

# Simultaneous Multiple-Jet Impacts in Concrete – Experiments and Advanced Computational Simulations

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The simultaneous impact of multiple shaped-charge jets on a concrete target has been observed experimentally to lead to the formation of a larger and deeper entrance crater than would be expected from the superposition of the craters of the individual jets. The problem has been modeled with the 3-D simulation code ALE3D, running on massively parallel processors. These calculations indicate that the enlarged damage area is the result of tensile stresses caused by the interactions among the pressure waves simultaneously emanating from the three impact sites. This phenomenon has the potential for enhancing the penetration of a follow-on projectile.

## INTRODUCTION

A new generation of advanced computational facilities and codes is now becoming available in the U.S. DOE laboratories, leading to capabilities for three-dimensional (3-D) continuum mechanics simulations with the type of resolution previously achieved only in 2-D. An example of such a simulation is the simultaneous impact of multiple shaped-charge jets on a concrete target. The interaction of the overlapping pressure waves from the multiple jets can lead to the formation of a larger and deeper entrance crater than would be expected from the superposition of the craters of the individual jets. This phenomenon has the potential for enhancing the penetration of a follow-on projectile, and there is a need to understand it from a calculational point of view.

An experiment was conducted in which a triangular array of three 66-mm Viper shaped charges was fired into a large cylindrical concrete target, creating a multiple-jet entrance crater. Down to a depth of about 100 mm, the craters from the three

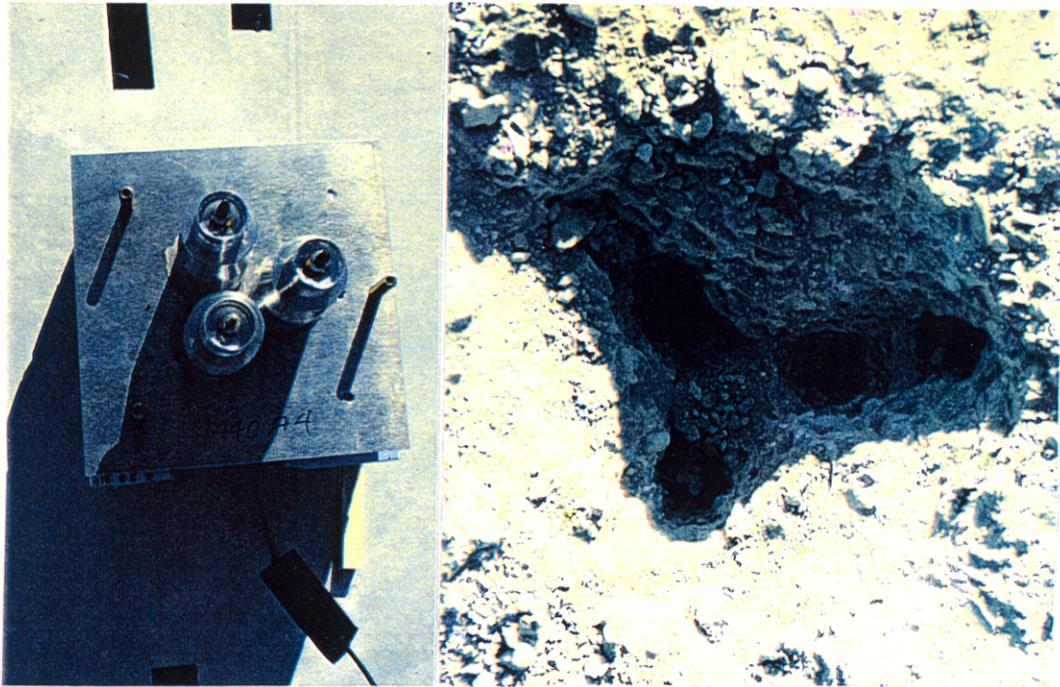


FIGURE 1. Photos of (a) Viper array on top of concrete target and (b) resulting “Y”-shaped crater.

jets merged into one common crater with an extended “Y” shape and straight sides (Figure 1). The branches of the Y extended about twice as far from the center of the array as the jet holes. Below this depth, the three individual jet tunnels were seen. In follow-on experiments, steel projectiles were launched at the multiple-impact target and at comparison targets. In the multiple-impact target, penetration was increased by an amount corresponding to the depth of the Y-shaped entrance crater.

The problem has been modeled with the 2-D continuum mechanics simulation code CALE [1] and with the 3-D simulation code ALE3D [2], which can achieve relatively high resolution by running on massively parallel processors. The calculations with both codes indicate that the enlarged damage area results from tensile stresses caused by the interactions among the pressure waves simultaneously emanating from the three impact sites.

In the following sections, the experiments will be described, and the results of the calculations will be presented.

## EXPERIMENTS

The target-conditioning experiment was done in May, 1996. This experiment used a triangular array of three 66-mm Viper shaped charges, spaced 77 mm apart, placed at a standoff distance of 198 mm, and aimed inward at an angle of  $1.67^\circ$ . These were fired simultaneously into a 1.5-m diameter, 1.2-m high, concrete cylin-

der, creating a multiple-jet entrance crater (see Figure 1). Down to a depth of approximately 100 mm, the craters from the three jets merged into one common crater with an extended Y shape. The branches of the Y extended about twice as far from the center of the array as the jet holes. Below this depth, the three individual jet tunnels were seen. It should be noted that the entrance crater is not just the typical 45°-angle cone. Within this cone is a straight-sided tunnel, with a Y-shaped cross section in the case of this three-Viper experiment. It is this empty tunnel that results in a gain in penetration, provided that its effective diameter is large enough to accept a following projectile.

In follow-on experiments in November 1997, 70-mm diameter steel projectiles with ogive noses were launched at comparison targets and at the preconditioned multiple-impact target. In the preconditioned target, penetration was increased by an amount corresponding to the depth of the Y-shaped entrance crater. Below this crater, the tip of the projectile encountered essentially undamaged concrete, and the small damage area surrounding each separate jet tunnel was found to provide only a small increment in penetrability.

## CALCULATIONS

The tensile stress patterns that lead to crater enlargement have been investigated with the Lawrence Livermore National Laboratory continuum mechanics simulation codes CALE and ALE3D. Both the 2-D CALE code and the 3-D ALE3D code use Arbitrary Lagrangian-Eulerian (ALE) meshes. With both codes, a single impact site with three-fold symmetry was used to model the experiment.

The CALE calculation may be somewhat easier to interpret. It was done in planar geometry at a depth of 50 mm in the target. The jet impact is modeled as an expanding ring of hot copper, since at each level in the target the collision with the target material causes the jet material to turn from moving axially to moving radially. The results are shown in Figure 2 for a time of 200  $\mu$ s. The interaction of the expanding pressure waves emanating from the three jet locations produces tensile stresses in certain locations, such as on either side of each symmetry plane and at the center of the three impact sites.

The cavity around each jet continues to grow until the compression of the concrete has absorbed the kinetic energy of the expanding jet material. The concrete then rebounds, but in this case the contraction is asymmetrical, owing to refraction and reflection of the waves from the three expanding jets.

Because of this asymmetrical contraction, it is found that along a line from the center of the array through a jet location a portion of the cavity wall moves inward. There is even a tendency for jetting to occur on the sides of the hole on the opposite side from the center of the impact pattern. This is similar to the jetting that occurs in the collapse of cavitation bubbles in water next to a wall or next to a propeller

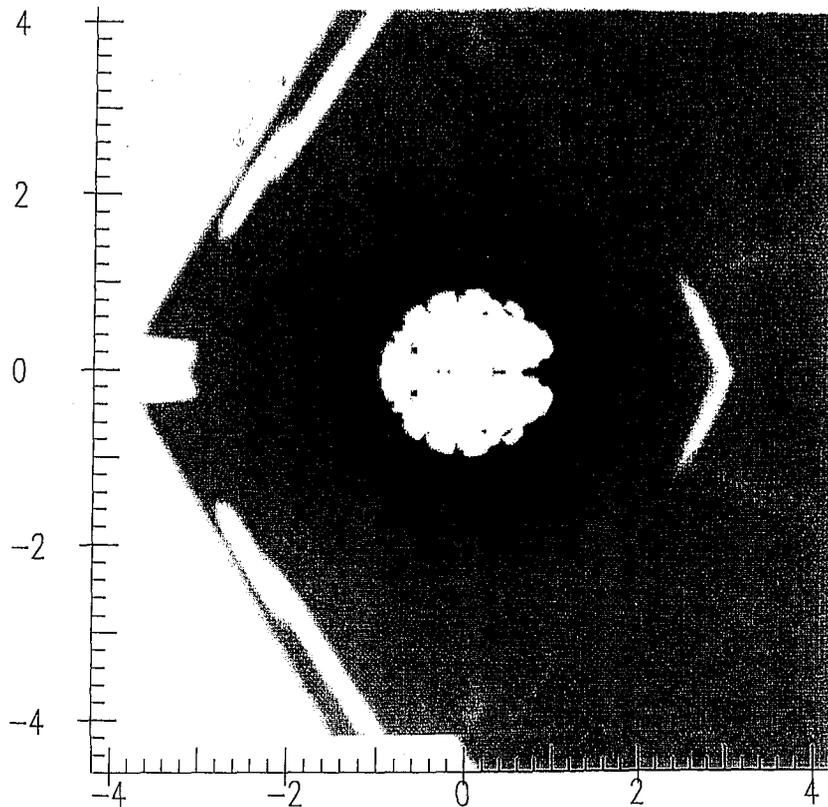


FIGURE 2. Density plot (from 2.0 to 2.5 g/cm<sup>3</sup>) at 200  $\mu$ s of CALE calculation showing damage produced by simultaneous impacts in an x-y plane at depth  $z = 50$  mm; symmetry planes at  $y = 0$  and at  $60^\circ$  (dimensions in cm).

blade. The result is the formation of a tensile crack at about  $1.75\times$  the jet spacing, which is interpreted as giving rise to the Y-shaped pattern seen in the experiment.

The ALE3D calculation models the oblique impact in three-fold symmetry of a stretching Viper jet at an angle of  $1.67^\circ$  and an off-set from the center of 39 mm. As the calculation proceeds, the jet pushes into the target. The penetration is followed until 200  $\mu$ s (Figure 3). In this calculation, the jet material is enlarging the hole in the axial as well as the radial direction, in accordance with conservation of momentum. The entrance hole begins to narrow at a depth of 90-100 mm, in response to the mass distribution of the incoming jet. This corresponds to the end of the enlarged tip section that is characteristic of the Viper shaped-charge jet. This is regarded as indicating the bottom of the Y-shaped entrance hole, as in the experiment. A slice is taken at a depth of 50 mm (Figure 4), which corresponds to the depth of the CALE planar calculation. The diameter of the crater is about 16 mm, which agrees with the planar calculation. The damage pattern is in reasonable agreement with that seen in the planar calculation. In particular, a damaged region is found beyond the jet location, at about 100-120 mm along the y-axis. As in the CALE cal-

## RESULTS AND CONCLUSIONS

In an experiment done with an array of three Viper shaped charges, the effect of simultaneous passage of the jets through each successive increment of depth in the top 100 mm of the entrance crater caused more damage than would have been produced by the overlap of individual craters.

The effect has been modeled with the Arbitrary Lagrangian-Eulerian codes CALE (2-D) and ALE3D (3-D). In the CALE calculations, a planar slice was taken through the crater, and the impacts were modeled by expansion of jet material against the walls of the holes.

In the ALE3D calculations, similar resolution was achieved in 3-D as in 2-D, which resulted from the application of massively parallel processors (typically 30-300). With the new capability, not only are the planar stresses developed directly from the jet impacts, but also the axial momentum transfer and the interaction with the free surface are modeled. Fine zoning has been found to be essential for understanding the key phenomena. These involve asymmetries in the rebound of the individual jet crater walls under the influence of the reflected and refracted multiple-impact pressure waves. These calculations indicate that the enlarged Y-shaped damage area is the result of tensile stresses caused by the interactions among the pressure waves simultaneously emanating from the three impact sites. This phenomenon is considered to have the potential for enhancing the penetration of follow-on projectiles.

## ACKNOWLEDGEMENTS

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1. Tipton, Robert E. 1998. "CALE Users Manual", private communication.
2. Dube, Eveline I., J. Robert Neely, Albert L. Nichols, Richard W. Sharp, and Richard G. Couch. 1999. "Users Manual for ALE3D", private communication.

ulation, this is expected to develop eventually into a Y-shaped entrance crater corresponding to the phenomenon observed in the experiment.

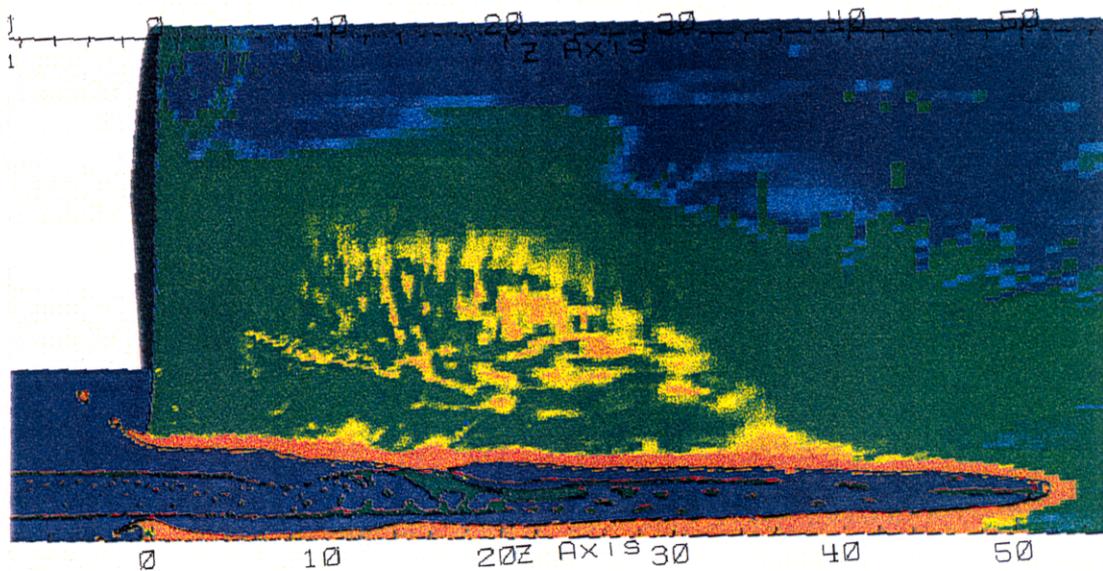


FIGURE 3. ALE3D calculation showing damage pattern from stretching Viper jet impacting concrete target at angle of  $1.67^\circ$  and 39 mm from center, three-fold symmetry, at  $t = 200 \mu\text{s}$  (dimensions in cm).

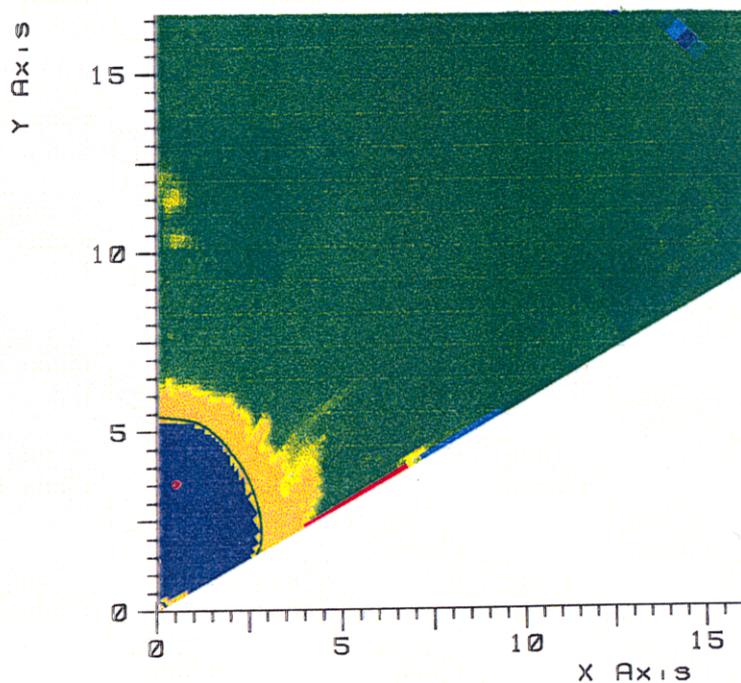


FIGURE 4. Damage pattern in ALE3D calculation in x-y plane at  $z = 50 \text{ mm}$  at  $t = 200 \mu\text{s}$  (dimensions in cm).