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A study of detonation timing and fragmentation using 3-D finite element techniques and a damage constitutive model *

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ABSTRACT: The transient dynamics finite element computer program, PRONTO-3D, has been used in conjunction with a damage constitutive model to study the influence of detonation timing on rock fragmentation during blasting. The primary motivation of this study is to investigate the effectiveness of precise detonators in improving fragmentation. PRONTO-3D simulations show that a delay time of 0.0 sec between adjacent blastholes results in significantly more fragmentation that a 0.5 ms delay.

1 INTRODUCTION

One of the advantages of precise detonators (microsecond accuracy) appears to be enhanced fragmentation. The reasons for this are not clearly understood but it has been surmised that complimentary wave interaction in the region between two detonating blastholes results in better fragmentation. To address this question a study has been undertaken using the 3-D transient dynamic computer code PRONTO in conjunction with a damage material constitutive model.

PRONTO-3D (Taylor and Flanagan, 1989) has been continuously evolving at Sandia National Laboratories for many years. As an explicit transient dynamics finite element code, PRONTO is capable of addressing a large variety of dynamic simulations including: impact, metal forming and explosive/structure interaction. A wide range of material responses and large deformations and strains can be treated during any simulation. The damage constitutive model used in this study was specifically developed for predicting blast induced fragmentation in rock and has been exercised on several closely controlled crater field experiments with reasonable results (Thorne, 1990a&b, 1991).

The configuration examined in this study consists of two blastholes (crater style) located relatively close to on another. The geometry is similar to a single blasthole crater experiment that was used to qualify the damage constitutive model but with two blastholes instead of one. Two different delay times, 0.0 s and 0.5 ms, between the blastholes are simulated and the rock is assumed to be granite.

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2 DAMAGE CONSTITUTIVE MODEL

The damage model is intended to simulate the dynamic fracture of brittle rock. It is based on work started by Kipp and Grady, 1980 and continued by Taylor, Chen and Kuszmaul, 1986 and Kuszmaul 1987a. It was modified (Thorne, 1991) to extend it to large crack densities as suggested by Englman and Jaeger, 1987. Its essential feature is the treatment of the dynamic fracture process as a continuous accrual of damage in tension due to microcracking in the rock. The fundamental assumption of the model is that the rock is isotropic and permeated by an array of randomly distributed and oriented microcracks. These microcracks grow and interact with one another under tensile loading. A complete derivation of the damage model is given in Preece et al, 1994. A brief summary is presented in this paper as an aid to understanding the computational results.

Englman and Jaeger, 1987, introduce a regularized damage parameter, F, which is related to Budiansky and O'Connell's, 1976, crack density, C_d but takes into account the overlap between the damage vol-

umes of different cracks. To this end they define F by

$$F = 1 - exp(-\alpha C_d) \qquad 2.1$$

where $\alpha = 16/9$.

In order to relate stress to strain we will generate a system of equations which can be solved for the effective elastic moduli of the cracked medium. It is convenient to introduce a damage parameter, D, defined by

$$D = f(\nu_e)F \qquad 2.2$$

where ν_e is the effective Poisson's ratio. K_e is the effective bulk modulus of a cracked medium and is given in terms of the undamaged bulk modulus K by

$$K_e = (1-D)K \qquad 2.3$$

The crack density, C_d, can be related to an average flaw size, a, by

$$C_d = \Upsilon N a^3 \qquad 2.4$$

where N is the number of active cracks and Υ is a proportionality ratio.

At this point, it should be noted that there is variety of assumptions which can be made as to the form of N, and there is almost no agreement as to the proper form for a. Kipp and Grady, 1980, and Kuszmaul, 1987a, assume that the number of cracks activated at a volumetric strain ε is described by a Weibull distribution of the form.

$$N = k\varepsilon^m \qquad 2.5$$

where k and m are material dependent constants and the volumetric strain, ε, is one third of the time integral of the trace of the deformation tensor, $\boldsymbol{d}$ with ε being positive in tension. Equations 2.5 and 2.4 imply

$$C_d = k\varepsilon^m a^3 \qquad 2.6$$

Based on energy considerations at high strain rates, Grady, 1983 derives the following expression for the nominal fragment radius, r, for dynamic fragmentation of a brittle material

$$r = \frac{1}{2}\left[\frac{\sqrt{20}K_{IC}}{\rho c R}\right]^{2/3} \qquad 2.7$$

Here K_{IC}, ρ and c are the fracture toughness, density and sound speed of the undamaged material and R is the strain rate, which is assumed in the derivation to be both constant and large. This is an average fragment radius for the global response of a uniformly expanding sphere. We will assume that the local average flaw size, a, is proportional to the value of r appropriate to the local strain rate.

In order to apply equation 2.7 to the case where the strain rate is not constant, Taylor, Chen and Kuszmaul, 1986, replace the constant strain rate, R, in equation 2.7 with the maximum strain rate, R_{max}, which the material has experienced. Making some assumptions about the maximum strain rate and combining equations 2.6 and 2.7 yields an expression for C_d based on measurable material parameters.

$$C_d = \frac{5k\varepsilon^m}{2}\left[\frac{K_{IC}}{\rho c R_{max}}\right]^2 \qquad 2.8$$

In the constitutive model implementation, equations 2.1 through 2.8 form the basis for derivation of a coupled system of ordinary differential equations which can be integrated to define the response of the damaged material.

The material parameters for granite were measured by Olsson, 1989, and Chong et al, 1988, are listed in Table 2.1.

Table 2.1: Granite Material Properties

Density	$\rho = 2680\ kg/m^3$
Youngs' Modulus	$E = 62.8$ GPa
Poissons' Ratio	$\nu = 0.29$
k	$k = 5.3 \times 10^{26}/m^3$
m	6.0
Fracture Toughness	$K_{IC} = 1.68\ \text{MPa}\sqrt{m}$

3 FINITE ELEMENT MODEL

The cross-sectional geometry of the 3-D finite element model is shown in Figure 1. This simulation models two explosive columns that have a diameter of 120 mm, a height of 2.0 m, a separation of 3.0 m, buried 2.0 m deep and filled with 28.27 *kg* of emulsion explosive. Full coupling is assumed between the explosive and the surrounding granite. Detonation begins at the bottom of each explosive column and is modeled with a controlled burn based on a specified detonation velocity.

The finite element model employed here has 41760 3-D hexahedral elements and 45933 nodes. The spatial resolution of this model is too fine to be drawn in this paper. Detonation delay times of 0.0 s and 0.5 ms were treated in two separate calculations. Each calculation required approximately 4 days of cpu time on a SUN SPARCstation 10-41 workstation. The databases produced by these calculations contained time steps saved every 40 μs. The zero-delay-time database contained 36 time steps and had a size of 144 megabytes while the 0.5 ms delay-time-database contained 48 time steps and occupied 191 megabytes.

4 COMPUTATIONAL RESULTS

Figures 2 and 3 show the pressure distribution as a function of time for the two different delay times in this study. A time history of the pressure halfway between the two blastholes and 1/4 of the blasthole height from the top (see Figure 1) is given in Figure 4. This graph indicates a significant increase in the bulk pressure $(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$ in the case of the simultaneous detonation that is less obvious from Figures 2 and 3. Although the bulk pressure is generally compressive, the circumferential (hoop) component (in cylindrical coordinates) will be tensile at least part of the time during the passage of the wave. This is illustrated in Figure 5 which shows σ_{yy} at the point of interest on the front symmetry plane. At this location σ_{yy} is equal to the cicumferential stress and is tensile part of the time. It is this tensile stress that results in tensile volumetric strain and consequently damage in the material. In studying Figures 4 and 5 one should keep in mind that they represents the pressure and stress in the model at specific output times. As discussed in section 3, the model is so large that the number of output time steps had to be limited.

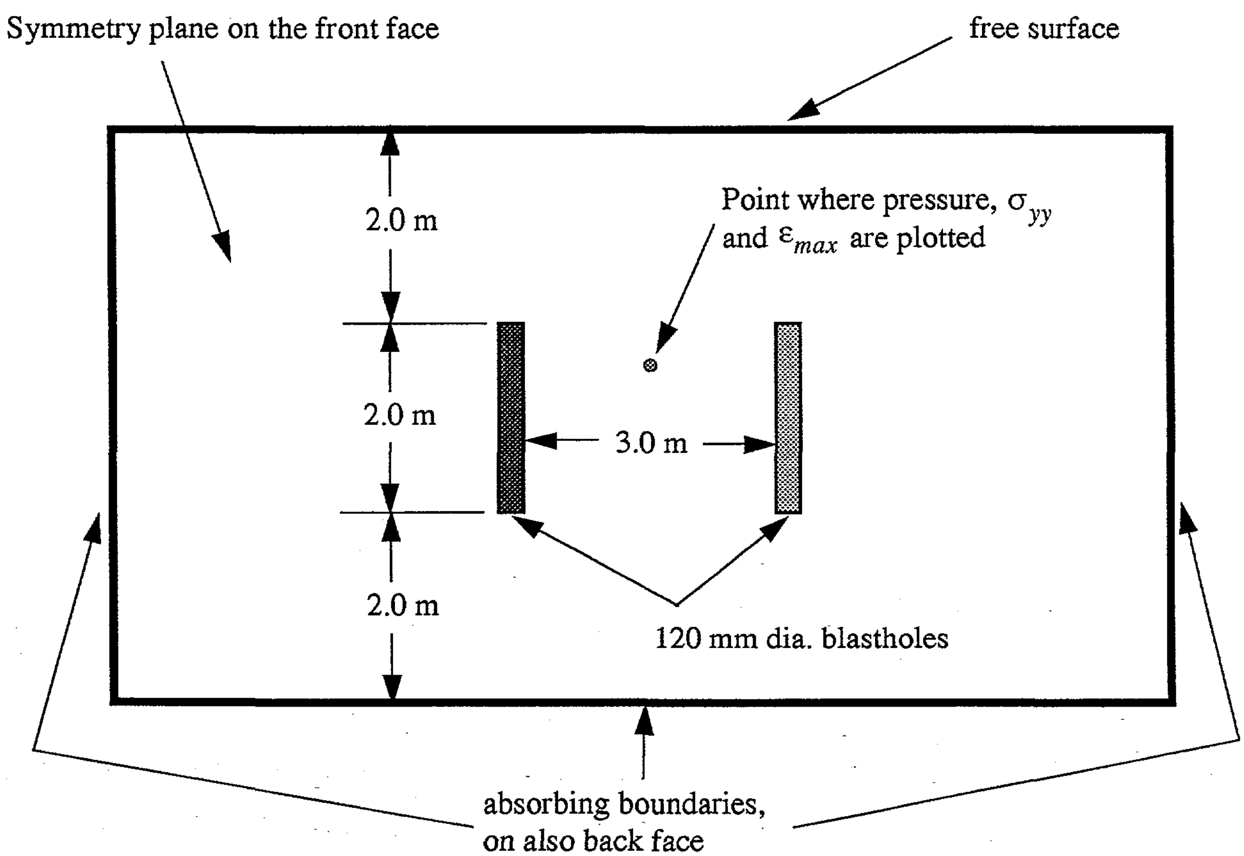

Figure 1: Two Blasthole Crater Geometry

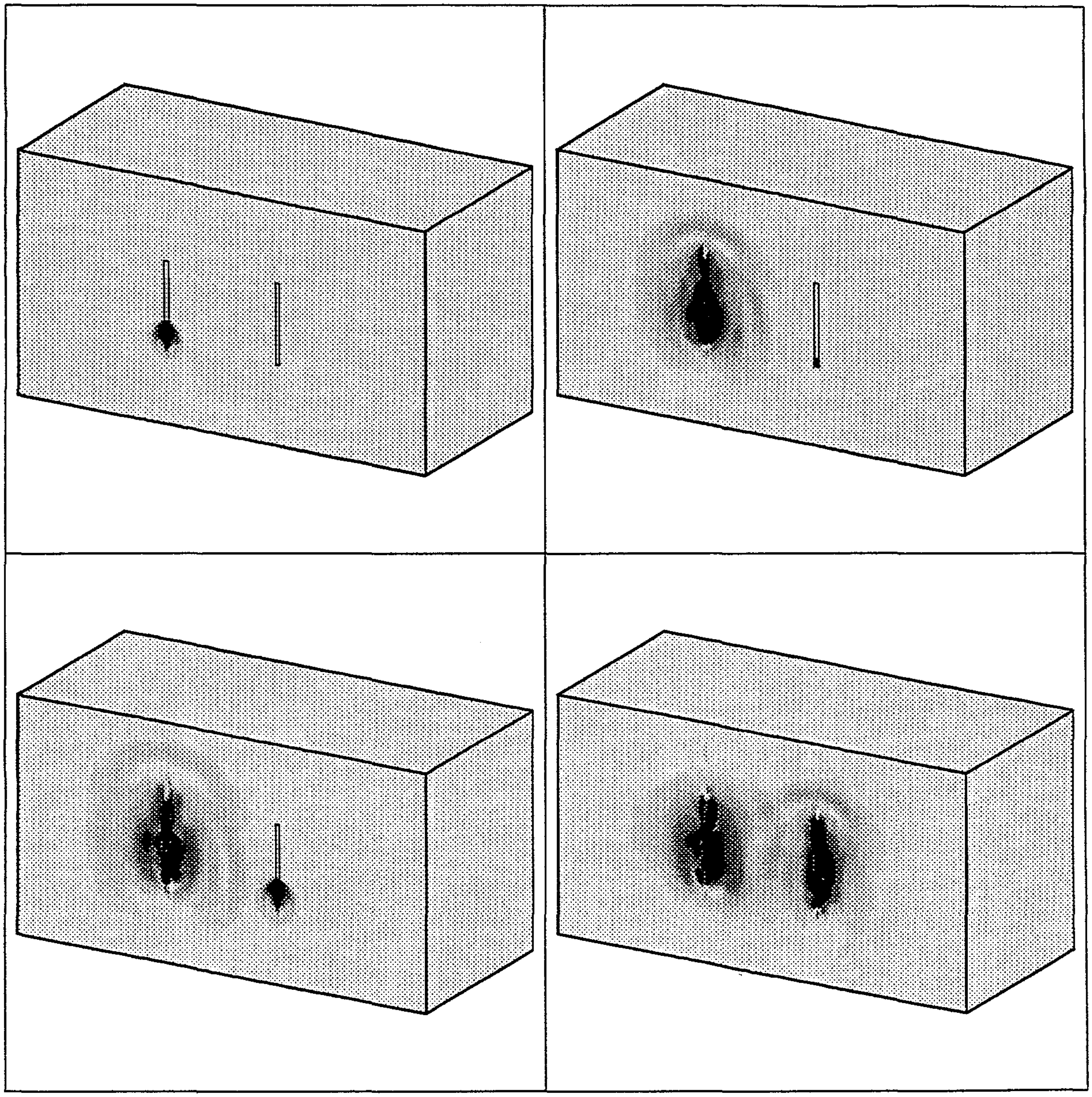

Figure 2: Pressure distribution at times 80 μs, 0.5 *ms*, 0.6 *ms* and 1.0 *ms* for a delay time of 0.5 *ms*. The gray-scale (light-to-dark) pressure range is from 0.0 to -400.0 *Mpa*. Pressures above and below the range are the same shade as the upper or lower limits. Tension is positive.

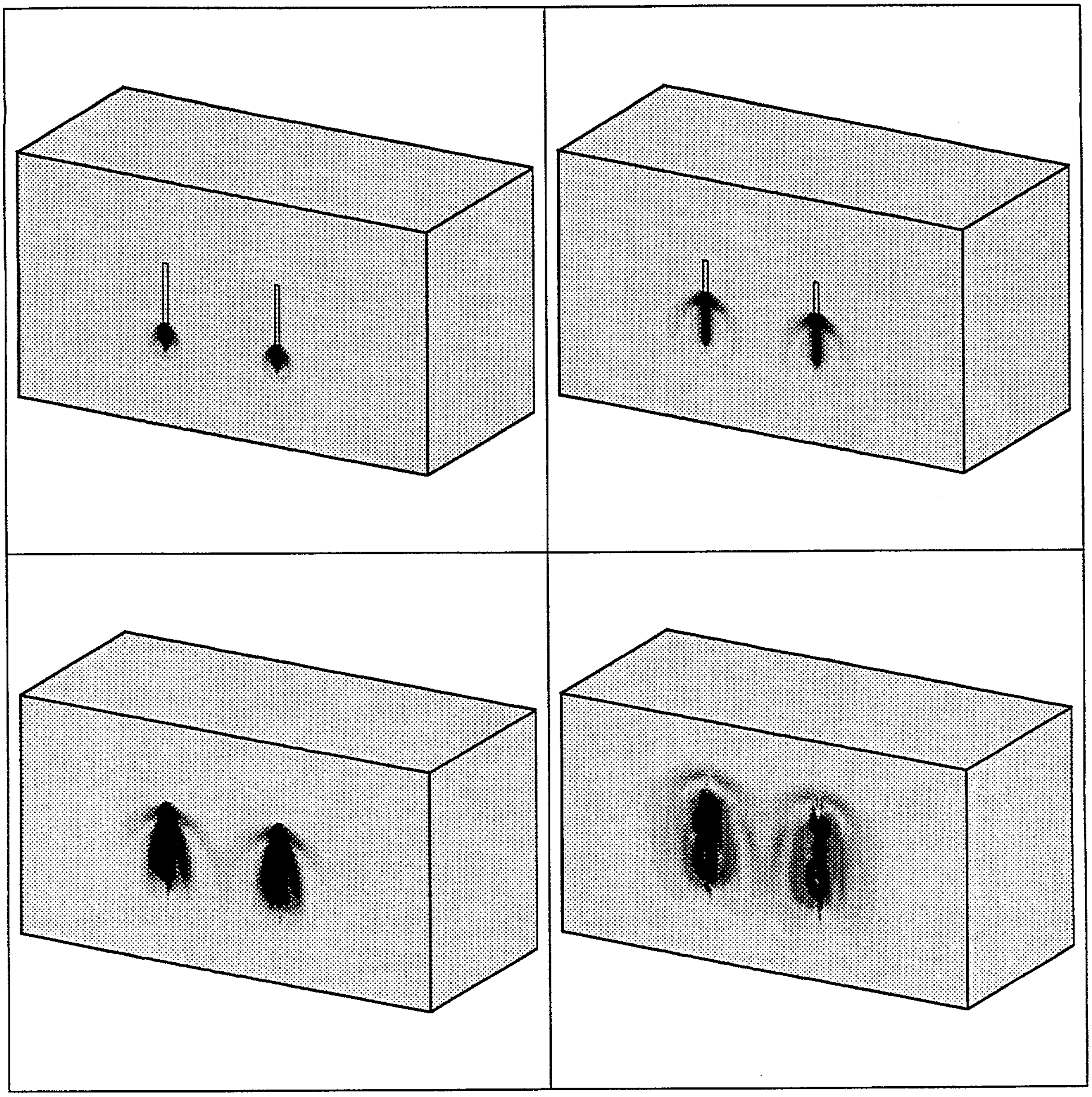

Figure 3: Pressure distribution at times 80 μs, 0.2 *ms*, 0.32 *ms* and 0.48 *ms* for a delay time of 0.0 *ms*. The gray-scale (light-to-dark) pressure range is from 0.0 to -400.0 *Mpa*. Pressures above and below the range are the same shade as the upper or lower limits. Tension is positive.

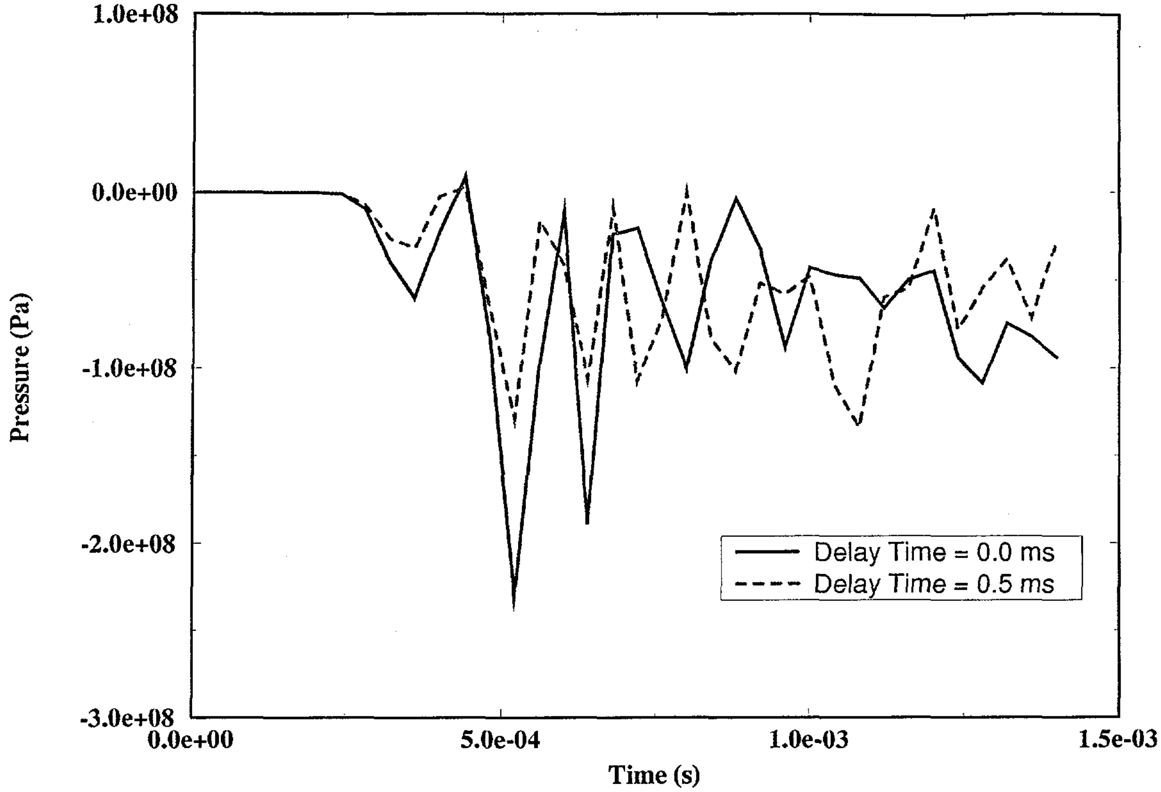

Figure 4: Pressure versus time at the point indicated in Figure 1 for delay times of 0.0 *ms* and 0.5 *ms*. Tension is positive.

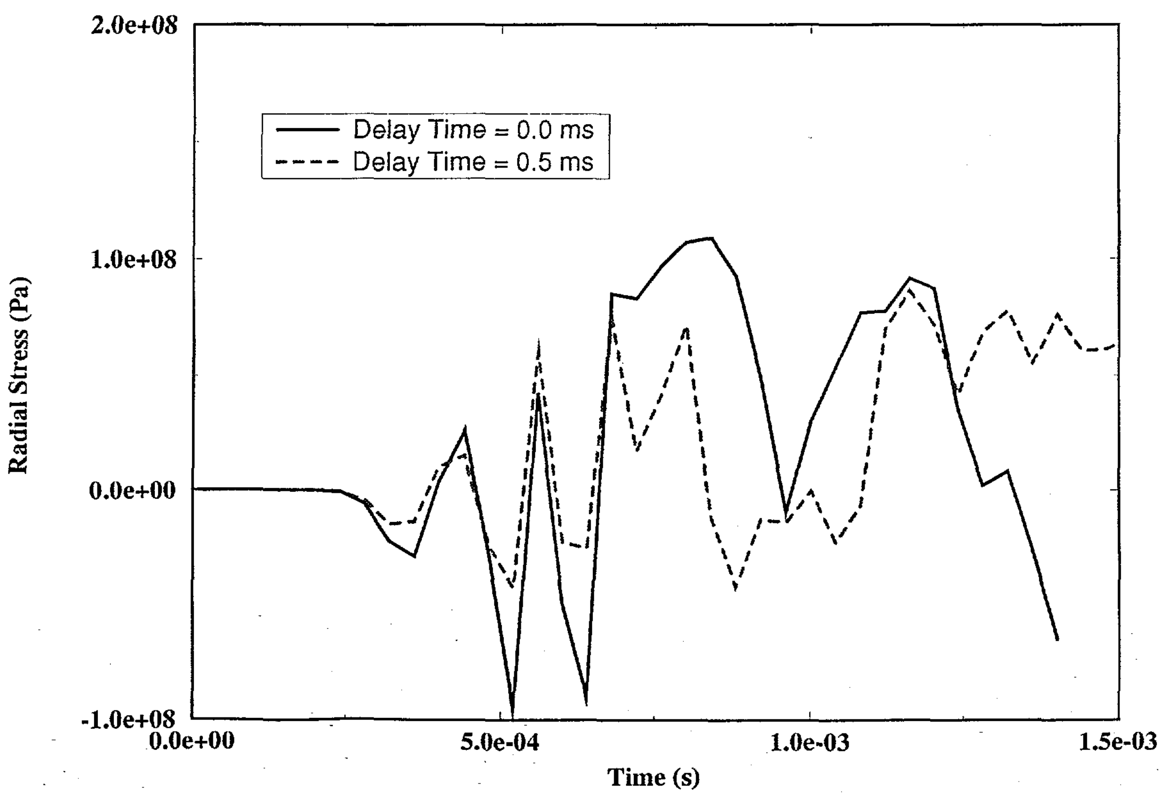

Figure 5: σ_{yy} versus time at the point indicated in Figure 1 for delay times of 0.0 *ms* and 0.5 *ms*. σ_{yy} at the point indicated is also the circumferential stress. Tension is positive.

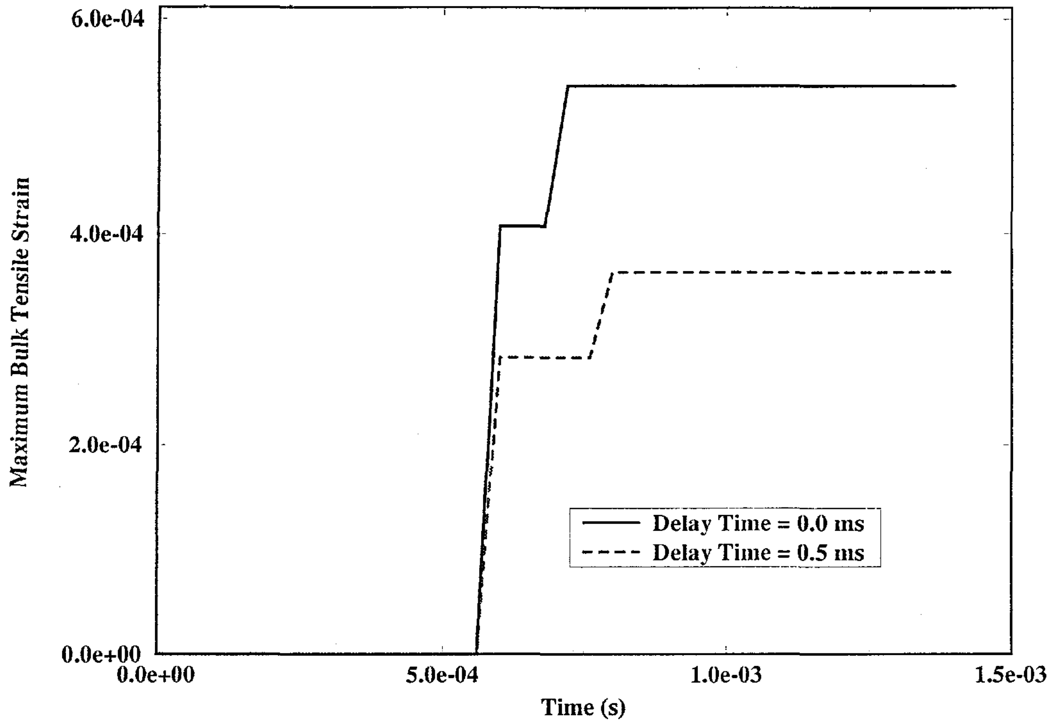

Figure 6: ε_{max} versus time at the point indicated in Figure 1 for delay times of 0.0 *ms* and 0.5 *ms*. Tension is positive

Figure 6 shows the maximum bulk tensile strain, ε_{max}, as a function of time and at the location indicated in Figure 1. ε_{max} is the maximum tensile volumetric strain at that point up to the time of interest and can only increase with time. Significantly higher values of ε_{max} are indicated in the simultaneous detonation case. The crack density, C_d, in equation 2.6 is an exponential function of the volumetric strain ε where the exponent, m, in this case (and for most rocks) is 6. Exponentiation to a power of 6 results in a large difference in the crack density and the damage produced by the two different delay times. These results are typical of the pressures and volumetric strains along a line of symmetry between the two blastholes and also for some distance on either side of that line.

The calculated spatial distribution of the damage at four different times is shown in Figure 7 for a 0.5 ms delay between detonations. A damage or crack density threshold value for fragmentation has been analyzed by Kuszmaul, 1987b and Thorne, 1990a&b. For the purposes of this study fragmentation is assumed to occur in the dark regions where the damage is close to one. The same plot is given for the simultaneous detonation in Figure 8. Comparison of these two Figures indicates a significant improvement in the damage and fragmentation with the simultaneous detonation case being superior. A weakness of this damage constitutive model is its inability to predict damage in compression. Thus the undamaged regions adjacent to the blastholes would, in reality, be damaged and fragmented.

5 CONCLUSIONS

The 3-D transient dynamics finite element computer program PRONTO has been employed along with a damage constitutive model to study the influence of delay timing on the fragmentation of rock during blasting. This constitutive model accumulates damage based on episodes of tensile volumetric strain. These simulations show that simultaneous detonation significantly improves the fragmentation between blastholes. The reason for this improvement is the positive reinforcement of waves from the two blastholes arriving at the same location at the same time. This positive reinforcement manifests itself in significant increases in pressure and volumetric strain which results in improvements in damage and fragmentation when the blastholes are detonated simultaneously.

This study has implications for the value of precision detonators which can deliver μs accuracy in the delay time between blastholes. This study indicates that improvements to fragmentation due to

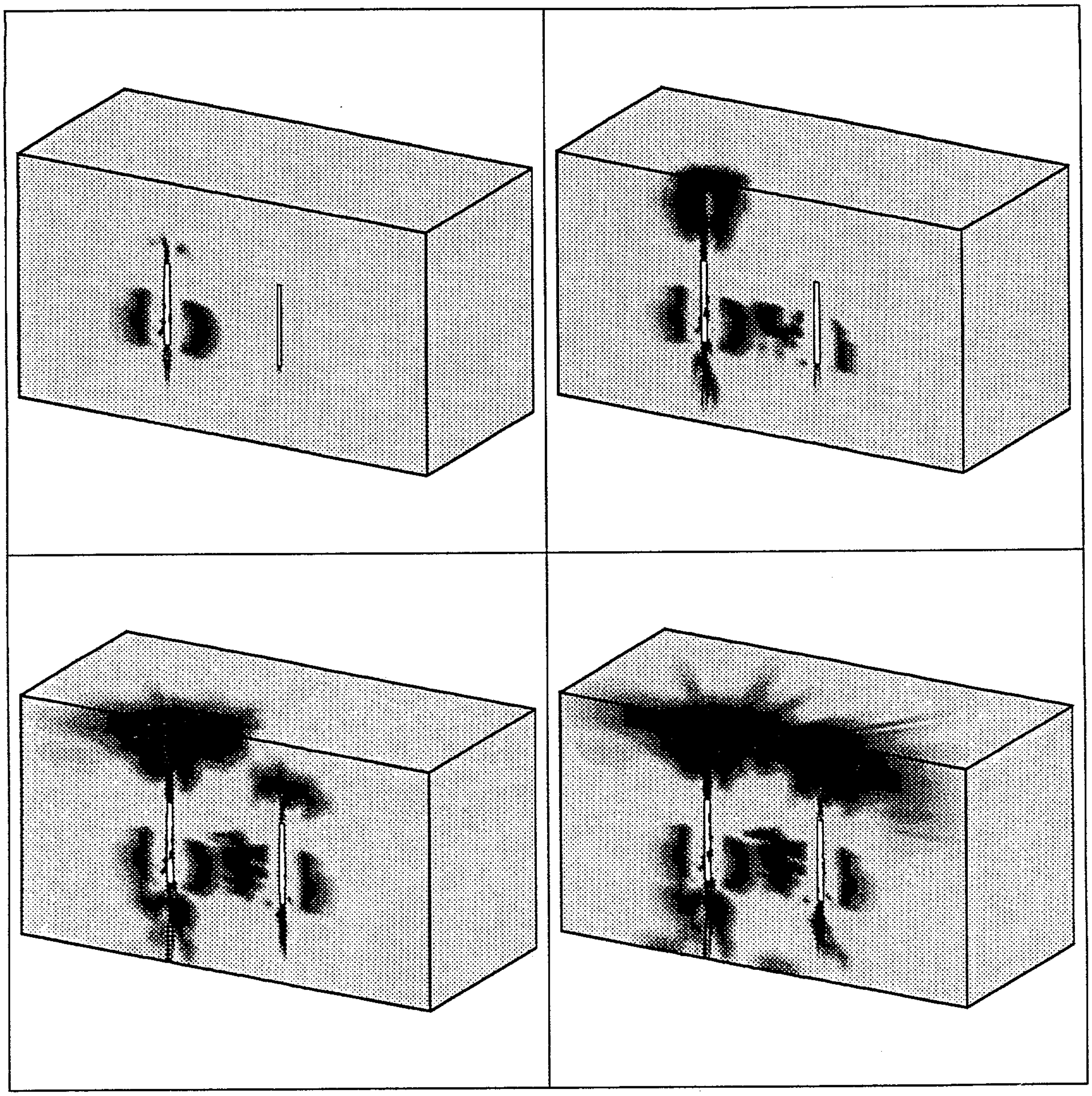

Figure 7: Damage distribution at times 0.5 *ms*, 0.8 *ms*, 1.2 *ms* and 1.88 *ms* for a delay time of 0.5 *ms*. The gray-scale (light-to-dark) damage range is from 0.0 to 1.0.

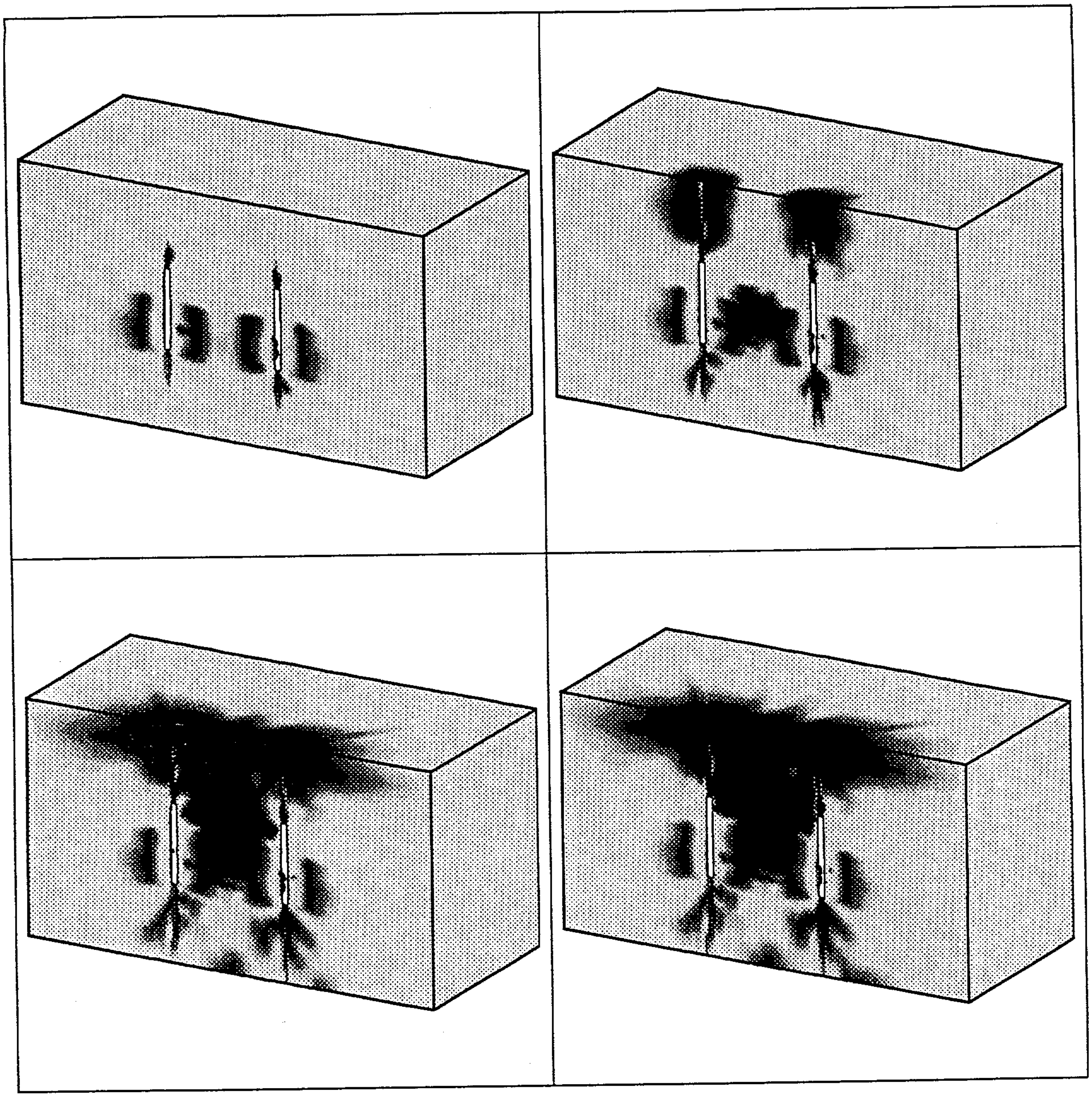

Figure 8: Damage distribution at times 0.5 *ms*, 0.8 *ms*, 1.2 *ms* and 1.4 *ms* for a delay time of 0.0 *ms*. The gray-scale (light-to-dark) damage range is from 0.0 to 1.0.

that improvements to fragmentation due to precision timing may well be worth the additional cost of the detonator.

This paper has demonstrated a numerical capability that can be used to study the influence of precision timing on fragmentation. The effects on timing and fragmentation of many other parameters such as blasthole spacing and depth as well as rock and explosive types can also be studied using the techniques presented in this paper.

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