontal” bands, which are not due to delamination but to transverse cracks in the external ply. Then, using these areas, it is possible to compute the temporal evolution of the delaminated area.

Using this methodology, the delamination propagation can be quantified. One should note that for the 1.22 m.s^{-1} and 1.73 m.s^{-1} impact tests, the area tracking is stopped when the delamination surface reaches the limits of the field of view. Figure 3 illustrates the results obtained in terms of distances between the outer boundaries of the delaminated areas and the impact position, propagation velocity of the delaminated area and area delaminated. For all tests, $t = 0$ corresponds to the impact. The graphs are plotted for the time at which the delamination becomes clearly visible in the images. The delamination velocity appears to be anisotropic, so it is here presented in two directions, denoted “horizontal” and “vertical”. Maximal velocities computed are 6.8 m.s^{-1} , 10.4 m.s^{-1} and 13 m.s^{-1} for respectively 0.94 m.s^{-1} , 1.22 m.s^{-1} and 1.73 m.s^{-1} impact tests. They are in the “horizontal” direction. In addition to these instantaneous quantities, Table 2 summarizes global quantities computed over the whole recording. In order to better compare the tests, global quantities are also compared for delamination ups to 500 mm^2 , which approximately corresponds to a quasi-linear propagation for all tests. These results are summarized in Table 3.

Unfortunately, there is no reference against which these results could be compared. Indeed, as stated in the introduction, there are only a few experimental works that deal with this topic, and they have been done either for different stacking sequences or for higher impact velocities. For instance, in [7] delamination speeds between 4.5 m.s^{-1} and 30 m.s^{-1} are found for impact speeds between 3.5 m.s^{-1} and 6.7 m.s^{-1} depending on the distance to the initial impact on ENF $[0^{\circ}, 90^{\circ}, 0^{\circ}]$ specimens. In [6] a 1 m.s^{-1} impact is performed on a quasi-iso stacking sequence, the delamination speed found is in the order of 500 m.s^{-1} .

4. Conclusions

In the present work, low velocity impact tests on cross-ply T700GC/M21 composite have been instrumented using a high-speed infrared camera in order to monitor the delamination

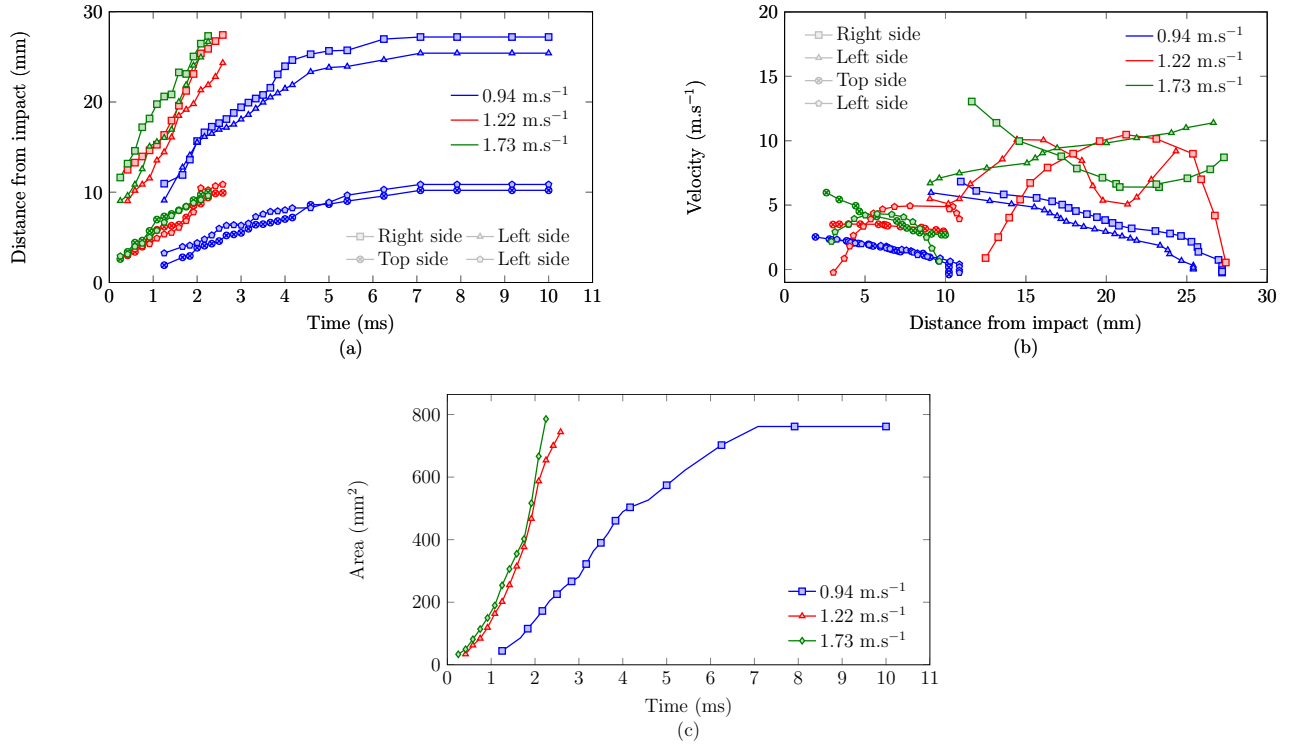


Figure 3: Progression of the higher temperature area in terms of - (a) - horizontal and vertical displacements - (b) - horizontal and vertical velocities - (c) - Area. In graphs (a) and (b) the colours denote the impact velocities and the marks the direction of the motion. The estimate of the propagation velocity given in Figure 3-(b) is computed by using cubic spline fitting to avoid noise amplification in the differentiation.

Table 2: Quantities of interest for the tests.

	0.94 m.s ⁻¹	1.22 m.s ⁻¹	1.73 m.s ⁻¹
“Horizontal” displacement recorded	16.2 mm	15.1 mm	17.6 mm
“Vertical” displacement recorded	7.9 mm	7.3 mm	7.0 mm
Propagation time observed	8 ms	2.6 ms	2 ms
Mean “horizontal” velocity ^a	2.0 m.s ⁻¹	5.8 m.s ⁻¹	8.8 m.s ⁻¹
Mean “vertical” velocity ^a	0.87 m.s ⁻¹	2.82 m.s ⁻¹	3.52 m.s ⁻¹
Max area observed	761 mm ²	744 mm ²	785 mm ²
Mean area growth rate	95.1 mm ² .s ⁻¹	286.1 mm ² .s ⁻¹	392 mm ² .s ⁻¹

^aOne should keep in mind that for the 0.94 m.s⁻¹ test, the whole delaminated area is contained in the images, so on the observed time the velocity ends up reaching zero. So the average velocity in this case is not directly comparable to the average velocity in the two other tests, for which only the propagations up to the time at which the delaminated areas reach the image boundary are observed.

process. Overall, it is found that this optical method enables tracking of the delamination propagation and gives access to the temporal evolution of this process. For the three impact velocities tested 0.94 m.s⁻¹, 1.22 m.s⁻¹ and 1.73 m.s⁻¹, average propagation velocities of 2.0 m.s⁻¹, 5.8 m.s⁻¹ and 8.8 m.s⁻¹ respectively have been observed in the main direction. These results give both target delamination rates for future characterization work and will serve in comparison with numerical simulations.

Table 3: Quantities of interest for the tests up to a propagation of 500 mm².

	0.94 m.s ⁻¹	1.22 m.s ⁻¹	1.73 m.s ⁻¹
“Horizontal” displacement recorded	12.0 mm	11.0 mm	12.2 mm
“Vertical” displacement recorded	6.1 mm	5.5 mm	6.3 mm
Propagation time observed	3.01 ms	1.54 ms	1.63 ms
Mean “horizontal” velocity	4.0 m.s ⁻¹	7.16 m.s ⁻¹	7.47 m.s ⁻¹
Mean “vertical” velocity ^a	2.28 m.s ⁻¹	3.83 m.s ⁻¹	3.32 m.s ⁻¹
Mean area growth rate	165.8 mm ² .s ⁻¹	324.9 mm ² .s ⁻¹	306 mm ² .s ⁻¹

Conflict of Interest The authors declare no conflict of interest.

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