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Application of a Damage Model for Rock Fragmentation to the Straight Creek Mine Blast Experiments

B. J. Thorne

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APPLICATION OF A DAMAGE MODEL FOR ROCK FRAGMENTATION
TO THE STRAIGHT CREEK MINE BLAST EXPERIMENTS

by

B. J. Thorne
Division 6253

ABSTRACT

Early attempts at estimation of stress wave damage due to blasting by use of finite element calculations met with limited success due to numerical instabilities that prevented calculations from being carried past the fragmentation limit. More recently, an improved damage model has allowed finite element calculations which remain stable and yield good agreement between calculated fragmented regions and excavated crater profiles for blasting experiments in granite. Application of this damage model to blast experiments at the Straight Creek Mine in Bell County, Kentucky were complicated by anisotropic conditions and uncertainties in material properties. It appears that significant modifications to the damage model and extensive material testing may be necessary in order to estimate damage in these anisotropic materials.

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INTRODUCTION

For a number of years Sandia National Laboratories has been involved in the development of numerical models for describing blasting processes. This work has developed two separate computational thrusts. The early time stress wave propagation is treated through use of a dynamic finite element computer program, PRONTO [1,2], and a constitutive model which attempts to describe the fracturing which occurs as a result of stress wave induced material deformation. A separate modeling effort [3,4] attempts to describe the motion of the broken rock as a result of gas flow loading.

As part of our numerical model development program, an experimental verification effort has been conducted jointly with Atlas Powder Company. Beginning in 1988, cratering experiments were conducted for the express purpose of generating data for comparison with model predictions. These experiments examined variations in geometry, rock type and explosive. Data collected include detonation velocity, high-speed photography of ground motion, mud pile profiles, excavated crater profiles and particle size information. These data have been used to guide our current approach and are being used to identify weaknesses which should be targeted in future research. These studies indicate the complexity of the mechanisms involved and are also serving as a basis for developing complementary numerical descriptions that emphasize alternate physical processes.

The current form of the damage model has evolved over a number of years [5,6,7,8,9]. Since stress wave induced fragmentation is a very complex process, any computational algorithm will only approximately represent a fracturing event. It is, therefore, very important that any model be compared in detail against controlled experimental data. The first in a series of blast experiments to provide this data was performed with Atlas Powder Company at the Pamona Quarry near Greensboro, North Carolina. Laboratory tests of granite from this site [10,11] revealed significantly anisotropic properties induced by a foliation at the site. Even though the current form of the damage model assumes homogenous isotropic material properties, it was possible to use this model, with averaged material properties, to calculate fragmented regions in good agreement with excavated craters at this site [8,9].

The second series of blast experiments with Atlas Powder Company was conducted at the Straight Creek Mine near Pineville, Kentucky. Tests of material from this site [11,12] revealed extremely anisotropic conditions induced by closely spaced horizontal bedding planes at the site. All attempts to use averaged properties for this site, as was done with the first series of tests, resulted in calculated fragmented regions which greatly exceeded the size of the excavated craters. Even attempts to use the maximum strengths that could be justified on the basis of the laboratory tests resulted in over-prediction of fragmented regions. This led to a series of material property sensitivity calculations aimed at determining what mechanisms were most important in situations similar to

the experiments at the Straight Creek Mine site. It is not practical to present the hundreds of calculations involved in this study. This paper will present a few selected calculations in an attempt to illustrate the general trends.

MODIFICATIONS TO THE DAMAGE MODEL

Since publication of the analysis of the Pamona Quarry craters [9] several minor modifications to the damage model have been implemented. These are included in the FORTRAN listings in Appendices A and B. After each modification all of the calculations for the Pamona Quarry craters were repeated. Only one of these changes resulted in predicted regions of fragmentation significantly different from those documented in the Pamona Quarry report [9]. Two of these modifications are significant enough to demand documentation here.

Strain Behavior

E. P. Chen pointed out that the cyclic uniaxial strain behavior illustrated by figure 1 (figure 3 of [9]) is at odds with work of Holcomb and Costin [13,14]. By using acoustic emissions to detect the onset of microfracturing, they found that microfracturing did not occur in cyclic uniaxial loading until the maximum strain occurring on previous cycles was exceeded. Once the previous maximum strain was exceeded, damage resumed at the same rate which occurred if a sample were taken directly to that strain without cycling.

The cyclic dilatancy strain, ϵ , was introduced into the damage model equations [9] based on a conviction that strain not contributing to tension should not contribute to damage. Based on Holcomb and Costin's observation, the formulation of the damage model has been modified by always taking $\epsilon=0$ and not allowing damage to accumulate until the previous maximum volumetric strain is exceeded. For the cyclic uniaxial strain case, this is in agreement with Holcomb and Costin's results and yields the cyclic uniaxial response illustrated by figure 2. This modification does not result in any significant changes to the calculated fragmented region profiles for the Pamona Quarry craters [9].

This new formulation of cyclic behavior in the damage model is in agreement with Holcomb and Costin's results only for the uniaxial case. When they applied the second strain cycle in a direction perpendicular to the first, they found that damage began as soon as the strain in that direction became tensile. This indicates that damage is as sensitive to the direction of the strain as it is to the magnitude. The use of the maximum volumetric strain in place of the maximum directional strain in this modification is correct for the uniaxial strain case as noted above. It should also be approximately correct for regions where tensile waves are reflected perpendicular to a free surface, such as near the center of a crater. However, it would become suspect along the edge of a crater where the direct and reflected tensile waves could be propagating in nearly perpendicular directions. For the calculations presented in this paper and the calculations of the Pamona Quarry craters [9], the direct tensile wave in this region was greatly attenuated and negligible damage was calculated until the reflected tensile wave arrived.

Cyclic Uniaxial Strain Test

Figure 1. Stress as a function of strain for a cyclic uniaxial strain calculation using the previous version of the damage model.

Cyclic Uniaxial Strain Test

Figure 2. Stress as a function of strain for a cyclic uniaxial strain calculation using the new version of the damage model.

The observation that strain direction is important contradicts the very basis of the current damage model, or any formulation based on volumetric strain. It has long been recognized that damage should depend on the direction of the strain as well as the magnitude. However, all attempts to develop numerical models which take the strain direction into account (e.g., [15]) have proven to be complex and have been considered too computationally expensive for dynamic stress wave calculations. With the current availability of very large, very fast computers, the possibility of developing a dynamic damage model which takes into account the full strain tensor should be vigorously pursued.

Plasticity

A modification to the way plasticity is treated is also included in the FORTRAN listings in Appendices A and B. In previous versions of the damage model the yield surface was used as long as the material was in compression. Since the average pressure over a uniaxial test sample is one third of the negative of the axial stress (where pressure is defined to be the negative of the volumetric stress), this allowed yielding to occur at pressures lower than those corresponding to a uniaxial test. This is unrealistic, since yielding in rocks requires high confining pressures. The current version of the damage model computes the intersection of the yield surface with the line corresponding to uniaxial test conditions and does not allow plasticity at pressures below this intersection. For sandstone from the Straight Creek Mine, where triaxial data showing indications of yielding were used to generate the inverse parabola yield surface, this intersection is at a pressure of 33MPa (figure 3) and the corresponding yield stress of 99MPa is approximately what would be expected for failure in a uniaxial test. However, for the Pamona Quarry calculations [9], where no yield data were available and a yield surface was constructed above the failure strength data, this intersection is at a pressure of 200MPa corresponding to a yield stress of 600MPa, more than 4.5 times the uniaxial failure strength measured for this material.

As might be expected, this modification made little difference in sandstone calculations. However, it dramatically increased the computed damage around the explosive charge and reduced both the radius and depth of the calculated fragmented region for the Pamona Quarry calculations. In fact, it was not possible to construct a yield surface which was above the average failure strengths of the granite from the Pamona Quarry experiment site and also resulted in calculated fragmented regions in agreement with the field data when this modification was included in the damage model. The main validation of the current damage model was the successful application to the Pamona Quarry granite calculations [9]. It now appears that these results were dependent on assumptions about plasticity which were probably incorrect. This indicates that proper treatment of the material behavior near the explosive charge is critical in this type of calculation. The current plasticity treatment was only intended to be an approximation. It is apparently not an adequate substitute for a comprehensive theory of the behavior of the material near the explosive charge.

Yield Parabola

Figure 3. Inverse parabolic yield function for sandstone intersected with the uniaxial test conditions line.

APPLICATION TO STRAIGHT CREEK MINE EXPERIMENTS

The Straight Creek Mine experiment site is typical of a coal overburden. Sandstone, siltstone and mudstone have been identified as the three main material types. For the purpose of these calculations, the site will be assumed to be made up of thick deposits of these three materials. However, this is only an idealization as there are many bedding planes within each material. In the sandstone, closely spaced irregular horizontal dark-colored streaks define the sandstone bedding. The siltstone is divided into layers several millimeters thick. Even thinner layers, with poor cohesion between them, divide the mudstone. This is further complicated by thin coal seams.[16]

Sandstone Material Properties

Olsson [11] reports properties measured on nine sandstone samples from the Straight Creek Mine experiment site. These samples gave an average density of $2,589\text{kg/m}^3$ with standard deviation 28kg/m^3 . A significant anisotropy is indicated by measurements of p-wave velocity on these nine samples. Vertical p-wave velocity averaged $2,800\text{m/s}$ with standard deviation 40m/s . Horizontal p-wave velocity averaged $3,390\text{m/s}$ with standard deviation 200m/s . Two triaxial tests at each of the confining pressures 50MPa, 100MPa and 200MPa were performed on six of these samples with the sample axis aligned in the vertical direction. For one of the tests at the 100MPa confining pressure, no Young's modulus or Poisson's ratio was reported. The other five triaxial tests gave an average Young's modulus of 16.3GPa with standard deviation 2.6GPa and an average Poisson's ratio of 0.112 with standard deviation 0.011. Using the 0.112 Poisson's ratio from the triaxial tests, the average p-wave velocities imply a Young's modulus of 28.9GPa in the horizontal direction and 19.7GPa in the vertical direction. For the vertical direction, this is only 1.3 standard deviations above the 16.3GPa Young's modulus indicated by the triaxial tests.

If it is assumed that the triaxial test samples are in a uniform stress state at peak stress difference, then the stress differences at peak stress can be plotted as a function of the pressure at peak stress, as in figure 4. The average stress differences at peak stress for these three confining pressures determine an inverse parabola, figure 4, which can be used as a yield surface for finite element calculations. As was previously noted, the finite element calculations allow plasticity only at pressures greater than those corresponding to uniaxial test conditions (figure 3).

Chong et al [12] report both p-wave and s-wave measurements in the vertical direction for ten sandstone samples from the Straight Creek Mine experiment site. For these samples, the average p-wave velocity was $4,558\text{m/s}$ with standard deviation 437m/s , much greater than the value obtained by Olsson. The average s-wave velocity was $2,453\text{m/s}$ with standard deviation 168m/s . These velocities imply a Poisson's ratio of 0.296 with standard deviation 0.064. Density and porosity were measured

Yield Parabola

Figure 4. Inverse parabolic yield function fit to triaxial data for sandstone.

on nine samples and resulted in an average density of 2,680kg/m³ with standard deviation 20kg/m³ and a porosity of 4.79% with standard deviation 0.26%. This implies a solid material density of 2,815kg/m³, which seems high for a sandstone. For a material with 2,680kg/m³ density, the ten p-wave and s-wave velocity pairs imply an average Young's modulus of 41.48GPa with standard deviation 5.51GPa. Fourteen semi-circular bend specimens gave an average K in the horizontal direction of 711KPa/m with standard deviation 151KPa/m and twelve chevron bend specimens gave an average K in the vertical direction of 703KPa/m with standard deviation 108KPa/m. These two data sets can be combined to give a direction independent K of 707KPa/m with standard deviation 132KPa/m.

In terms of the material properties needed for input to the damage model, these two data sets can be summarized as follows:

		<u>Chong</u>	<u>Olsson</u>	
SANDSTONE				
DENSITY	ρ	2,680kg/m ³	2,589kg/m ³	
YOUNG'S MODULUS	E_v	41.48GPa	19.7GPa	(Vertical)
	E_H	-	28.9GPa	(Horizontal)
POISSON'S RATIO	ν	0.296	0.112	
FRACTURE TOUGHNESS	K	707KPa/m		
YIELD PARAMETERS	CP1		50MPa	
	Y1		274MPa	
	CP2		100MPa	
	Y2		400MPa	
	CP3		200MPa	
	Y3		594MPa	

The material properties obtained by Chong differ dramatically from those based on Olsson's measurements. The density obtained by Chong is 3.5% higher, Poisson's ratio is higher by a factor of 2.4 and Young's modulus in the vertical direction is higher by a factor of 2.5. The most reasonable explanation would be that the two data sets do not represent the same material. This site appears inhomogeneous, so it is possible that the sandstone properties could vary dramatically over the site. In order to evaluate this conjecture, consider the positions from which the samples in these two data sets were obtained.

Figure 5 (from [16]) is an isopach map of the top of the sandstone at the Straight Creek Mine experiment site and shows the position of the exploratory holes. Eight of the nine samples for which Chong measured density and porosity are from Expl-4 at depths from 3.0m to 6.0m, with the other sample coming from Expl-5 at a depth of 7.6m. Of the ten samples for which p-wave and s-wave velocities were measured, five are from Expl-4 at depths from 3.0m to 6.0m, two are from Expl-5 at a depth of 7.6m and two are from Expl-2 at depths of 4.0m and 4.3m. The remaining sample is reported to be from Expl-2 at a depth of 8.2m. On the basis of the record of core sent to KPC & Associates, this sample is

Figure 5. Isopach map of top of sandstone showing location of exploratory holes, test holes, and pre- and post-blast core holes.

probably from Expl-1 at the 8.2m depth. Of the nine samples used by Olsson, eight are from Expl-1 at depths from 5.1m to 6.1m and one is from Expl-2 at a depth between 4.3m and 4.4m. This last sample is from a position only a few millimeters below Chong's sample from Expl-2 at a depth of 4.3m, and should represent the same material unless these two samples just happen to come from opposite sides of a major bedding plane. Olsson's sample gives a vertical p-wave velocity of 2,770m/s while Chong obtained a p-wave velocity of 4,162m/s. This difference is typical of the differences between the two data sets. Further, both data sets are self-consistent in spite of the fact that they both contain samples from opposite sides of the test site at various depths.

It seems reasonable to assume that the different material properties derived from the two sets of measurements are the result of systematic differences in sample preparation or measurement procedures rather than real differences in the material in the samples. This leaves open the question of which set of material properties, if either, should be considered correct. Clearly, we must rely on Chong's data for K and Olsson's data for constructing the yield surface. Parameter variation studies were conducted to determine the sensitivity of calculated damage to variations in the other material properties over the rather large range of possible values implied by the differences in these two data sets.

Sandstone Sensitivity Calculations

In order to understand the sensitivity of calculated damage to differences in material properties over the range of variation implied by these two data sets, a large number of cratering calculations were carried out in which a homogeneous sandstone was assumed. The finite element configurations used were the same as those used in the Pamona Quarry crater calculations [9], except that the radii of the elements along the axis of symmetry were reduced to 66.5mm to agree with the smaller 5.25 in diameter drill used at the Straight Creek Mine experiment site. Figure 6 shows a portion of the finite element configuration used to simulate a 3m depth-of-burial to the center of the explosive charge. The radial dimension of the elements was gradually increased with radius, requiring 101 elements between the axis of symmetry and a nonreflecting boundary at a radius of 15m. A vertical dimension of 62.7mm was used for elements between the bottom of the borehole at a depth of 3.5m and the free boundary at the surface. The vertical dimension of the elements below the borehole was gradually increased with depth. There are 101 elements between the surface and a nonreflecting boundary at a depth of 20m, for a total of 10,201 elements. The explosives charge was modeled by the 16 elements blacked out in figure 6 between the 2.5m and 3.5m depths. Sensitivity calculations at depths to the center of the explosives charge of 2m and 4m were also performed, but these will not be discussed here.

Figure 6. Finite element configuration used for 3m depth-of-burial calculations.

The explosive charge was modeled using the JWL equation-of-state subroutine [17] in the PRONTO 2D program [1]. Atlas Powder APEX 1220 and ANFO charges were simulated for each configuration. The APEX 1220 was modeled as having a 1250kg/m^3 density, a 6065m/s detonation velocity and a $2.6 \times 10^9\text{J/m}^3$ energy density. The ANFO was modeled as having a density of 810kg/m^3 , a detonation velocity of 3780m/s and an energy density of $6.91 \times 10^9\text{J/m}^3$. It should be pointed out that the behavior of ANFO is not ideal at this small diameter. The energy density used in the JWL equation-of-state is artificially high in order to obtain a JWL release isentrope consistent with 45% of the real energy being released before the CJ point and 55% released after the CJ point. The detonation velocities used agree with measurements made at the Straight Creek Mine experiment site [18].

Three of the calculations using ANFO at the 3m depth-of-burial will be presented to illustrate trends typical of these calculations. The first of these uses Chong's data for all possible parameters. This results in the the following input to the damage model:

SANDSTONE (Chong)

DENSITY	ρ	$2,680\text{kg/m}^3$
YOUNG'S MODULUS	E	41.48GPa
POISSON'S RATIO	ν	0.296
FRACTURE TOUGHNESS	K	707KPa/m
YIELD PARAMETERS	CP1	50MPa
	Y1	274MPa
	CP2	100MPa
	Y2	400MPa
	CP3	200MPa
	Y3	594MPa
RELOAD	β	0.0
RMIN	R	20/s

Here, Olsson's data are used for the yield surface and the value of R and RELOAD are the same values used for Pamona Quarry granite [9]. These last two parameters were also included in the sensitivity study, but no results will be presented here except to point out that the calculations were not sensitive to variations in these two parameters over reasonable ranges of values. The default value of k, which is computed from the other material parameters [9], was used for all calculations. No other values of k were included in the sensitivity study because no data were available which could be used to estimate how much variation from the default value is reasonable. Figure 7 gives the calculated edge of the fragmented region for this simulation. Since no experiments have been performed in a homogeneous sandstone, it cannot be claimed that this is known to be a reasonable result.

The second calculation presented uses Olsson's data for density and Poisson's ratio. The Young's modulus is determined from Olsson's average

horizontal p-wave velocity. This results in the following changes to the above input for the damage model:

SANDSTONE (Olsson, Horizontal)

DENSITY	ρ	2,589kg/m ³
YOUNG'S MODULUS	E	28.9GPa
POISSON'S RATIO	ν	0.112

Figure 8 gives the calculated edge of the fragmented region for this calculation. This is a dramatic decrease in the extent of the calculated fragmented region as compared to figure 7. Calculations varying these three parameters individually indicate that the calculated fragmented region is most sensitive to variations in the Young's modulus, second to variations in the Poisson's ratio and least sensitive to variations in the density.

In order to approximate the effects of the orthotropic material properties implied by Olsson's p-wave velocity measurements, the damage model was modified to reduce the vertical stress below that computed for the isotropic case. This is equivalent to using a vertical Young's modulus, E_v , smaller than the Young's modulus, E_H , used in the radial and circumferential directions. This is not a consistent orthotropic model, but does result in the proper horizontal and vertical p-wave velocities. The third calculation presented uses this modified version of the damage model to simulate a material with the same material properties as the second calculation presented except for the following orthotropic Young's moduli:

SANDSTONE (Orthotropic)

HORIZONTAL YOUNG'S MODULUS	E_H	28.9GPa
VERTICAL YOUNG'S MODULUS	E_v	19.7GPa

The predicted fragmented region for this calculation, shown in figure 9, is dramatically reduced from the calculation presented in figure 8. The damage model parameters were all computed using E_H , so they were the same for both calculations. Thus, this reduction in calculated damage is entirely due to the differences between isotropic and orthotropic wave propagation. An isotropic calculation using a Young's modulus of 19.7GPa resulted in even less damage and predicted no fragmentation at the surface.

From these three examples, it is clear that damage calculations in a homogeneous sandstone are extremely sensitive to differences in material properties as large as the differences implied by these two data sets, or even to the differences between the horizontal and vertical directions in Olsson's data set. Even with the same material properties being used in the damage model, orthotropic wave propagation dramatically reduced the calculated fragmented region.

Figure 7. Calculated fragmented region for a 3m depth-of-burial ANFO charge in a homogeneous isotropic sandstone using material properties measured by Chong et al.

Figure 8. Calculated fragmented region for a 3m depth-of-burial ANFO charge in a homogeneous isotropic sandstone using material properties based on horizontal p-wave velocities measured by Olsson.

Figure 9. Calculated fragmented region for a 3m depth-of-burial ANFO charge in a homogeneous orthotropic sandstone using material properties measured by Olsson.

None of the blast experiments at the Straight Creek Mine experiment site were in a homogeneous sandstone. Thus, the appropriate question for this test series is: How sensitive is cratering at the Straight Creek Mine experiment site to properties of the three materials at the site?

Siltstone Material Properties

Chong et al [12] report both p-wave and s-wave measurements in the vertical direction for ten siltstone samples from the Straight Creek Mine experiment site. For these samples, the average p-wave velocity was 3,600m/s with standard deviation 191m/s, and the average s-wave velocity was 1,739m/s with standard deviation 144m/s. These velocities imply a Poisson's ratio of 0.342 with standard deviation 0.046. Density and porosity were measured on eleven samples and resulted in an average density of 2,720kg/m³ with standard deviation 20kg/m³ and an average porosity of 3.82% with standard deviation 0.41%. This implies a solid material density of 2,828kg/m³. With the 2,720kg/m³ average density, the ten p-wave and s-wave velocity pairs imply an average Young's modulus of 21.96GPa with standard deviation 2.89GPa. Twelve semi-circular bend specimens gave an average K in the horizontal direction of 622KPa/m with standard deviation 48KPa/m, and five chevron bend specimens gave an average K in the vertical direction of 332KPa/m with standard deviation 80KPa/m. This indicates an anisotropy, which is consistent with the layered appearance of this material. Since p-wave and s-wave velocities were not measured in the horizontal direction, it is not known how this anisotropy might effect the elastic constants.

In terms of the material properties needed for input to the damage model, this data set can be summarized as follows:

SILTSTONE

DENSITY	ρ	2,720kg/m ³	
YOUNG'S MODULUS	E	21.96MPa	(Vertical)
POISSON'S RATIO	ν	0.342	
FRACTURE TOUGHNESS	K	622KPa/m	(Horizontal)
		332KPa/m	(Vertical)

Mudstone Material Properties

Chong et al [12] report both p-wave and s-wave measurements in the vertical direction for ten mudstone samples from the Straight Creek Mine experiment site. For these samples, the average p-wave velocity was 3,136m/s with standard deviation 488m/s, and the average s-wave velocity was 1,082m/s with standard deviation 108m/s. These velocities imply a Poisson's ratio of 0.428 with standard deviation 0.020. Density and porosity were measured on nine samples and resulted in an average density of 2,690kg/m³ with standard deviation 80kg/m³ and an average porosity of 5.98% with standard deviation 0.61%. This implies a solid material density of 2,861kg/m³. With the 2,690kg/m³ average density, the ten p-wave and s-wave velocity pairs imply an average Young's modulus of 9.07GPa with standard deviation 1.77GPa. Sixteen semi-circular

bend specimens gave an average K in the horizontal direction of 374 KPa/m with standard deviation 44 KPa/m. All attempts to measure K in the vertical direction by use of chevron bend specimens resulted in separation at layer interfaces before a crack could develop at the notch tip [12]. This is a thinly layered material with very weak cohesion between layers.

In terms of the material properties needed for input to the damage model, this data set can be summarized as follows:

MUDSTONE

DENSITY	ρ	2,690 kg/m ³	
YOUNG'S MODULUS	E	9.07 GPa	(Vertical)
POISSON'S RATIO	ν	0.428	
FRACTURE TOUGHNESS	K	374 KPa/m	(Horizontal)

Straight Creek Experiment Site Stratigraphy

While it would be possible to perform sensitivity studies unrelated to the blast experiments, it seems prudent to concentrate efforts on situations of experimental significance. A pre-blast core and two post-blast cores were taken adjacent to the three-blast experiment boreholes designated as A3D12A, A4D15B and A5D19A in figure 5. No natural fractures were detected in any of the pre-blast cores [16]. This allows the post-blast cores to be used to estimate the extent of fracturing from these blasting experiments. Of these three blast experiments, only A3D12A resulted in a crater. Sensitivity studies were concentrated on, but not limited to, modeling of this blast experiment.

Figure 10 (from [16]) is a schematic diagram of the lithography near the A3D12A blast experiment borehole. It shows the approximate excavated crater profile, the distance of the post-blast core holes from the blast experiment borehole, a generalized stratigraphy and the location of blast induced fractures. The blast experiment borehole is assumed to have the same lithology as the pre-blast core. Notes on lost circulation during the coring operation are also included in figure 10. In the segments where no core was recovered, the driller reported that the core bit was pushing rather than cutting the rock, suggesting that the rock was rubblized and that there was available volume into which the rock could be pushed [16].

Figure 11 shows the position of the explosive charge and the position of the material interfaces in the finite element approximation to the A3D12A blast experiment. Note that the top of the explosive charge extends 270 mm into the siltstone. It had been planned to position the top of the explosive charge at the interface between the sandstone and the siltstone, as shown in figure 10, but measurements taken during preparation of the blast experiment imply that the geometry shown in figure 11 is more accurate [18]. The position of the post-blast core holes are indicated by the vertical lines 0.4 m and 1.0 m from the center line of the blast experiment borehole. The size and number of elements used was as near as possible to the same as was used for the sandstone material property sensitivity studies (figure 6).

Figure 10. Schematic diagram of the lithography near the A3D12A blast experiment borehole.

Figure 11. Position of explosive charge and material interfaces in the finite element approximation to the A3D12A blast experiment.

Site-Specific Sensitivity Calculations

In addition to uncertainties in the sandstone properties, there is considerable uncertainty about the proper material properties to use in modeling the siltstone and mudstone. For the siltstone, K varies by a factor of almost two between the horizontal and vertical directions. For the mudstone the uncertainty in K is even greater, as it was impossible to measure K in the vertical direction. Since the K values measured in the horizontal direction represent the maximum possible strength of both materials, the calculations presented here use these values and give a lower bound on the amount of calculated damage as compared with several calculations using smaller values of K.

No triaxial tests were performed on siltstone or mudstone samples. Thus, no data on which to base a yield surface for these materials were available. Since the top of the explosive charge extended into the siltstone for the A3D12A blast experiment, the yield surface assumed for the siltstone could possibly have a significant effect on calculated damage. The calculations presented here assume that the yield surfaces of the siltstone and mudstone are the same as used for the sandstone. It was also assumed that the values of both R and RELOAD used in the sandstone could be used for both the siltstone and the mudstone. The default value was used for k in all calculations.

(1) Material Properties

It would be very difficult to present the results of all of the calculations involved in this sensitivity study. Instead, a few of these calculations will be presented to illustrate trends. The first three calculations presented address the issue of sensitivity to properties of the sandstone. The above material properties for the siltstone and mudstone were used in these three calculations. Calculations were performed using each of the three sets of sandstone material properties discussed in the section on sensitivity to sandstone material properties.

Figure 12 shows the limit of the predicted fragmented region for the calculation using sandstone material properties based on Chong's data. The approximate profile of the excavated crater is indicated by the dashed line and the location of the post-blast core holes is indicated by the vertical lines. Figure 13 gives the corresponding results for a calculation using material properties for the sandstone based on Olsson's data and using a Young's modulus based horizontal p-wave velocity measurement. Figure 14 shows the results of using the orthotropic approximation based on Olsson's data for sandstone. There are no significant differences in the extent of the fragmented region in these three calculations. This indicates that damage calculated in the Straight Creek Mine experiment site stratigraphy is not sensitive to variations in material properties of the sandstone within the range of values implied by the two available data sets.

Figure 12. Calculated fragmented region for the A3D12A blast experiment using material properties measured by Chong et al.

Figure 13. Calculated fragmented region for the A3D12A blast experiment using isotropic sandstone material properties based on horizontal p-wave velocities measured by Olsson.

Figure 14. Calculated fragmented region for the A3D12A blast experiment using orthotropic sandstone material properties measured by Olsson.

Clearly, these calculations overestimate the extent of the fragmented region. Variation of the material properties for the siltstone and mudstone over reasonable sets of values resulted in calculated fragmented regions comparable to or larger than those shown in figures 12 through 14. None of these calculations were found to be sensitive to the yield surface, the value of R or the value of RELOAD assumed for any of the materials.

Certainly, the layered appearance of the siltstone and mudstone and the large anisotropy in K for both materials indicate that the elastic properties of these materials are likely to be at least as anisotropic as the sandstone. The most reasonable assumption would be that the p-wave velocity in the horizontal direction would be larger than the values measured for the vertical direction. A calculation was performed using the orthotropic approximation assuming that the difference between the horizontal and vertical Young's moduli for the siltstone and mudstone were in the same ratio as in Olsson's data for the sandstone. This calculation resulted in a calculated fragmented region greatly exceeding those shown in figures 12 through 14, which are already much larger than indicated by the excavated crater and post-blast cores.

Figure 15 shows the predicted fragmented region for a calculation based on an interesting, but hard to justify, set of assumptions. Since the data sets of Chong and Olsson resulted in different vertical p-wave velocities for the sandstone, it is reasonable to speculate that Olsson might have obtained lower p-wave velocities for siltstone and mudstone if he had been asked to measure these values. In fact, if the differences in the sandstone p-wave velocities for the two data sets are the result of some systematic difference in sample preparation, it might be reasonable to conjecture that Olsson would have measured p-wave velocities for the siltstone and mudstone materials which would be lower by the same ratio as in the sandstone. If that ratio is calculated using Olsson's vertical p-wave velocity, then the resulting Young's moduli for siltstone and mudstone would be 10.4 GPa and 4.3 GPa, respectively. The calculation corresponding to figure 15 differs from the calculation corresponding to figure 13 only in the use of these values for the Young's moduli of the siltstone and mudstone. As would be expected, the reduced values of the Young's moduli used in these calculations reduce the amount of calculated damage in both the siltstone and mudstone. However, the size and shape of the fragmented region is still in poor agreement with the excavated crater and post-blast core.

(2) Effects of Layering

In an attempt to estimate the effects of the thin coal seams shown in figure 10, three thin layers of elements using material properties for coal from another site were inserted into the finite element model at approximately the proper depth in the mudstone. The coal was modeled using the damage model with the following material properties:

Figure 15. Calculated fragmented region for the A3D12A blast experiment using reduced Young's moduli for siltstone and mudstone.

COAL

DENSITY	ρ	1,600kg/m ³
YOUNG'S MODULUS	E	2.95GPa
POISSON'S RATIO	ν	0.39
FRACTURE TOUGHNESS	K	50KPa/m

All other damage model parameters for the coal seams were chosen to be the same as in the other three materials. Material properties for the sandstone were isotropic and based on Olsson's data using the Young's modulus based on his horizontal p-wave velocities. The siltstone and mudstone material properties were based on Chong's data. Thus, this calculation differed from the one corresponding to figure 13 only in that the coal seams were included.

Figure 16 shows the location of the three thin coal seams and the limit of the fragmented region for this calculation. The excavated crater profile and the location of the post-blast core holes are also shown. Even though the coal is much weaker than the mudstone, including the thin coal seams in the model reduced the radius of the calculated fragmented region at and just above the depth of the coal seams. This may be because the weak coal seams inhibit the propagation of tensile waves by breaking easily.

It seems possible that delamination of the thin layers in the mudstone could have a similar effect. As a test of this hypothesis, three thin layers of elements were inserted into the mudstone above the coal seams. These three layers were given the same material properties as the mudstone, except that the value of K was taken to be 10KPa/m to simulate very weak delamination zones. Figure 17 shows the location of these three thin layers of weak elements above the three thin coal seams, and also the excavated crater profile and the location of the post-blast core holes. The radius of the limit of the predicted fragmented region for this calculation, also shown in figure 17, is significantly reduced in the region above the coal seams as compared to figure 16.

While three thin seams of weak material cannot be claimed to be a good approximation to delamination along hundreds of closely spaced bedding planes, the reduction of calculated damage in the mudstone using this simple approximation indicates that ignoring the anisotropic nature of the fracture strength in the mudstone is probably one source of the excessive calculated damage shown in figure 13. Even though the largest experimentally justifiable value of K was used in the isotropic finite element model, the amount of calculated damage was reduced by including thin seams of materials with very low values of K resulting in reduced tensile wave propagation in the vertical direction. This same effect would be expected to apply, possibly to a lesser extent, to the siltstone where the value of K for the vertical direction was a little more than half of the value for the horizontal direction.

Figure 16. Calculated fragmented region for the A3D12A blast experiment including three thin coal seams.

Figure 17. Calculated fragmented region for the A3D12A blast experiment including three thin coal seams and three thin weak seams.

Figure 18. Calculated fragmented region for the A3D12A blast experiment including three thin coal seams, three thin weak seams and using reduced Young's moduli for the siltstone and mudstone.

A final calculation is shown in figure 18, where the predicted fragmented region is shown for a calculation including both the three coal seams and the three thin weak seams, as in the calculation corresponding to figure 17, and using the reduced values for Young's moduli from the calculation shown in figure 15. In this calculation the predicted fragmented region is in reasonable agreement with the excavated crater profile. The calculated fragmented region below the crater might also be considered to be in roughly the same position as the region for which no core was recovered. However, it would be hard to justify considering the rough agreement between this calculation and the field data to be a validation of the damage model, especially when the amount of speculation involved is considered.

CONCLUSIONS

Comparison of calculations with blast experiments in granite at the Pamona Quarry [9] indicated that reasonable results could be obtained with an isotropic damage model, even using average material properties for a significantly anisotropic material. However, application of the current version of this damage model to analysis of the Straight Creek Mine blast experiments indicates that anisotropy cannot be ignored. Comparison with experiments in a wide variety of isotropic rocks must be carried out before it will be known whether or not the current version of the model is a useful engineering tool in isotropic materials. More precisely controlled experiments are likely to indicate areas where the current version of the damage model can be improved. Even for isotropic materials, a tensor damage measure based on the entire strain tensor is probably needed to adequately model the accumulation of damage and the effects of damage on material response.

The current damage model allows numerically stable calculations even when large amounts of damage are predicted. These calculations can be carried out in as little as one percent of the computer time required for calculations with older versions of the damage model. This increased speed has allowed efficient parameter variation studies to evaluate the effects of variation in material properties over the considerable range of uncertainty indicated by laboratory data for the Straight Creek Mine experiment site. As would be expected from the equations [9], the damage calculated is very sensitive to the ratio of the Young's modulus of the material to the fracture toughness of the material, E/K . In fact, the range of uncertainty for the Young's modulus of the sandstone at the Straight Creek experiment site results in a range of calculated damage varying from a large fragmented region intersecting the surface when the maximum value is used to no fragmentation at the surface when the minimum value is used.

Anisotropic wave propagation effects the damage predicted even when compared to isotropic wave propagation using the same material properties for calculation of the damage model parameters. In addition, anisotropic fracture toughness may effect the material response in a complex way, as indicated by the fact that less damage was calculated when thin layers of a very weak material were included in the finite element model for the mudstone at the Straight Creek Mine experiment site. A consistent model for anisotropic wave propagation and a damage model for anisotropic materials are both necessary for damage prediction at layered sites similar to the Straight Creek Mine experiment site.

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APPENDIX A

PRONTO CHANGES TO IMPLEMENT THE NEW DAMAGE MODEL

The only difference between the FORTRAN shown here and that included in PRONTO 2D version 4.5.6 is that in the FORTRAN below the intersection of the yield surface and the uniaxial test conditions line is calculated and the corresponding pressure is passed as PROP(11). In subroutine MATINT at step 12 substitute the following FORTRAN for the old material model 15 initiation:

```

C-----
C
C KIPP/GRADY/TAYLOR/CHEN/KUSZMAUL/ENGLMAN/JAEGER/THORNE DAMAGE MODEL
  ELSE IF( MKIND .EQ. 15 ) THEN
C Check Poisson's ratio:
  IF( PROP(2) .LE. 0.0 .OR. PROP(2) .GE. 0.5 ) THEN
    WRITE( KOUT, 3040 )
    IERR = IERR + 1
    PROP(2) = 0.0
  END IF
C RELOAD:
  PROP(5) = MIN( PROP(5), 1.0 )
  PROP(5) = MAX( PROP(5), 0.0 )
C Bulk modulus:
  PROP(13) = PROP(1) / ( 1.0 - 2.0 * PROP(2) )
C CDCON:
  IF( PROP(3) .LE. 0.0 ) THEN
    PROP(3) = MAX( PROP(4), 1.0E-6 * PROP(13) )
    FUNC4 = (1.0-2.0*PROP(2))/((1.0+PROP(2))*(1.0-PROP(2)**2))
    PROP(3) = 0.0032 * FUNC4 * ( PROP(13) / PROP(3) )**6
    WRITE(KOUT,3061) PROP(3)
  END IF
C
  DENOM = PROP(1) * RHO0
  IF( DENOM .NE. 0.0 ) THEN
    CON = PROP(4) * PROP(4) / DENOM
  ELSE
    CON = 0.0
  END IF
C
  PROP(14) = 15.0 * PROP(3) * CON
C
C Lambda:
  XLAM = PROP(1)*PROP(2)/((1.0+PROP(2))*(1.0-2.0*PROP(2)))
C Mu:
  PROP(1) = PROP(1) / ( 2.0 * ( 1.0 + PROP(2) ) )
  TWOMU = 2.0 * PROP(1)
C Lambda plus two mu:
  DATMOD = XLAM + TWOMU

```

```

C Yield Function Pressures:
  P1 = PROP(6) + PROP(9)/3.0
  P2 = PROP(7) + PROP(10)/3.0
  P3 = PROP(8) + PROP(11)/3.0
C CACON:
  PROP(6) = 0.5 * ABS( 20.0 * CON ) ** (1.0/3.0)
C
C Yield Function:
  IF( PROP(9) .EQ. PROP(10) ) THEN
C   Perfectly Plastic:
    WRITE( KOUT, 3024 )
    PROP(3) = PROP(9)
    PROP(4) = 0.0
    PROP(7) = 1.0
    PROP(8) = 1.0
    PROP(9) = 0.0
    PROP(10) = 0.0
    PROP(11) = PROP(3) / 3.0
    IF( PROP(3) .LE. 0.0 ) THEN
      WRITE( KOUT, 3021 )
      IERR = IERR + 1
    END IF
  ELSE IF( PROP(10) .EQ. PROP(11) ) THEN
C   Linear:
    WRITE( KOUT, 3025 )
    IF( P1 .EQ. P2 ) THEN
      WRITE( KOUT, 3021 )
      IERR = IERR + 1
      P1 = 1.0
      P2 = 2.0
    END IF
    PROP(4) = ( PROP(10) - PROP(9) ) / ( P2 - P1 )
    PROP(3) = PROP(9) - PROP(4) * ABS( P1 )
    PROP(7) = 1.0
    PROP(8) = 1.0
    PROP(9) = 0.0
    PROP(10) = 0.0
    WRITE( KOUT, 3026 ) PROP(3), PROP(4)
    IF( PROP(4) .GE. 3.0 ) THEN
      WRITE( KOUT, 3021 )
      IERR = IERR + 1
      PROP(4) = 0.1
    END IF
    PROP(11) = PROP(3) / ( 3.0 - PROP(4) )
  ELSE

```

```

C      Parabolic:
      WRITE( KOUT, 3022 )
      IF( PROP(11) .EQ. PROP(9) ) THEN
        WRITE( KOUT, 3021 )
        IERR = IERR + 1
        PROP(9) = 1.0
        PROP(10) = 2.0
        PROP(11) = 3.0
      END IF
      PROP(7) = ( ( PROP(10) - PROP(9) ) * ( P3 - P2 )
*              - ( PROP(11) - PROP(10) ) * ( P2 - P1 ) )
*              / ( ( PROP(11) - PROP(10) ) * ( PROP(10) - PROP(9) )
*              * ( PROP(11) - PROP(9) ) )
      PROP(8) = ( P2 - P1 ) / ( PROP(10) - PROP(9) )
*              - PROP(7) * ( PROP(10) + PROP(9) )
      PROP(9) = P1 - PROP(9) * ( PROP(7) * PROP(9) + PROP(8) )
      PROP(3) = 0.0
      PROP(4) = 0.0
      PROP(10) = 1.0
      WRITE( KOUT, 3023 ) PROP(7), PROP(8), PROP(9)
      IF( PROP(9) .GT. 0.0 .OR. PROP(7) .EQ. 0.0 ) THEN
        WRITE( KOUT, 3021 )
        IERR = IERR + 1
        PROP(7) = 1.0
        PROP(9) = 0.0
      END IF
      PROP(11) = ( ( 1.0 - 3.0*PROP(8) )
*              + SQRT( ( 1.0 - 3.0*PROP(8) )**2
*              - 36.0*PROP(7)*PROP(9) ) ) / ( 18.0*PROP(7) )
      END IF
      IF( PROP(11) .LE. 0.0 ) THEN
        WRITE( KOUT, 3021 )
        IERR = IERR + 1
      END IF
      WRITE( KOUT, 3027 ) PROP(11)
C-----
3021 FORMAT( 10X, '***** ERROR: ILLEGAL YIELD FUNCTION*****' )
3022 FORMAT( 10X, 'PARABOLIC YIELD FUNCTION:' )
3023 FORMAT( 10X, 'PARABOLIC COEFFICIENTS: A=', 1PE10.3,
*          4X, 'B=', 1PE10.3, 4X, 'C=', 1PE10.3 )
3024 FORMAT( 10X, 'PERFECTLY PLASTIC:' )
3025 FORMAT( 10X, 'LINEAR YIELD FUNCTION:' )
3026 FORMAT( 10X, 'INTERCEPT=', 1PE10.3, 6X, 'SLOPE=', 1PE10.3 )
3027 FORMAT( 10X, 'UNIAXIAL-TEST PRESSURE:', 1PE10.3 )
3061 FORMAT(      T15, 'CALCULATED VALUE FOR K: ', 1PE11.3 )

```

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APPENDIX B

DAMAGE MODEL SUBROUTINE

SUBROUTINE MAT4A(NBLK,NINSV,DT,PROP,SIG,D,SV,STRAIN)

C*****

C

C KIPP/GRADY/TAYLOR/CHEN/KUSZMAUL/ENGLMAN/JAEGER/THORNE DAMAGE MODEL

C

C A damage model based on micro-crack growth and interaction,
C with Engleman and Jaeger's extension of Budianski and O'Connell's
C bulk and shear moduli based on crack density.

C

C Reloading of damaged material uses a fraction of the damage
C to reduce the bulk modulus. Strain must exceed maximum strain
C before damage can increase.

C

C Plasticity is used with yield radius a function of volumetric
C stress, P:

C

C The linear option, $Y(P) = YIELD + DYDP * ABS(P)$, is based
C on a line through the maximum stress difference for two
C triaxial tests showing plastic behavior. The zero pressure
C intercept of this line is YIELD and its slope is DYDP.
C YIELD and DYDP must be greater than 0 and DYDP less than 3.

C

C DYDP=0 for perfectly plastic.

C

C The parabolic option,

C $Y(P) = (\sqrt{B^2 + 4*A*(ABS(P) + C)} - B) / 2*A$,
C is based on an inverse parabola through the maximum stress
C difference for three triaxial tests showing plastic behavior;
C $-P(Y) = A*Y^2 + B*Y + C$.

C

C Yield radius is multiplied by 1e12 at stresses above that
C corresponding to zero confining pressure.

C

C FORMAL PARAMETERS:

C NBLK INTEGER Number of Elements in this Block
C NINSV INTEGER Number of Internal State Variables
C DT REAL Time Increment
C PROP REAL Material Properties
C SIG REAL Stresses
C D REAL Strain Rates
C STRAIN REAL Strains
C SV REAL Internal State Variables:

C

C (1,*) = damage
C (2,*) = maximum volumetric strain rate
C (3,*) = maximum volumetric strain
C (4,*) = crack density
C (5,*) = equivalent plastic strain
C (6,*) = fragment size rate factor

C

C CALLED BY: UPDSTR

C

C*****

```

PARAMETER (THIRD=1.0/3.0, TWOTHD=2.0/3.0, S9THS=16.0/9.0 )
C
PARAMETER (NSPC=2,NELNS=4,NESNS=2,NSYMM=4,NASYM=1,NONSYM=5,NHGM=1,
*          NEBLK=512,MFIELD=22)
C      NSPC      INTEGER      Number of Spatial Coordinate Components
C      NELNS      INTEGER      Number of Element Local Nodes
C      NESNS      INTEGER      Number of Element Side Nodes
C      NSYMM      INTEGER      Number of Symmetric Tensor Components
C      NASYM      INTEGER      Number of Asymmetric Tensor Components
C      NONSYM      INTEGER      Number of Non-Symmetric Tensor Components
C      NHGM      INTEGER      Number of Hourglass Modes
C      NEBLK      INTEGER      Number of Elements per Vector Block
C      MFIELD      INTEGER      Number of fields that the free field
C                               reader will allow on each line
C
DIMENSION PROP(*),SIG(NSYMM,NBLK),D(NSYMM,NBLK),SV(NINSV,NBLK),
*          STRAIN(NSYMM,NBLK)
C
F1(X) = ( 1.0 - X * X ) / ( 1.0 - 2.0 * X )
F3(X) = ( 1.0 - 2.0 * X ) / ( 1.0 + X )
C
C Material Properties
C1      = SQRT(TWOTHD)
TWOMU   = PROP(1) * 2.0
XNU     = PROP(2)
YIELD   = PROP(3)
DYDP    = PROP(4)
RELOAD  = PROP(5)
CACON   = PROP(6)
COEFA   = PROP(7)
COEFB   = PROP(8)
COEFC   = PROP(9)
PARAB   = PROP(10)
YPLIM   = PROP(11)
BLKX3   = PROP(13)
CDCON   = PROP(14) * DT
HDT     = 0.5 * DT
DT2MU   = DT * TWOMU
BLK3DT  = DT * BLKX3
XNUI    = 1.0 / XNU
TERM    = 1.0 / TWOMU
STBLK   = 3.0 * S9THS * BLKX3
C
DO 10 I = 1,NBLK
C
C Volumetric stress at beginning of time step
PF = THIRD * ( SIG(1,I) + SIG(2,I) + SIG(3,I) )
C Volumetric and Deviatoric Strain Rates at center of time step
DAVG = THIRD * ( D(1,I) + D(2,I) + D(3,I) )
DDEV1 = D(1,I) - DAVG
DDEV2 = D(2,I) - DAVG
DDEV3 = D(3,I) - DAVG
C Elastic Volumetric Stress Increment
PEINC = BLK3DT * DAVG

```

```

C Update Strains to center of time step
  STRAIN(1,I) = STRAIN(1,I) + HDT * D(1,I)
  STRAIN(2,I) = STRAIN(2,I) + HDT * D(2,I)
  STRAIN(3,I) = STRAIN(3,I) + HDT * D(3,I)
  STRAIN(4,I) = STRAIN(4,I) + HDT * D(4,I)
C Volumetric and Deviatoric Total Strains at center of time step
  EAVG = THIRD * ( STRAIN(1,I) + STRAIN(2,I) + STRAIN(3,I) )
  EDEV1 = STRAIN(1,I) - EAVG
  EDEV2 = STRAIN(2,I) - EAVG
  EDEV3 = STRAIN(3,I) - EAVG
  EDEV4 = STRAIN(4,I) - EAVG
C Update Strains to end of time step
  STRAIN(1,I) = STRAIN(1,I) + HDT * D(1,I)
  STRAIN(2,I) = STRAIN(2,I) + HDT * D(2,I)
  STRAIN(3,I) = STRAIN(3,I) + HDT * D(3,I)
  STRAIN(4,I) = STRAIN(4,I) + HDT * D(4,I)
C----- Begin Damage Model Calculations -----
C Maximum strain rate
  SV(2,I) = MAX( SV(2,I), DAVG )
  EINV = 1.0 / ( SV(2,I) * SV(2,I) )
C Update Multiplier for Average Fragment Size
  SV(6,I) = CACON * EINV**THIRD
C RFAC = 1: When expanding at center of time step
  RFAC = 0.5 + SIGN( 0.5, DAVG )
C EFAC = 1: When expanded beyond previous maximum strain at center of time step
  EFAC = 0.5 + SIGN( 0.5, EAVG - SV(3,I) )
C Update maximum volumetric strain
  SV(3,I) = MAX( SV(3,I), EAVG )
C PFAC = 1: When in tension at center of time step
  DFAK = 1.0 - SV(1,I) * RELOAD
  PFAC = 0.5 + SIGN( 0.5, PF + 0.5 * PEINC
    *
    * ( RFAC + ( 1.0 - RFAC ) * DFAK ) )
C Damage can occur only when all three conditions are met
  TFAC = EFAC * RFAC * PFAC
C Crack Density Increment
  CDINC = TFAC * CDCON * EINV * DAVG * EAVG**5
C Update Crack Density to end of time step
  SV(4,I) = SV(4,I) + CDINC
C Effective Poisson's ratio at center of time step
C Use elastic Poisson's ratio in compression
  XNUB = XNU * EXP( S9THS*( 0.5*CDINC - SV(4,I) ) * PFAC )
  FUNC3 = F3( XNUB )
C Effective Poisson's ratio at end of time step
  XNUE = XNU * EXP( -S9THS * SV(4,I) )
  FUNC1 = F1( XNUE )
C Damage Increment
  DINC = TFAC * ( FUNC1 * ( 1.0 - XNUE * XNUI ) - SV(1,I) )
C Update Damage to end of time step
  SV(1,I) = SV(1,I) + DINC
C Effective damage at center of time step
  DFAC = 1.0 - ( SV(1,I) - 0.5 * DINC )
C Use elastic properties in compression
C EFAK = 1: When at a positive strain at center of time step
  EFAK = 0.5 + SIGN( 0.5, EAVG )
C Use a fraction of the damage to reduce elastic contracting in tension
  DFAK = 1.0 - ( SV(1,I) - 0.5 * DINC ) * RELOAD * PFAC * EFAK

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C Volumetric Stress Increment
  PINC = ( DFAC * PEINC - BLKX3 * EAVG * DINC ) * TFAC
  *      + DFAK * PEINC * ( 1.0 - TFAC )
C Increment of deviatoric stress
  DMUDT = STBLK * DFAC * CDINC * XNUB / ( 1.0 + XNUB )**2
  *      - BLKX3 * FUNC3 * DINC
  S1INC = TFAC * ( DMUDT * EDEV1 + BLK3DT * DFAC * FUNC3 * DDEV1 )
  *      + ( 1.0 - TFAC ) * BLK3DT * DFAK * FUNC3 * DDEV1
  S2INC = TFAC * ( DMUDT * EDEV2 + BLK3DT * DFAC * FUNC3 * DDEV2 )
  *      + ( 1.0 - TFAC ) * BLK3DT * DFAK * FUNC3 * DDEV2
  S3INC = TFAC * ( DMUDT * EDEV3 + BLK3DT * DFAC * FUNC3 * DDEV3 )
  *      + ( 1.0 - TFAC ) * BLK3DT * DFAK * FUNC3 * DDEV3
  S4INC = TFAC * ( DMUDT * EDEV4 + BLK3DT * DFAC * FUNC3 * D(4,I) )
  *      + ( 1.0 - TFAC ) * BLK3DT * DFAK * FUNC3 * D(4,I)
C Total stress at end of time step
  SIG(1,I) = SIG(1,I) + S1INC + PINC
  SIG(2,I) = SIG(2,I) + S2INC + PINC
  SIG(3,I) = SIG(3,I) + S3INC + PINC
  SIG(4,I) = SIG(4,I) + S4INC
C
C Radius of yield surface (Parabolic, Linear or Constant)
  PF = PF + PINC
  RADIUS = C1 * ( YIELD + DYDP * ABS(PF)
  *      + PARAB * ( SQRT( COEFB**2 + 4.0 * COEFA
  *      * ( ABS(PF) - COEFC ) ) - COEFB )
  *      / ( COEFA + COEFC ) )
C Elastic when below pressure corresponding to uniaxial test
  PFAC = 0.5 + SIGN( 0.5, PF + YPLIM )
  RADIUS = RADIUS * ( 1.0 + PFAC * 1.0E12 )
C Deviatoric Trial Stress
  TRIAL1 = SIG(1,I) - PF
  TRIAL2 = SIG(2,I) - PF
  TRIAL3 = SIG(3,I) - PF
C Magnitude of the Trial Stress
  DSMAG = SQRT( TRIAL1**2 + TRIAL2**2 + TRIAL3**2 + 2.0 * SIG(4,I)**2 )
C Determine the Factor for Plasticity (Zero for Elastic).
  DIFF = DSMAG - RADIUS
  EFAC = 0.5 + SIGN( 0.5, DIFF )
C Determine the addition factor for when DSMAG is Zero.
C Since there is no Plasticity, EFAC will be Zero and ADDFAC One.
  ADDFAC = 1.0 - EFAC
  DSMAG = DSMAG + ADDFAC
C Plastic relaxation factor
  XLAM = EFAC * TERM * DIFF
C Update Stresses for Plasticity
  TFAC = 1.0 - XLAM * TWOMU / DSMAG
  SIG(1,I) = TFAC * TRIAL1 + PF
  SIG(2,I) = TFAC * TRIAL2 + PF
  SIG(3,I) = TFAC * TRIAL3 + PF
  SIG(4,I) = TFAC * SIG(4,I)
C Update equivalent plastic strain.
  SV(5,I) = SV(5,I) + C1 * XLAM
C
10 CONTINUE
C
  RETURN
  END

```

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