Modelling plastic deformation of ultra-high molecular weight polyethylene composites under blast loading

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Introduction

Ultra-high molecular weight polyethylene (UHMWPE) fiber reinforced composites are widely used in military applications to resist threats like projectiles, debris, and blast. In the current investigation, the dynamic response of the UHMWPE composites subjecting to blast loading was numerically studied. The elastoplastic model proposed by Chen et al. [1] was modified by using a strain-rate dependent hardening; this model was implemented in user subroutine VUMAT of ABAQUS. The numerical model was validated by the experimental data of Fallah et al. [2].

Numerical model

Numerical analyses were carried out using the commercial FE software ABAQUS. **Figure 1** shows the geometries of the model, which are basically consistent with the experimental configuration in Ref. [2]. A quarter model was used due to the symmetry. The coupled Eulerian-Lagrangian (CEL) analysis was applied to model the interaction between the blast waves and the UHMWPE plate. The Eulerian elements had a side length of 1 mm and the Lagrangian elements had a side length of 2 mm to achieve a reasonable fluid-structure interaction (FSI). The Eulerian region was removed from the simulations 0.3 ms after the detonation when the FSI process basically ended. The simulations stopped at a total time of 6 ms while the UHMWPE plate still oscillated at this moment. Therefore, the data at the oscillation equilibrium point was used for estimating the permanent mid-point deflection of the plate, which was then compared with corresponding results in Ref. [2].

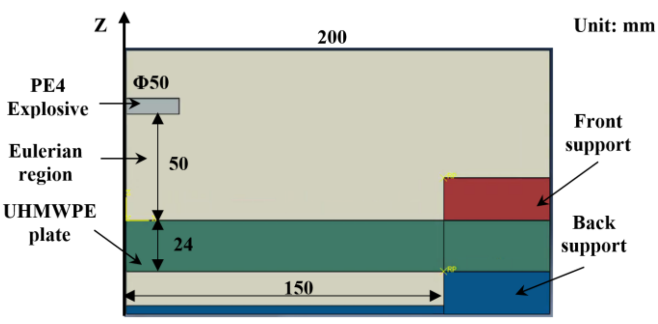

Figure 1. The geometries of the numerical model

Table 2. The parameters of the UHMWPE laminate [3]

Parameter	Value	Parameter	Value
E_{11}	51 GPa	a_{11}	0.0006
E_{22}	51 GPa	a_{22}	0.0006
E_{33}	7 GPa	a_{33}	0.025
υ_{12}	0	a_{12}	0
υ_{23}	0.013	a_{23}	0
υ_{13}	0.013	a_{13}	0
G_{12}	192 MPa	a_{44}	1
G_{23}	2 GPa	a_{55}	1.7
G_{13}	2 GPa	a_{66}	1.7

A strain-rate dependent hardening was applied for modeling the elastoplastic behavior of UHMWPE cross-ply laminate. The yield surface can be expressed as:

$$F = f(\boldsymbol{\sigma}) - \bar{\sigma}\left(\overline{\varepsilon^p}, \dot{\overline{\varepsilon^p}}\right) \quad (1)$$

where $f(\boldsymbol{\sigma})$ and $\bar{\sigma}\left(\overline{\varepsilon^p}, \dot{\overline{\varepsilon^p}}\right)$ are expressed in Eqs. (2) and (3).

$$f = \begin{array}{l}(a_{11}\sigma_{11}{}^2 + a_{22}\sigma_{22}{}^2 + a_{33}\sigma_{33}{}^2 + 2a_{12}\sigma_{11}\sigma_{22} + 2a_{13}\sigma_{11}\sigma_{33} \\ \quad +2a_{23}\sigma_{22}\sigma_{33} + 2a_{44}\sigma_{12}{}^2 + 2a_{55}\sigma_{13}{}^2 + 2a_{66}\sigma_{23}{}^2)^{1/2}\end{array} \quad (2)$$

$$\bar{\sigma} = \bar{\sigma}_0\left(\frac{\dot{\overline{\varepsilon^p}}}{\dot{\overline{\varepsilon^p_0}}}\right)^m \quad (3)$$

where $\bar{\sigma}$ is the effective stress, $\dot{\overline{\varepsilon^p}}$ and $\dot{\overline{\varepsilon^p_0}}$ are the effective plastic strain rate and reference effective plastic strain rate, respectively, $\bar{\sigma}_0$ is the effective stress at the reference strain rate, and m is the strain rate coefficient.

Results and discussion

As shown in **Figure 2,** the simulations underestimated the impulses I for the cases with 15 to 36 g PE4 explosives. All the simulations underestimated the blast resistance of the UHMWPE laminates, i.e. the permanent mid-span deflections predicted by the simulations were larger than the corresponding data measured in the experiments. Nevertheless, δ predicted by the model with a strain-rate dependent hardening is evidently closer to experimental data than that predicted by the model without a strain- rate dependent hardening.

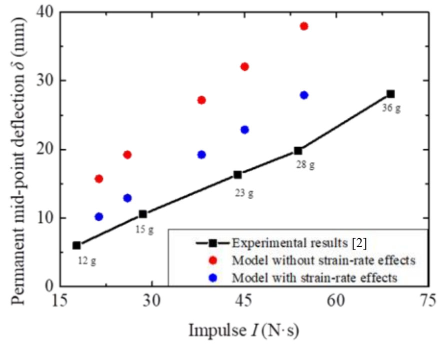

Figure 2. The plot of permanent mid-point deflection versus impulse

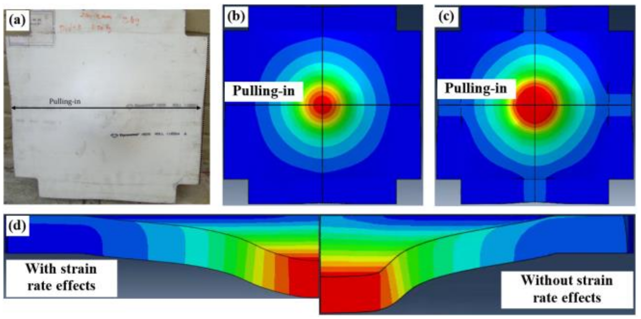

Figure 3. Deformation characteristics of the UHMWPE plates after the explosion of a 36 g PE4 explosive: (a) rear surface in the experiment [2], (b) rear surface in the simulation with a strain-rate dependent hardening, (c) rear surface in the simulation without a strain-rate dependent hardening and (d) section views of the two plates in the simulations

As observed in the experiments (**Figure 3**), the UHMWPE laminates underwent pulling-in of sides. Using a strain-rate dependent hardening led to a smaller pulling-in. In addition, the bulge predicted by the strain-rate dependent hardening model was smoother than that predicted by the model without a strain-rate dependent hardening. An alternative way to account for the increase in the hardening rate at high strain rates is simply applying the dynamic properties of materials, which might also lead to a good prediction in mid-point deflection. However, this method cannot account for the different strain rates varying with the distance to the detonation point.

Conclusions

i) The numerical models generally underestimate the blast resistance of the UHMWPE laminates and the impulse compared with the corresponding experimental results. The model with a strain-rate dependent hardening provides a more accurate prediction in the permanent mid-point deflection than a model without a strain-rate dependent hardening.

ii) The bulge of the UHMWPE plate with a strain-rate dependent hardening is smoother than that without a strain-rate dependent hardening. This is caused by the different strain rates within the plate that vary with the distance to the detonation point, stressing the necessity of modeling the strain-rate dependent hardening behavior.

Reference

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