New protection levels of UHMWPE armour: From a hydrocode model of HB26 to new generation Dyneema® for armour applications.

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Abstract. A plasticity-based general hydrocode model for DSM’s UHMWPE (ultra-high molecular weight polyethylene) armour grade HB26 was derived from an extensive experimental static, dynamic and shock characterization program. This model, implemented in Ansys® Autodyn, captures the main energy absorption mechanisms during impact, such as shock properties, orthotropic non-linear strength and composite failure criteria with regularized softening. The model and a successful validation from high to hypervelocity impact in terms of residual velocities and depth of penetration are shortly reviewed. This validated approach was then used to highlight the sensitivity of the ballistic limit on relevant mechanical parameters. Encouraged by these model predictions, new UHMWPE fibres from DSM Dyneema with exceptional strength in fibre direction were produced and manufactured into cross-plied unidirectional composites. The experimental ballistic results are reported and discussed. The results show that with the new generation of Dyneema® fibres and composites very significant weight reductions of up to 25% or more can be obtained compared to state-of-the-art armour materials.

Keywords: UHMWPE fibre, composite, constitutive model, armour.

1. INTRODUCTION

Oriented ultra-high molecular weight polyethylene (UHMWPE) fibres were discovered in the late 1970 and commercialized by DSM, branded as Dyneema®. On a weight basis, it is the strongest commercially available fibre. Due to its high specific strength and specific modulus, it is successfully used as armour in parallel to applications in commercial marine, sports and leisure industries [1,2]. DSM Dyneema produces 0°/90° cross-plied uni-directional fibre composites from yarns and selected matrices. Stacks of these laminates can be hot-pressed into hard monolithic panels. In Figure 1, a cross-section is shown of a hot-pressed panel of HB26 material, clearly showing the cross-ply construction and the filaments within the plies.

Figure 1. Cross section of a HB26 hot-pressed panel (optical microscopy, dark field).
This paper discusses the development and validation of a general numerical hydrocode model for DSM’s HB26 armour. The sensitivity of the model to relevant fibre parameters, i.e. strength and modulus is investigated. Subsequently experimental ballistic results of new Dyneema® grades with substantially increased ballistic performance are presented.

2. GENERAL NUMERICAL HYDROCODE MODEL

The model presented is a non-linear plasticity and shock compression model in the sense that the main energy absorption mechanisms during an impact event are addressed [3]. The energy of the projectile is absorbed by breaking the strong fibres while perforating layers. During that process, the localized kinetic energy of the impactor is spread out to an increasing volume of the target. Besides this, permanent plastic deformation and delamination absorb energy. The model uses a continuum finite element framework developed for high-velocity impact into orthotropic materials [4]. Choosing the concept of orthotropic material behaviour is justified by the cross-ply construction (Figure 1). Selecting the macroscopic approach in contrast to explicit modelling of fibre and matrix is dictated by the demand of having models to simulate realistic components with reasonable computation time. As a consequence, we model the effective behaviour of a continuum with directional dependent properties. The four basic phenomenological blocks of the constitutive model are shown in Figure 2 and described in detail in [3]. It is known that the Dyneema® fibre, as main constituent of the laminate, shows only rate-sensitivity in the creep regime but hardly from quasi-static to ballistic strain rates [5]. Therefore, the material characterization program utilized quasi-static mechanical testing for the orthotropic linear elastic properties, the non-linear plasticity and failure parameters. Dynamic characterization was carried out to derive the equation of state describing shock compression and release states.

In our approach, typical experimental characterizations were carried out and subsequently numerically validated. Very basic input is derived from in-plane tensile tests on 2mm thick HB26 laminates shown in Figure 3. 0°/90° tensile tests (Figure 3a, reprinted from [3]) were evaluated to provide the moduli and strength parameters along the fibre directions, ±45° tests (Figure 3b) allowed deriving in-plane shear parameters and to fit the effective plastic stress-strain curve controlling the non-linear orthotropic deformation.

![Building blocks of the constitutive model](image.png)
To characterize the shock behaviour of HB26 for high velocity impacts, inverse flyer plate tests were carried out as shown in Figure 4. The data obtained in these tests allows derivation of a polynomial equation of state and the construction of the particle velocity $u_p$ / shock velocity $U_s$ diagram to compare with other studies. The resulting parameter set is available in the appendix. Further details are described in [3].

3. VALIDATION OF THE HYDROCODE MODEL AGAINST EXPERIMENTAL DATA

As first validation case the impact of 6mm diameter aluminium spheres on 200mm x200mm HB26 panels of areal density 15 kg/m² (i.e. about 15mm thickness) is considered. One shot was placed per target. The specimen was clamped with a steel frame covering 10mm along the edges and leaving an exposed area of about 180mm x 180mm. The panel was oriented perpendicular to a two-stage light gas gun used to accelerate the projectiles. For the simulation, a full Lagrangian model of the panel was considered with a fine mesh in the impact zone (approximately 6 cells across the diameter). The steel fixture was modelled by prescribing a zero velocity boundary condition to all nodes along the side edges of the panel. For the target, the derived constitutive model for HB26 dataset TL3.0 [3] was used with a geometric erosion strain of 150%. The aluminium sphere was modelled by a Johnson-Cook plasticity model with non-linear equation of state and strain based failure criteria. An external gap contact algorithm was utilized with the option to retain the inertia of eroded nodes, since the projectile highly fragmented at these speeds. The simulation is able to capture the experimentally measured residual velocity very well and also predicts the stop cases as shown in Figure 5.
Figure 5. Validation at high velocities: residual velocities of the projectile after impacting a HB26 panel (areal density = 15 kg/m$^2$).

In the second validation case we considered the depth of penetration of 5.5mm diameter hard steel spheres in 100mm x 100mm Dyneema® HB26 panels of areal density 25 kg/m$^2$ (thickness approx. 25mm). The experimental results were discussed with some consideration of the energy absorption behaviour and resulting stresses on the projectile in [7]. The fixture and representative cross section cuts are depicted in Figure 6.

Figure 6. Depth of penetration study. (a) fixture with a 70mm wide hole. (b) cross sections of partially penetrated HB26 panels (areal density=25 kg/m$^2$)

Since significant volume change occurs during penetration, it is necessary to define a physically meaningful definition of the “depth of penetration” (DOP). The proposed variable is the penetrated areal density. Due to delamination and piling up of material at the strike face (see Figure 6b) measuring the length of the impact channel does not provide this information. If the sample was not pressed, one could open up the pack and count the penetrated layers. For the hard ballistic panels investigated here, we define the DOP as initial panel thickness minus the remaining thickness under the stopped projectile, using the notation of Figure 7, this is DOP = length(1) – length(4).
Figure 7. Definitions to derive the experimental depth of penetration

For the simulation we use a consistent approach. We use a model with 25 layers (i.e. one layer per mm) over the thickness and place a gauge point in each layer directly under the projectile. Those gauge points deform with the element and allow the evaluation of transient data during the simulation. The coordinate system is defined in a way that $x$ is the through-thickness direction and $y$ and $z$ are global orthogonal directions in the plane of the panel. In the plot of $x$-position of the gauge points vs. time in Figure 8 we see that the line labelled ‘series 11’ (=10mm initial depth) ends by element erosion along the penetration channel, while the gauge ‘series 12’ (=11mm initial depth) records data until the end of the simulation. Hence the numerical DOP is 10mm. The model is a quarter-model with symmetry boundary conditions. The steel sphere is in this lower velocity regime modelled as elastic material without element erosion strain, the HB26 panel uses the derived material model with equivalent instantaneous erosion strain of 150%. External gap contact is selected and inertia of eroded nodes is not retained as the sphere does not fragment.

Figure 8. Definition of the numerical DOP. (a) quarter-model with surviving gage points (b) position vs. time plot for the gauge points. Gauge 1 is the projectile centre, gauges 2-26 are in the plate 1mm apart.

Comparing the experimentally determined DOP with the simulation, shown in Figure 9, we see a good match over the whole velocity regime. The dimensions of the hard steel spheres used in the experiment were measured after the test and no deformation could be detected. Therefore it is justified to model the steel sphere as elastic.
Figure 9. Depth of penetration in a HB26 plate (areal density=25 kg/m²).
Experimental and simulation results

4. SENSITIVITY STUDY

The manufacturing process of Dyneema® allows modification of fibres strength and modulus. So it is interesting to study the sensitivity of the numerical model with respect to these parameters. The settings from the first validation case, the 6mm aluminium sphere impacting on 15kg/m² of HB26, are used for a sensitivity study. As baseline, the overmatch case with impacting velocity of 6591 m/s and residual velocity of 2178 m/s was chosen. The residual velocities were determined for half and 1.5 times the in-plane strength and modulus. In the resulting Figure 10, lower residual velocities mean better ballistic performance. The predicted trend is that higher strength and lower modulus give better ballistic performance. This is in general agreement with the predictions of the scaling laws of Cunniff [8].
5. EXPERIMENTAL RESULTS OF THE NEW DYNEEMA® FORCE MULTIPLIER TECHNOLOGY PLATFORM

From the analytical, empirical and numerical analyses on the ballistic performance of fibre based composites treated here [8,9,10] it can be observed that increase of the fibre strength will be a very important parameter to increase ballistic performance at constant weight. UHMWPE fibres can in principle be prepared with exceptionally high strength. In the literature, on lab-scale, values up to 7.2 GPa have been reported by various research groups [11,12]. Until now, typical strength values of commercial-scale UHMWPE fibres are about 3.5 GPa.

DSM Dyneema has recently completed a proprietary industrial development of Dyneema® fibres with significantly increased tensile strength for application in fibre based composites for ballistic application (Dyneema® Force Multiplier Technology Platform). The essential achievements in ballistic performance will be presented here.

In Figure 11, the experimental V50 for 1.1 gr FSP versus the areal density of hot-pressed hard panels is given for the state-of-the-art fibre based composite, HB50, and a new composite HB212 based on the higher strength Dyneema® fibre. Both composites use the same matrix material (based on Kraton® rubber), and can be compared straightforwardly. Figure 11 shows, for pressed panels, the possibility to reduce weights by 25 % and more, at a given level of V50.

Similar information is reported in Figure 12 for flexible packs. The experimental V50 for 1.1 gr Fragment Simulating Projectiles (FSP) versus pack areal density is given for a state-of-art fibre based flexible composite SB21, and a new significantly stronger fibre based composite SB115 which is commercially available within the new Dyneema® Force Multiplier Technology platform. The use of a higher strength fibre clearly results into strong weight reductions. For example, in order to achieve a V50 of 450 m/s, SB115 needs about 28 % lower weight. Additionally, the flexibility of the SB115 (sheet areal density = 80 gr/m²) is much higher than that of SB21 (sheet areal density = 145 gr/m²) and thus wearing comfort will be additionally increased [15,16]. The new fibre thus opens up unprecedented possibilities to increase ballistic performance and wearing comfort for ballistic vests.
Figure 11. V50 versus areal density of pressed panels of state-of-the-art HB50 and the newly developed HB212, for 1.1 gr FSP.

Figure 12. V50 versus areal density of flexible packs of state-of-the-art SB21 and the newly developed SB115, for 1.1 gr FSP.

6. CONCLUSIONS

For DSM’s HB26 UHMWPE fibre composite panel, we have derived a plasticity-based general hydrocode model from extensive static and dynamical characterization. The model, using the constitutive
framework of a commercial hydrocode (Ansys® Autodyn), can be readily used by experience users. It has been successfully validated from high to hypervelocity impact in terms of residual velocities and depths of penetration.

Encouraged by the predictions and sensitivity analysis of this and earlier models, new Dyneema® fibres with exceptional strength and its fibre-based composites were produced. The experimental ballistic results of the Force Multiplier Technology platform show that with these new Dyneema® fibres a new generation of UHMWPE based armour materials has been obtained enabling already up to 25% or more weight reduction compared to the previous state-of-the-art materials. The UHMWPE fibre technology is unique because it has the potential to achieve even further significant weight reductions in the future.

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References

10. van der Werff, H; Heisserer, U & Phoenix, S.L. Modeling of ballistic impact on fibre composites Personal Armour Systems Symposium, Quebec 2010, 2010
APPENDIX

Material parameter set for Ansys® Autodyn v. 14.5 and later
(coordinates 1=through thickness, 2 & 3 along orthogonal fibre directions in the plane)

To be used with the double precision version of Autodyne. We used an axisymmetric Lagrangian model
with hexahedral elements. Under the projectile the mesh is refined with 5 elements over the projecticle
radius. Over the thickness one element per mm thickness is used. The nodes along the outer boundary are
fixed over the whole thickness. Contact algorithm was gap contact.

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Additional material Data

| Reference density [g/cm³] | 9.81E-01 |

* taken from literature [13], Poisson ratios calculated from the moduli according to Bower [14], Section 3.2.13

** high value means no failure by this parameter