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Modeling unidirectional composites by bundling fibers into strips with experimental determination of shear and compression properties at high pressures

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ABSTRACT

Numerical models of unidirectional panels of ultra-high-molecular weight polyethylene (UHMWPE), like Dyneema® HB80 or Spectra®, have been a difficult challenge. The problem arises from the intimate structure of the material. It is a huge collection of fibers loosely held together by a matrix. For example, for HB80 the fibers are very small in diameter (~17 μm) but extremely strong (~3.5 GPa). The amount of matrix is small (~20% in volume) and very weak.

The "natural" scale to use in the numerical model for this material is the fiber scale (~17 μm). This scale would provide the right sound speed, transverse wave speed, failure strain, strength of the laminate, deflection, slippage between the fibers/layers, etc. which are all *essential* details if we want to have predictive capability. But even with the very powerful computers available nowadays we are still very far from being able to simulate a real-size laminated target (for example 30 cm wide and 1 or 2 cm thick) at the fiber scale.

This paper proposes an "intermediate" scale that bundles or consolidates many fibers together so that the numerical problem is solvable in a few hours (or maximum one or two days for thick targets) of computation in a single board (24 processors). The scale is chosen precisely so that the essential physics of the ballistics problem is kept and the material properties used are the ones measured in the lab for the fiber and matrix. A similar approach was presented in a previous paper for fabrics (Kevlar, Dyneema, and PBO) where a yarn-level model was able to reproduce both the wave propagation patterns and the ballistic limits.

This paper first describes new material test results (shear and compression at low and high confinement pressures). These were essential in properly capturing the delamination of the material. Then, for completeness, transverse wave propagation and ballistics results in Dyneema published elsewhere are briefly presented. Finally the numerical model in LS-DYNA is developed and comparison with deflection history and ballistic limits is conferred.

1. Introduction

Ultra-high-molecular-weight polyethylene (UHMWPE) fibers are being increasingly used for applications like ropes, ballistics, and medical devices. These fibers were commercialized in the late 1970s by DSM®, a Dutch chemical company. The fibers can be arranged in different forms to create, for example, non-woven blankets, woven fabrics, and unidirectional composites.

The unidirectional composite "single layer" manufactured by DSM is a $(0/90)_2$ lay-up composed of approximately 84% fibers (in weight) and 16% polyurethane matrix. These "single layers" are hot-pressed together to get consolidated into a rigid unidirectional (UD) panel with the desired thickness. Dyneema HB80®, in particular, is a UD panel that has outstanding ballistic performance and is used extensively as an armor material. Obtaining accurate material properties of the material is essential to understand its

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behavior and the first step before starting to perform ballistics computations, see for example [1].

Numerous authors have measured the material properties of UD single layers or lay-ups in tension with different levels of success [2–8]. Due to the small friction coefficient of Dyneema it is very difficult to grip the specimen during a tensile test so, in some tests, the specimen actually fails because of delamination and not in tension. One way to mitigate this problem is to use cartan grips (see Heisserer [9]), where the layer is rolled on a cylinder so that friction on the large grip area wound around the cylinder avoids slippage off the grip. Additionally this arrangement does not damage the fibers or layer, as opposed to grips that compress or pinch the specimen. Some of the papers mentioned above have measured tensile properties both at low and high strain rates but, because of the slippage problem, it is difficult to differentiate between an intrinsic strain rate effect and an artificial one due to avoiding slippage at higher rates. The fiber-level study by Hudspeth et al. [10] has shown that the strain rate effects are small for rates above 0.01 s^{-1} at that scale.

The test with cartan grips provides very satisfactory results as the strength of the layer is basically the result of adding the strength of the individual fibers [9], i.e. if the fibers have a strength of 3.5 GPa then the lay-up just follows the rule of mixtures. Consequently, since the plies at 90° have negligible strength, and the matrix content is 16% (also negligible strength), the $(0/90)_2$ lay-up is expected to have a strength of $3.5/2 * 0.84$–1.5 GPa, which is very close to the one in measured in [9].

Numerical simulation of impact on UD Dyneema or Spectra has been a huge challenge mainly because of the multiscale nature of the material and lack of important properties like shear or compression strength at low and high pressures. Clearly the high modulus and strength of the fiber is a very important component of the material but one difficult, if not impossible, to capture at the continuum level. An orthotropic model with the fiber properties would just be too stiff when compared to the real material. Continum approaches were performed, for example, by Hayhurst et al. [11], Grujicic et al. [12], Krishnan et al. [13], Ong et al. [14] and Bürger et al. [15].

Since the tensile strength has already been explored extensively in the literature, this work focusses on other properties that are needed during impact computations, namely compression in and out-of-plane and in-plane shear, both at atmospheric and high pressures. The properties under high pressure confinement are particularly important since during ballistic impact the pressure in the laminate might be very high due to the compression waves propagating through the material. The literature on shear properties of UD laminate is much more scarce, see, for example, Levi-Sasson et al. [3] and, as far as the authors know, no data are published with shear or compression tests at high confinement pressures.

The properties measured are then used to estimate the material constants needed in the numerical simulations of impact on Dyneema HB80. The approach used is similar to the one presented for Kevlar® fabric by Chocron in [1] where the authors "bundled" the fibers in yarns and performed yarn-level computations. The Kevlar yarn-level computations were carefully validated by first impacting single yarns and single layers and checking that transverse wave velocities as well as the minimum impact velocity for yarn failure were properly predicted.

For Dyneema UD the validation tests were only slightly different since instead of (numerically) bundling the fibers in yarns they were bundled in strips and the results compared to the experiments published in Chocron et al. [16]. Validation also happened at the single layer and lay-up levels with the results shown below.

2. Materials

All the materials tested in this project were received from DSM-Dyneema through a joint-research project. All the materials (yarn, single layer composite and multi-layer composites) are based on the same fiber, SK76, for consistency.

2.1. Filament and yarns

Although no testing or impact simulation is performed at the fiber level, the properties of the fibers are what makes UHMWPE an outstanding material. The following properties were provided by Van der Werff (personal communication): modulus of 1350 cN/Tex (132 GPa), strength of 38.4 cN/dtex (3.8 GPa), linear density of 2 dtex (0.0002 g/m), strain to failure of 3.5%, diameter 16.1 μm, density of 980 kg/m^3, which provide a sound speed of 11.6 km/s. These come from single filament tests at a speed of 25 mm/min in specimen with a 50 mm gage length. These properties agree with the ones measured by Hudspeth et al. [10].

2.2. Single layers

Single layers of HB80 were also provided by DSM with an approximate size of 20 in × 20 in. These are SK76 yarns in a polyurethane matrix. The architecture of the single layers is described in [9]. The single layers consist of 4 "plies" with $[0/90]_2$ fiber orientation, see sketch in Fig. 1. Each "ply" actually has approximately 2.5 filaments through the thickness. The HB80 single layer (i.e. four plies) has an areal density of 0.145 kg/m^2.

The matrix material is polyurethane and a simple estimate performed in Chocron et al. [16] provides a 16% matrix content by weight (correcting a numerical error in the reference). The reader is encouraged to refer to [16] for a thorough description of the architecture.

2.3. HB80 Laminates

Laminates were manufactured by DSM North America from the single layers described in the previous section. A complete description of the laminates used is provided in Table 1 where the number of layers, areal density, and curing pressures are provided. The

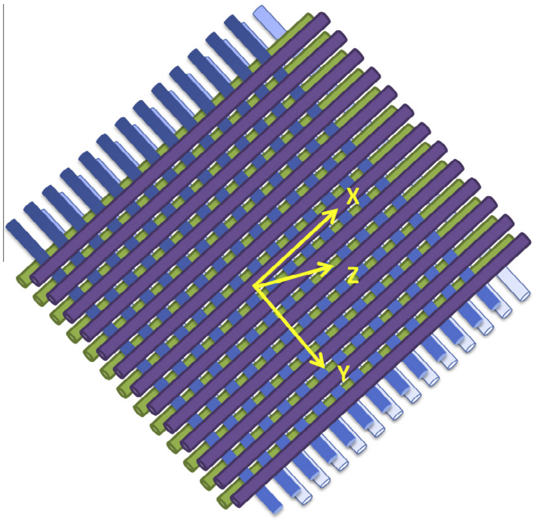

Fig. 1. Sketch of the $[0/90]_2$ laminate with material coordinates. Z is the out-of-plane direction. Global and material coordinates match initially.