AN ASSESSMENT OF EXPERIMENTAL TECHNIQUES FOR MEASURING THE MODE I FRACTURE TOUGHNESS OF UHMW-PE COMPOSITES

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Keywords: UHMW-PE, mechanical testing, delamination, fracture toughness, DCB

Abstract
Ultra-high molecular weight polyethylene (UHMW-PE) composites belong to the material class for protection systems with one of the best weight-specific performance against most common threats. Typically, ballistic composites show material specific deformation and failure phenomena during ballistic impact. Besides elastic-plastic deformation, shear plugging and failure of matrice and/or fibers, delamination of layers are on of the most important energy absorption mechanisms. The degree of delamination defines the amount of energy absorbed and the shape of back face bulge of the target. The back face bulge must be predicted throroughly, particularly for components close to the body, such as vests and helmets. The most common experimental technique for determining the fracture toughness is the Double Cantilever Beam test (DCB). Typically, tests are carried out using standardized DCB specimens. However, as will be shown in this paper, the standard test method is not suitable for measuring the mode I fracture toughness of UHMW-PE composites. If the standard test procedure is followed, the cantilever portions of the DCB specimen break due to the relatively low bending stiffness of the material. For this reason, several modifications to the standard test setup were tested and evaluated for their potential to produce reliable mode I fracture toughness data. This paper presents a discussion on the advantages and limitations of the different test setups. Finally, an alternative specimen geometry and test setup, which are particularly suitable for flexible composites, are presented.

1. Introduction

Polymer composite materials have been used in a wide range of applications due to its excellent strength to weight ratio, and therefore outstanding role in light-weight engineering. However, high-strength composite materials prevailed not only for civil use but also for protective applications such as personnel vests or helmets and structural amour in vehicles or aircrafts [1-7].
Ultra-high molecular weight polyethylene (UHMW-PE) composites, due to their excellent ballistic performance and low weight (density < 1 g/cm³), are increasingly used in protection systems [8]. The laminated cross-plied structure consists of layers with 0/90° orientation [9]. The response of UHMW-PE composite panels subjected to ballistic impact loading is mostly governed by two different failure mechanisms, namely shear plugging during the initial penetration followed by delamination and the formation of a bulge at back side of the panel [10]. The design process of armor systems incorporating UHMW-PE composites requires accurate predictions of the size of the bulge as this may affect passengers inside a vehicle or police or military personal equipped with personal armor. Numerical simulation is a powerful tool for analyzing the initiation, growth and final extent of delamination in composite materials. Typically, crack growth problems are solved using fracture mechanics, thus

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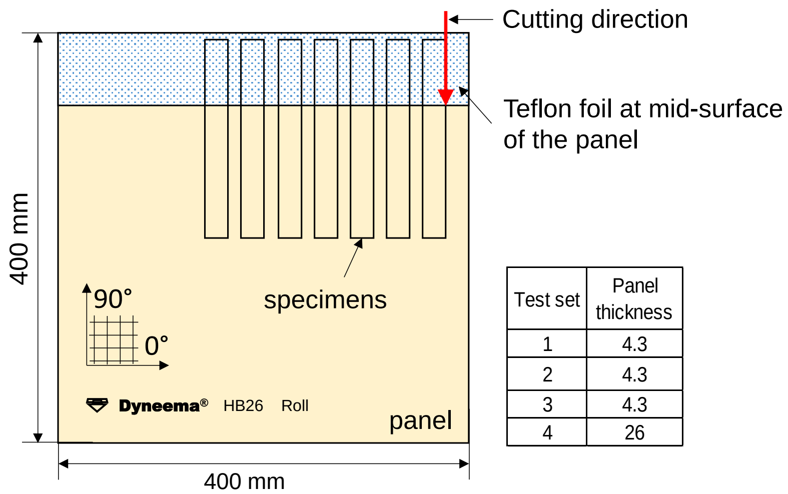
requiring input for the critical energy release rate associated with the failure mode under investigation. In terms of delamination caused by ballistic impact, the mode I fracture toughness is the most critical parameter. The best results for quasi-static and high-rate tests were achieved using thick DCB-type specimens. A companion paper will elaborate more on the high-rate data [11].
The procedure for DCB tests is standardized in ASTM D-5528-01 [12] and has proven its worth for many brittle composite materials such as CFRP or GFRP. However, this testing technique was found unfeasible for UHMW-PE composites due to the material’s notably weak bending stiffness and strength. The subsequent experimental study deals with four different setups that are supposed to identify possible improvements towards detecting fracture toughness in mode I.

2. Experimental study

2.1. Specimen preparation

It was found that UHMW-PE composite materials are particularly difficult to machine. Therefore, the specimens were cut out of 400 x 400 mm panels via water-jet cutting (Fig. 1). In order to implement a very sharp pre-crack a telfon foil was inserted at panel’s mid-surface. Due to the fact that Teflon does not bond to UHMW-PE during hot-pressing process the Teflon foil could be easily removed before testing.



Test set	Panel thickness
1	4.3
2	4.3
3	4.3
4	26

Figure 1. Specimen preparation out of UHMW-PE composite panels via water-jet cutting.

2.2. Experimental programme

In this study four test sets were carried out using two different sample geometries and four different loading conditions. In the first test set the setup, sample geometry and loading condition provided by ASTM D5528-01 [12] was used. In the second set, the bending stiffness of the cantilever portions was artificially increased by aluminum and metal sheets that were bonded on specimen’s top and bottom side. In the further course, the specimen were tested using two convex roller beams in order to avoid an early breaking of the cantilever portions. For the last set, specimens with higher bending stiffness and increased thickness were tested. This tests were carried out at 5 mm/min using a servo-hydraulic testing machines type Instron 8801/8872. Figure 2 provides an overview of the different test setups used within the experimental program.

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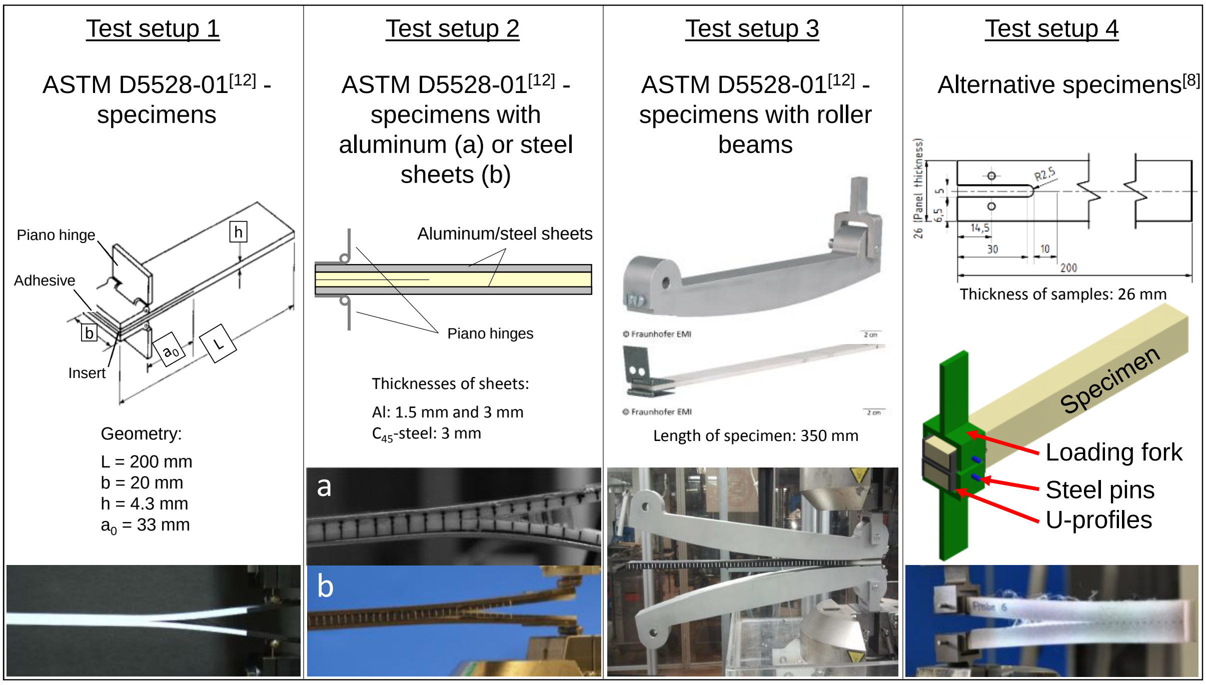

Figure 2. Experimental programme for testing UHMW-PE composites for various DCB test configurations.

Hereafter, the four test setups are assessed with regards to their feasibility and determining realistic values for the fracture toughness mode I. In the following, the four test sets are described in detail.

Results of test set 1

For the first set, relatively thin specimens (as proposed in [12]) were used (Fig. 2). Two metal hinges were bonded with high-strength two-component adhesive (epoxy-based) onto the UHMW-PE specimen. During the tests no visible crack growth was detected. All specimens failed by kinking of one of the cantilever portions at the position of the notch root (Fig. 3). Therefore, it was not possible to determine fracture toughness mode I, G_{IC}.

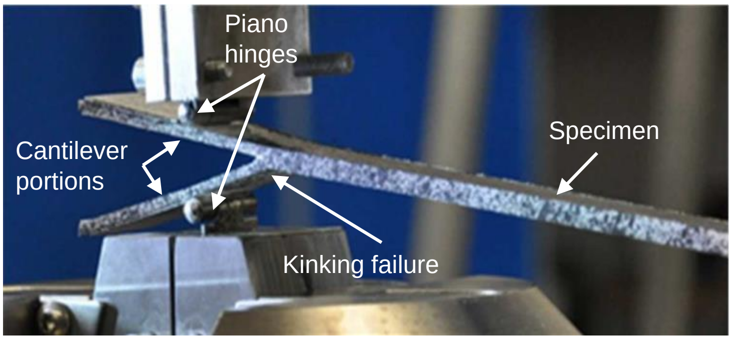

Figure 3. Typical failure of specimen detected at test set 1.

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Results of test set 2

Specimens used in test set 1 failed by kinking of the cantilever portions due to the flexible beams. Dransfield and her co-workers had addressed this problem by stiffening the cantilever portions using additional tabs [13, 14]. Therefore, the specimens here, were stiffened by bonding aluminum/steel sheets on upper and lower side. Four tests using aluminum stiffening were carried out, two with thickness 1.5 mm and 3 mm, respectively. Tests using the aluminum stiffening showed large plastic deformation of the aluminum sheets and, therefore were not feasible for G_{IC} detection. Unless the plastic deformation energy of the aluminum sheets is taken into account it is not possible to obtain a realistic value of G_{IC} based on elastic beam theory.
Subsequently, to increase bending resistance steel stiffenings with thickness of 3 mm were used for three additional tests. Compared to the tests using aluminum sheets, deformation of all components remain pure elastic throughout the tests using C_{45}-steel sheets. However, it was not possible to realise a continual crack growth due to failure of the adhesive bond. Non of these tests provided results in terms of visble crack lengths or values for G_{IC}. The characteristics of test set 3 are summarized in Table 1. The main problems using test setup 3 are visualized in Fig. 5.

Table 1. Characteristics of test set 3.

Test No.	Stiffening	Plastic deformation	Bonding	Crack growth
1	Al, 1.5 mm	strong	no failure	yes
2	Al, 1.5 mm	strong	no failure	yes
3	Al, 3 mm	moderate	no failure	yes
4	Al, 3 mm	moderate	no failure	yes
5	C_{45}-steel, 3 mm	no	conditional	no
6	C_{45}-steel, 3 mm	no	failed	no
7	C_{45}-steel, 3 mm	no	conditional	no

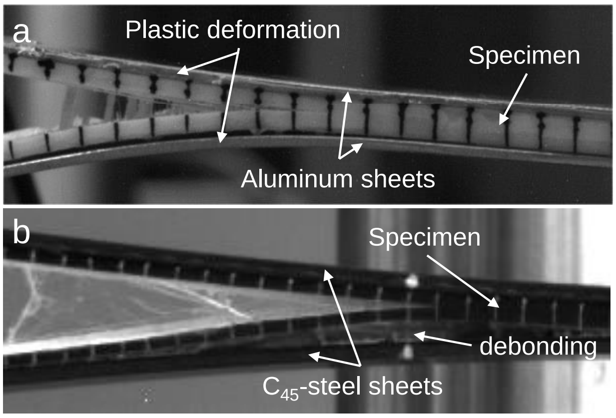

Figure 5. Typical failure of specimen stiffend with aluminum (a) and C_{45}-steel sheets (b) detected at test set 2.

The tests of set 2 showed that the stiffening of specimen neither by aluminum nor steel sheets lead to feasables results in terms of a continous crack growth and, therefore determination of fracture toughness mode I.

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Results of test set 3

For this test set specimens of the length of 350 mm were cut. Then, the piano hinges were bonded back to front at the positions suggested in [12]. In order to avoid kinking of on of the cantilever portions the specimen should be suppressed by two big rollers (Fig. 4, b). Before, the minimum radius ($r_{min} \geq 1000$ mm) of the rollers was determined by a coupon compression test (Fig. 4, a).

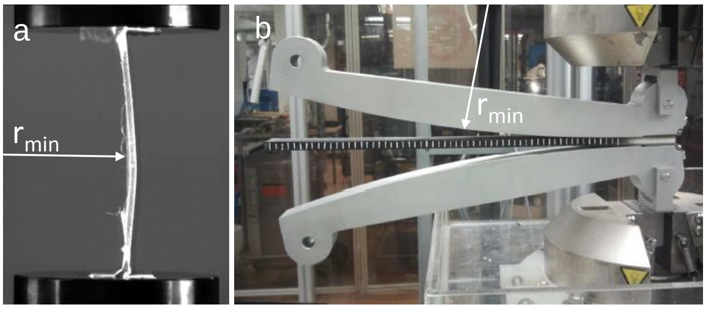

Figure 4. Determining the minimum radius of the roller beams (a) and the test setup of test set 3 (b).

The experiments of test set 3 showed, that it is not possible to obtain realistic values for fracture toughness mode I using this apparatus. The problem with kinking failure detected in test set 2 could not fully be solved using this approach. Right from the beginning, the cantilever portions also failed by kinking detecting only a little crack growth. The crack growth obtained was not feasible for determining mode I fracture toughness G_{IC}.

Results of test set 4

For the last test set the specimen's cantilever portion heights were increased. For that, specimens were cut out of a panel with a thickness of 26 mm. The thicker specimens supported by a form-fit (via steel pins) and adhesive bondes clamping condition showed a continuous crack growth. For these tests growth of multiple cracks was observed. Multiple cracks (a) and the typical crack surface (b) detected during these tests are exemplarily displayed in Fig. 6.

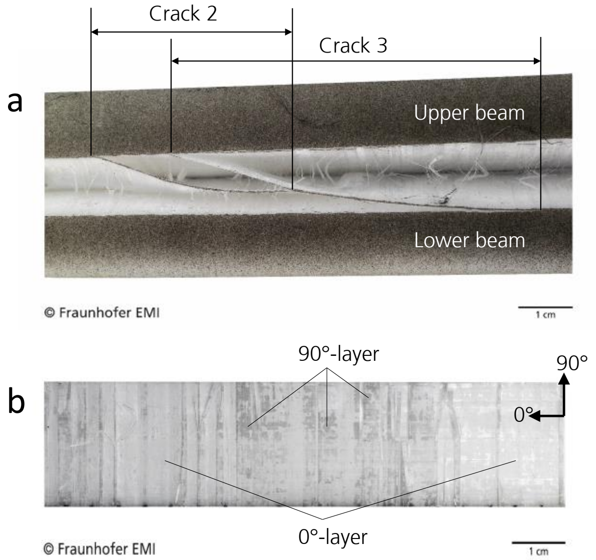

Figure 6. Growth of multiple cracks (a) and crack surface (b) of DCB specimen.

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Fig. 6a shows the growth of multiple cracks that was obtained during all tests using test setup 4. This means the increase of crack surface by additional cracks must be taken into account and, therefore also considered in the evaluation of G_{IC}. Fig. 6b shows the resulting crack surface. It was found that the crack propagates through a 90°-layer. Fiber bundles of that layer were found at the crack surface of both cantilever beams. In summary, comparing test set 1 to 3, test set 4 provided a feasible crack growth and, therefore a good basis for evaluating fracture toughness G_{IC}.

2.2. Evaluation of mode I fracture toughness

The test sets using the standardized samples according to ASTM D5528-01 are not suitable for realizing an evaluable crack growth. Therefore, only the fourth test set was used for determining mode I fracture toughness G_{IC}. For G_{IC} determination several approaches are available such as the Modified Beam Theory (MBT) or Complaince Calculation Method (CC) [12, 15]. Here, G_{IC} is determined using the Area Method (AM) with the total energy W_{ges} by subtraction of the elastic deformation energy W_{el} (Fig. 7).

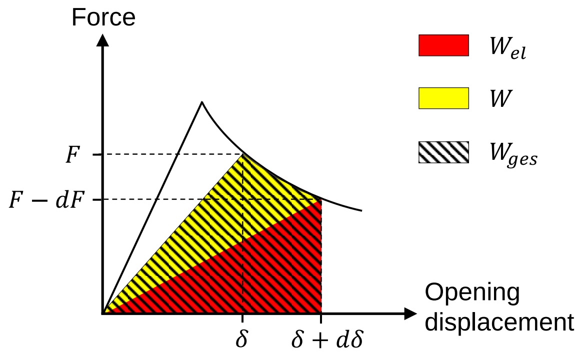

Figure 7. Scheme of energy balance in opening-force-displacement curves for G_{IC} determination.

G_{IC} is defined as relation of the energy W and progating crack surface:

$$G_{IC} = \frac{dW}{dA} = \frac{W_{ges} - W_{el}}{B \cdot a_{eff}} \quad (1)$$

Here, dW is the change of energy by crack propagation, B is the specimen width, a_{eff} the effective crack length and dA the propagating crack surface. For optical dA determination, a_{eff} was measured by crack summation with respect to multiple crack growth. Under the assumption no crack propagation occurs until the maximum opening-force is reaches it is mandatory to determine G_{IC} using the decreasing part of the opening-force-displacement curve. The opening-force displacent-curve (a) and the resulting G_{IC}-crack propagation curve (b) is presented in Fig.7.

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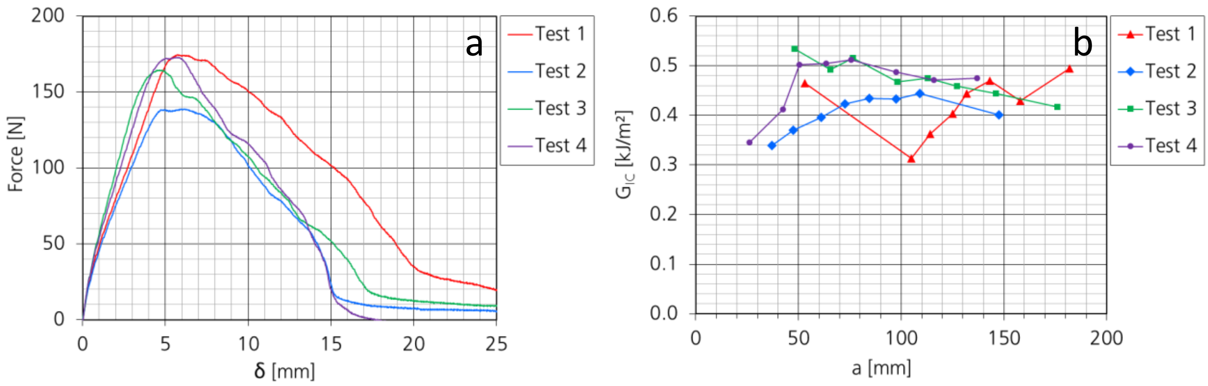

Figure 7. Experimental opening-force displacement-curves (a) and G_{IC} against crack propagation a (b) for four tests.

The evaluation results of the mode I fracture toughness is finally listed in Table 2. Here, $\bar{X}_{abs}$ is the mean value and COV the coefficient of variation. The averaged value of G_{IC} was determined as 441.8 J/m² which appeared to be 19 % lower than the value presented by Grujicic (544.7 kJ/m²) [16].

Table 1. Fracture toughnesses mode I derived by DCB test set 4 under quasi-static loading.

Test No.	G_{IC} (J/m²)	$\bar{X}_{abs}$ (J/m²)	COV (-)
1	422.8	441.8	0.111
2	405.2		
3	475.3		
4	463.8		

3. Conclusions

Delamination failure is known as an important absorption mechanism for composite materials in ballistic impact situations. The fracture toughness in mode I is the most important characteristic value for describing the capacity of energy caused by this failure type. In the course of the present study, four DCB test setups with different specimen geometries and clamping conditions were investigated. It was found that the specimen geometry provided by ASTM D5528-01 was not feasible for UHMW-PE composites due to the weak bending stiffnesses and strength and, therefore flexible cantilever portions. The cantilever portions broke early before an useable crack growth could be detected. In order to increase strength and stiffness of the cantilever beams, thin aluminum and metal sheets were bonded onto the standardized [12] specimens. It was found that a useful crack growth could only be realized using the aluminum sheets. However, the aluminum sheets showed plastic portions of deformation that prevent a regular determination of fracture toughness. By contrast, the C_{45}-steel sheets deformed pure elastic but the adhesive bonding failed due to the low strength and the high stiffness jump between specimens and steel sheets. However, to avoid kinking behind the free cantilever portions the specimen were cut out of thicker panels. Then, the specimen were prepared with a new apparatus that ensured a regular opening of the cantilever portions realizing a continuos crack growth. The fracture toughness mode I was determined using the Area Method. In summary, a test setup and evaluation technique is presented that can be used for flexible composite materials for determination of fracture toughness mode I.

Acknowledgments

The authors would like to thank Mr. Holger Mohrmann for material testing and Dr. Ulrich Heisserer and Dr. Harm van der Werff from DSM Netherlands for material support.

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