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A non-linear orthotropic hydrocode model for ultra-high molecular weight polyethylene in impact simulations

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ABSTRACT

This paper presents detailed experimental characterization of quasi-static anisotropic directional strength properties as well as the shock behavior of ultra-high molecular weight polyethylene (UHMWPE) for the development of an advanced material model for this class of materials. Specifically, we consider Dyneema® HB26 – pressed from uni-directional (UD) tapes in a 0/90° stacking sequence. A material model based on a constitutive law with orthotropic, non-linear strength, shock response, composite failure and softening criteria is presented. A set of material parameters is derived for applications in hydrocodes (here: ANSYS AUTODYN). High- and hypervelocity impact tests with different impact velocities are used for preliminary validation and discussion of the predictive capabilities in view of future application.

1. Introduction

In recent years there has been a continuously increasing demand for high-performance composite materials that are suitable for ballistic armor applications, for personnel and vehicle protection, respectively [1–7]. These very specific applications demand for an optimized light-weight armor solution. Thus, polymer-matrix composite armor systems became more and more beneficial in reducing weight [4–6]. Many modern armor systems include polypropylene fibers (Tegris®, Curv®), Aramid fibers (Twaron®, Kevlar®) and fibers of ultra-high molecular weight polyethylene UHMWPE (Dyneema®, Spectra®) [8]. Predictive hydrocode models, based on thorough material characterization, are necessary for effective and customized design of protection systems. This paper is focused on experimental analysis, derivation of material constants and numerical validation of a non-linear orthotropic material model as implemented in ANSYS AUTODYN. Due to its high specific strength to weight ratio (in fiber direction) and its high energy absorption the investigated material Dyneema® HB26 is a promising candidate for protection against a large field of impacting threats such as bullets and fragments [7–9]. Typically, composites under high velocity impact situations show several damage and failure mechanisms such as interlaminar delamination, permanent non-linear deformation and fiber breaking within the perforated layers [8,10,11]. Furthermore, observations showed that the membrane properties significantly influence the ballistic performance as well as the bulging on the rear face. Additionally, Karthikeyan et al. [12] found that the ballistic performance can be improved by decreasing the in-plane shear strength. In connection to the aforementioned use for ballistic armor applications there are several literature reports that provide investigations that show fundamental improvements towards modeling composite materials [13–15]. When considering the micromechanical properties of the orthotropic material behavior, the linear elastic properties, the orthotropic yield surface with a non-linear hardening description [16], a non-linear shock equation of state [17], and a three-dimensional failure criterion supplemented by a linear orthotropic softening description [13,18], should be taken into account. It is important to consider all relevant mechanisms that occur during ballistic impact, as the quality of the numerical prediction capability strongly depends on a physically accurate description of

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contributing energy dissipation mechanisms. The relevant phenomena are as follows: Initially, a transverse shock wave runs through the layers of the material. The damage mechanism dominating within the top plies is through-thickness shearing caused by the projectile cutting through the target. In the meantime, the shock wave is reflected at the back face, causing through-thickness tensile stresses. These tensile stresses can cause separation of the plies (delamination). The final phase is dominated by tensile membrane deformation, which manifests itself as the typical back face bulging and delamination [19,11]. A material model that takes into account all of the required damage mechanisms described above for modeling ballistic impact on composite materials was proposed and validated in Refs. [20–22]. Within the current paper this material model is applied to simulating the response of Dyneema® HB26 subjected to high- and hypervelocity impact loading. A substantial experimental testing program was carried out to enable model calibration. This includes stiffness and strength data for in-plane as well as through-thickness directions, mode I fracture toughness [23], and the shock equation of state (EOS) [24]. The resulting data set, in the following referred to as data set "TL3", is given in the Appendix of this paper.

An overview of the experimental program is presented in Table 1.

For verification purposes, some of the aforementioned material tests were simulated and the measured signals were compared to the calculated ones. This step concerns the following characterization components: the orthotropic yield surface, characterizing the hardening effects and calibrating the equation of state against inverse planar plate impact tests. Finally, a new orthotropic material data set is determined which can be used for further investigations of the material behavior under highly dynamic loading. This will be illustrated by modeling some experimental impact tests in which an aluminum sphere (diameter 6 mm) was fired at Dyneema® HB26 with impact velocities from 2052 to 6591 m/s. These numerical simulations shall highlight predictive capabilities and remaining deficiencies for future ballistic investigations on ultra-high molecular weight polyethylene composite materials.

2. Experimental investigations

2.1. Laminate microstructure

Dyneema® fiber is produced via gel-spinning followed by hot drawing. The resulting fibers, consisting of highly oriented molecules, are coated with a polyurethane (PU) resin (matrix material) and form the UD ply precursor (for Dyneema HB26). These plies are stacked in alternate directions and hot-pressed, such that a desired layer sequence of $[0/90]_n$ is obtained. The production scheme was presented in detail by Russell et al. [25]. A microsection of the layered structure using dark field microscopy is given in Fig. 1.

Due to its cross-ply layup, Dyneema® HB26 is assumed to be orthotropic. For the presented modeling purposes, the material properties of 0°- and 90°-directions are therefore taken to be equal.

In this work the 0°- and 90°-direction of the laminate is associated to the 11- and 22-direction, respectively, and therefore 33 is the through-thickness direction. The 45°-direction, which will be discussed below, is defined as the direction 12 for the in-plane shear test.

2.2. Tensile tests of 0/90°-specimen

For determining the in-plane properties in fiber direction tensile tests were carried out. For that purpose specimens were cut out from 2 mm thick plates, with the layer sequence $([0/90]_2)_5$, via water-jet cutting in 0°-direction. To prevent sliding of the inner layers in the clamping when using standard norm specimens such as DIN EN ISO 527-4 [26], a form-fit clamping condition was used to lock each layer simultaneously. An account of challenges to test these composites is given in Russel [25] and Levi-Sasson [27]. Hence, a specimen was developed by Russell et al. [25] and was adopted in this study as shown in Fig. 2.

As shown in the drawing, the specimen was clamped form-fit with M4-Bolts. The tensile tests were carried out using a servo-hydraulic testing machine shown in Fig. 3.

A force history curve and a displacement history curve were obtained from the load cell and crosshead, respectively. Additional, an optical strain analysis was carried out using a high-speed camera and the optical analysis software ARAMIS® [28]. To enable enough contrast the specimens were marked on the surface with an inhomogeneous black speckled pattern. The resulting true stress true strain curves are reported in Fig. 4 and Table 2 including the arithmetic average and the coefficient of variation (COV).

Here, grey solid lines show the results of tensile tests in 0/90°-direction and the dashed black line the numerical validation simulation using a one-cell FE-model providing material data set "TL3".

The typical true stress – true strain curves of 2 mm thick Dyneema® HB26 is given by Fig. 4. This chart represents the results of five 0/90°-samples under quasi-static tensile loading. Note that the stress-strain relation remains linear-elastic during the loading procedure until fracture, clearly represented by the sudden drop of stress. In the five tests, an averaged maximum stress of 753 MPa was obtained. The Young's modulus $E_{11} = E_{22} = 26.9$ GPa was obtained at values of strain between 0.05 and 0.25 percent, as specified in Ref. [26].The longitudinal strain was obtained using the side view to disregard obstruction by a failing top ply. Furthermore,

Table 1
Material characterization program for UHMWPE Dyneema® HB26.

Type of test	Repetitions	Velocity	Gauge length	Property
0/90° -tension	5	1 mm/min	50 mm	E_{11}, E_{22}, σ_{11fail}, σ_{22fail}
±45° -tension	5	1 mm/min	50 mm	G_{12}, τ_{12fail}
Through-thickness tension	5	1 mm/min	25 mm	σ_{33fail}
Ultrasonics [25]	–	–	–	E_{33}
Through-thickness shear	5	1 mm/min	–	G_{13}, G_{23}, τ_{13fail}, τ_{23fail}
Double Cantilever Beam test (DCB)	3	1 mm/min	–	G_{IC}
Inverse planar plate impact test (PPI)	5	229–868 m/s	–	shock and release

11- and 22-directions unfold the plane of lamina.

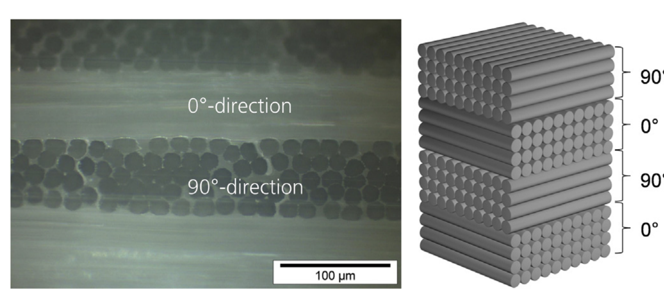

Fig. 1. Microsection analysis of Dyneema® HB26, dark field microscopy.