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RATES AND LARGE STRAINS

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MECHANICAL STRENGTH MODEL FOR PLASTIC BONDED GRANULAR MATERIALS AT HIGH STRAIN RATES AND LARGE STRAINS

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Modeling impact events on systems containing plastic bonded explosive materials requires accurate models for stress evolution at high strain rates out to large strains. For example, in the Steven test geometry reactions occur after strains of 0.5 or more are reached for PBX-9501. The morphology of this class of materials and properties of the constituents are briefly described. We then review the viscoelastic behavior observed at small strains for this class of material, and evaluate large strain models used for granular materials such as cap models. Dilatation under shearing deformations of the PBX is experimentally observed and is one of the key features modeled in cap style plasticity theories, together with bulk plastic flow at high pressures. We propose a model that combines viscoelastic behavior at small strains but adds intergranular stresses at larger strains. A procedure using numerical simulations and comparisons with results from flyer plate tests and low rate uniaxial stress tests is used to develop a rough set of constants for PBX-9501. Comparisons with the high rate flyer plate tests demonstrate the viscoelastic based model show that the observed characteristic behavior is captured by this model.

INTRODUCTION

Materials that display viscoelastic behavior have a distinctive signature when tested in a standard flyer plate geometry. Tests done recently on a plastic bonded high explosive material showed viscoelastic characteristics, but when modeled as purely viscoelastic with constants derived from long term experiments, details of the behavior were not replicated. A PBX is basically a granular material with a polymeric binder. Although modeled successfully at small strains with a viscoelastic model, at the higher strains encountered in the flyer plate experiments some behavior of the granular filler emerged. Granular materials are usually modeled with a cap type plasticity formulation. Our goal here is to construct a model that combines some features of both. This is done by developing

micromechanically motivated additions to a viscoelastic model and comparing numerical predictions with the measured velocity histories.

VISCOELASTIC WAVE PROPAGATION

Viscoelastic materials do not necessarily respond with an abrupt change in strain or stress, that is a shock, when loaded with a step velocity input. The waves that are generated are not steady and gradually decay with time or distance traveled, or depending on loading and material properties can get steeper. This behavior was extensively studied (1,2,3) more than a decade ago, particularly the possibility of generating steady acceleration waves. This behavior is quite different from that observed in elastic-plastic materials as described in the detailed summary of Davison and Graham (4).

Recently high quality visar experiments on some plastic bonded explosive materials were done by Jerry Dick (5) to characterize the high rate behavior of these materials. While the data can be reduced in standard $u_s - u_p$ form, by ignoring the gradual initial response, the velocity histories are clearly not shock loading waves, but rather a slowly responding wave with viscoelastic characteristics. Figure 1 shows a particular experimental trace, Jerry Dick's G1061, and two computed approximations. In this particular experiment a flyer of Kel-F 800 5.889 mm thick impacts a 10.018 mm thick slab of PBX-9501, backed by 22.9 mm thick PMMA visar window. The visar records the velocity history at the interface between the PBX-9501 and the PMMA. An elastic-plastic model, even though fitted to the stiffness of a viscoelastic model, shows the characteristic sharp shock response of elastic materials. A viscoelastic model result, using a power law in time as the relaxation function, shows more the more gradual loading behavior of the experiment, but misses the details of the rise time. Adjustments in the material constants can improve the fit in particular regions, but the overall behavior cannot be matched.

FIGURE 1. Comparison of visar measured particle velocity and computed results from two preliminary models.

BEHAVIOR OF GRANULAR MATERIALS

Shock loaded granular materials were studied as porous materials by Herrman (6) and others. The soil mechanics community has studied granular materials extensively under many loading conditions and generated an extensive literature, see (7,8) and their references. The essential characteristics are irreversible bulk behavior, usually modeled by a plasticity model, and dilatancy. Dilatancy, or the generation of volume under shear deformation is a very important characteristic of granular materials.

MORPHOLOGY OF PBX MATERIALS

Plastic bonded explosives (PBX) exhibit a mixture of granular and viscoelastic behaviors. In the common manufacturing process, an organic explosive, in crystalline form, is coated with a rubbery polymer used as binder to allow easy fabrication and use. Explosive materials usually only contain 5-10 weight % of binder. At small strain levels modeling with viscoelastic behavior is a good approximation, even over very wide ranges of strain rate. This is the accepted technique for modeling long time behavior and, as we shall see, should be used as well for shock loading conditions if faithful reproduction of experimental results is desired. At larger strain levels we have evidence of granular behavior such as dilatation. For example, cores taken from recovered samples in the Steven Test geometry, where strain rates are 1000/s and there is substantial lateral confinement, still show lower densities than the original material. This is expected based on the observed microstructure. Optical microscopy and particle size analysis done by Skidmore(9) show the wide range of particle sizes, packing of smaller particles between interstitial spaces of the larger particles and binder filling the remaining space. The large number of fines, less than 1 micron in size, are likely acting as reinforcements to the binder but otherwise not involved with the larger particles.

INTERGRANULAR STRESS STIFFENING

A pressing operation at elevated temperatures, 100 C, and high pressures, 100-200 MPa, is used to consolidate the PBX molding powder. Because of the differences in coefficients of thermal expansion and bulk modulus between the crystalline material

and the polymer binder, the material is left in a stressed and/or porous state upon cooling back to ambient conditions of 20C and 0.1 MPa. Estimates of the mismatch indicate residual void volumes of a few percent, assuming no residual stress, in rough agreement with observed densities for as pressed parts. This estimate shows the volume change from pressure change to be larger than that from temperature change, so the binder grows more than the crystal under release of pressure. One mental picture of this situation is to take an array of cubes, remove material from each corner to hold the binder at its volume under pressure. When the cubes are assembled under pressure with the binder, we have small pyramids of binder between the corners of the cubes. As the pressure is released, and temperature lowered, the pucks of binder separate the faces of the cubes, producing some free volume. The actual situation is somewhat more complex because of the distribution of particle sizes and shapes, but the net result is similar. This mental picture leads to behavior that would primarily reflect the binder at low strain levels, but at high pressures the faces of the crystals would again come into contact, generating substantial inter-crystalline forces.

CONSTITUTIVE MODEL

One approach to merging the small strain viscoelastic behavior, binder heating, and intercrystalline forces at high pressures is to add a density dependent set of stresses that represent the intercrystalline forces. Because we are primarily interested in the effects in flyer plate experiments we simplify the intercrystalline force model to generate only pressures, as a function of the current density and a reference density taken as the peak value of the density history. For general strain states shear stresses must be included as well.

The total stress is taken as the sum of a viscoelastic binder stress and interparticle or crystalline stress, $\sigma = \sigma_b + \sigma_c$. The binder stress comes from a standard hereditary integral formulation,

$$\sigma_b(t) = \int_{\tau=0}^{\infty} E(t-\tau) \dot{\epsilon}(\tau) d\tau, \quad (1)$$

where the relaxation function is usually taken as $E(t) = at^{-n}$. (2)

Temperature effects are included by using a WLF shift function, that accelerates the apparent time by a factor w , calculated as

$$\log_{10}(w) = \frac{c_1(T - T_o)}{c_2 + T - T_o}. \quad (3)$$

This is implemented numerically using a Prony series approximation to the power law relaxation function. The general form is

$$E(t) = e_0 + \sum_{i=1}^m e_i \exp(-b_i t) \quad (4)$$

The time lags b_i are selected to cover a time interval, usually with a constant ratio from term to term. Enough terms must be used to cover the times encountered in the numerical problem. The coefficients e_i are determined using a least squares fitting procedure.

The intercrystalline force contribution is taken as a pure pressure for these calculations, $\sigma_c = -p_c$, where the pressure and corresponding stiffness are obtained from the Hertz contact solution for two spheres, so

$$p_c = k(\epsilon_{rel})^{1.5} \quad (5)$$

if $\epsilon_{rel} = \epsilon_v - \epsilon_o$ is positive, and 0 otherwise.

NUMERICAL RESULTS

This model is implemented in a UMAT routine (10) for use with the structural analysis code ABAQUS. The routine could be adapted to other codes however ABAQUS is well suited for evaluating the viscoelastic part of the model. A detailed model of the flyer plate experiment was developed using several hundred elements in each layer of material. Figure 2 shows one comparison of the experimental trace and the calculated response with the intercrystalline forces calculated with k of 25000 MPa and ϵ_o of 0.01. The viscoelastic model constants are a of 526. MPa, for time units of seconds, and n is 0.148. The ABAQUS routine actually has separate Prony series representations for

the bulk and shear moduli; for these calculations the two are proportional with values equivalent to a Poisson's ratio of 0.37. The characteristic behavior of the material is captured, although we still need to improve some details of the model in order to better match the initial loading rate and the arrival of the relief wave at late times.

FIGURE 2. Comparison of experimental particle velocity and viscoelastic model result with interparticle stiffening.

CONCLUSIONS

One interesting feature of this study is the extension of a basic viscoelastic model over eight decades of strain-rate with reasonable agreement. Although the polymer physics community might not find this surprising, many in the shock wave community seem to find it odd. Clearly additional work needs to be done before any claims are made about the application range of the model developed. The inclusion of shear strengthening mechanisms in the granular stress is essential, and thermal softening of the binder might be important. The problem is finding appropriate experimental data to support the modeling work. At low rates, bi-axial experiments are used to separate or delineate the bulk and deviatoric behaviors. Under high rate loading conditions this type of experiment is very difficult to arrange. Perhaps the unloading waves seen in long time recordings from flyer plate experiments could be used to obtain some information under non-1D

strain loading situations. We also hope to create detailed numerical models at the microstructural level to study the local binder-particle interactions.

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REFERENCES

1. Warhola, G. T. and Pipkin, A. C., IMA Journal of Applied Mathematics **41**, 47-66 (1988).
2. Nunziato, J. W., Polymer Engineering and Science **18**, No. 14, 1101-1108 (1978).
3. Nunziato, J.W., Walsh, E.K., Schuler, K.W. and Barker, L.M., pp. 1-108 in Encyclopedia of Physics, Vol. VIa/4, Springer-Verlag, 1974.
4. Davison, L. and Graham, R. A., Physics Reports **55**, No. 4, 255-379 (1979).
5. Jerry Dick, Los Alamos National Laboratory (personal communication).
6. Hermann, W., J. Applied Physics, **40**, No. 6, 2490-2499 (1969).
7. Lade, P. V. and Pradel, D., J. of Engineering Mechanics, **116**, No. 11, 2532-2550 (1990).
8. Pradel, D. and Lade, P. V., J. of Engineering Mechanics, **116**, No. 11, 2551-2566 (1990).
9. Skidmore, C.B., Phillips, D.S., Son, S.F., and Asay, B.W., "Characterization of HMX particles in PBX-9501", presented this conference.
10. Macek, R., Los Alamos National Laboratory, personal communication.

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Visar experiments

- Flyer plate
impacts target
assembly
- Visar measures
particle velocity at
back of sample.

Comparison of elastic-plastic and viscoelastic behavior with experiment.

- Visar measured particle velocity clearly shows viscoelastic behavior.
- Elastic-Plastic models will always have a shock response.
- Power law viscoelastic behavior can not match both the arrival time and the loading rate after arrival of the stress wave.

Structure of PBX materials

200 μ m

- Particulate crystalline solid with rubbery binder.
- Large range of particle sizes
- Binder and crystal properties are very different.

Viscoelastic Formulation

- Hereditary integral viscoelasticity
- Power law relaxation function
- Temperature modeled with WLF shift function
- Numerically implemented with Prony series
- Separate series for bulk and shear behavior
- In this study, bulk and shear response is proportional and equivalent to Poisson's ratio of 0.37
- Constants derived from long term creep tests

Interparticle stress formulation

- In unloaded state binder separates particles
- After some bulk compression, characterized by a volumetric strain, the particles come into contact.
- Use Hertz contact solution for two spheres to develop a pressure-volume relation.

Intergranular Stress Model Results

- Arrival time controlled by viscoelastic behavior.
- Intergranular stresses give steep stress rise after arrival of loading wave.
- Still need to improve detailed fit in the initial part of the loading and the release wave timing.
- Overall behavior is captured.

Conclusions

- Viscoelasticity is important even at micro-second time scales.
- Binder-filler interactions play an important role at higher strain levels.
- New types of experiments are needed to provide bi-axial strain loading histories.
- Numerical models of the microstructure may supply the needed information for improved models.

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