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

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Abstract. Ultra-high molecular weight polyethylene (UHMWPE) fiber reinforced composites are widely used in military applications to resist threats like projectiles, debris, and blast waves due to their high specific modulus, high strength and low density. In this investigation, numerical simulations were carried out to model the dynamic response of the UHMWPE cross-ply plates under blast loading. An elastoplastic model including strain-rate dependent hardening was implemented in user subroutine VUMAT and was used to describe the anisotropic characteristics of the UHMWPE composites. The coupled Eulerian-Lagrangian (CEL) analysis in ABAQUS was applied to model the blast waves caused by the detonation of an explosive and their interaction with the UHMWPE plate. The numerical model was validated by the corresponding experimental results in the literature. The numerical results demonstrate that the strain rate effects made the deflection of the plate smaller and smoother, indicating that it is necessary to use a strain-rate dependent hardening.

1. Introduction

Ultra-high molecular weight polyethylene fiber reinforced composites are widely used in military applications to resist threats like projectiles, debris, and blast waves due to their high specific modulus, high strength and low density. When subjecting to blast loading, these composites usually undergo progress loss of material strength and stiffness as a result of various failure mechanisms, such as fiber-matrix debonding, ply splitting and delamination [1].

Extensive experimental and numerical studies have been conducted to study the ballistic impacts of UHMWPE composites [2-5]. However, relatively limited studies focused on the dynamic response of these composites under blast loading. Fallah et al. [1] carried out explosion experiments on UHMWPE Dyneema® laminates by detonating different masses of PE4 explosives to induce localized blast loading. The UHMWPE laminates underwent larger plastic deflection with the increase of the PE4 mass; delamination and pulling-in of materials were the dominant failure mechanisms. Karthikeyan et al. [6] investigated the dynamic response of the UHMWPE beam with different matrices under the localized blast loading induced by the soft impact of a foam projectile. Travelling shear hinges that emanated from the impact location and propagated towards the supports were found to be the primary
deformation mode. Nazarian et al. [7] also carried out soft impact tests on UHMWPE laminates to study the laminates’ response to blast loading. Pulling-in and in-plane shear were found to be the dominant response of the laminates.

Numerical simulation is an important alternative method for blast-resistant structures design considering that the blast experiments are expensive and difficult to carry out. Accurately representing the elastoplastic characteristics is essential for the modeling of the UHMWPE composites. One of the widely used elastoplastic models for fiber composites is proposed by Chen et al. [8]; this model adopts a quadratic yield function and is available in the finite element (FE) software AUTODYN. The numerical works conducted by Nguyen et al. [9] and Shen et al. [5] have proved that this model is accurate enough in predicting the projectile residual velocity and dynamic deflection a UHMWPE plate under ballistic impact. However, this model has not been validated for the blast loading condition. When subjecting to blast loading, the strain rate effects of the UHMWPE composites should be more pronounced, which was not considered in the aforementioned model.

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. [8] 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. [1].

2. Numerical model

2.1. The structure of the 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. [1]. The UHMWPE plate has an in-plane size of 400 mm by 400 mm and a thickness of 24 mm. This plate was clamped between two steel supports and had a 300 mm by 300 mm exposed area. These two supports were modelled as rigid bodies and fixed during the analyses. The blast waves were produced by the detonation of a disc-shaped PE4 explosive with a diameter of 50 mm. And the stand-off distance of this explosive was 50 mm. Five cases with different-mass PE4 explosives were simulated, as shown in table 1.

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 PE4 explosive and the air were modelled by Eulerian algorithm; the UHMWPE plate and the steel supports were modelled by the Lagrangian algorithm. 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

![Figure 1. The geometries of the numerical model.](image-url)
(FSI). Based on the experimental results of the increase in panel thickness in Ref. [1], limited delamination formed in the UHMWPE plates for the cases in the current investigation. To save the computational time, the UHMWPE composite was modelled as a monolithic plate. In addition, the Eulerian region was removed from the simulations 0.3 ms after the detonation. Preliminary numerical analyses indicated that after 0.3 ms the FSI process basically ended because the momentum (along direction z) of the UHMWPE plate had already begun to decrease. The simulations stopped at a total time of 6 ms. It should be noted that 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. [1].

Table 1. Simulation matrix for different masses of PE4 explosives.

| Case No. | Charge mass (g) in the experiments [1] | Charge mass (g) in the simulations |
|----------|----------------------------------------|-----------------------------------|
| 1        | 12                                     | 12.0                              |
| 2        | 15                                     | 15.0                              |
| 3        | 23                                     | 22.8                              |
| 4        | 28                                     | 28.0                              |
| 5        | 36                                     | 36.0                              |

2.2. Material models and properties

In the experiments [1], the UHMWPE laminates were Dyneema® HB26. Nguyen et al. [9] proposed a methodology for hydrocode analysis of UHMWPE cross-ply laminates under ballistic impact and performed simulations for HB26 laminates. They applied the yield function proposed by Chen et al. [8] to represent the laminate’s elastoplastic characteristics. In the current simulations, the same yield function was used. Considering the facts that under blast loading the strain rates within the laminate are quite high and the matrix-dominated plastic behavior has strong rate effects, a strain-rate dependent hardening was applied. The yield surface can be expressed as:

\[
F = f(\sigma) - \tilde{\sigma}(\dot{\varepsilon}^p, \dot{\varepsilon}^p)
\]

Where \( f(\sigma) \) and \( \tilde{\sigma}(\dot{\varepsilon}^p, \dot{\varepsilon}^p) \) are expressed in Eqs. (2) and (3).

\[
f = \left( a_{11}\sigma_{11}^2 + a_{22}\sigma_{22}^2 + a_{33}\sigma_{33}^2 + 2a_{12}\sigma_{11}\sigma_{22} + 2a_{13}\sigma_{11}\sigma_{33} + 2a_{23}\sigma_{22}\sigma_{33} + 2a_{44}\sigma_{12}^2 + 2a_{55}\sigma_{33}^2 + 2a_{66}\sigma_{23}^2 \right)^{1/2}
\]

Where \( a_{ii} \) are plasticity coefficients and \( \sigma_{ii} \) the stresses in the principal directions (11 and 22 are the in-plane reinforced directions while 33 is the thickness direction).

\[
\tilde{\sigma} = \tilde{\sigma}_0 \left( \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0^p} \right)^m
\]

Where \( \tilde{\sigma} \) is the effective stress, \( \dot{\varepsilon}^p \) and \( \dot{\varepsilon}^p_0 \) are the effective plastic strain rate and reference effective plastic strain rate, respectively, \( \tilde{\sigma}_0 \) is the effective stress at the reference strain rate, and \( m \) is the strain rate coefficient. In the current investigation, the reference strain rate is 0.001 s\(^{-1}\) and \( m \) is 0.08 [7]. Very limited fiber fracture was found in the experiments [1] and thereby fiber failure is not considered in the current model. This modified elastoplastic model was implemented in user subroutine VUMAT in ABAQUS. The parameters for the HB26 laminates are shown in Table 2, which are mainly cited from Ref. [9]. Figure 2 gives the input plot of effective stress versus effective plastic strain at the reference strain rate, which was determined based on the in-plane shear test results in Ref. [10].

The JWL equation of state was applied to describe the detonation of the PE4 explosive. And, the ideal gas equation of state was applied to describe the air material. Parameters for these two materials
are listed in table 3, which were cited from Refs. [11] and [12], respectively. As aforementioned, the steel supports were modelled as rigid bodies. An elastic model was applied for them with a density of 7.85 g/cm³ and a Young’s modulus of 200 GPa.

Table 2. The parameters of the UHMWPE laminate [9]

| 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 |
| $v_{12}$  | 0     | $a_{12}$  | 0     |
| $v_{23}$  | 0.013 | $a_{23}$  | 0     |
| $v_{13}$  | 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   |

Figure 2. Effective stress and effective plastic strain at the reference strain rate, based on the shear test result in Ref. [10].

Table 3. The parameters of the PE4 explosive and the air.

| Material | $\rho_0$ /g·cm⁻³ | $D$ /m·s⁻¹ | $E_0$ /kJ·m⁻³ | $A$ /GPa | $B$ /GPa | $R_1$ | $R_2$ | $\omega$ |
|----------|------------------|------------|----------------|---------|---------|-------|-------|---------|
| PE4 [11] | 1.6              | 8180       | 8.12×10⁶       | 718.2   | 11.85   | 4.7   | 1.3   | 0.25    |

| Material | $\rho_0$ /g·cm⁻³ | $P_0$ /MPa | $C_v$ /J·(t·K)⁻¹ | Gas constant |
|----------|------------------|-----------|------------------|--------------|
| Air [12] | 1.225×10⁻³       | 0.101325  | 718000           | 287058       |
3. Numerical results analyses

3.1. Permanent mid-point deflection

For comparison, both of the simulations using UHMWPE materials with and without strain-rate dependent hardening were carried out. The results of permanent mid-point deflection $\delta$ and the impulse $I$ exerted on the target in each simulation were obtained. Permanent mid-point deflections are usually used for evaluating the blast resistance of a plate.

Figure 3 compares the numerical and experimental results of the $\delta - I$ plots. The simulations underestimated the impulses $I$ for the cases with 15 to 36 g PE4 explosives. It might be because the mesh size of the Eulerian elements was not fine enough. However, further decreasing the mesh size requires much more computational time. On the contrary, the simulations overestimated the impulses $I$ for the cases with a 12g PE4 explosive. It should be attributed to the incomplete detonation of this explosive in the experiment [1] because it only had a thickness of ~3.8 mm. 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. It might be because the hardening rate (figure 2) determined by experimental data from [10] was smaller than the actual properties of the HB26 laminate used in the explosion experiments [1]. Nevertheless, $\delta$ 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 3. The plot of permanent mid-point deflection versus impulse.](image)

3.2. Deformation characteristics

The deformation characteristics of the UHMWPE plates were compared to further determine the strain-rate effects. Figure 4 shows the deformation characteristics of the UHMWPE plates after the explosion of a 36 g PE4 explosive in the experiments [1] and simulations. As observed in the experiments, the UHMWPE laminates underwent pulling-in of sides. Using a strain-rate dependent hardening led to a smaller pulling-in because the materials became stiffer. In addition, as shown in Figure 4(d), the bulge predicted by the strain-rate dependent hardening model was smoother than that predicted by the model without a strain-rate dependent hardening; i.e. the bulge of the latter was more localized. The smoother bulge appeared to be more similar to experimental observation shown in
Figure 5 in Ref. [1]. An alternative way to account for the increase in the hardening rate at high strain rates is simply applying the dynamic properties of materials; this method was used in many numerical studies in the literature. This might also lead to a good prediction in mid-point deflection that is close to the experimental data in some cases. However, this method cannot account for the different strain rates varying with the distance to the detonation point, which is the reason for the more localized bulge found in the current simulations.

Figure 4. Deformation characteristics of the UHMWPE plates after the explosion of a 36 g PE4 explosive: (a) rear surface in the experiment [1], (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.

4. Conclusions
In the current investigation, an elastoplastic model with a strain-rate dependent hardening was used to numerically investigate the blast resistance of a UHMWPE cross-ply composite. The coupled Eulerian-Lagrangian (CEL) analysis in ABAQUS was applied to model the interaction between the blast waves and the UHMWPE plate. It can be concluded:

(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, i.e. the latter is more localized. 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.

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