Numerical sensitivity studies of a UHMWPE composite for ballistic protection

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Abstract

Ultra-high molecular weight polyethylene (UHMWPE) has a high potential for ballistic armor applications due to the excellent weight specific strength inherent to this type of material. In this paper, a non-linear orthotropic material model for the UHMWPE, based on the product DYNEEMA® HB26, is used for assessing the influence of the material properties on the ballistic performance. The model, implemented in the commercial hydrocode ANSYS AUTODYN uses initially linear-orthotropic elasticity, subsequent non-linear strain hardening, multiple stress-based composite failure criteria and post-failure softening. The strength model is coupled with a polynomial equation of state. An experimentally supported material data set for UHMWPE, presented before, is used as a baseline for the numerical studies on high velocity impact. Parameter sensitivities are studied for these impact situations. The numerical predictions are compared to available experimental data over a wide range of impact velocities (1 km/s up to 6 km/s). The objective of this paper is to assess the influence of different material parameters on the predictive capability of high velocity impact simulations and subsequently provide guidelines for the required experimental characterization of UHMWPE under shock loading.
Keywords: high velocity impact simulations, numerical parameter study, hydrocode model, UHMWPE.

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1 Introduction

In recent years an increasing demand for thorough investigations of UHMWPE composite material for hypervelocity ballistic response occurred. At present, UHMWPE composites become indispensable for military and civil enforcement groups in a wide field of applications such as vehicle, aircraft and personnel protection systems against various kinds of threats. Different energy dissipating phenomena occur during ballistic impact. The most important ones are interlaminar delamination, fiber breaking within the perforated layers and permanent non-linear deformation. Various investigations of UHMWPE behavior towards deformation effects caused by ballistic impact were carried out i.e. by Iremonger [5], Greenhalgh *et al.* [6] or Karthikeyan *et al.* [7]. It was found that the deformation of the target panels was caused by different energy dissipating phenomena such as interlaminar delamination, permanent non-linear deformation and fiber breaking within the perforated layers. Thus, ongoing efforts investigating the oriented UHMWPE material's behavior in terms of predicting the ballistic performance were carried out and are presented in this work. In previous work, an extensive experimental program was carried out to determine the orthotropic material behavior [4]. In the course of these investigations, it is clearly apparent that some material characteristics are very difficult to obtain (i.e. in through-thickness direction). In order to get an impression which material parameter are sensitive to the ballistic performance a parameter study is presented. In this study, two different ballistic impact scenarios are presented to clarify the influence of change of parameters. Simulations were carried out increasing and decreasing a parameter by 50% of its initial value comparing the results of both analyses to the simulation containing the original material data set TL3. Based on this, useful information can be provided in terms of future material enhancements.

2 Material model and data set TL3

The starting point for this study was a non-linear numerical material model that describes the material behavior of Dyneema® HB26 crossply composite under highly dynamic loading. Development of this model was presented by Lässig *et al.* [4] based on former publications by Wicklein *et al.* [8] and Riedel *et al.* [9]. The four major parts of the material model involve orthotropic elastic deformation, non-linear hardening, stress based failure, linear post failure softening and a shock equation of state. Therefore, the model takes many physical phenomena into consideration which are important for the energy dissipation during ballistic impact and have an important influence on the ballistic performance of the material. An extensive experimental effort followed by multiple verification simulations allowed a compilation of material properties summarized in data set "TL3" [4].

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Table 1: Material data set "TL3", according to ANSYS AUTODYN coordinate system (22- and 33-directions define the plane of lamina) [4].

Orthotropic linear elastic model (stiffnesses and Poisson's ratios)		Polynomial EOS (coefficients)		Orthotropic failure and softening (tens. fail. stresses and fracture toughnesses)	
E_{11} [GPa]	3.62	A_1 [GPa]	6.08	σ_{11fail} [MPa]	1.07
E_{22} and E_{33} [GPa]	26.9	A_2 [GPa]	10	σ_{22fail} and σ_{33fail} MPa]	753
ν_{12} [-]*	0.013	A_3 [GPa]	0	τ_{12fail} [MPa]**	1.01E20
ν_{31} [-]*	0.5	B_0 [-]	2.95	τ_{23fail} [MPa]	35.2
ν_{23} [-]*	0	B_1 [-]	2.95	τ_{31fail} [MPa]**	1.01E20
G_{12} [MPa]	30.7	T_1 [GPa]	6.08	G_{C11} [J/m²]	790
G_{31} [MPa]	30.7	T_2 [GPa]	0	G_{C22} and G_{C33} [J/m²]*	30
G_{23} [MPa]	42.3	T_{ref} [K]	293	G_{C31} [J/m²]*	1.46
		Spec. Heat [J/kgK]	1.85E+03	G_{C12} [J/m²]*	1.46
		Thermal Conductivity	0	G_{C23} [J/m²]*	1.46
				Dam. Coupl. Coeff.	0

Orthotropic hardening model (coefficients and effective σ-ε-values)					
Plasticity coefficients		Effective stress-strain-values			
a_{11} [-]	0.03	$\sigma_{eff\#1}$ [kPa]	1.76E+02	$\varepsilon_{eff\#1}$ [-]	1.82E-04
a_{22} [-]	1.00E-05	$\sigma_{eff\#2}$ [kPa]	9.89E+02	$\varepsilon_{eff\#2}$ [-]	1.20E-03
a_{33} [-]	1.00E-05	$\sigma_{eff\#3}$ [kPa]	1.74E+03	$\varepsilon_{eff\#3}$ [-]	3.11E-03
a_{12} [-]	1.00E-06	$\sigma_{eff\#4}$ [kPa]	2.42E+03	$\varepsilon_{eff\#4}$ [-]	6.92E-03
a_{13} [-]	1.00E-06	$\sigma_{eff\#5}$ [kPa]	3.10E+03	$\varepsilon_{eff\#5}$ [-]	1.13E-02
a_{23} [-]	1.00E-06	$\sigma_{eff\#6}$ [kPa]	5.97E+03	$\varepsilon_{eff\#6}$ [-]	2.83E-02
a_{44} [-]	1	$\sigma_{eff\#7}$ [kPa]	1.20E+04	$\varepsilon_{eff\#7}$ [-]	5.78E-02
a_{55} [-]	1.75	$\sigma_{eff\#8}$ [kPa]	2.07E+04	$\varepsilon_{eff\#8}$ [-]	1.06E-01
a_{66} [-]	1.75	$\sigma_{eff\#9}$ [kPa]	3.46E+04	$\varepsilon_{eff\#9}$ [-]	1.061E-01
-		$\sigma_{eff\#10}$ [kPa]	2.02E+08	$\varepsilon_{eff\#10}$ [-]	1
Additional material Data					
ρ_{ref} [g/cm³]	0.98				

*taken from literature [7] and calculated using assumptions by Bower [11].
**no failure.

The data set presented in [4] is the state of the art for ballistic simulations in ANSYS AUTODYN using UHMWPE. The majority of the material's properties were either obtained experimentally (light grey) or obtained by numerical verification and validations simulations (light blue), respectively, a few values were taken from literature [7].

3 Parameter study

3.1 The case investigated

a) Experimental
Dyneema® HB26 crossply composite was characterized, a commonly used material for hard ballistic applications. Dyneema® HB26 is a polymeric composite material consisting of 0°-/90°-layered sheets which are hot-pressed to form a plate with areal density of 15 kg/m². Subsequently, specimens were cut from this panel via water jet cutting using a dimension of 200 x 200 mm. For the ballistic impact tests the specimen were clamped with a steel frame and perpendicularly oriented to the discharge opening of the two-staged light gas gun using laser technique. The experimental setup is indicated in Figure 1.

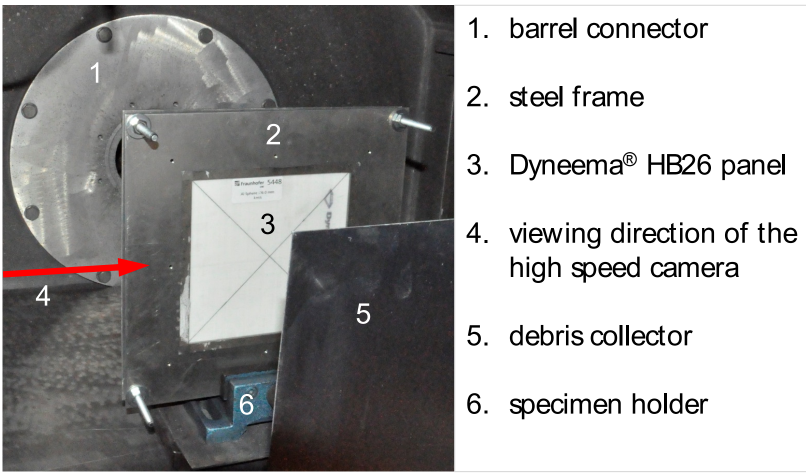

Figure 1: Experiment setup of ballistic impact tests; target configuration.

The panel's fixture was derived form-fit by surrounding a 10 mm wide strip at the edges in impact direction. The remaining free area (~180x180 mm) was modeled as substitute FE-model as follows (Figure 2):

b) Numerical substitute FE-model
In order to avoid numerical artefacts, i.e. accumulation of nodes of eroded elements at the symmetrical axis (significantly causes critical time steps), the full setup was modeled (Figure 2). Fine mesh at the vicinity of the impact and coarse meshes away from the center of the Dyneema® HB26 plate were generated using eight-noded brick elements exclusively. The vicinity of the impact was

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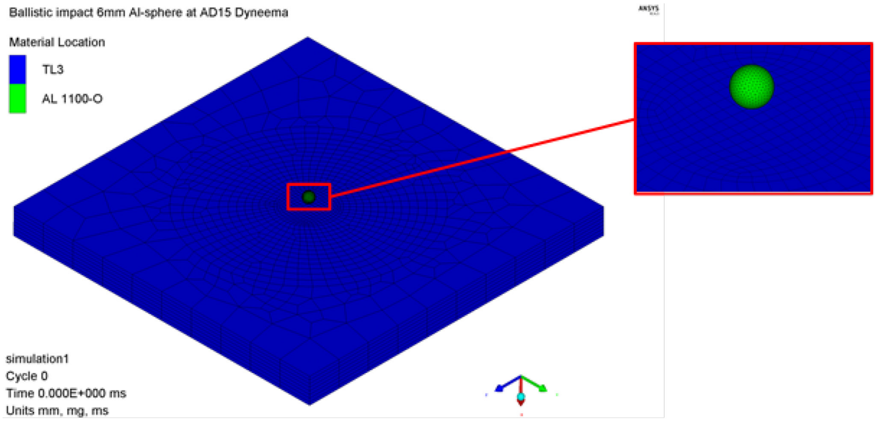

Figure 2: Substitute FE-model for simulating ballistic impact situations of a panel with AD = 15 kg/m² and a 6 mm diameter aluminum sphere projectile [4].

constantly meshed with eight-noded brick elements with an edge length of 1.5 mm. A fineness of 0.1 mm was chosen for the tetrahedral elements of the sphere mesh. Furthermore, the hourglassing reducing damping factor was switched to 0.1. The edges were fixed due to a zero velocity boundary condition according to the clamping (steel frame) used for the experiment. In order to avoid physically unsound deformation behavior and, therefore, preventing extremely small time increments, an erosion model was used with an instantaneous geometric erosion strain of 150 percent for UHMWPE and 250 percent for the aluminum sphere.

This substitute FE-model was used for former validation simulations by Lässig *et al*. [4].

4 Results

In the course of the study, the before mentioned impact case was investigated for two different scenarios. First, the ballistic impact situation with an impact velocity of 2052 m/s where the projectile had been stopped and second, with an impact velocity of 6591 m/s where the projectile completely penetrates the panel and a residual velocity was measured. As a result of an extensive experimental effort the data set “TL3” could be generated. Based on the typical behavior of UHMWPE a lot of unpredictable technical challenges had to be solved. However, not all the tests provided completely satisfying results. It is therefore enormously important for the materials ballistic performance to identify which parameters are the most sensitive.

Within the scope of this work a chart with experimentally determined parameters is investigated (Table 2).

Table 2: Material parameters investigated towards their sensitivity to the ballistic performance of UHMWPE.

Parameter:	Initial value	Decreased (-50%)	Increased (+50%)
E_{11}	3.62 GPa	1.81 GPa	5.43 GPa
$\sigma_{11\text{fail}}$	1.07 GPa	0.54 GPa	1.61 GPa
$E_{22/33}$	26.9 GPa	13.45 GPa	40.4 GPa
$\sigma_{22/33\text{fail}}$	753 MPa	377 MPa	1130 MPa
G_{23}	42.3 MPa	21.2 MPa	63.5 MPa
τ_{23fail}	35.2 MPa	17.6 MPa	52.8 MPa
$G_{12/31}$	30.7 MPa	15.4 MPa	46.1 MPa
A_2 (EOS)	10 GPa	5 GPa	15 GPa
G_{IC}	790 [J/m²]	395 [J/m²]	1185 [J/m²]
G_{IIC}	1.46 [J/m²]	0.73 [J/m²]	2.19 [J/m²]

Table 2 lists the parameters for the materials stiffnesses and strengths in all principle directions (E_{ii}, σ_{ii}), the in-plane and through-thickness shear properties (G_{ij}) as well as the second coefficient of the polynomial equation of state (A_2) and the fracture toughness in Mode I (G_{IC}) [4, 9, 10]. It should be noted here that the parameters from the equation of state A_2 and A_3 are free compared to A_1 which is the automatically calculated bulk modulus (function of constants of the orthotropic stiffness matrix).

4.1 Case 1: projectile stopped

For permitting a quantitative assessment towards the ballistic performance in terms of changing the materials parameters, the expansions of the delamination areas were measured. This areas were obtained by top view (through-thickness direction) of the FE-model after the projectile was stopped in terms of damage in 11-direction of 90 to 100 percent Figure 3 (red areas). Here, the vertical and horizontal expansions, in the top view, were measured and the elliptical area was calculated. With this method it is possible to derive a quantitative perspective of the amount of energy absorbed by delamination (fracture Mode I).

Figure 3 shows exemplary the quantitative derivation of the dimension of the delamination areas in terms of fracture toughness in Mode I. These areas, illustrated by dashed black lines, were obtained for a fracture toughness of 395 J/m², 790 J/m² and 1185 J/m². A clear correlation can be found where increasing fracture toughness in Mode I cause smaller delamination areas.

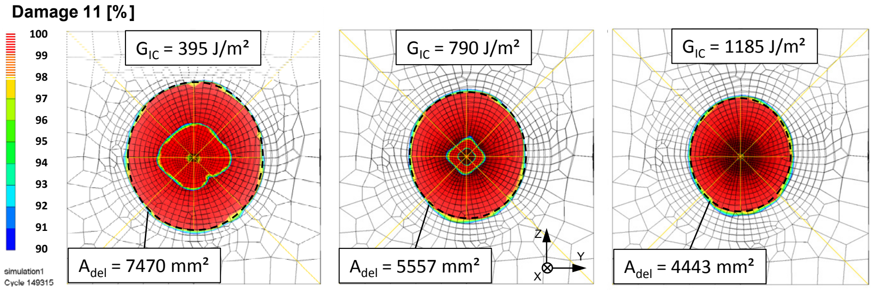

Figure 3: Quantitative derivation of the delamination areas obtained by the FE-model.

Furthermore, the Mode I delamination occur in upper layers pictured by the smaller red area around the impact center (left and middle picture, Figure 3).

The other material parameters offered by Table 2 in connection to their sensitivities towards the delamination areas are listed in Table 3.

Table 3: Dimensions of delamination areas and evaluation of sensitivities.

parameter:	Delamination area* [mm²] decreased value -50%	Delamination area* [mm²] increased value +50%	sensitivity
E_{11}	14647 (264%)	5128 (92%)	high
σ_{11fail}	4573 (82%)	5521 (99%)	low
$E_{22/33}$	4868 (88%)	5549 (99%)	low
$\sigma_{22/33fail}$	4271 (77%)	6661 (120%)	moderate
G_{23}	5573 (100%)	5552 (100%)	low
τ_{23fail}	5497 (99%)	5613 (101%)	low
$G_{12/31}$	5374 (97%)	5622 (101%)	low
A_2 (EOS)	5500 (99%	5639 (101%)	low
G_{IC} (G_{C11})	7470 (134%)	4443 (80%)	moderate
G_{IIC} (G_{C12})	5523 (99%)	5598 (101%)	low
initial value from TL3	5557 (100%)		-

* in top view.

Table 3 shows the quantitative comparison of the delamination areas obtained by the simulation. Moreover, with this method it can be supposed that several material parameters have a clearly influence on the energy dissipation during ballistic impact. Here, it was found that the stiffness in through-thickness direction E_{11}, the failure stress in fiber direction $\sigma_{22/33\mathrm{fail}}$ and the fracture toughness in Mode I G_{IC} directly impact the plane dimensions of the delamination areas when the projectile was stopped. For a decreased E_{11} a complete perforation of the panel can be noticed (Table 3).

4.2 Case 2: full perforation

The second case of this parameter study should provide reasonable assurance that the energy dissipation strongly depends on several material properties. For that purpose the substitute FE-model was investigated for the impact situation with an impact velocity of 6591 m/s and a residual velocity of 2178 m/s. By putting gauge points into several elements in the cross section of the projectile as well as on the back face of the panel the residual velocity of the fastest element was obtained. To get information about the sensitivity of the ballistic performance the change in residual velocity is compared to the velocity obtained by the model using the base data set TL3. The comparison of the experiment to the FE-model for three points in history is given by Figure 4.

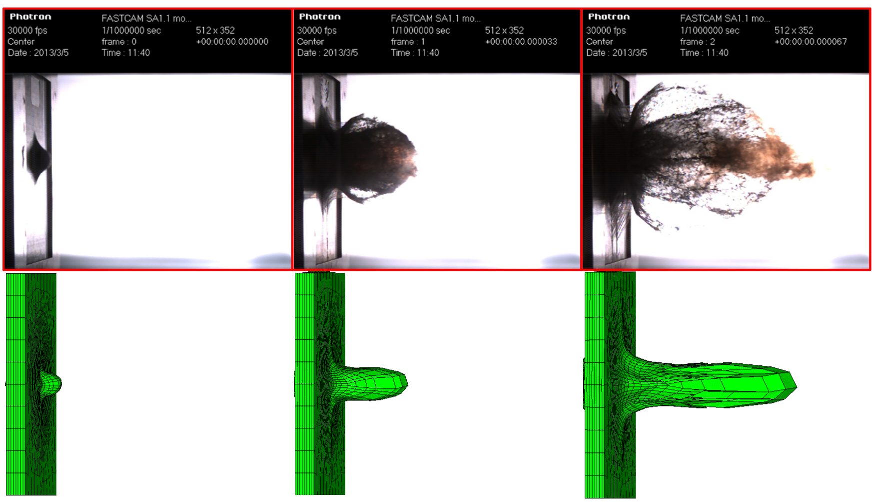

Figure 4: Comparison of the back side bulge of experiment and simulation for three points in history.

Figure 4 indicates that the back side bulge cannot yet be modelled satisfactorily. However, the simulated bulge peaks seem to be in good agreement with the high speed camera pics from the experiment. The experiment arises a projectiles (yields) residual velocity of 2457 m/s. Whereas, the simulation showed a residual velocity of 2178 m/s which is an indication for a minor underestimation but an overall good agreement of the ballistic performance. The material parameters were investigated towards the ballistic performance analog impact case 1. The results are summarized in Table 4.

Table 4: Variation of residual velocities obtained at t = 0.01 ms.

Parameter:	Predicted v_{res} [m/s]		Sensitivity
	Decreased value -50%	Increased value +50%	
E_{11}	2334 (107%)	1616 (74%)	high
σ_{11fail}	2077 (95%)	2189 (101%)	low
$E_{22/33}$	1680 (77%)	2362 (108%)	high
$\sigma_{22/33fail}$	2324 (107%)	1859 (85%)	high
G_{23}	2029 (93%)	2267 (104%)	low
τ_{23fail}	2104 (97%)	2181 (100%)	low
$G_{12/31}$	1805 (83%)	2255 (104%)	high
A_2 (EOS)	1934 (89%)	2368 (109%)	high
G_{IC} (G_{C11})	2293 (105%)	2103 (97%)	low
G_{IIC} (G_{C11})	2113 (97%)	2205 (101%)	low
for initial value in TL3	2178 (100%)		-

In Table 4 the residual velocity results of the fastest element of projectile after panel penetration is presented. As in impact case 1 the ballistic performance exhibits several sensitivities regarding material parameters. The study of the investigated impact case 2 reveals a strong sensitivity of the stiffness in through thickness direction, the in-plane stiffnesses, the strength in fiber direction $\sigma_{22/33fail}$, the through-thickness shear stiffnesses $G_{12/31}$ and the coefficient A_2 of the equation of state. On the one hand the ballistic performance was highly increased by increasing the stiffness E_{11} in through-thickness direction, but was weakened by increasing the stiffness in fiber direction and the EOS coefficient A_2. Moreover, it was established that the shear stiffnesses $G_{12/31}$ in through thickness direction showed a moderate influence on the residual velocity.

5 Discussion and evaluation

Prior to this parameter study, a hydrocode model for ultra-high molecular weight polyethylene (UHMWPE) was presented by Lässig *et al.* [4] that showed a suitable applicability for hyper velocity impact simulations. Due the typical behavior of the material the experimental showed a lot of difficulties obtaining specific material properties. In several cases new test fixtures or specimen forms had to be developed and verified for better experimental results. Due to the extensive experimental effort associated to the non-linear orthotropic material model, it is hard to improve every testing method. For this reasons, a parameter study is presented in this publication that should clarify and highlight the parameters which are sensitive to the simulated impact results. Here, two cases were investigated where an aluminum sphere projectile at two different impact velocities was shot onto a UHMWPE composite panel with an area density of 15 kg/m². In case one, the projectile was stopped and the occurring delamination areas (failure in through-thickness direction) were shown against the parameter change. In case two, the highest residual velocities of the projectiles parts (elements) after penetrating the UHMWPE panel were compared again to the parameter change.

For instance, for the case when the projectile was stopped, the delamination area (failure in through-thickness direction) is mainly sensitive towards the stiffness in through-thickness direction, the fiber strength and the fracture toughness Mode I in through-thickness direction. In order to characterize changes of ballistic performance at hyper velocity a full perforation case was simulated. Here, the parameter change showed a clear influence towards the residual velocity of the debris cloud. A very strong sensitivity was noticed for change of the value of stiffness in in-plane and through-thickness direction, the strength in fiber direction, as well as for the chosen coefficient of the EOS. The shear stiffness in through-thickness direction showed a moderate influence to the ballistic performance.

Finally, this study should clarify in which direction future material improvements may lead to for better high end protection systems. It should be mentioned here that material improvements must be balanced with economical restrictions.

Nonetheless, a quite satisfying data set was presented that is prospectively suitable for a large field of applications.

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