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IMPLEMENTATION OF A FINITE DEFORMATION HYPERELASTIC-PLASTIC COMPOSITE MATERIAL MODEL WITHIN A SHOCK PHYSICS HYDROCODE

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ABSTRACT This work details the implementation and application of a novel kinematic finite deformation hyperelastic composite material model (Criscione et al. [2003]) in a shock physics hydrocode. The material model captures the response of a ultra-high-molecular-weight polyethylene (UHMWPE) composites under high velocity impact. The model is implemented into a material point method (MPM) hydrocode framework (Schumacher et al. [2013]) to accurately capture the large deformations, wave propagation, and high pressures associated with high-velocity impact. The original hyperelastic model was formulated to include plasticity through the strain attributes that represent shearing.

INTRODUCTION: Fiber reinforced composite materials are often used in applications where low density and high strength characteristics are desired. Of particular interest is UHMWPE cross-ply composites, which are chosen due to their material and microstructural features, that allow for large amounts of energy absorption through large strains to failure, plasticity, delamination and fracture. The materials tend to be significantly weaker in their shear deformation response as compared to their normal or fiber direction response and exhibit ultimate shear strains that can exceed 20% without exhibiting material failure (Russell et al. [2013]). The ability to achieve large shear deformations, combined with the resulting fiber rotations cause the material to exhibit a highly membrane-like or “netting” response which leads to increased energy absorption.

Traditional composite material models are unable to capture the unique kinematic and constitutive behaviors of UHMWPE under finite deformations. Criscione’s work expands from isotropic materials to two-fiber (cross-ply) family composites and incorporates a hyperelastic formulation within a novel kinematics formulation that utilizes fiber bisectors and normals to track the primary fiber directions during deformation. The objective of this work is to modify the original model of Criscione to include a plastic response in the shear directions and implement the model into a hydrocode to demonstrate its ability to capture the response of UHWMPE composites under high-velocity impact events.

PROCEDURES, RESULTS AND DISCUSSION: The kinematics formulation of Criscione et al. [2003] defines the two undeformed fiber direction unit vectors ($\overline{M_1}$ and $\overline{M_2}$), their corresponding bisector unit vectors ($\overline{M_A}$ and $\overline{M_B}$), two deformed fiber unit vectors ($\overline{m}_1$ and $\overline{m}_2$) and their set of deformed bisector unit vectors ($\overline{m}_a$ and $\overline{m}_b$). The relationship between the deformed and undeformed fiber unit vectors is given by Eqn. (1) and the two pairs of bisector unit vectors are always orthogonal to one another.

$$\overline{m}_1 = \frac{\bar{\bar{F}}\cdot\overline{M_1}}{\sqrt{\overline{M_1}\cdot\bar{\bar{C}}\cdot\overline{M_1}}};\ \overline{m}_2 = \frac{\bar{\bar{F}}\cdot\overline{M_2}}{\sqrt{\overline{M_2}\cdot\bar{\bar{C}}\cdot\overline{M_2}}};\ \bar{\bar{C}} = \bar{\bar{F}}^T\cdot\bar{\bar{F}}, \tag{1}$$

where $\bar{\bar{F}}$ is the deformation gradient. In the rotating bisector coordinate system, the deformation can be expressed with six scalar strain attributes, each of which has direct physical interpretations. The six strain attributes are defined as ξ_1 through ξ_6 where ξ_1 is the volumetric strain; ξ_2 is the distortional area strain; ξ_3 is the change in angle between m_1 and m_2 (in-plane shear); ξ_4 is the fiber extension ratio; ξ_5 and ξ_6 are the out-of-plane shear strains. Casting these strain invariants into a hyperelastic framework given by Eqn. (2), results in kinematic stress tensors that are mutually orthogonal.

$$\bar{\bar{\sigma}} = \frac{1}{J}\sum_{i=1}^{6}\frac{\partial W}{\partial \xi_i}\bar{\bar{\Xi}}_i, \tag{2}$$

where J is the determinate of $\bar{\bar{F}}$, W is the strain energy function, and $\bar{\bar{\Xi}}_i$ are kinematic tensors. The uniqueness of these stress and strain components is that the shear components are decoupled from the normal components, which allows for the determination of the material constants through traditional composite material test methods. For this work, a simple plasticity model was incorporated into the original hyperelastic model which included combined isotropic/kinematic hardening. The plasticity model was only applied to the in-plane shear (ξ_3) and out-of-plane shear (ξ_5 and ξ_6) components, which are the primary matrix dominated deformation components. To demonstrate the kinematic capabilities of the model, it was compared to experimental data from [±45]s laminate tensile tests of Herakovich et al. [2000]. From Figure 1, it is observed that there is good agreement between the fiber bisected angle change from the experimental tests and the numerical predictions.

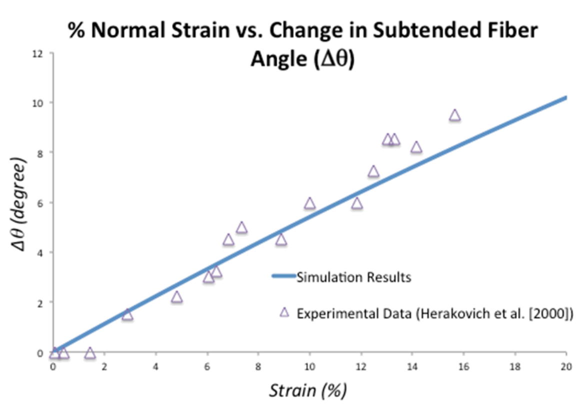

Fig. 1 – Compares the angle changes predicted by the Criscone model to the experimentally determined value.

As an initial evaluation of the hyperelastic-plastic model, a [0/90]s cross-ply UHMWPE laminate panel was subjected to a high-velocity impact by a metallic sphere. This problem was chosen because it demonstrates the models ability to capture large deformations of the UHMWPE composite under these conditions. Fig. 2 shows the predicted panel deformation and plastic strain at a selected time during the impact event. From the side view in this figure it is observed that the sphere induced large out-of-plane deformations in the panel without penetration. Also, at the center of each free-each edge of the panel, inward deformation or “pulling” of the panel towards the central impact point is evident. This deformation behavior is also evident from the in-plane plastic strain plot which is what causes the “netting” type behavior exhibited by this material.

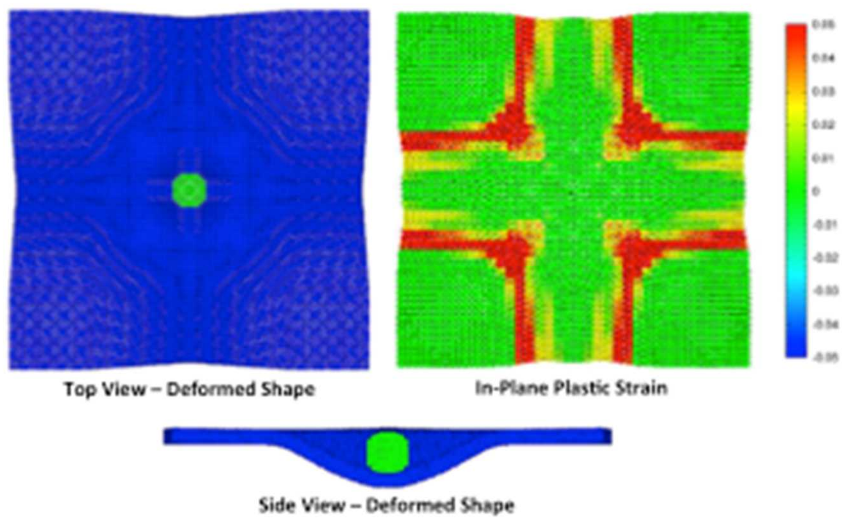

Fig 2 - Predicted composite deformation and plastic strain response under impact loading.

CONCLUSIONS: The hyperelastic and kinematic framework implemented into the shock physics hydrocode shows good agreement with both measured and know behaviors of UHMWPE under high-velocity impact. Future experimental testing will be performed to further evaluate the model and calibrate the material parameters of the model for composite material systems of interest.

REFERENCES:

Criscione, J.C. and W.C. Hunter, “Kinematics and elasticity framework for materialswith two fiber families,” Continuum Mech. Thermodyn. (2003) 15: 613-628.

Schumacher, S.C. and K.P. Ruggirello, “CTH Reference Manual: Marker Technologies,” SAND2013-1675, March 2013.

Russell, B.P., K. Karthikeyan, V.S. Deshpande and N.A. Fleck, “The high strain rate response of Ultra High Molecular-weight Polyethylene: From fibre to laminate,” Int. J. Impact Eng (2013) 60: 1-9.

Herakovich, C.T., R.D. Schroedter III, A. Gasser and L Guitard, “Damage evolution in [±45]s laminates with fiber rotation,” Comp. Sci. Tech. (2000) 60: 2781-2789.