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VISCOELASTIC MODELS FOR EXPLOSIVE BINDER MATERIALS

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An improved model of the mechanical properties of the explosive contained in conventional munitions is needed to accurately simulate performance and accident scenarios in weapons storage facilities. A specific class of explosives can be idealized as a mixture of two components: energetic crystals randomly suspended in a polymeric matrix (binder). Strength characteristics of each component material are important in the macroscopic behavior of the composite (explosive). Of interest here is the determination of an appropriate constitutive law for a polyurethane binder material.

This paper is a continuation of previous work in modeling polyurethane at moderately high strain rates and for large deformations. Simulation of a large deformation (strains in excess of 100%) Taylor Anvil experiment revealed numerical difficulties which have been addressed. Additional experimental data have been obtained including improved resolution Taylor Anvil data, and stress relaxation data at various strain rates. A thorough evaluation of the candidate viscoelastic constitutive model is made and possible improvements discussed.

INTRODUCTION

The ability to bridge the gap between the mechanical loading of an explosive and its initiation is a useful tool for assessing munitions performance. It is essential for simulating accident scenarios, where determination of whether or not initiation occurs is the objective. To bridge this gap requires accurate constitutive modeling of the explosive. Of interest, in the long term, is the mechanical characterization of a class of explosives composed of a mixture of energetic crystals and a rubber-like, polymeric binder.

The class of explosives considered may be idealized as random, two-component composites, i.e. energetic crystals randomly suspended in a polymeric matrix. The first step in determining the composite's averaged response is accurately characterizing the constitutive behavior of the individual constituents. This paper is a continuation of work on the characterization of Adiprene-100, a rubber-like polymeric binder. In previous work (1) it was found that this material behaves in a strongly rate-dependent fashion,

and exhibits creep, stress-relaxation, and recovery. A classical viscoelastic construction formed the basis for a constitutive model, which was calibrated with quasi-static compression tests and used to model a Taylor Anvil experiment. The modeling was reasonably successful. However, modeling shortcomings were apparent, and, due to very large deformations, the Taylor test simulation was hampered by numerical difficulties. This paper discusses improvements to the constitutive formulation.

EXPERIMENTAL RESULTS

The Taylor Anvil impact test shows clearly how rubber-like the binder material behavior is. A 30 caliber cylinder of polyurethane (diameter 7.44 mm, length 22.53 mm) was launched with velocity 303 m/s. A high speed camera photographed the cylinder as it impacted the anvil. Digitization of the photographs gave profiles of the cylinder at various times after impact as shown in Fig. 1. Despite the extreme defor-

FIGURE 1. Taylor Anvil profiles at various times after impact. The initial configuration profile is shown in the top left frame. The top right frame shows the cylinder profile 17 μ s after impact, the bottom left frame 39 μ s after impact, the bottom right 55 μ s after impact.

mation, when the specimen was retrieved it had returned to its initial configuration.

In an effort to better understand the material response, additional data were gathered. The resolution of the photographic data was improved by performing 50 caliber (diameter 12.37 mm, length 63.22mm) shots at half the velocity (152 m/s), and focusing the camera on the impact surface. Quasistatic uniaxial stress tension and compression tests were performed, as well as stress relaxation tests. The original data set used to calibrate the viscoelastic model comprised the tension and compression tests. The stress relaxation tests were performed approximately one year later. The material mechanical properties were found to change with age (a stiffening is observed). Aging is beyond the scope of the model to date, so this data could not be used directly, although stress decay rates guided model parameter selection.

CONSTITUTIVE MODEL

The approach taken in the constitutive modeling is described in detail elsewhere (1,2). Here the main features of this model are recapped,

and a modification presented. A 1-D spring and dashpot construction exhibits the essential features of the 3-D constitutive formulation, and provides physical insight. The standard linear solid, which consists of a Maxwell element in parallel with a linear spring, provides the basic framework. The spring returns the model to its initial configuration when it is left stress free and unconstrained, a feature observed in the Taylor Anvil experiment. The Maxwell element provides rate dependence, which is made non-Newtonian by selecting for the dashpot viscosity the function

$$\eta(\dot{\epsilon}) = \eta_{\infty} + \frac{(\eta_0 - \eta_{\infty})}{(1 + (\lambda\dot{\epsilon})^2)^{(1-n)/2}} \quad (1)$$

which serves to decrease the viscosity η from its initial value η_0 for strain rate $\dot{\epsilon} = 0$ to η_{∞} as $\dot{\epsilon} \rightarrow \infty$ and consequently provides for shear thinning. Parameters λ and n adjust the rate at which η approaches η_{∞} for large $\dot{\epsilon}$. The total stress is the sum of the stress in the Maxwell element, σ^V , and that in the spring, σ^E , i.e. $\sigma = \sigma^V + \sigma^E$.

The 3-D, finite deformation constitutive law is a straight-forward generalization of the 1-D model. The deviatoric and equation of state behaviors are treated separately. It is postulated that the equation of state is hypoelastic

$$\dot{p} = -3K\dot{\epsilon}_v \quad (2)$$

where $p = -\sigma_{ii}/3$ is the hydrostatic pressure, $\dot{\epsilon}_v = D_{ii}/3$ is the volumetric strain rate, and K is the bulk modulus. The Cauchy stress tensor is denoted by σ_{ij} and the rate of deformation tensor by D_{ij} . The deviatoric behavior is postulated to have a viscous character. Summing viscoelastic and hypoelastic stresses as in 1-D, the constitutive law relating the deviatoric stress s_{ij} and the deviatoric deformation rate D'_{ij} may be written

$$s_{ij} + \tau \nabla s_{ij} = s_{ij}^E + 2\tau(G^E + G^V)D'_{ij} \quad (3)$$

$$\nabla s_{ij}^E = 2G^E D'_{ij}$$

where $s_{ij} = s_{ij}^V + s_{ij}^E$, G^E and G^V are the hypoelastic and viscoelastic shear moduli respectively,

and $\dot{\mathbb{S}}_{ij}$ denotes an objective rate of s_{ij} . The time constant is defined by $\tau(\dot{\epsilon}_e) = \eta(\dot{\epsilon}_e)/2G^V$ and the viscosity is given by (1) where the equivalent strain rate $\dot{\epsilon}_e = \sqrt{2D_{ij}D_{ij}}/3$ is used.

This model gave good results (1), indicating that viscoelasticity provides a good modeling approach. However, once numerical difficulties had been overcome, it became clear that the formulation lacked an essential ingredient. Once the cylinder reached the most deformed state in Fig. 1, it began to (slowly) unload. The hypoelastic deviatoric stress model is too compliant under large compressions, resulting in continued deformation in the simulation.

To better modeling stiffening under large compression, a nonlinear, rubber elastic deviatoric constitutive model was incorporated in place of hypoelasticity. The Cauchy stress is given by

$$\sigma_{ij}^R = \frac{2}{\sqrt{\mathbb{I}_c}} \left\{ \left(\frac{\partial W}{\partial I_c} + I_c \frac{\partial W}{\partial \mathbb{I}_c} \right) B_{ij} - \frac{\partial W}{\partial \mathbb{I}_c} B_{ik} B_{kj} + \mathbb{I}_c \frac{\partial W}{\partial \mathbb{I}_c} \delta_{ij} \right\} \quad 4$$

where I_c , $\mathbb{I}_c$, $\mathbb{I}_c$ are the invariants of the right Cauchy-Green tensor (F_{ij} is the deformation gradient) $C_{ij} = F_{ik}^T F_{kj}$, and $B_{ij} = F_{ik} F_{kj}^T$ is the left Cauchy-Green tensor. The elastic deviatoric stresses are then

$$s_{ij}^E = \sigma_{ij}^R - \delta_{ij} \sigma_{kk}^R / 3 \quad 5$$

Specifically, a Blatz-Ko formulation was used. The energy density is given by

$$W = \frac{G}{2} \left(\frac{I_c}{\mathbb{I}_c} + 2\sqrt{\mathbb{I}_c} - 5 \right) \quad 6$$

FIGURE 2. Comparison of constitutive model (dashed lines) and experimental data (solid lines). The left graph corresponds to $\dot{\epsilon} = .001$, the right to $\dot{\epsilon} = .1$.

Constitutive constants were obtained by matching uniaxial stress (quasistatic) data, using stress relaxation and sound speed data for guidance (3). A comparison of experimental data and constitutive model prediction is given in Fig. 2. The data are for two constant rate loading/unloading tests, at different rates $|\dot{\epsilon}| = .001, .1$. The unloading rate is the same magnitude as the loading rate. The constitutive model fit is excellent at low to moderate strains. It stiffens somewhat too quickly at higher strains, but gives the correct trend.

COMPARISON AND CONCLUSIONS

The finite deformation, nonlinear viscoelastic constitutive model developed in the previous section was implemented in the explicit, Particle in

FIGURE 3. Comparison of data (outline) and calculation (points) for the 50 caliber Taylor Anvil shots, at 37 μ s (top), 85 μ s (middle) and 141 μ s (bottom) after impact.

Cell code FLIP (4,5). The Particle in Cell technique is a mix of Lagrangian and Eulerian approaches, Lagrangian particles move through an Eulerian grid, well suited for modeling large material deformation. The isotropy of the material and test geometry allowed an axially symmetric calculation to be performed.

Comparisons of 50 caliber cylinder profiles are shown in Fig. 3 at 37, 85 and 141 μ s after impact. The dark outlines are data from photographs. The shaded region (Lagrangian particles) are the simulation results. Agreement is very good throughout the deformation. Most notable is the successful modeling of the "bulking up" (i.e. the manner in which the deformation proceeds axially) of the cylinder seen at 141 μ s.

Comparison of 30 caliber cylinder profiles are shown in Fig. 4 at 17, 39 and 55 μ s after impact. Note the inclusion in the simulation of the plug which follows the cylinder. This plug is used in the experiment to isolate the cylinder from detonation products, and has some impact on the deformation. The lift-off of the outer edge of the cylinder at 17 μ s is not seen in the data. The calculation is frictionless. Addition of a small amount of friction may be enough to prevent this in the simulation. Agreement actually improves as the deformation progresses. The shape of the cylinder is well predicted, although the data indicates that the cylinder is somewhat more compressible.

From the data gathered it appears that the proposed constitutive model is quite accurate over the range of strain rates investigated. For this particular very rubbery material, the incorporation of rubber elasticity provides an essential stiffening mechanism for modeling large deformations. The modeling success demonstrated indicates that dominant material characteristics have been incorporated.

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FIGURE 4. Comparison of data (outline) and calculation (points) for the 30 caliber Taylor Anvil shots, at 17 μ s (top), 39 μ s (middle) and 55 μ s (bottom) after impact.

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