# FORMATION OF RADIAL FRACTURING IN ROCK UNDER THE ACTION OF EXPLOSIVES

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Fracturing in rock under the actions of explosives is caused by large forces exerted on rock during and after detonation. This paper presents numerical and experimental evidence as to how the blast loading is transformed into a stress state that causes radial fracturing in rock. We show that propagating radial fractures trail behind the shock wave in a tensile zone and that the Johnson-Holmquist strength and failure models provide numerical results that match experimental studies. This provides new evidence regarding how shock waves create radial fractures and advances the current understanding regarding the mechanism of crack formation under the action of explosives.

## INTRODUCTION

Cylindrical-shaped explosive charges are widely used in mining, quarrying, and construction industries to break rock. Numerical simulation to predict fracturing and crushing in rock under the action of explosives is a difficult problem and explosive engineers often rely heavily on making substantial adjustments to an initial blast design for efficient and effective implementation. A design-by-trial approach works well for mining and quarrying where many blasts will be conducted at the same location in the same rock mass. For endeavors that require a limited number of blasts, the ability to numerically predict fracturing and crushing in rock can be a great benefit. Other researchers have identified that the compressive shock wave and expanding gases are the two mechanisms that cause fracturing in rock [1, 2, 3]. However, further research is needed to adequately define the contribution of each mechanism to cause fractures. In this paper we present new experimental and numerical evidence regarding how a compressive shock wave causes radial fractures in rock.

Detonation of a contained explosive charge produces high heat and high-density gases. The velocity of detonation is proportional to the amount of energy released and the pressure rise time, both of which are governed by chemical properties, density of the solid explosive, the size of the charge, and the confinement of the charge. Typical explosives used for breaking rock exhibit velocities of detonations that range from around 3000 m/s to 8000 m/s with corresponding bulk densities of 0.80 g/cm$^3$ to 1.6 g/cm$^3$, respectively [4]. Pressure rise times are on the order of microseconds with peak pressures exerted on the rock of ¼ to ½ of the detonation pressure depending on coupling with the surrounding rock [1] with detonation pressures on the order of 5 to 20 GPa varying based on the explosive composition.

During detonation of a charge confined in rock, the nearly instantaneous pressure-rise causes outward radial displacement of the rock and initiates a compressive shock wave that propagates into the surrounding rock. At distances close to the charge, compressive stresses are much greater than the compressive strength of the surrounding rock and significant amounts of the energy are lost as the rock surrounding the charge is crushed. Crushed zone extents are typically on the order of 1 to 2 borehole diameters. Outside of the crushed zone, the shock wave amplitude is less than the compressive strength of the rock but radial fractures develop and often extend significant distances past the crushed zone. Figure 1 illustrates representative crushing and fracturing around a borehole under the action of explosives in a rock mass. Spencer et al. (1970) [5] proposed an empirical cube-root scaling of the explosive weight to predict fracture distances that results in lengths on the order of 10 borehole diameters. However, the influence of the shock wave on the development of radial fractures has not been well defined. This is important in order to determine a well-proportioned charge for the desired effect. For example, increasing the size of an explosive charge past a given point has been shown not to increase the length of the fractures but to increase the radius of the crushed zone [1].

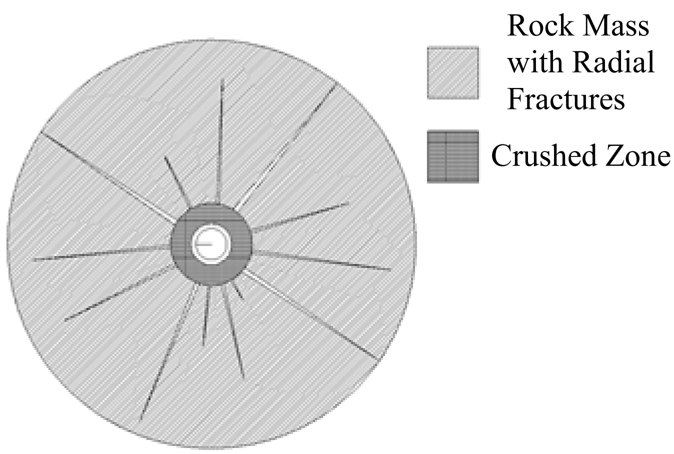


Fig 1. Plan view of damage zones in a rock mass under the action of explosives

Kutter and Fairhurst [1] and McHugh [2] demonstrate experimentally and theoretically that radial fractures are developed by both the shock wave and expanding gases. McHugh provides evidence that gas pressures increase crack lengths by a factor of 5 to 10 times that of fractures caused by the compressive shock wave alone. Kutter and Fairhurst conclude that the shock wave is necessary to precondition the rock in order that the expanding gases can extend cracks but that gas pressure alone without a precursor shock wave will not create significant radial cracking. The research shown in [1] and [2] has identified the tangential or hoop stress component of the shock wave causes radial fractures when gas pressures are not present. The tangential component of the stress wave, however, is coincident to the shock wave and most fracture propagation velocities are much less than the velocity of the shock wave. We provide experimental results that show the location of propagating crack tips trails significantly behind the shock wave in 39 cm Plexiglas cubes and use finite element analysis to evaluate the stress state in which these cracks grow.

Banadaki and Mohanti [3] provide experimental and numerical simulations aimed at predicting fracturing in Barre Granite under the action of explosives with a focus on the effects of the shock wave alone. Their research presents an experimental method for determining input parameters for the Johnson-Holmquist [6] model and validates the numerical model by qualitative comparison of experimental and numerical results. In this paper, we use the parameter values determined by Banadaki and Mohanti for the Johnson-Holmquist strength and failure models to study the location of the shock wave relative to the location of the crack tips. We find that in both the numerical simulations and experimental results, the location of the crack tip trails behind the compressive shock wave by a significant distance. To the author's best knowledge, this is the first time the relative locations of the crack tip and shock wave have been shown. These results provide further evidence regarding the mechanisms that are creating radial fractures.

Figure 2 illustrates the differences between the mechanism developed in [1] and [2] (left-hand-side) and the new mechanism developed by the authors of this study (right-hand-side). The left-hand-side of Figure 2 shows a shock wave at t and t+ε seconds after detonation of the charge. Two adjacent square-shaped particles are shown below the charge before (blue) and after (red) the shock wave passes. The fracture is shown to trail immediately behind the shock wave because hoop stresses are coincident to the location of the shock wave. The right-hand-side of Figure 2 illustrates the mechanism proposed in this study: the outward movement of particles in all directions creates a tensile zone behind the shock wave and the crack tip occurs at a significant distance from the shock wave.

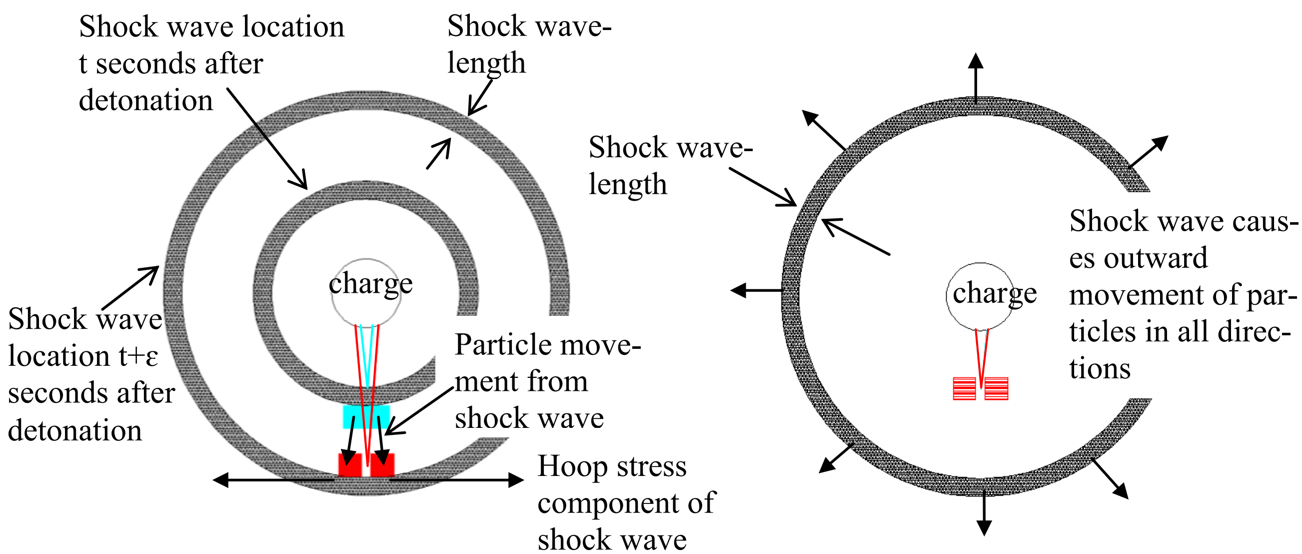


Fig 2. Crack tip location relative to shock wave location.

## EXPERIMENTS

Blast experiments were conducted in 39 cm Plexiglas cubes by drilling a hole and then inserting an exploding bridge-wire detonator and placing epoxy around the detonator to secure the charge in place and prevent venting of the expanding gases. Figure 3 illustrates that the location of the crack tips trail the shock wave by about 50 mm. Distortion of the fudicial grid behind the Plexiglas cube indicates the location of the shock wave. This image shows for the first time the location of the crack-tips relative to the location of the shock wave.

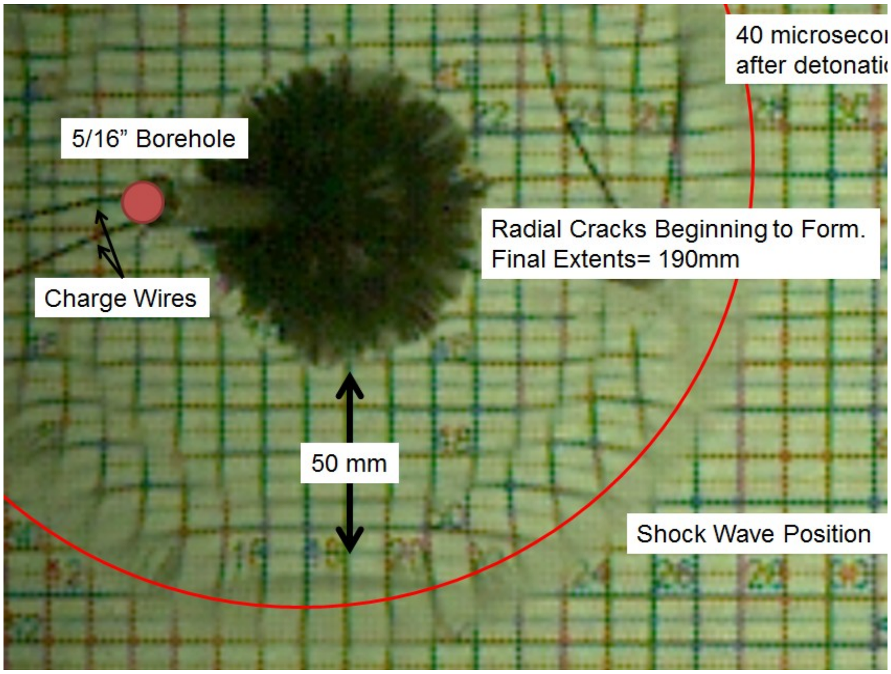


Fig. 3 Shock wave location vs. crack tip location in 39 cm cube of tranparent Plexiglas

**NUMERICAL MODELS**

We use ANSYS AUTODYN to develop and evaluate an explicit Eularian-Lagrangian 2D plane strain finite element model. To model the blast, we use the AUTODYN library defaults for the Jones Wilkens Lee (JWL) equation of state. To model the rock, we use the parameter values developed by Banadaki and Mohanti [3] for a polynomial equation of state and Johnson-Holmquist strength and failure models for Barre Granite. Figure 4 illustrates the circular pressure (kPa) contours 308 microseconds after detonation of a 25 mm diameter charge surrounded by Barre Granite. The fractures in the image are approximately half the final fracture length and are during shock wave propagation away from the center of the circular contours. The darker blue colored contours inside the shock wave demonstrate a trailing tensile zone in which fractures grow.

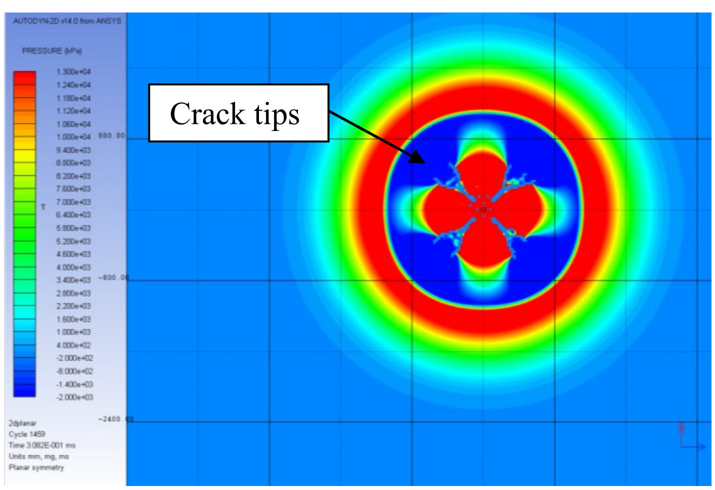


Fig. 7 Pressure contours 308 microseconds after detonation

## CONCLUSIONS

In this paper, we present experimental and numerical results that demonstrate that cracks propagate behind the compressive shock wave. We show new evidence from blast experiments in Plexiglas and numerical models of rock that further the current understanding of how a compressive shock wave creates tensile stresses to fracture rock. Overall, this evidence can be used to advance numerical models that predict fracturing under the action of shock waves and lead to further investigations to determine the relative influences of shock wave and expanding gases on fracturing.

This paper presents evidence that indicates that the radial fracturing is partially caused by a tensile field inside of the shock wave which is the result of radial movement of particles outward from the borehole. This mechanism of causing radial fractures is different than that identified by others, which identified the tangential component of the shock to cause radial fracturing. This study also validates the Johnson-Holmquist model by showing that the location of the crack tips trail behind the shock wave in both the experimental and numerical results.

## REFERENCES


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