EXPERIMENTAL CHARACTERIZATION OF THE OUT-OF-PLANE SHEAR STRENGTH OF ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE COMPOSITE BY USING THE SPLIT HOPKINSON BAR DEVICE

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Keywords: UHMW-PE, high strain-rate, out-of-plane shear strength, Split Hopkinson Bar, dynamic increase factor

Abstract

The material behavior under dynamic processes, such as ballistic impacts, demands a deep knowledge of high-rate testing techniques, dynamic material response and dynamic material models. In this field, ultra-high molecular weight polyethylene (UHMW-PE) composites have been proven to be extremely effective against such threats. During a ballistic impact, a transverse shock wave travels through the material layers. When the shock wave is reflected at the rear face of the component, tensile stresses are created through the material thickness. This dynamic sequence produces a damage mechanism which combines shearing within the top plies of the material, and bulging and delamination at the rear face of the component.

The number of scientific works related to the dynamic characterization of such composites have increased within the last years, including experimental programs, material models, and hydrocode simulations. Nevertheless, there is still a lack of information on the dynamic behavior of such composites under out-of-plane shear loading. An experimental way to characterize the shear strength of laminar material is by using the Split Hopkinson Bar (SHB) device in the so-called shear punch tests. The mechanism is simple – the SHB device is modified by including a sample holder which enables the material to deform by shearing and not by bending. Several authors have used this technique satisfactorily to characterize brittle solids, metals and some epoxy and tungsten fiber composites, but still, none of them have proportionated data from UHMW-PE composites.

This work presents the experimental characterization of out-of-plane shear strength of Dyneema® HB26. Quasi-static and dynamic punching tests were performed in laminar specimens using a UTS and a SHB device. Furthermore, an optimization of the experimental variables affecting the failure mode is also included in this work. The results are very promising, filling the existing gap in the investigation of the dynamic behavior of such a material.

1. Introduction

The demand for high-performance composite materials like polymer-based fiber-reinforced composites has increased continuously within the last years [1, 2]. These composites are extremely effective against small ballistic threats and therefore, very suitable for ballistic armour applications

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(for personnel and vehicle protection) [1-4] or as contact spall liners [5]. For such applications, a light-weight armour solution is necessary where the use of polypropylene fibers (Curv®, Tegris®), Aramid fibers (Kevlar®, Twaron®) or ultra-high molecular weight polyethylene (UHMW-PE) composites (Spectra®, Dyneema®) fit perfectly.

During a high velocity impact event, these composites typically show several damage and failure mechanisms [6-8]. Thus, it is important to understand all mechanisms that occur during such an event [1]. The ballistic performance of UHMW-PE composites differs as a function of its thickness. Although for thin targets the behavior of such composites is well known [6, 9], there is still limited understanding of the damage and penetration mechanism of thick UHMW-PE targets [2]. The works from Greenhalgh et al. [6] and Iremonger [7] discovered that thicker laminates show two different stages of penetration. The first stage is characterized for by shear failure of fibers, while the second one is defined by delamination and bulge or break away, leading to deflection and bending [2]. Whereas the second stage appeared similar to the damage mechanism suffered by thin laminates [10], with fiber failure in tension as dominant mechanism close to the ballistic limit, the first stage has not yet been fully investigated. The shear plugging stage determines the perforation of the material [2]. For its characterization, the energy required to produce a shear plug is based on multiple variables as the effective out-of-plane shear strength of the laminate, the penetrated thickness at that stage, and the projectile radius. It is then clear that the out-of-plane shear strength is an important parameter for the determination of a penetration model and the characterization of the ballistic limit.

In recent years, investigations about the experimental characterization of UHMW-PE composites have appeared focusing on different properties of the material [1, 11-13]. However, the experimental characterization of the out-of-plane shear strength (quasi-static or dynamic) has not been deeply analyzed yet. Although, it was found that the out-of-plane shear properties affect significantly the ballistic performance [2, 14]. On this basis, this paper presents to experimentally characterize the quasi-static and dynamic shear behavior of Dyneema® HB26. The idea is to improve the material database existing on this material and to improve or develop new numerical material models where the material behavior is as realistic as possible.

2. The use of the Split Hopkinson Bar (SHB) technique for the dynamic characterization of shear of materials

The Split Hopkinson Bar is used for the dynamic characterizations of materials under well-defined conditions. The apparatus, based on the findings of Hopkinson [15] and Kolsky [16], uses the propagation of stress waves in a long thin and solid bar. A typical SHB setup consists of a loading device, a set of bars (incident, transmission and striker), and a data acquisition and recording system. The experiments are performed by placing a specimen between the incident and transmission bars. The striker is propelled using a gas gun striking the incident bar and creating a compressive wave in the incident bar. The compressive wave travels through the incident bar. When reaching the specimen, the wave divides into two parts, one continues through the transmission bar, while the other wave part reflects and travels back into the incident bar. The actual instrumentation of the conducted experiments consisted of several strain gauges and a high-speed camera for displacement measurement.

The SHB is commonly used for the characterization of material under tension and compression loading, but it can as well be used for the dynamic shear strength characterization of materials, where in the last decades some authors have succeeded in this objective by using the SHB device [17-19]. The methodology uses the SHB in its compression configuration and is modified by including special fixation systems and/or specimen geometries. For this work, a modified version of a punch-test is used. The so-called punch-test, first introduced by Werner and Dahran in 1986 [19], modifies the Hopkinson bar to simulate a short beam shear configuration (Figure 1). Depending on the configuration of the planar specimen, two different loading configurations can be analyzed: interlaminar or transverse shear.

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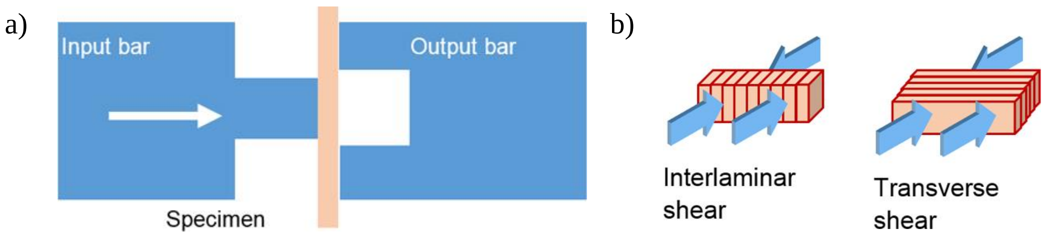

Figure 1: a) Principle of a punch SHB test, b) possible shear loading configurations [18].

3. Experimental procedure

3.1. Analyzed Material

In this study, Dyneena® HB26 fibers were used. This composite consists of 0º/90º layers, where the plies are hot pressed to the desired layer thickness. Due to this layered microstructure, Dyneena® HB26 is assumed to be orthotropic. Dyneema® HB26 has an areal density of 261 g/cm², and it was manufactured under a pressure of 165 bar.

3.2. Quasi-static experiments

Some authors have already tried to characterize the out-of-plane shear behavior of composite materials, but without success [20, 21], since these configurations are prone to bending. On that basis, a new test method was developed at EMI, minimizing bending and easing shear deformation [22]. Considering a loading punch and a fixed fork such as shown in Figure 2, the shear stresses as well as the corresponding shear angles can be directly obtained from the experimental force-displacement curve, based on the following equations:

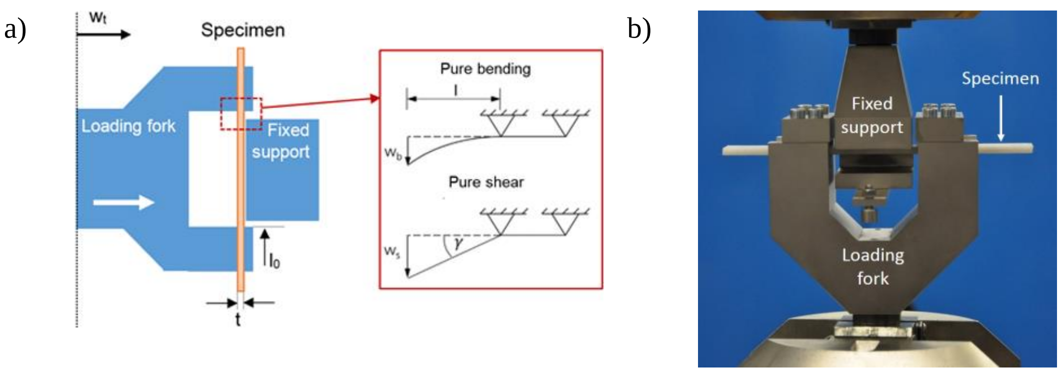

Figure 2: a) Schematic configuration for quasi-static shear tests in out-of-plane direction and definition of variables w_s, w_b and w_t; b) Real setup. Figures from [1].

$$\gamma = \arctan\left(\frac{w_s}{l}\right) \quad \text{, where } w_s = w_t - w_b, \quad \text{with } w_b = \frac{4 \cdot F \cdot l^3}{E \cdot b \cdot t^3}. \tag{1}$$

where w_t is the total displacement of the punch, w_b is the displacement derived from the bending mechanism, and w_s is the displacement derived from the shear mechanisms; l_0 is the free gap between fixed fork and loading punch, F is the loading force, E is the Young's modulus of the tested material, and b and t are the width and thickness of the specimen.

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3.3. Dynamic SHB experiments

For the dynamic characterization of the shear behavior of the material, the fixation system was modified in order to minimize the free gap between the punch and the fork, now settled to 0.1 mm (Figure 3). In this case, the SHB bars and the fixation system are made of steel. The optical extensometer (optical measurement, OM) follows the white-black signals defined in the punch and fork. Since the free gap (l_0) is equal to 0.1 mm, the displacement based on the bending mechanism w_b is reduced to $2.7 \cdot 10^{-3}$ %, and the total displacement can be considered as the shear displacement $(w_s \approx w_t)$.

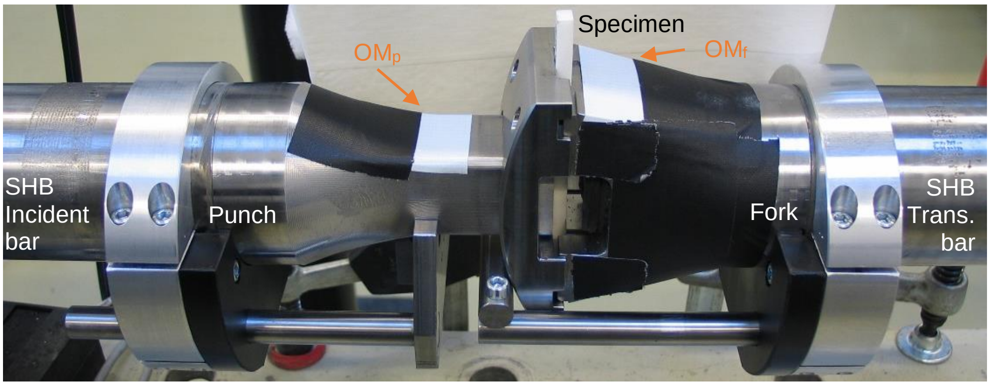

Figure 3: Punch-fork system developed by EMI for the SHB experiments.

4. Experimental results and discussion

4.1. Quasi-static experimental results

In order to investigate the shear properties in though-thickness direction diverse test configurations have been examined in the past, e.g. by Feraboli [20] and Kim [21]. However, these test configurations were prone to bending. Thus, an alternative test method was developed at EMI [22], that minimizes bending compared to shear deformation (Figure 2). Here, strips with a dimension of 200 mm x 25 mm x 4.3 mm were used for the characterization of the shear behavior of Dyneema® HB26. The strips were water-jet cut to avoid boundary failure or stress concentration.

The shear stress (τ) was defined as a function of the force applied and the geometry of the specimen, following:

$$\tau(t) = \frac{F}{2 \cdot b \cdot t} = \frac{A \cdot E \cdot \varepsilon_t(t)}{2 \cdot b \cdot t} \qquad (2)$$

where A and E are the cross-sectional area and Young's modulus of the SHB bar, $\varepsilon_t(t)$ is the transmitted signal, and b and t are the specimen width and thickness, respectively. The shear strain (γ) was calculated following the Eq. 1. Figure 4 presents the experimental results of the quasi-static shear tests in out-of-plane direction.

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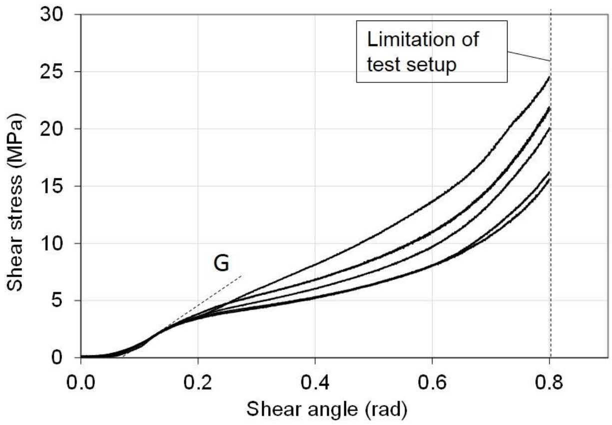

Figure 4: Experimentally obtained quasi-static shear stress-shear angle curves.

The quasi-static experimental results (Fig. 4) show the shear stress-shear angle-curves of five runs. In order to avoid collision between loading fork and fixed support, the testing device was limited in displacement. Therefore, the shear tests (Fig. 4) show no complete failure of the specimens at shear angle of 0.8 rad. The yield shear stress τ_{yield} and the stiffness G (tangent modulus) were obtained at the slope's turning points of between shear angles of 0.1 and 0.15 rad. The results are summarized with the coefficient of variation COV in Table 1.

Table 1: Quasi-static results shear in out-of-plane direction of Dyneema® HB26.

Strain rate	G	τ_{yield}	COV G	COV τ_{yield}
(s^{-1})	(MPa)	(MPa)	(-)	(-)
~$2\cdot10^{-4}$	30.7	2.61	0.07	0.02

Since the results obtained using this test setup did not result in a total failure of the material, a new set of experiments were performed. For that, the punching system was used during the dynamic characterization (SHB tests). The experiments were done at a deformation speed of 0.001 mm/s, which corresponds to a strain rate of ~$2\cdot10^{-4}$ s^{-1}. Figure 5 presents the new results and a comparison with the previous ones. The new results are characterized for shear strength of the order of 100 MPa and a shear angle at failure of around 1.5 rad.

a)

b)

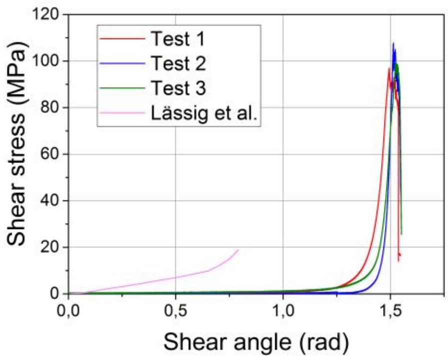

Figure 5: Quasi-static shear tests: a) setup, b) results and comparison with the average curve from Figure 4.

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4.2. Dynamic SHB experimental results

The dynamic shear strength-strain results obtained using the punching system shown in Figure 3 are presented in Figure 6-a. The determination of the shear strength was done following Eq. 3, while the shear strain was calculated using the optical extensometer measures (OM) recorded during the SHB experiment:

$$w_b = \frac{4 \cdot F \cdot l^3}{E \cdot b \cdot t^3} \rightarrow l = 0.1\,mm \rightarrow w_b \approx 0\ ,\ w_s = w_t = OM_p - OM_f\ ,\ \gamma = tan^{-1}\left(\frac{OM_p - OM_f}{l}\right) \qquad (3)$$

where OM_p and OM_f are the measured values taken from the optical extensometer in both positions (punch and fork). As an example, Figure 6-b shows a specimen after dynamic shear testing with global failure achieved.

a) b)

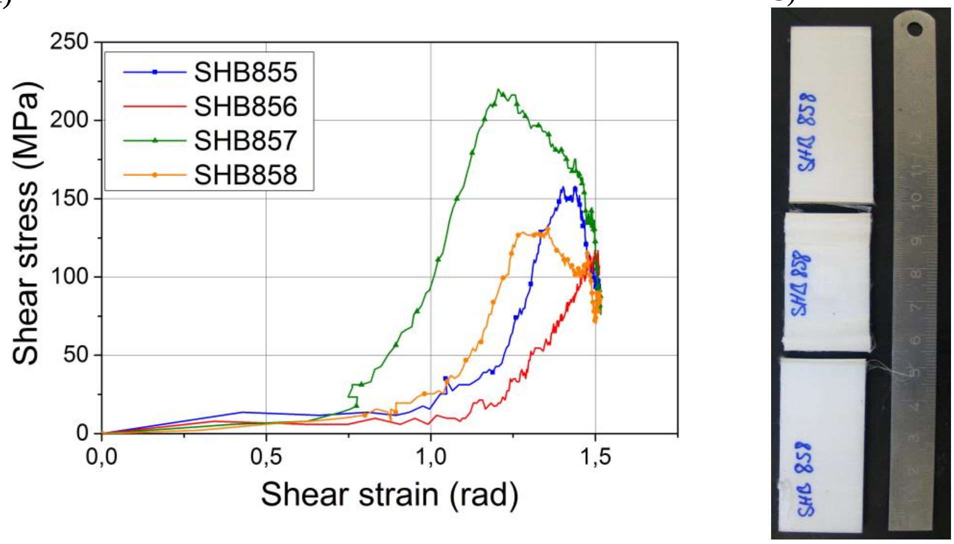

Figure 6: a) Obtained shear stress- strain curves, including the quasi-static results from Lässig et al. [1], b) Specimen after dynamic shear testing.

As a summary, Table 2 presents a comparison between the averaged quasi-static and dynamic shear properties and the obtained Dynamic Increase Factor (DIF). The standard deviation of the parameters is also included (parenthesis). As it can be seen, the shear strength DIF obtained is about 1.5, and 0.91 for the shear strain DIF. The values here obtained could not be compared with the ones from literature since no scientific work was found on the dynamic characterization of composites under shear loading conditions.

Table 2: Comparison between the quasi-static and dynamic shear properties of Dyneema® HB26.

	Strain rate	τ_{max}	$\gamma_{failure}$	DIF τ	DIF γ
	(s^{-1})	(MPa)	(rad)	(-)	(-)
Quasi-static	$\sim 2 \cdot 10^{-4}$	101.51 (4.54)	1.51 (0.01)	--	--
Dynamic	$\sim 3.5 \cdot 10^{3}$	156.00 (39.92)	1.37 (0.11)	1.54	0.91

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5. Conclusions

This paper presents the experimental characterization of the quasi-static and dynamic shear behavior of the composite material Dyneema® HB26. This characterization is made under strain rates of the order of $3.5 \cdot 10^3$ s^{-1} for specimens with a thickness of 4.3 mm.

The quasi-static shear characterization was done with punch tests, using a new punching system designed and developed at EMI. For its design, geometrical aspects were considered in order to minimize the failure by bending guaranteeing failure by pure shear. Thus, the free gap between punch and fork was minimized at the end to 0.1 mm. The dynamic shear characterization was done by punch tests using the same punching system and adjusting it to a SHB device.

The results show a concordance between quasi-static and dynamic experiments. Both follow the same curve slope and just the shear strength and shear angle at that point differ between quasi-static and dynamic loadings. In order to compare both, the Dynamic Increase Factor for that thickness is determined. It is clear that the shear strength is dependent on the strain rate, while for the shear angle that dependence is not observed. However, these results need to be confronted and validated with more experimental results, varying the strain rate and the specimen's thickness. These results will be presented in the close future.

The experimental results obtained in this research enhance the ones obtained by Lässig et al. [1], describing the shear behavior in a large regime of strain rates, without being limited by the experimental technique. Moreover, the data can be included for the development of new analytical or numerical models (hydrocodes) or can be used for the improvement of the existing ones, as for example the ones described by Lässig et al. [1] or Nguyen et al. [2].

Future work will be soon presented where the quasi-static and dynamic out-of-plane shear behavior as a function of the material thickness is analyzed.

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