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An Explicit Model of Expanding Cylindrical Shells Subjected to High Explosive Detonations

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ABSTRACT

A viscoplastic constitutive model was formulated to model the high strain-rate expansion of thin cylindrical shells subjected to internal explosive detonations. This model provides insight into the development of plastic instabilities, which occur on the surface of the shells prior to failure. The effects of shock heating and damage in the form of microvoid nucleation, growth, and coalescence were incorporated using the Johnson-Cook strength model with the Mie-Grüneisen equation of state and a modified Gurson yield surface. This model was implemented into ABAQUS/Explicit as a user material subroutine.

A cylindrical copper shell was modeled using both axisymmetric and plane strain elements. The high explosive material inside of the cylinder was simulated using the high explosive burn model in ABAQUS/Explicit. Two experiments were conducted involving explosive-filled, copper cylinders and good agreement was obtained between the numerical results and experimental data.

Introduction and Background

The elastic/viscoplastic behavior of materials is an area of study that encompasses a variety of scientific disciplines with industrial and military applications. Applications for this research include hypervelocity accelerators, explosive containment vessels for terrorist threats and power plants, and flux compression generators. When a thin-walled circular cylinder flux

generator is subjected to an internal explosion, a significant amount of radial expansion occurs at very high velocities prior to failure by fragmentation. In time, multiple plastic instabilities appear on the surface of these shells in a quasi-periodic pattern. These instabilities will continue to develop into bands of localized shear and eventually form cracks before causing the shell to fragment.

The expansion of shells was first documented in 1943 by Gurney [1], who derived a widely used model for predicting the terminal velocities of fragments from shells subjected to internal explosive detonations. The failure of cylindrical shells was examined in 1944 as a fragmentation problem by G. I. Taylor [2]. Later, Mott [3] attempted to predict the distribution and size of fragments from a tubular structure based on the assumptions of a perfectly plastic material model and probability theory. In 1967, Slate and others [4] concluded that the thicker the shell, the more evident the surface cracking and, in addition, the higher the strain to rupture. Hoggatt and Recht [5] furthered the study of fragmenting cylinders and developed a mathematical model assuming the fractures occur along lines of maximum shear. In addition, Hoggatt and Recht observed different types of failures based on the amount of high explosive (HE) and the detonation pressures. Al-Hassani and others [6] provided an analytical expression for the hoop and radial stress in the vessel wall assuming a perfectly plastic material and confirmed the strain behavior observed by Taylor.

In 1978, Taylor and others [7] developed a formulation for modeling dynamic plastic instabilities in a thin sheet. Their approach was based on hydrodynamic principles and demonstrated that the size and appearance of the instabilities are dependent on the material's strain-rate and work hardening. In 1983, Johnson [8] examined the one-dimensional ductile failure of rapidly expanding rings. Johnson describes the time dependent heterogeneous plastic deformation in terms of the differential equations of thermoplasticity, conservation of mass, and conservation of momentum. Anderson, Predebon, and Karpp [9] developed a two-dimensional

finite difference code to model expanding cylinders. In 1997, Hao and Brocks [10] implemented a void nucleation and growth constitutive model into the ABAQUS/Standard code to study problems involving creep and quasi-static type loading.

Several authors have examined instabilities associated with both uniaxial and bi-axial states of stress under quasi-static conditions, but most have not considered materials subjected to multiaxial stress states at strain rates on the order of 10^4 s^{-1} . Considering the results in the literature, it is clear that strain-rate, material density, temperature, and inertial effects are important when numerically modeling problems with large high strain-rate deformation and plastic instabilities.

Numerical Model

A viscoplastic constitutive model was formulated to include the high pressure shock effects, the rate-dependent strength effects, and the microdefects are simulated as microvoids. This constitutive model was implemented into ABAQUS/Explicit as a material subroutine (VUMAT). The VUMAT subroutine consists of a main "driver" routine and several smaller routines, which are activated at the user's discretion. A flowchart of the VUMAT subroutine and the calling order for each additional routine are shown in Figure 1.

The HE burn model used in this research is maintained by HKS for ABAQUS/Explicit. Their model uses the Jones-Wilkens-Lee (JWL) equation of state and a program burn model to detonate the HE and calculate the conversion of the chemical energy to dynamic pressures. In the present work, the resulting increment in strain is passed from ABAQUS/Explicit into the VUMAT subroutine to solve for the state of stress, solution-dependent variables, internal energy, and plastic work.

Upon activation, the EOS routine is the first routine called from the VUMAT. This routine modifies the bulk modulus and determines the shock heating effects. The formulation for this part of the constitutive model follows the work of Johnson [9] and uses the material's

equation of state and current volumetric strain. These results are then returned to the main VUMAT and the GTN routine is called to determine the new state of stress in the material.

The GTN routine immediately calculates the current strain-rate and passes it along with plastic strain and material temperature to the Johnson-Cook strength routine, which was formulated from the model by Johnson and Cook (1983). Their empirically based model returns the allowable flow stress to the GTN routine where the code iterates to converge to a point on the yield surface. The yield surface implemented in this research is a function of the allowable yield stress, void volume fraction, equivalent stress, and pressure and is a combination of the work by Gurson [11], Needleman [12], and Tvergaard [13]. The iteration technique adopted for this research is called the cutting-plane algorithm and is described by Ortiz and Popov [14]. This algorithm is based on linearization of the plastic consistency condition for the current iteration and satisfaction of the plastic consistency for the new iteration. The cutting plane algorithm is very efficient and demonstrates reasonable accuracy. Upon convergence, the stresses, plastic work, energies, and temperatures are updated and passed back to the main subroutine.

Next the main VUMAT subroutine calls the void routine. The void routine determines the nucleation, growth, and coalescence rate for the microvoids and passes back the material's updated volumetric void concentration. The mechanical properties used in the constitutive model were taken from the current literature and were not adjusted for this work. A detailed listing of the VUMAT subroutine and the formulations described here can be found in Martineau [15].

Model Verification

An experiment was conducted to benchmark the numerical model and to add credence to the formulation of the constitutive model. The experiment used a 406.4 mm long oxygen-free-electronic grade copper tube filled with a high explosive. The copper had a 102.06 mm inner diameter and a wall thickness of 2.54 mm. The copper tube was annealed after the machining process, which resulted in a Rockwell F hardness of 23 and a grain size of approximately 40 μm .

A solid HE cylinder of PBX-9501, with a diameter of 101.8 mm was used as the high explosive inside of the copper tube. A detailed listing of the physical properties for the copper and HE are tabulated in Martineau [15].

A plane wave lens was bonded to the end of the high explosive cylinder and detonated at its apex with a SE-1 detonator. This caused the walls of the copper cylinder to expand radially outward in a conical form resulting in a strain variation in the longitudinal direction. Two forms of diagnostics were used in the experiment, fast framing camera and Fabry-Perot. Fabry-Perot is a type of laser or visar interferometer, which is capable of recording radial velocity information at a single point on the surface of the expanding shell. The fast framing camera diagnostic provides 25 photographic images of the expanding cylinder at predetermined increments in time. The hoop strain and the development of the instabilities observed on the surface of the expanding shell can be extracted from the photographs and plotted as a function of time.

The numerical analysis was conducted using an axisymmetric model of the solid cylinder of HE and the copper shell. Four node, linear, axisymmetric elements were used throughout the analysis for both the HE and copper cylinder. There were five elements through the thickness of the copper cylinder shells and the size of the HE elements was twice that of the copper cylinder elements. As shown in Figure 2, the HE and copper cylinder were uniformly meshed with a 0.127 mm gap separating the two materials. A sliding contact surface was prescribed at this gap to model the interactions between the HE and the cylinder.

The plots shown in Figure 3 compare the predicted radial displacement of the cylinder with the experimental data at specific points in time. The outward radial displacement of the copper shell is plotted as a function of time in Figure 4. The displacement curves shown in this figure were taken at eight different longitudinal locations on the cylinder wall. The longitudinal locations are shown in the text on the right side of the figure. The plots shown in Figure 5 compare the numerical and empirical radial velocities with the limit velocity obtained from the

model proposed by Gurney [1]. Good agreement is shown between the experimental data and the numerical predictions and both approach the Gurney velocity, thus lending credibility to the numerical model.

The experiments documented as part of this work were designed to verify the numerical model and good agreement is shown in Figures 3, 4 and 5. The comparisons shown here illustrate that the user supplied constitutive parameters for the numerical model are reasonable. Good agreement is shown for a large displacement thus indicating that element distortion in the numerical model is not affecting the solution. Instabilities were observed on the surface of the expanding shell in the experiment. Each photograph from the fast framing camera was digitized and enlarged to determine the number of instabilities for a small characteristic length on the surface of the cylinder. This length and the quantity of instabilities were then used to determine the total number of instabilities on the entire circumference of the shell.

The instabilities observed on the surface of the expanding cylinder appear to occur and propagate down the longitudinal axis of the cylinder. The axisymmetric geometry is not capable of predicting a circumferential pattern of quasi-periodic instabilities, which occurs in the longitudinal orientation. As a result, a plane strain model consisting of 20 elements through the thickness of the shell was constructed to examine the development of the instabilities. In this model, a dynamic pressure loading was applied uniformly to the entire inner surface and a random distribution of voids was applied to the mesh.

Results from this model illustrate the formation of an oscillatory pattern of equivalent plastic strain. The pattern is observed as early as 7.6 microseconds and becomes more pronounced with time. By 34 microseconds, localized zones of intense plastic strain connect the inner and outer surfaces of the expanding shell as shown in Figure 6. These localized zones of intense shear are orientated approximately 45° from the outward radial direction and are thought to be related to the instabilities observed in the photographs obtained from the fast framing

camera. In the experiments, a total of 343 instabilities were observed on the outer surface the expanding shell at a longitudinal location where the hoop strain was approximately 150%. The numerical model predicted 354 instabilities at approximately the same corresponding strain.

A much less sophisticated experiment was conducted in an attempt to obtain a bulged copper sample illustrating the development of instabilities prior to fragmentation. This experiment consisted of a 30.48 cm long OFE grade copper tube with a 2.54 cm inner diameter and a 6.35 mm thickness. The copper tube was placed on end in 2.54 cm of sand. A slug of Composition C-4 explosive was placed inside the top lip of the copper tube and detonated on one end. The shock wave reflected off the surface of the sand, resulting in an internal overpressure. The overpressure caused the tube to bulge and fracture, but not fragment. A picture of the bulged tube is shown in Figure 7. The arrows shown in this figure indicate the locations of the instabilities. This bulged tube was cross-sectioned through the instabilities to obtain the photomicrographs shown in Figures 8 and 9.

Conclusions

The simulations shown here illustrate the onset and development of plastic instabilities that are associated with rapidly expanding shells. In general the numerical simulations are in good agreement with the experimental data. The onset of a periodic pattern is observed as early as 7.6 microseconds and localized areas of intense plastic strain, which extend from the inner to the outer surfaces, are directly related to the shear bands and cracks documented by early experimentalists. The photomicrographs shown in Figures 8 and 9 illustrate excessive plastic deformation and shear localization that is similar to the illustrations shown in Figure 6. The orientation of the dashed lines shown in the last frame of Figure 6 compares well with the lines shown in Figure 9, which adds credibility to the numerical model. In addition, the total number of instabilities predicted by the numerical model is fairly close to the number of instabilities observed from the experimental data.

In conclusion, the experimentally verified constitutive model developed in this research provides a useful tool for further analytical work on the expansion of explosively loaded cylindrical shells. In addition, the comparisons presented provided useful insight into the development and growth of the quasi-periodic instabilities observed on the surfaces of these cylinders.

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Figure 1: Flow Chart of VUMAT Subroutine

Figure 2: Axisymmetric Mesh of HE and Copper Cylinder

Deformed Geometry at Time $t=20.3$ microseconds

Deformed Geometry at Time $t=49.6$ microseconds

Figure 3: Deformed Geometry at 20.3 and 49.65 microseconds

Figure 4: Radial Displacement as a Function of Time at Eight Locations Along the Longitudinal Axis

Figure 5: Radial Velocity as a Function of Time

Figure 6: Numerical Prediction of Quasi-Periodic Instabilities

Figure 7: Bulged Tube from C-4 Experiment

Figure 8: Enlarged Shear Band from Bulged Tube Experiment

Figure 9: Shear Bands from Bulged Tube Experiment