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A methodology for hydrocode analysis of ultra-high molecular weight polyethylene composite under ballistic impact

Long H. Nguyen [a,c,d,*], Torsten R. Lässig [b], Shannon Ryan [c], Werner Riedel [b], Adrian P. Mouritz [a], Adrian C. Orifici [a]

[a] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, GPO Box 2476, Melbourne, Australia
[b] Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Eckerstraße 4, D-79104 Freiburg, Germany
[c] Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend, Victoria 3207, Australia
[d] Defence Materials Technology Centre, 24 Wakefield St, Hawthorn, Victoria 3122, Australia

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ABSTRACT

Ballistic performance analysis of ultra-high molecular weight polyethylene (UHMW-PE) is critical for the design of armour systems against ballistic threats. However, no validated modelling strategy has been published in literature for UHMW-PE composite that captures the penetration and damage mechanisms of thick targets impacted between 900 m/s and 2000 m/s. Here we propose a mechanistically-based and extensively validated methodology for the ballistic impact analysis of thick UHMW-PE composite. The methodology uses a non-linear orthotropic continuum model that describes the composite response using a non-linear equation of state (EoS), orthotropic elastic–plastic strength with directional hardening and orthotropic failure criteria. A new sub-laminate discretisation approach is proposed that allows the model to more accurately capture out-of-plane failure. The model is extensively validated using experimental ballistic data for a wide range of UHMW-PE target thicknesses up to 102 mm against 12.7 mm and 20 mm calibre fragment simulating projectiles (FSPs) with impact velocities between 400 m/s and 2000 m/s. Very good overall agreement with experimental results is seen for depth of penetration, ballistic limit and residual velocity, while the penetration mechanisms and target bulge behaviour are accurately predicted. The model can be used to reduce the volume of testing typically required to design and assess thick UHMW-PE composite in ballistic impact applications.

1. Introduction

Composites reinforced with ultra-high molecular weight polyethylene (UHMW-PE) fibres are increasingly being used in protection against ballistic threats due to their high resistance to penetration and low weight. The material shows a mass efficiency against fragment simulating projectiles (FSP) threats of 300–500% compared to armour steel and 130–160% for polymer matrix composites reinforced with aramid, carbon or glass fibre [1]. Due to the extensive deformation exhibited by UHMW-PE composite under ballistic impact, multiple large targets are required to determine a single ballistic limit velocity. Such testing can be prohibitively expensive when considering a range of thicknesses and armour configurations against multiple ballistic threat types. In order to reduce testing efforts, it is highly desirable to establish computationally efficient numerical models that accurately predict the ballistic response of the material.

Chocron et al. [2] proposed a meso-scale model of UHMW-PE composite that discretises the laminate into strips of fibre bundles. The approach uses a linear-elastic orthotropic material model to represent the fibre bundles, and was successful in predicting the response of UHMW-PE composite strips, layers ($[0/90]_2$), and targets up to 11.5 mm against 7.62 mm diameter FSPs. However, the computational cost of meso-scale models is very high, making them impractical for thick UHMW-PE composites where a large number of bundle elements would be needed. Other models have been proposed to analyse the ballistic impact response of UHMW-PE composite, including multi-scale [3] and continuum [4] approaches. However, only limited validation of these models for impact velocities below 900 m/s has been performed and no validation has been conducted for higher impact velocities. At higher impact velocities, a non-linear equation of state (EoS) is

* Corresponding author at: Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend, Victoria 3207, Australia. Tel.: +61 (3) 9626 8622.
E-mail address: long.nguyen@dsto.defence.gov.au (L.H. Nguyen).

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required to account for the non-linear shock compressibility of the material; this is not captured with these models.

Lässig et al. [5] characterised the properties of UHMW-PE composite (Dyneema® HB26) and derived material parameters for a continuum non-linear orthotropic model [6–9]. The model was validated for the impact of 15 mm thick UHMW-PE composite plates by spherical projectiles at hypervelocity (2052–6591 m/s), with good predictions of the residual velocity. The approach was assessed against thicker UHWE-PE targets (up to 50 mm) impacted by FSPs at velocities below 2000 m/s by Nguyen et al. [10]. At these lower velocities, material strength becomes increasingly important in controlling the deformation and penetration response of the material. Results showed very poor prediction of deformation and significant under-prediction of the ballistic limit velocity. This was found to be predominantly due to coupling between out-of-plane tension and out-of-plane shear failure modes, which resulted in premature through-thickness shear failure of the composite under ballistic impact.

In this paper, a methodology is proposed for ballistic impact analysis of thick UHMW-PE composites using a continuum non-linear orthotropic model. A sub-laminate target discretisation approach is proposed that allows the out-of-plane tensile and shear failure modes to be decoupled in the bulk material, which overcomes the out-of-plane failure coupling problem in the material model. A new erosion model is introduced that accounts for the directional-dependent failure of the composite and a new material data set for UHMW-PE composite is derived based on experimental data from literature. The methodology is validated against a large amount of experimental ballistic impact data reported by Nguyen et al. [11]. Validation includes depth of penetration (DoP) of semi-infinite UHMW-PE composite targets against 20 mm FSP and ballistic limit velocity (V_{50}) predictions for UHMW-PE composite targets up to 102 mm thick against 12.7 mm and 20 mm FSPs. Quantitative validation of the model is also made of the target bulge geometry in terms of the propagation of the apex and hinge positions.

2. Ballistic impact model

2.1. UHMW-PE material model

The non-linear orthotropic material model developed in [6–9] and implemented in ANSYS® AUTODYN® is used to model the ballistic impact response of UHMW-PE composite. The material model includes orthotropic coupling of the material volumetric and deviatoric response, non-linear equation of state, orthotropic hardening, stress-based composite failure criteria, and orthotropic energy-based softening. The material parameters for the UHMW-PE composite that were used are detailed in Table 1. For completeness the model will be briefly described below; more details are given in [5,7–9,12].

2.1.1. Equation of state

The thermodynamic (EoS) response of a material and its ability to carry tensile and shear loads (strength) is typically treated separately within hydrocodes such that the stress tensor can be decomposed into volumetric and deviatoric components [13]. However, anisotropic materials exhibit coupling of these two responses, i.e. hydrostatic stresses lead to deviatoric strains and vice versa. Anderson et al. [14] proposed a constitutive formulation for anisotropic materials which allows the use of the theory of shock waves propagating through orthotropic materials with a limited amount of coupling of the volumetric and deviatoric response in the elastic regime. Here the pressure is composed of the volumetric and deviatoric components, and is defined by:

$$p = p(\varepsilon_{vol}, e) - \frac{1}{3}(C_{11} + C_{21} + C_{31})\varepsilon_{11}^d - \frac{1}{3}(C_{12} + C_{22} + C_{32})\varepsilon_{22}^d - \frac{1}{3}(C_{13} + C_{23} + C_{33})\varepsilon_{33}^d \quad (1)$$

where C are coefficients of the stiffness matrix and $\varepsilon_{11,22,33}^d$ are the deviatoric strains in the principal directions. The pressure contribution from the volumetric strain $p(\varepsilon_{\text{vol}}, e)$ is described using the Mie–Grüneisen EoS:

$$p(\varepsilon_{vol}, e) = p_r(v) + \frac{\Gamma(v)}{v}[e - e_r(v)] \quad (2)$$

where v is the volume, e is the internal energy and $\Gamma(v)$ is the Grüneisen coefficient. $p_r(v)$ and $e_r(v)$ refer to a reference pressure and internal energy, respectively. The shock Hugoniot is typically used as a reference condition.

The shock formulation of the Mie–Grüneisen EoS is applied here, where an empirical linear relationship defines the shock and particle velocity relationship:

$$U_S = c_0 + Su_p \quad (3)$$

where U_S is the shock wave velocity, c_0 is the bulk sound speed, S is the slope of the shock-particle velocity curve, and u_p is the particle velocity. The reference pressure, density and internal energy are then calculated from the Rankine–Hugoniot equations. Conditions off the Hugoniot reference curve are approximated with the Grüneisen coefficient (Γ) from the second term in Eq. (2).

In the non-linear orthotropic model, c_0 is calculated from the elastic orthotropic constants and the slope of the U_S–u_p relationship, S is empirically adjusted to match flyer plate impact test results. The shock response of UHMW-PE composite has previously been shown by Hazell et al. [15] to be similar to that of polyethylene, therefore it is assumed the off-Hugoniot response of UHMW-PE composite is also similar. Thus, a Grüneisen coefficient for polyethylene of 1.64 is used in this work [16].

Fig. 1 shows measurements by Lässig et al. [5] of the free surface velocity determined by inverse planar plate impact tests on UHMW-PE composite plates. Using the model, numerical results from one-dimensional simulations are also plotted, demonstrating good agreement of the initial and subsequent release waves up to about 3000–3500 ns post impact. After this time the one-dimensional strain assumption used in the simulation is no longer valid because the stress waves propagating from the lateral edge of the target specimen affect the free surface velocity measurements.

2.1.2. Strength model

The quadratic yield surface proposed by Chen et al. [17] is used to describe non-linear, irreversible hardening of the material:

$$f(\sigma_{ij}) = a_{11}\sigma_{11}^2 + a_{22}\sigma_{22}^2 + a_{33}\sigma_{33}^2 + 2a_{12}\sigma_{11}\sigma_{22} + 2a_{23}\sigma_{22}\sigma_{33} + 2a_{13}\sigma_{11}\sigma_{33} + 2a_{44}\sigma_{23}^2 + 2a_{55}\sigma_{31}^2 + +2a_{66}\sigma_{12}^2 = k \quad (4)$$

where the nine plasticity coefficients, a_{ij}, represent the degree of plastic anisotropy of the material, σ_{ij} are stresses in the principal material directions, and k is a state variable that defines the current limit of the yield surface. To describe strain hardening, k is replaced by a master effective stress-effective plastic strain curve, defined by 10 piecewise points. It allows the determination of the stress states in any orthotropic direction from the plasticity coefficients a_{ij}. The master effective stress $\overline{\sigma}$ and master effective plastic strain $\overline{\varepsilon}^p$ in the normal direction is defined by:

$$\overline{\sigma} = \sigma_{ii}\sqrt{\frac{3a_{ii}}{2}} \text{ and } \overline{\varepsilon}^p = \varepsilon_{ii}\sqrt{\frac{2}{3a_{ii}}} \quad (5)$$

and in the shear direction by: