NEW TEST SET-UP FOR MEASURING RATE-DEPENDENT MODE-I DELAMINATION PROPERTIES OF UNIDIRECTIONAL AND WOVEN COMPOSITES

S.W.F. Spronk[1,2], J. Degrieck[1], F.A. Gilabert[1,2], F. Allaeys[1] and W. Van Paepegem[1]

[1]Department of Materials Science and Engineering, Faculty of Engineering and Architecture, Ghent University, Technologiepark-Zwijnaarde 903, B-9052 Zwijnaarde, Belgium
Email: Siebe.Spronk@UGent.be, Web Page: http://www.composites.ugent.be
[2]SIM vzw, M3 Program, Technologiepark-Zwijnaarde 935, B-9052 Ghent, Belgium

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Abstract

Impacts are highly dynamic events. Quasi-static test- and data reduction methods can thus not be used to characterize the response under impact, especially when the examined material is strain-rate sensitive. Delamination is a dominant failure mechanism in composite materials and the role played by the strain-rate in the material's integrity has to be studied under realistic load conditions. This work presents a new experimental setup designed to investigate the delamination process in mode-I when the specimen endures an impact load. A contactless optical technique is used to track the position and rotation of the specimen during the test. A finite element model is developed with the aim of correlating the features of the dynamic response with the value of fracture toughness. This experimental-numerical approach shows the importance of the inertia effects, which are clearly reflected on the speed of delamination. An adequate data reduction process is required to get a reliable value of the fracture toughness.

1. Introduction

By definition, impact events do not occur at quasi-static deformation rates. If composites are to be applied in automobiles effectively, their failure behaviour at impact rates of deformation needs to be known, especially for their most notorious failure mode: delamination. There is evidence for the variation of mechanical properties of composites with strain rate [1–3]. There is, however, no general consensus in the literature on whether the mode-I fracture toughness of composites increases or decreases with delamination speed [4]. The goal of this work is to develop a setup which is suitable to assess the rate-dependence of delamination properties of composites in mode I. Automotive-grade carbon/epoxy and glass/PA-6 material systems are used to evaluate the setup, either of them in both unidirectional and woven configurations.

Several set-ups have been proposed in the literature to perform dynamic delamination tests on composites, roughly classifiable in three categories.

1. The first category makes use of a screw-driven or a hydraulic universal testing machine in two different ways. Either a double cantilever beam (DCB) specimen is mounted directly in the clamps and a number of crosshead speeds are applied [5–13], or the machine is used indirectly to excite a structure that in turn loads the specimen with springs [14] or hinge arms [15].
2. The second category implements a drop tower, with variants that adapt it to excite a DCB specimen [16, 17] or a simple cantilever beam (SCB) specimen [11], a variant which should produce mode-I loading by out-of-plane impact of a cracked plate [18], or a variant that uses a specially designed specimen to fit in a Charpy impact setup [19].

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3. The third and final category uses a split Hopkinson pressure bar where a wedge cleaves into the crack of a DCB specimen [20].

2. Method

The authors of this work propose a drop-tower-based setup. This choice implies that some adaptation is needed to transform the normally compressive load applied by the weight to a tensile load that pulls two parts of a composite laminate apart. At higher excitation velocities, a low mass of moving parts is usually recommended, leading to a need for small structures. The compliance in large, light structures would namely lead to oscillations in load introduction [15]. In contrast to other researchers' work to delaminate composites using a drop-tower, the load introduction is performed *through* the composite specimen with a slender pin (figure 1) rather than *around* the specimen with a larger structure as is done in [16] and [17]. This choice requires to make a hole in the specimen as well as in the top block, see also figure 2, which comes with the advantage of an easy to align system that produces a clean specimen excitation, free of torsion. The top block rests in a support structure and can rotate around its axis, the bottom block is left free to move. The structure design allows the use of specimen outer dimensions which follow the ASTM standard for mode-I delamination testing [21].

Data acquisition using the load cell of the drop tower to which the pin is attached is not expected to lead to satisfactory results because two reasons. Firstly, there is inherent noise when the force is measured this way [16] and secondly, permanent contact between the impactor pin and the bottom block is not guaranteed during the experiment. It is therefore decided that a contactless optical tracking method be applied for the bottom block, which also allows the bottom block to be free of restraint as there is no need for it to stay aligned with the impactor. This has the advantage that there are no (unknown) friction forces between the bottom block and a vertical guidance system.

Figure 1. Dynamic delamination concept before (left) and after impact (right)

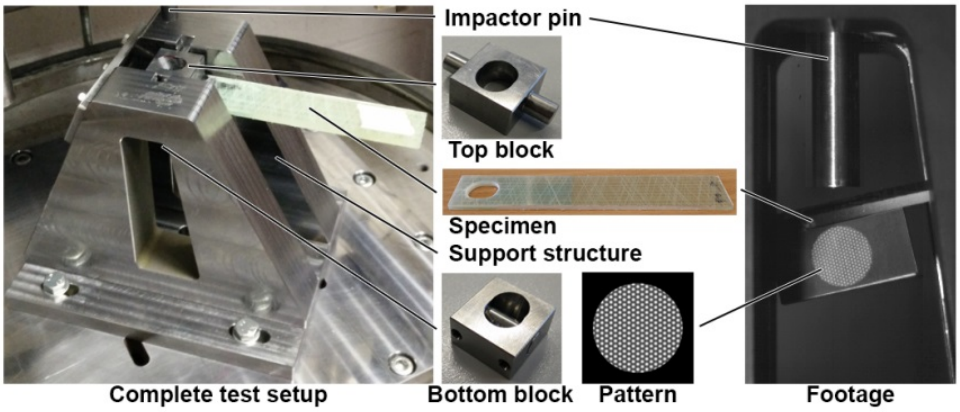

Figure 2. Overview of test setup and footage.

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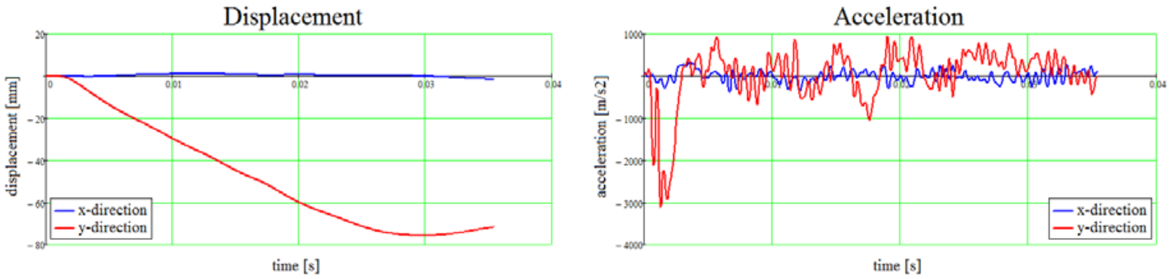

a **b**

Figure 3. Typical displacements (a) and accelerations (b) in horizontal (x) and vertical (y) direction.

An optical pattern is attached to the bottom block with the aim of tracking its position and rotation. This pattern consists of a series of three superimposed line gratings with a 60-degree rotational offset. An in-house developed algorithm tracks the circular shape of the pattern on footage recorded using high-speed cameras. Further processing of the images by means of an equally in-house developed algorithm allows for an accurate determination of the in-plane position and rotation. Velocities and accelerations can be obtained by differentiation of the results. Typical test results are shown in figure 3, showing the displacement and acceleration components for the bottom block during a test. Recordings clearly show that the bottom block accelerates away from the impactor after it has been hit, proving that the load cell is incapable of measuring the actual delamination load. A single line grating is also attached to the impactor body, to accurately determine the impactor position.

Delamination progression is recorded by filming the side of the specimen during testing. The crack tip is found by applying an edge detection algorithm to the images, using the Prewitt approximation to the derivative of the grayscale values. Subsequently, the intersection is determined of two polynomial approximations to the edges that constitute the top and bottom crack flanks.

Three Photron high-speed cameras are used at 20,000 frames per second to record each test: one is pointed at the impactor line grating pattern, one at the bottom block line grating pattern, and one at the side of the specimen.

3. Test results

Two material systems are tested: PYROFIL™ carbon/epoxy from Mitsubishi Rayon Co., Ltd. and Cetex® E-glass/nylon from Ten Cate Advanced Composites B.V., both in woven and in pure unidirectional configurations. All the specimens have a layup such that the final thickness is approximately 4 mm. An even number of plies was used each time, with an insert in the midplane to serve as precrack. All dimensions follow the ASTM standard for mode-I delamination [21].

Different rate parameters for dynamic delamination tests can be found in the literature [9]. This work uses the time derivative of the delamination length, termed delamination speed. Figure 4 shows a typical result of delamination progress versus time for a woven carbon/epoxy specimen. The dynamic response shows a clear non-constant delamination speed. The speed variation depends on the deformation of the specimen which occurs by waves travelling up and down the specimen length. These inertial effects can strongly affect the instantaneous stress distribution at the crack front. Another cause for the variation can be found in the stepwise cracking behaviour that typically occurs when woven composites are delaminated. Figure 5 shows that the maximum delamination speed depends on the velocity at impact despite the aforementioned variation.

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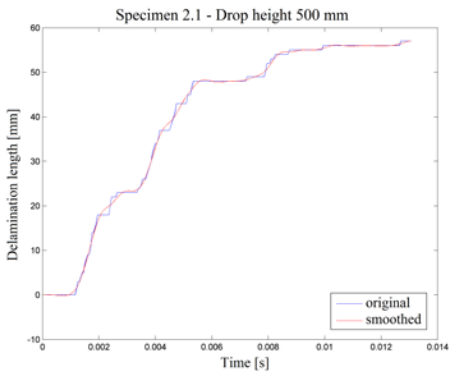

Figure 4. Delamination progress versus time

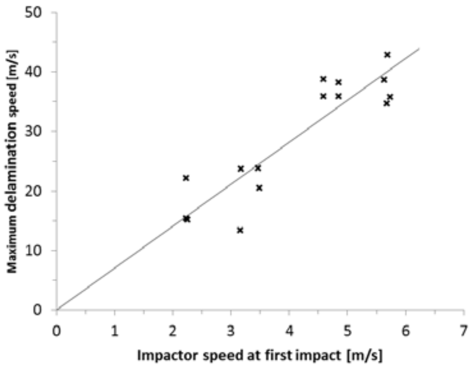

Figure 5. Delamination speed vs. impactor speed

This setup generates a successful delamination process when carbon/epoxy specimens are used. It allows to attain different delamination velocities in order to assess the rate dependence of the interface properties. In contrast, when specimens with a nylon-based matrix are tested, the amount of energy transferred to the bottom block upon impact is insufficient to produce a significant crack propagation. These specimen types are more compliant and a larger amount of energy is required to trigger the delamination. However, this situation can be prevented. A possible solution relies on using a thicker specimen with the aim of increasing its bending stiffness. Additionally, using a longer impactor with a small damping patch on its tip might keep the specimen in contact during the whole trajectory downwards. In this way, the two halves can be forced apart by the impactor rather than relying solely on the inertia of the bottom block. Another possible solution is to use a universal testing machine with a sufficiently high displacement range and actuation velocity as is used in [13].

4. Data reduction and discussion

Figures 3 and 4 show that the specimen response to the impact is highly dynamic. The data reduction procedure typically used under quasi-static conditions cannot be applied due to the effects of inertia. The acceleration of the bottom block shows large variation in time, even though it has been filtered during differentiation above a frequency of 1 kHz.

Although the amount of vibrations in the loading structure have been reduced to a minimum by impacting the bottom block with a small pin and letting it move freely, it might be that another loading structure and guidance system are beneficial to reach a relatively stable cracking velocity as is seen in [17]. An alternative to calculate the crack opening moment is proposed in [16], where the instantaneous crack length and arm displacement of the specimen during the dynamic test is used to calculate the force exerted on the bottom leg, based on an experimentally obtained flexural modulus using quasi-static three-point bending tests. The question remains whether the beam bending formulae used are valid when there is no static equilibrium and, especially when a nylon matrix is used, whether the quasi-static bending stiffness matches the dynamic stiffness of the specimen during a dynamic test.

With the above in mind, it is decided to obtain the dynamic fracture toughness using a combined experimental-numerical method. To this end, a 3D solid finite element (FE) model is developed for an explicit solver. The model makes use of the cohesive surface technique to represent the delamination process (see figure 6). This technique prevents the use of thin cohesive elements for the interface layer, which would lead to very small increment times for the solver. The model dimensions, the material densities and the mechanical properties are made to match the specimens as closely as possible. In terms of validation, this model provides a good agreement with the experimental results under quasi-static conditions when the fracture toughness of the interface is set to the same value measured from quasi-static mode-I delamination tests. Under dynamic conditions, the model allows

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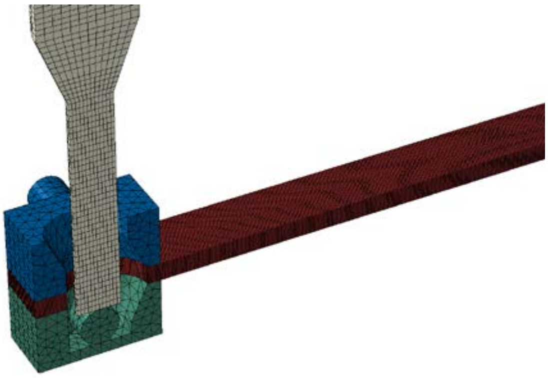

Figure 6. Finite element model

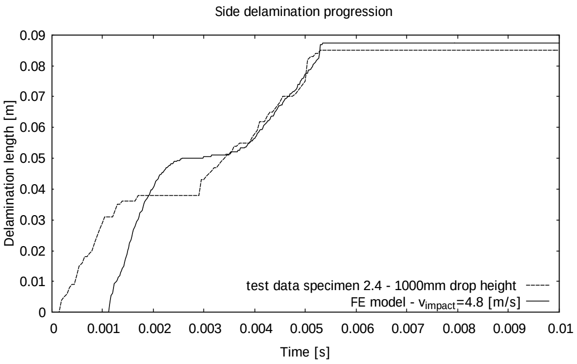

Figure 7. Comparison between test and model output

for a direct comparison with the experimentally obtained results, as it is shown in figure 7, where the delamination length versus time is presented. Although the simulated behaviour is similar to what has been found experimentally, the results of this model suggest that the details of the load introduction have an important effect on the progression of delamination. This subject is currently under research.

5. Conclusions

A new test setup for dynamic mode-I delamination has been designed and tested. An optical technique using the tracking of a pattern of line gratings provided successful contactless measurements of the position and rotation of the specimen. This tracking cannot be carried out using the impactor because of a lack of continuos contact during the whole process of delamination.

Two types of composites have been tested: carbon/epoxy and glass/nylon composites. This setup has successfully delaminated carbon/epoxy specimens at several delamination speeds. However, to achieve sufficient delamination of glass/nylon composites, the current design requires some adaptations. Two possible options are proposed: (i) to use a thicker specimen with a longer impactor equipped with a damping patch, or (ii) to make use of a universal testing machine capable of applying larger displacements at sufficiently high speeds.

The inertia effects hinder the correlation between the fracture toughness and the delamination speed. In that sense, the methods conceived to deal with quasi-static load conditions cannot be used when the specimen is impact-loaded. Accurate load measurements using the load cell are not possible due to inherent noise and the aforementioned lack of continuous contact with the specimen for the complete duration of a test. It is also found that the accelerations measured in the bottom block attached to the specimen vary too quickly due to specimen vibrations to allow for a translation into load. Moreover, using the instantaneous crack length and displacement values to obtain the force with beam bending formulae would disregard the dynamics of the problem. Therefore, a combined experimental-numerical method has been adopted. A finite element model that makes use of the cohesive surface technique is developed for an explicit solver. This model has been validated under quasi-static conditions and it has already produced promising results under impact conditions. More research is currently in progress to validate it for high deformations rates.

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