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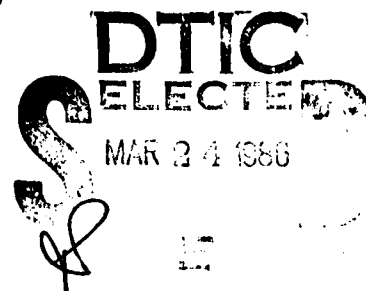
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CONTACT SURFACE EROSION
FOR HYPERVELOCITY PROBLEMS

Kent D. Kimsey
Jonas A. Zukas

February 1986

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CONT
of the computational grid leading to large truncation errors or minuscule temporal integration increments resulting in uneconomical computations. The contact surface erosion algorithm outlined in this paper permits sliding interfaces to be dynamically relocated as materials exceed their load-bearing capability without a prior specification of the damage region. Results obtained with EPIC-2 into which this algorithm has been incorporated show good agreement with experimental data for deep penetration situations as well as for finite plate perforations at striking velocities of 1.1 - 3.75 km/s. *Revised*

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I. INTRODUCTION

The mechanics of penetration and perforation of solids has long been of interest for military applications and is currently being applied to a number of industrial applications such as the integrity of nuclear reactor pressure vessels, crashworthiness of vehicles, protection of spacecraft from meteoroid impact, and explosive forming and welding of metals.

Impacts at velocities in excess of 1 km/s excite the high frequency modes of the colliding solids. The response is confined to a localized region (typically 2 to 3 projectile diameters) and is characterized by the presence of shock waves and high hydrodynamic pressures which, on contact, can exceed the material strength by an order of magnitude. For ordnance velocity impacts (1-3 km/s) the pressures decay rapidly due to the presence of free surfaces and the effects of material strength and, except at the interface, oscillate at values comparable to the material strength. Under hypervelocity conditions (4-12 km/s), hydrodynamic pressure dominates the behavior of the solids for the bulk of the penetration process. Material strength effects become significant only in the very late stages of the process. Superimposed on these is extensive plastic deformation, large localized heating and material failure due to a number of mechanisms (i.e., petalling, spall, adiabatic shear). The failure mechanism(s) activated depend on geometry, loading history and material constitution. Strain rates of 10^5 s^{-1} at the impact interface and $10^2 - 10^3 \text{ s}^{-1}$ elsewhere are not uncommon. Penetration and perforation are formidable physical problems and it is not surprising that the bulk of the research in this area has been experimental in nature.

A complete mathematical description of the dynamics of impacting solids must account for the geometry of the interacting bodies; elastic, plastic, and shock wave propagation; hydrodynamic flow, finite strains and deformations; thermal and frictional effects, and the initiation and propagation of failure in the colliding solids. During the past decade, rapid progress has been achieved in computational penetration mechanics.¹ Today, two- and three-dimensional simulations of high velocity impact phenomena, are routinely performed in conjunction with experimental studies in terminal ballistics.

Numerical simulation of penetration phenomena can be performed with both Lagrangian (mass reference) and Eulerian (laboratory reference) descriptions. In the laboratory reference scheme, the computational mesh remains stationary with material being transported through it based on velocity gradients present in the flow field. Such a description is ideally suited for modeling severe material deformations that occur in hypervelocity impacts, explosive-metal interactions and the penetration of thick targets (i.e., situations wherein the ratio of target thickness to penetrator diameter, t/D , exceeds 3). In the mass reference description the computational mesh is fixed in the material and distorts with it in accordance with applied loads. The Lagrangian approach offers the advantages of being conceptually straightforward (due to the lack of convective terms to represent mass flow) and permitting material boundaries to be delineated without ambiguity. However, irregular mesh shapes arising from severe material deformations lead to inaccuracies in the numerical approximation which can grow to unacceptable levels. In addition, since

almost all Lagrangian wave propagation codes use explicit temporal integration schemes (in which the maximum time step is limited to satisfy a stability condition), violent distortion of the computational mesh leads to a reduction of the time step to such a low value that continuing the calculation becomes economically prohibitive. These problems can be overcome through the use of rezoning, coupled Lagrangian-Eulerian descriptions, and contact surface erosion algorithms.

In rezoning, a new Lagrange computational mesh is overlaid on the old one and a rezone algorithm maps mesh quantities of the severely distorted mesh onto the new mesh such that conservation of mass, momentum, total energy and the constitutive relationship are satisfied. Rezoning can be a costly and nontrivial process. For very thick target penetration studies (plate thickness to projectile diameter ratios greater than 10) 30 to 50 rezones are not uncommon. Frequent rezoning renders the computational mesh semi-Eulerian in that large distortions are realized but material history and location of material boundaries are diffused.

Many impact situations are not simulated very well with Lagrangian or Eulerian descriptions alone (i.e., fluid-structure interaction problems). Coupling methodologies for combining Lagrangian and Eulerian descriptions exploit the respective advantages of each. In general, the Eulerian portion of the computational mesh behaves as a pressure boundary acting on the Lagrangian regions, while the Lagrangian regions represent obstacles in the Eulerian flow field. This technique does not circumvent the possibility of excessive diffusion of material history. While cumbersome and time-consuming logic for abating diffusion of material interfaces and histories have been demonstrated, the computational penalties for such logic are high.

A most promising technique to extend the capability of Lagrangian codes to deep penetration and spaced plate perforation problems is the concept of contact surface erosion. The Lagrangian codes developed in the seventies required that the contact surface or sliding interface specified at the beginning of the problem remain unchanged throughout. This requirement was imposed not from physical considerations but to simplify the interface logic. Its effect was to prohibit total failure of material dictated by the physical problem, resulting in either unrealistic distortions of the computational mesh leading to large truncation errors or to temporal integration increments which render further computation uneconomical.

The eroding contact surface concept has been under active investigation at a number of centers since 1978 and is now finding its way into production codes. The most comprehensive treatment is to be found in the DYSMAS/L code developed by Massmann, Poth and their associates at Industrieanlagen-Betriebsgesellschaft mbH (Ottobrun, W. Germany). The contact processor in

DYSMAS/L²⁻⁴ is based on a generalized master-slave concept. Structural surfaces which are to be controlled by the contact processor are defined as master planes and slave points. Both master surface erosion and internal cracking can be treated. In the case of element separation (crack opening) the separated nodal masses of the affected elements are designated as slave points to permit calculation of momentum exchange in case of further contact. Redefinition of the contact surface in case of erosion or cracking is treated automatically, requiring no user intervention.

Methods for dynamic redefinition of sliding interfaces in the presence of total element failure have also been developed by Johnson.^{5 6} The earlier approach, implemented in the EPIC-3⁵ code, had several limitations and restrictions (i.e., only obliquities of 45° or less could be treated and users had to specify a priori the extent of target damage) and has not been used extensively. Many of these have been removed from the techniques now used in current versions of EPIC-2 and EPIC-3. Snow⁷ implemented logic to dynamically redefine the master surface as element failure occurs in the EPIC-2 code. The approach retained the requirement in the original version of the code that the master surface remain continuous and employed an asymmetric interface treatment. Most recently Belytschko⁸ has introduced eroding contact surface concepts into the EPIC-3 code, making use of eight node hexahedral elements and hourglass viscosity to stabilize spurious deformation modes caused by one point integration.

II. CONTACT SURFACE EROSION FOR LAGRANGIAN COMPUTATIONS

Contact surfaces or sliding interfaces are appropriate in situations where large relative motions can be expected at material boundaries. Situations involving the interactions of gases and fluids with solid walls, the penetration of targets by projectiles, and contact between colliding bodies require the use of sliding interfaces. They prove useful also in regions where large shears or fractures develop. Most sliding interface methods are based on the decomposition of acceleration and velocity into components normal and tangential to the interface. Motions in the normal direction are continuous when materials are in contact but independent when they are separated. Tangential motions are independent when materials are separated or the interface is frictionless but are modified if there is contact and a frictional force is present. Materials on either side of an interface may separate if a user-specified criterion is exceeded or if materials are in tension, and may collide again if previously separated. A comprehensive discussion of sliding interface treatments is given by Hallquist.^{9 10}

The sliding interface algorithm in the EPIC-2 code⁷ has been restructured to simulate contact surface erosion during impact. Initially, a series of nodes lying on the interface are identified and labelled as either master or slave nodes. In the method employed here, a set of nodal points that define element edges or segments which have both nodes declared to be master nodes define unique master segments of the master surface on which slave nodes are not permitted to intrude. These master segments are not required to define the master surface in a continuous manner. When penetration of a slave node through the master surface occurs, the velocities of the master and slave nodes are adjusted to conserve angular and linear momentum as described in reference 11. Once the intrusions are removed, the designation of master and slave is interchanged and the procedure is repeated. Each temporal integration increment is comprised of the following steps:

1. Determine master segments, on one side of the interface, that circumscribes elements which have not exceeded the user specified failure criterion.

2. For each slave node, find the master segments which encompass the slave node within the search radius R which is ~ 0.6 of the length of the segment.

3. Once all segments associated with a given slave node have been located, determine if penetration of the segment has occurred. If only one segment is penetrated, proceed with steps 4-7. If penetration of more than one segment is indicated by the above check, a decision must be made as to the master segment to which the slave node is to be moved. In the current procedure, the normal projection of the slave node onto each candidate segment is computed. The slave node is then repositioned onto the master segment that results in the minimum change to its kinetic energy. Note that the maximum kinetic energy permitted by physical laws is the kinetic energy for unobstructed (i.e. nonintruding) slave node travel. This condition serves as an effective discriminant in selecting the appropriate master segment for relocation of the slave node.

4. If there is intrusion, position the slave node on the master segment in a direction normal to the segment.

5. Update master and slave node velocities to conserve linear and angular momentum.

6. Update nodal forces to account for change in nodal velocities.

7. At the option of the code user, interchange master and slave designations and repeat steps 1-6.

III. FINITE PLATE PERFORATION

Figure 1 shows results for the perforation of a 2.54cm armor steel plate by a 65 gram, hemispherically-nosed S-7 tool steel rod with a striking velocity of 1103 m/s. Figure 2 shows similar results for a plane strain simulation at an obliquity of 60° and a striking velocity of 1647 m/s. Table 1 shows a comparison of computed residual masses and velocities with those obtained experimentally by Lambert¹² from radiographic data. The agreement is quite good for the normal impact case. The higher residual mass and velocity for the oblique impact case is characteristic of plane strain analyses due to differences in energy-displacement relationships for exact and plane strain formulation of computational elements.¹³

IV. PENETRATION OF SEMI-INFINITE TARGETS

A number of calculations with effectively semi-infinite targets struck by long rods ($L/D = 10$) at velocities of 1550, 2560, 3114, and 3750 m/s were also performed and compared with experimental data published by Hohler and Stimp.¹⁴ The rods were made of C110W2 steel, had a diameter, D , of 0.43cm, length, L , of 4.3cm and density of 7.85 g/cc. The target material was Hzb20 armor steel. In both calculations and experiments, the projectile was totally consumed. Also in both cases, the target thickness was at least twice the expected penetration depth. Figure 3 summarizes the initial conditions.

**PENETRATION SEQUENCE FOR
AXISYMMETRIC IMPACT , 1103 M/S**

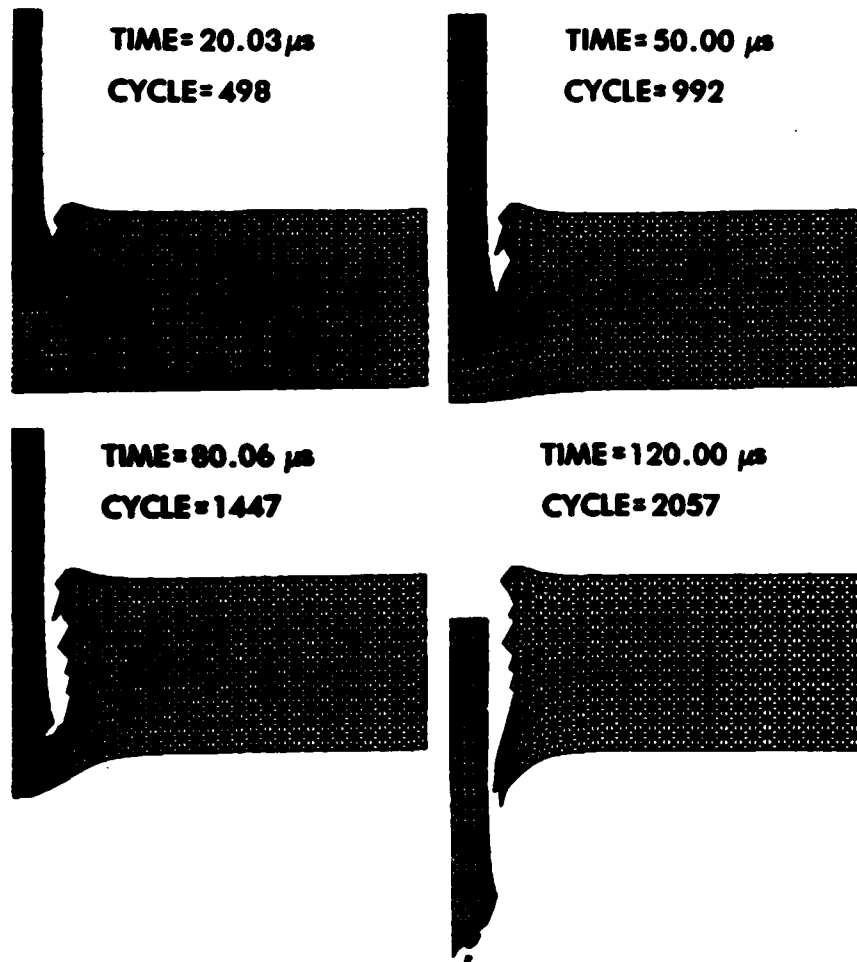


Figure 1. Deformation Profiles for Normal Penetration of Finite Target

**PENETRATION SEQUENCE FOR
60 DEGREE IMPACT , 1647 M/S**

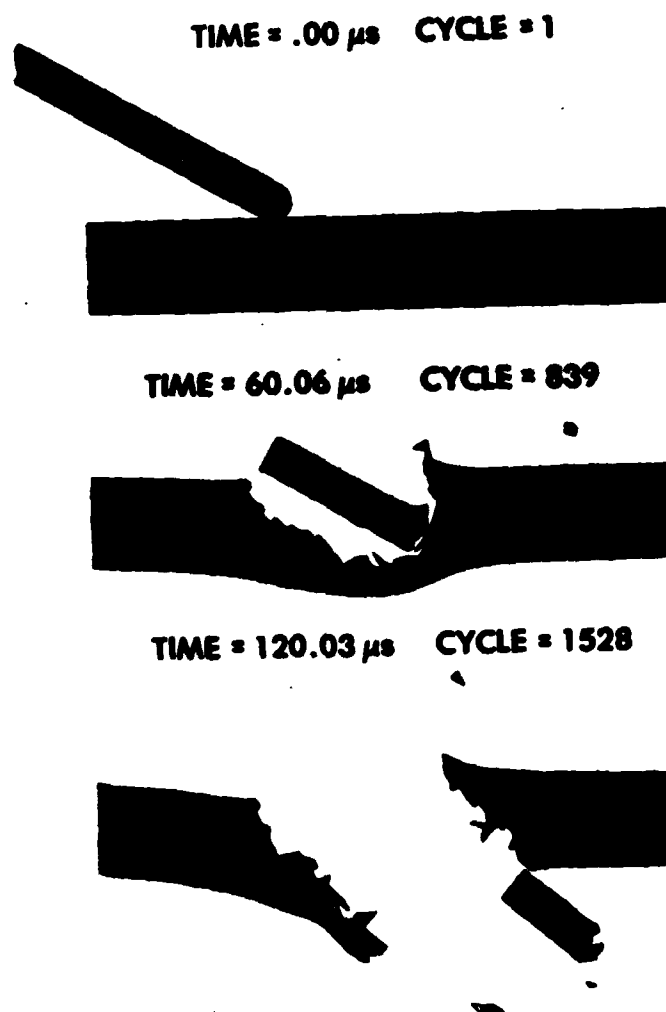


Figure 2. Plane Strain Results for Oblique Perforation of Finite Target

PENETRATION OF SEMI - INFINITE TARGETS

PROJECTILE: C110W2 STEEL

L/D 10

L 4.3 CM

7.85 GRAMS/CC

TARGET: HZB20 ARMOR STEEL

BHN 260 - 330 KP/ SQ. MM

SOUND VELOCITY, C 5950 M/S

Figure 3. Initial Conditions for Semi-infinite Target Penetration Study

Table 1. Results for Finite Target Penetration

CALCULATED AND MEASURED RESIDUAL PARAMETERS

$L/D = 10$ 65 grams $D = 1.0\text{cm}$

θ	$V_s(\text{m/s})$	Residual Velocity (m/s)		Residual Mass (g)	
		Calculated	Measured*	Calculated	Measured*
0°	1219	925	910	34.5	39.1**
0°	1103	709	690	32.1	32.7
60°	1647	1202	1145	22.9	16.8

* Ref: ARBRL - TR - 02072, May 1978

** Estimated from radiograph

Results for the 3114 m/s impact condition are shown in Figures 4-7. Computed normalized penetration depth and crater diameter are compared with data from Hohler and Stilp¹⁴ in Table 2 and Figures 8-10.

The computed values for penetration depth and crater diameter in Table 2a were obtained using the static material properties for projectile and target given in reference 14. Table 2b shows results using high strain rate data for the steel target obtained from Meyer's dissertation¹⁵ with projectile strengths taken from reference 14. Both Table 2 and Figures 8-10 use computed values at the time when the projectile has been totally consumed ($\sim 45 \mu\text{s}$ for $v/c = 0.26$, between 22-30 μs for the remaining cases). Agreement with experimental results is generally good, except for the lowest striking velocity. In this regime, the impact response of materials is very strongly influenced by material strength. Evidently high strain rate data for the projectile material are required here, as well as a better material description (an elastic, perfectly-plastic model was used throughout). As striking velocity increases the influence of material strength decreases and agreement with experiment improves. The rather large overprediction of penetration depth at $v/c = 0.26$ (1550 m/s) using quasi-static ($\sim 10^{-4}/\text{s}$) data clearly suggests that dynamic characterization of materials is a necessary adjunct to impact experiments and code calculations in the ordnance velocity (0.5 - 2 km/s) regime.

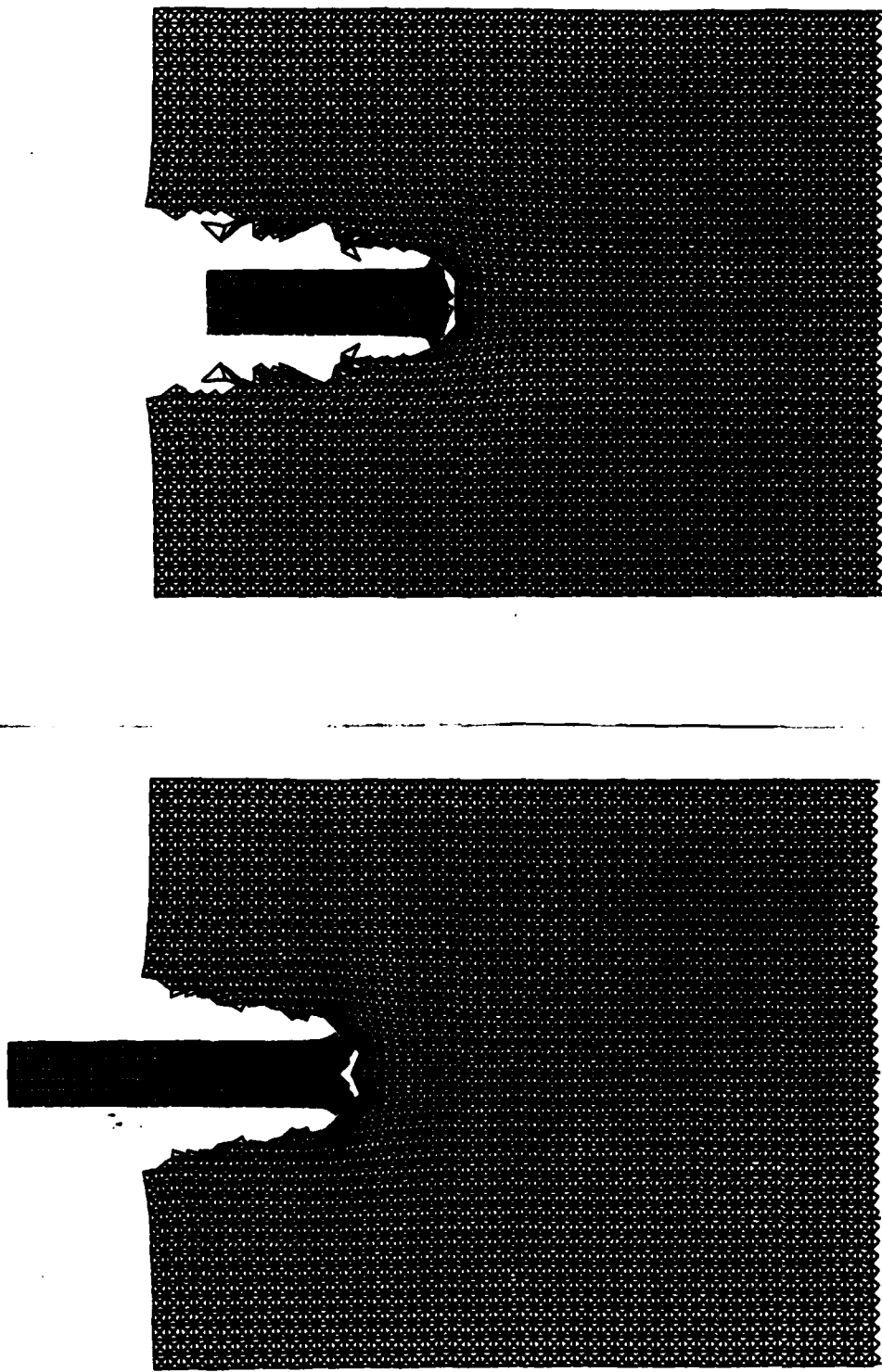


Figure 4. Deformation at 10 and 15 Microseconds after Impact

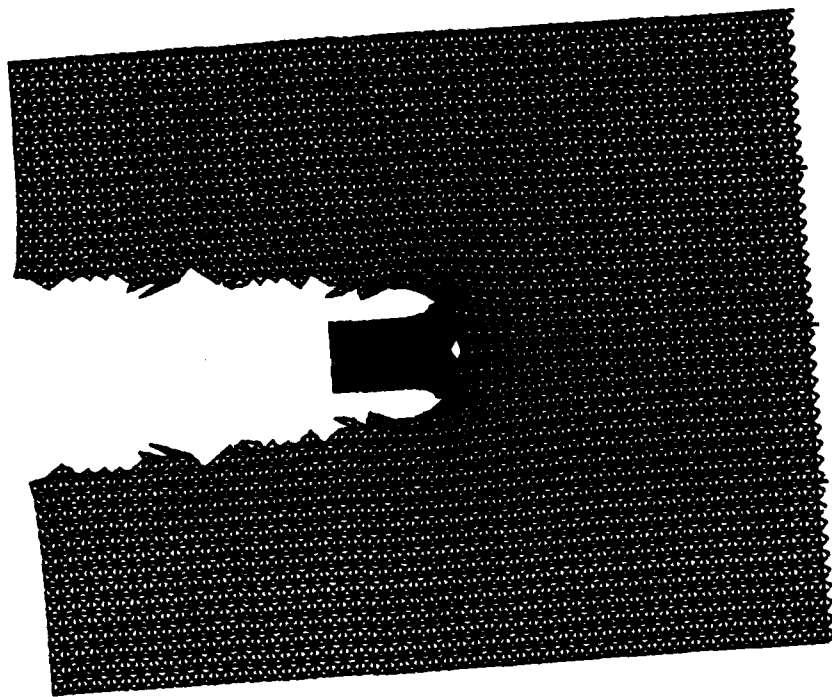
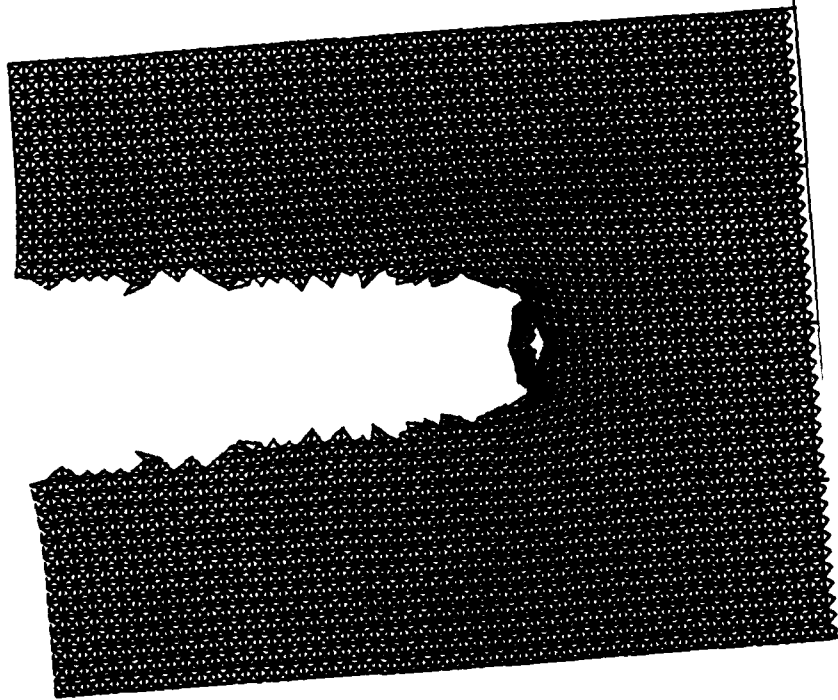
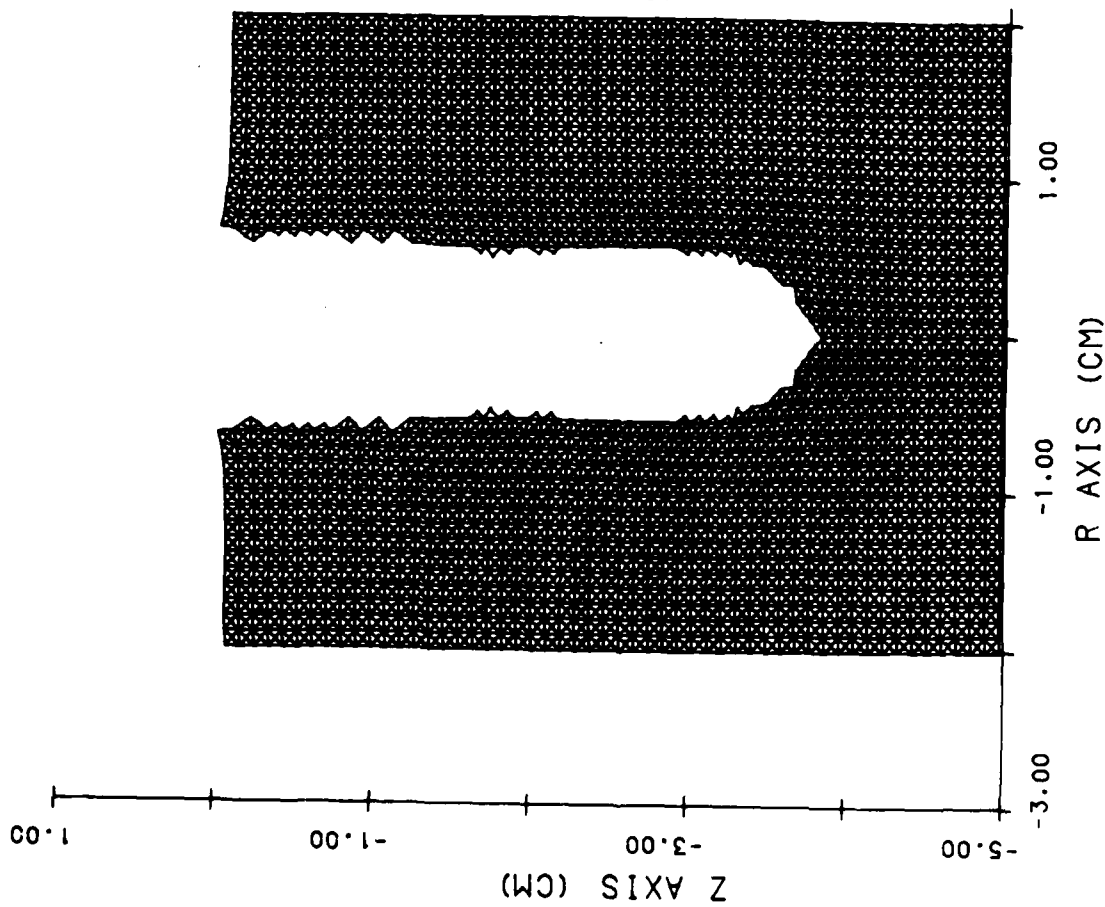


Figure 5. Deformation at 20 and 24 Microseconds after Impact



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Figure 6. Computed (at 100 Microseconds after Impact) and Experimental Hole Profiles

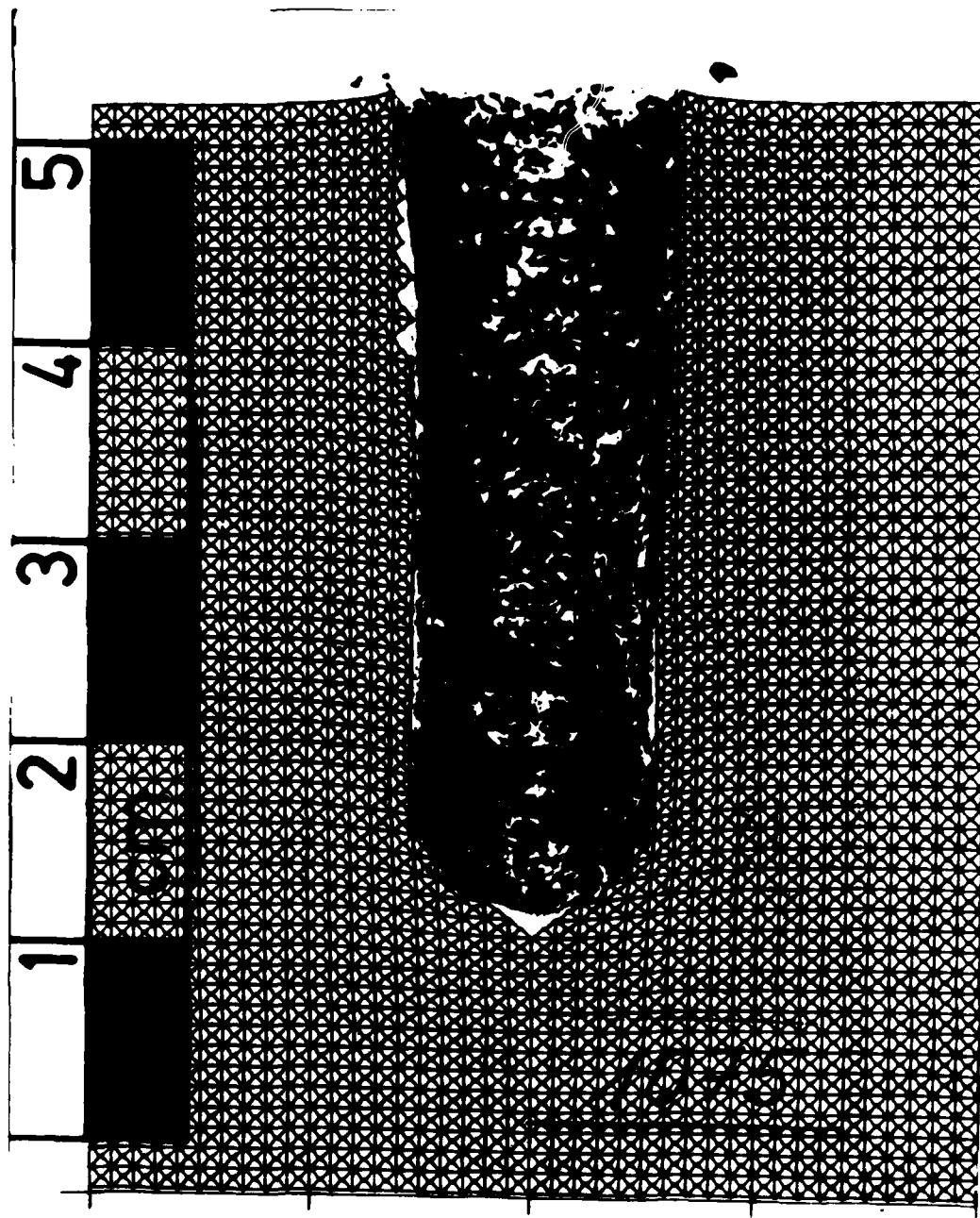


Figure 7. Overlay of Computed and Experimental Hole Profiles, $v_s = 3.114$ km/s

v/c	P/L		P/d		d/D	
	EXP (+0.06)	CODE	EXP (+0.15)	CODE	EXP	CODE
0.26	0.33	0.58	1.5	2.5	2.2	2.3
0.43	0.80	0.86	2.9	3.0	2.7	2.8
0.52	0.90	0.91	3.0	3.0	3.0	3.1
0.63	0.93	0.93	2.7	2.8	3.5	3.3

v/c	P/L		P/d		d/D	
	EXP (+0.06)	CODE	EXP (+0.15)	CODE	EXP	CODE
0.26	0.33	0.40	1.5	1.8	2.2	2.3
0.43	0.80	0.75	2.9	2.9	2.7	2.8
0.52	0.90	0.85	3.0	3.0	3.0	3.0
0.63	0.93	0.88	2.7	2.8	3.5	3.3

Target

H2B20
BHN = 260-330 kp/mm²

21

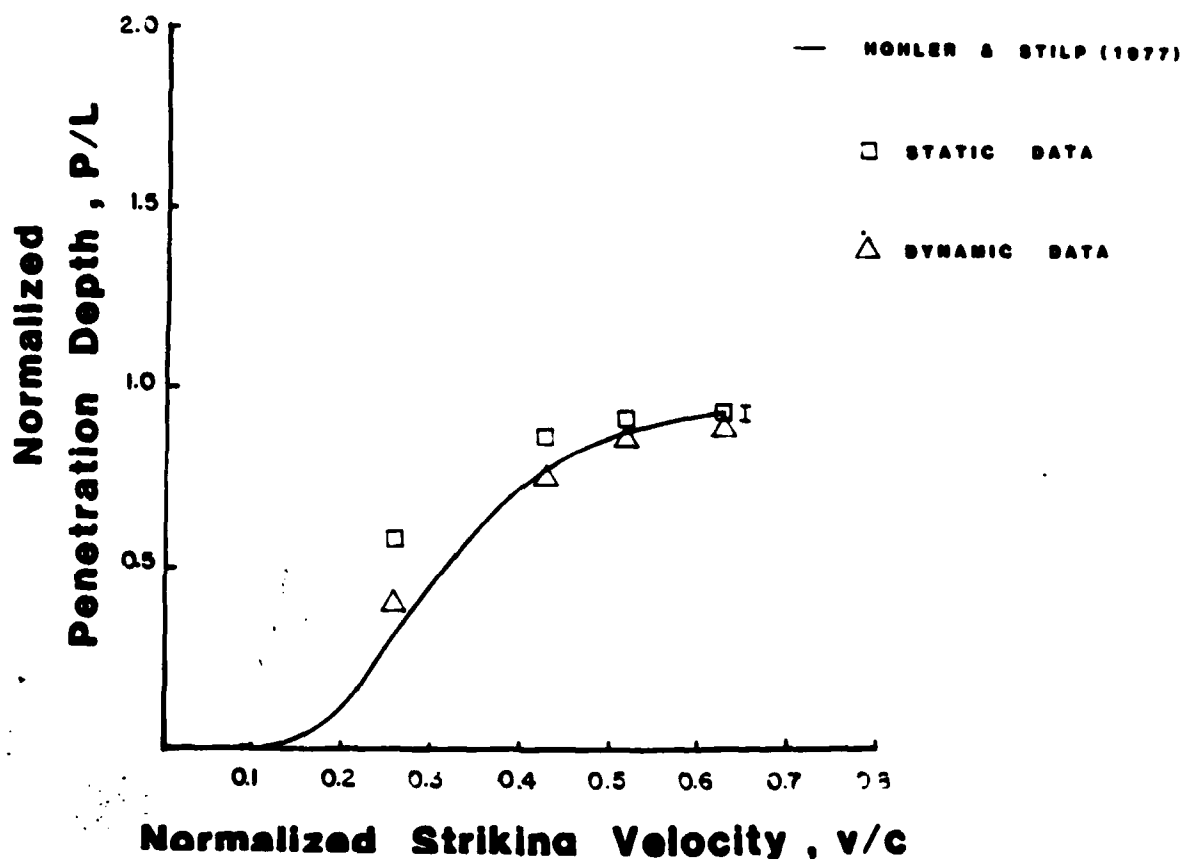


Figure 8. Comparison of Computed and Experimental Normalized Penetration Depth (P/L) vs Normalized Striking Velocity (v/c)

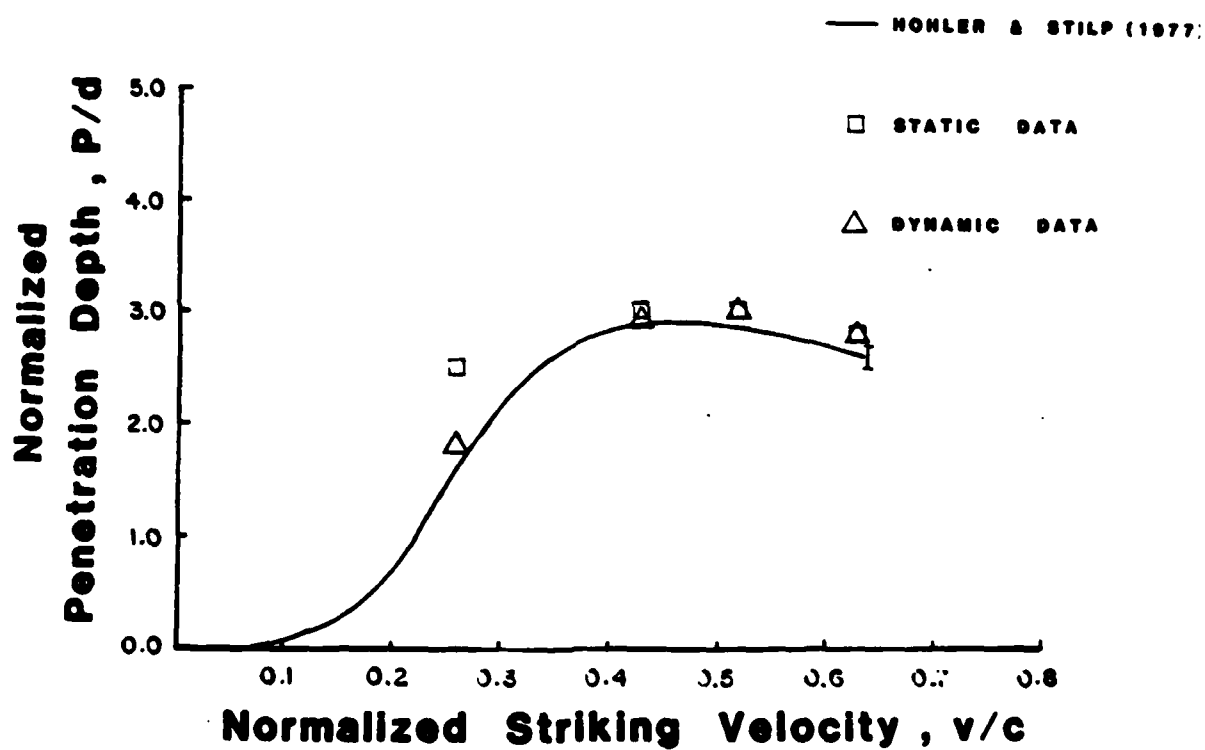


Figure 9. Comparison of Computed and Experimental Normalized Penetration Depth (P/d) vs Normalized Striking Velocity (v/c)

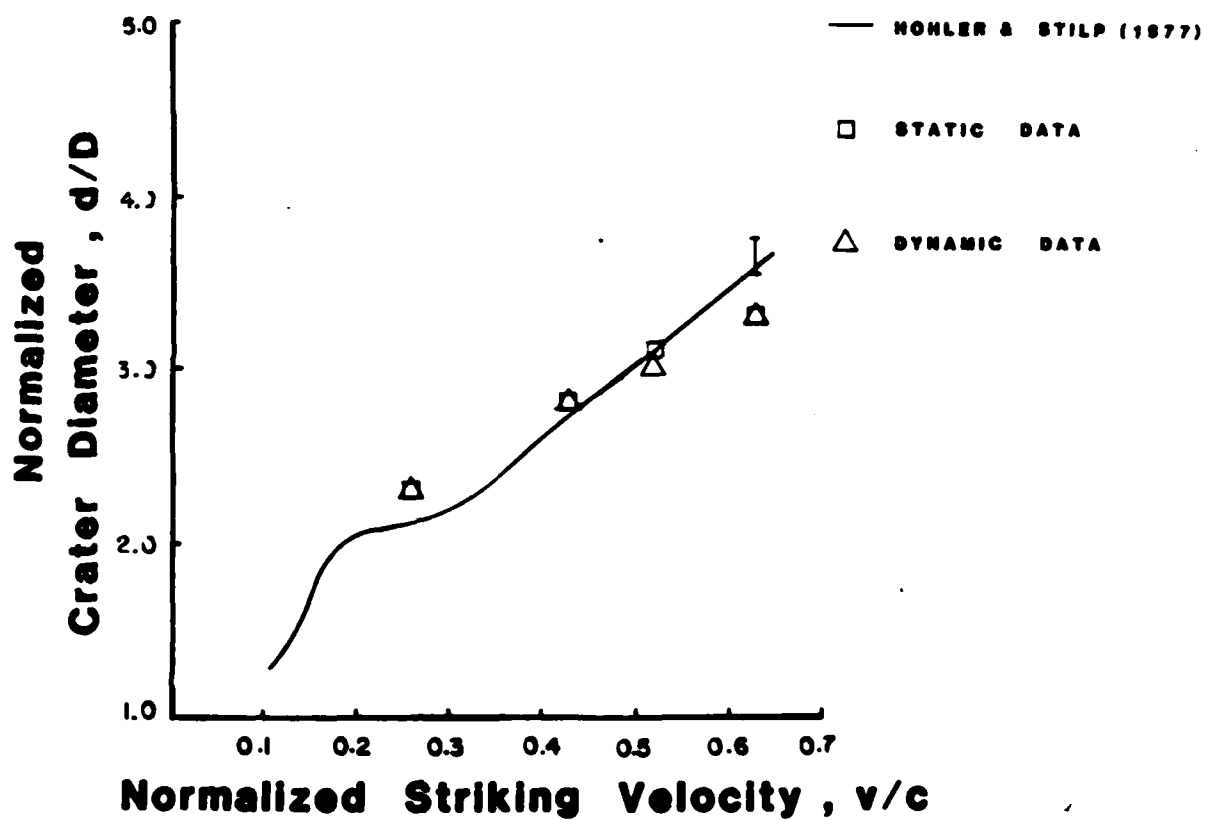


Figure 10. Comparison of Computed and Experimental Normalized Crater Diameter (d/D) vs Normalized Striking Velocity (v/c)

typically occur between 80-100 μ s for all cases studied). The extent of this growth is shown in Table 3 which compares the experimentally measured (non-dimensionalized) penetration depth and hole diameter with those obtained computationally (using data from reference 15 for the target material) at a time when the projectile is totally consumed and also at 100 μ s after impact. Changes in the diameter are negligibly small while hole growth is on the order of 3-5%.

Table 3. Residual Hole Growth

v/c	(P/L) _{t1}	(P/L) _{t2}	(P/L) _{EXP}	(d/D) _{t1}	(d/D) _{t2}	(d/D) _{EXP}
0.26	0.40	0.45	0.33	2.30	2.33	2.3
0.43	0.75	0.80	0.80	2.80	2.80	2.8
0.52	0.85	0.89	0.90	3.0	3.0	3.0
0.63	0.88	0.97	0.93	3.3	3.2	3.3

Note: t_1 = time at which projectile is totally consumed. For v/c of 0.26, 0.43, 0.52 and 0.63. This occurs at 45, 32, 26 and 22 μ s respectively.

t_2 = 100 μ s (time at which stresses & pressures are below target material yield strength).

V. CONCLUSIONS

The simulation of contact surface erosion in Lagrangian analyses of high velocity impacts appears to be a most promising refinement which extends the capabilities of Lagrangian codes for problems involving perforation of solids. The methodology permits simulation of deep penetration which previously was limited to Eulerian codes. Furthermore, the methodology has been demonstrated to yield residual parameters that are in good agreement with experimental data at a considerable reduction in CPU time and memory requirements for a comparable Eulerian analysis.

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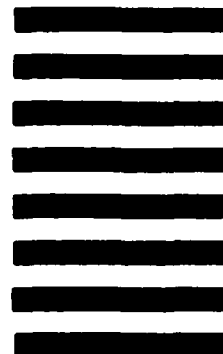


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