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A NUMERICAL INVESTIGATION OF THE RESULTS SCATTER OBTAINED WITH THE DEPTH OF PENETRATION TECHNIQUE

by

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ABSTRACT

A test program recently completed at the Defence Research Establishment Valcartier (DREV) to study the performance of various ceramics using the Depth of Penetration (DOP) method generated a significant scatter in the results. The test results were presented, analysed and discussed in another publication (DREV R-9522). It was not possible to explain the differences in the results obtained for firings performed under very similar conditions by the impact conditions (total yaw angle or impact velocity), nor by differences in the target composition or assembly. Using hydrocode simulations where the ceramic was modelled using the Johnson/Holmquist constitutive model, the scatter in the experimental results was investigated and the analysis is discussed.

RÉSUMÉ

Des essais effectués récemment au Centre de recherches pour la défense Valcartier (CRDV) afin d'étudier les performances de diverses céramiques en utilisant la méthode de profondeur de pénétration résiduelle (PPR) a produit une grande variation dans les résultats. Les résultats des tests ont été présentés, analysés et discutés dans le cadre d'une autre publication (CRDV R-9522). Il n'a pas été possible d'expliquer les grandes différences observées dans les résultats d'essais effectués dans des conditions très similaires, soit par les conditions d'impact (angle total du projectile ou vitesse d'impact), soit par les différences possibles dans la composition ou l'assemblage des cibles. À l'aide de simulations par hydrocode dans lesquelles la céramique a été modélisée à l'aide du modèle de Johnson et Holmquist, on a pu étudier la variabilité des résultats et discuter de l'analyse produite.

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EXECUTIVE SUMMARY

The CF are in the process of acquiring a number of new vehicles for the army, including a reconnaissance vehicle, an armoured personnel carrier (APC) and an armoured combat vehicle (ACV). A key requirement in the specification of these vehicles is their ballistic protection. At the request of the Director Land Requirements (DLR), Defence Research Establishment Valcartier (DREV) undertook an extensive task to study the effectiveness of various materials used in armour systems. The study, called the Armour Effectiveness Investigation (AEI) task, was initiated in 1990 and includes both standard (i.e. metallic) and novel materials, such as polymeric composites and ceramics.

A series of tests performed on ceramics using the residual Depth of Penetration (DOP) method generated a large variation in the results. It was not possible to explain the differences in the results obtained for firings performed under very similar conditions by the total yaw angle at impact, nor by differences in the target composition or assembly. Using hydrocode simulations, where the ceramic was modelled using the Johnson/Holmquist constitutive model, the scatter in the experimental results was investigated; the analysis is also discussed. The hypothesis used to explain the results was that intrinsic variations in the ceramic mechanical properties were the main cause of the large variations observed. By varying the tensile hydrostatic pressure T^*, it was possible to arrive at variations comparable to those of the experimental results.

The results of this investigation will be useful to determine the cause of the variations observed with the DOP method, and will help to establish method standards that will produce more reliable and reproducible results, hence making the evaluation of materials such as ceramics more realistic.

1.0 INTRODUCTION

Ceramics are now a relatively common component to any modern armour system. Their relatively low areal densities required to defeat a given threat make them attractive alternatives to more conventional materials. Ceramics are difficult to characterise, due to their inherent high hardness and brittleness that generally make them capable of withstanding only one impact. Their efficiency is also dependent on the backing material with which they are combined (steel, aluminium, polymeric composites, etc.). One of the most common method used for preliminary screening of ceramics is the residual Depth of Penetration (DOP) test, which consists in measuring the total depth of penetration of a given threat into a semi-infinite backing. By comparing the results with and without the ceramic tile, it is possible to compute various efficiency factors to characterise the ceramic performance, such as mass and space efficiencies (E_m and E_s, respectively).

A test program was recently completed at Defence Research Establishment Valcartier (DREV) to study the performance of various ceramics using the DOP method. Commercial aluminium cylinders were used to measure the residual penetration of a 0.50-cal projectile. Various confinement configurations were tested to investigate their effect on the ceramic performance. The results of this program are presented in another publication (Ref. 1). The most striking observation concerns the very large scatter in the results obtained for firings that were performed under very similar testing conditions. From the X-ray results it was difficult to explain this anomalous behaviour in terms of the total yaw angle at impact.

As a first attempt to investigate the cause of the variability in the results, hydrocode simulations of the impact problem were performed. A constitutive model for brittle materials was implemented in the hydrocode LSDYNA2D (Ref. 2) and used to model the ceramic target. The results of this investigation were presented at the 16th International Symposium on Ballistics held in San Francisco, California, in September

1996. This work was performed at DREV between May and July 1996 under Thrust 2BB15, Ballistic Protection and Survivability, Numerical Modelling of Ballistic Events.

2.0 THE DOP METHOD

2.1 General

The residual Depth Of Penetration (DOP) method remains the most common method used to characterise the performance of ceramic materials as armour components. It consists in measuring the residual penetration of a given projectile into a semi-infinite target placed on the back of the material to be evaluated. The method is mainly used to characterise the performance of ceramic materials, but could also find applications for other types of materials. The backing most often used is monolithic Rolled Homogeneous Armour (RHA) steel. The method consists in measuring the penetration capability of a given projectile into the baseline target (semi-infinite backing) at various impact velocities (Ref. 3). These baseline results are then compared with the results obtained at similar impact velocities, but with the added protection of a plate of the material to be studied in front of the semi-infinite backing.

2.2 DREV Tests

Within the framework of the Armour Effectiveness Investigation (AEI) task, DREV investigated the performance of numerous ceramics obtained from various sources. In order to obtain a better accuracy of the ballistic performance of these ceramics, it was decided to use commercial aluminium as the semi-infinite backing material. It was hoped that the increase in the overall penetration obtained (as compared with that in a RHA steel backing) would translate into a better accuracy of the measurements. This could in part compensate for the limited number of tests in each condition that could be afforded (generally three shots per configuration tested).

A complete description of the tests performed, the range, the targets and the projectile, along with the results are presented in Ref. 1. For the purpose of the current study, it is sufficient to say that commercial Al 6061-T6 cylinders 178 mm in diameter and 254 mm in length were used as semi-infinite backings to measure the residual penetration of a 0.50-cal Saboted Light Armour Penetrator (SLAP) projectile, fired at an impact velocity of approximately 985 m/s. The penetrator was made of commercial tungsten alloy, and had a mass of 23.5 g.

3.0 TEST RESULTS

Only a few examples of the results are discussed here, basically to illustrate the large variability observed for tests performed under very similar conditions. Table I presents the results on which the present study was focused. Although large variations were observed for various grades and types of ceramics, those obtained with various grades of Al_2O_3 are deemed representative enough to perform the study, as the residual penetration obtained were significant, and the factor *F* was also typical for all ceramics. This factor *F* is obtained by dividing the largest result by the smallest (equation 1), for each test series performed under similar conditions. *F* was also computed for firings performed without ceramic plate in front of the semi-infinite aluminium backing (the average of these results was used as the baseline to compute the mass efficiency of the various ceramics tested). Against the bare aluminium, *F* is as low as 1.05, which thereby establishes that the cause of the variability is indeed related to the ceramics.

$$F = \frac{(DOP_n)_{\max}}{(DOP_n)_{\min}} \qquad [1]$$

where:	F	is the variation factor	(m/s)
	DOP_n	is the normalised DOP	(mm)

Since it is very difficult to always obtain a constant impact velocity in this type of experiment, it was deemed appropriate to account for the variation of the velocity in the measured residual penetration. A fairly simple correction was hence applied to the measured residual depths of penetration, according to the actual impact velocity. The correction is made assuming the penetration is directly proportional to the kinetic energy at impact. The adjusted DOP is determined by multiplying the measured value by the ratio of the squared nominal impact velocity to the squared measured impact velocity, as shown in the following equation:

$$DOP_n = DOP_m \left[\frac{V_n^2}{V_i^2} \right] \qquad [2]$$

where: DOP_n is the normalised DOP (mm)

DOP_m is the measured DOP (mm)

V_n is the nominal impact velocity (993.5 m/s)

V_i is the measured impact velocity (m/s)

TABLE I

Typical residual penetration results obtained with Al_2O_3

Target (dimensions, mm)	Yaw angle at impact (°)	Normalised Residual DOP (mm)	Variation Factor *F*
Al_2O_3 98% (152 x 152 x 12.7)	0.0	18.1	3.26
	4.6	26.1	
	1.7	8.0	
	1.6	14.3	
Al_2O_3 (152 x 152 x 10mm)	2.9	27.7	2.13
	2.6	21.2	
	0.4	13.0	
	0.5	13.5	
Al_2O_3 98% (circular ϕ 127 mm x 12.7 mm)	1.9	22.7	4.90
	0.0	5.1	
	4.5	25.0	
Al_2O_3 95% (circular ϕ 127 mm x 12.7 mm)	2.1	49.4	1.97
	0.0	50.7	
	1.2	25.8	

4.0 NUMERICAL SIMULATIONS

4.1 Method

Brittle materials, such as ceramics, undergo little strain before the onset of fracture and failure which typically occurs during the stress rise within the material. This makes it difficult to predict the performance of a ceramic target under high velocity impact. One of the few ceramic models that can be readily implemented in a hydrocode is the widely used Johnson-Holmquist (J-H) constitutive model for brittle materials (Ref. 4). In this model, the yield strength σ_y, is basically expressed as a function of a damage variable D and the pressure P according to

$$\sigma_y(P,D) = (1-D)\sigma_i(P) + D\sigma_f(P) \qquad [3]$$

where σ_i and σ_f are the yield strength for intact and fragmented material, respectively. σ_i and σ_f depend on the pressure according to

$$\sigma_i(P) = \sigma_{HEL} A(P/P_{HEL} + T^*)^N (1 + C\ln\dot{\varepsilon}) \qquad [4]$$

$$\sigma_f(P) = \sigma_{HEL} B(P/P_{HEL})^M (1 + C\ln\dot{\varepsilon}) \le S_{f\max}\sigma_{HEL} \qquad [5]$$

where A, B, C, M, N, and $S_{f\max}$ are material constants. $\dot{\varepsilon}$ is the strain rate and T^* is the maximum normalised tensile hydrostatic pressure that the material can withstand. σ_{HEL} and P_{HEL} are the stress and pressure at the Hugoniot Elastic Limit (*HEL*).

The damage in the material is given by

$$\varepsilon_f(P) = D_1(P/P_{HEL} + T^*)^{D_2} \qquad [6]$$

where ε_f is the fracture strain and D_1 and D_2 are damage constants that are experimentally determined.

4.2 Tensile Hydrostatic Pressure T^*

Over the years it has been shown that a high hydrostatic pressure can cause significant changes in the mechanical properties of materials such as rocks, polymeric composites and, to a lesser extent, metals (Ref. 5). In this work, an attempt is made to investigate the variability in the depth of penetration by temporally and spatially varying the hydrostatic tension in order to represent some type of inhomogeneity within the ceramic. The J-H constitutive model lends itself quite easily to conduct such a study since it explicitly contains the required terms. To implement variability in the hydrocode, the hydrostatic tensile pressure, T^* was randomly selected from a uniform distribution about an average value with a fixed variance. T^* was thus different for each element, and was also different at each time step for any given element. In this study, variances (+/-) of 25% and 40 % were used.

All simulations were done using the two-dimensional lagrangian code LSDYNA2D (Ref. 2) which includes an erosion algorithm. Due to the axisymmetric nature of the problem only half of the domain was simulated. The 2D half domain consists of a total 8007 4-node quadrilateral elements of which 557 are in the projectile, 6250 are in the aluminium target and 1200 in the ceramic. The areas that experience large and intense deformation are finely gridded to minimise the overlapping of the projectile and target elements during the penetration process. A mesh sensitivity analysis was performed and as a result the mesh used for the simulations is optimised for the problem. For all the numerical simulations presented, the projectile and the aluminium target were modelled using the hydrodynamic-elastic-plastic model which uses the effective plastic strain as the governing erosion parameter. The ceramic target was modelled using the J-H constitutive model for brittle material. The material properties used for the modelling of the projectile and the target materials are given in Tables II and III.

TABLE II

Metallic material properties used for the simulations

Material Property	Tungsten	Al 6061-T6
Density (g/cm^3)	17.73	2.768
Elasticity Modulus (Mbars)	4.85	0.6895
Poisson's Ratio	0.3	0.34
Failure strain	2.0	0.54
Tangent Modulus (Mbars)	0.0405	0.0030
Yield Stress (Mbars)	0.01215	0.00278
Bauschinger Effect	1.0	1.0

TABLE III

Ceramic material properties used for the simulations

Material Property/Parameter	Al_2O_3
Density (g/cm^3)	3.8
Shear Modulus (Mbars)	2.0
Effective Stress at HEL (Mbars)	0.083
Pressure at HEL (Mbars)	0.437
A	0.989
B	0.77
C	0.007
N	0.3755
M	1.0
$S_{f\max}$	0.5
T^*	0.3167
D_1	0.01
D_2	1.0

5.0 DISCUSSION AND ANALYSIS

5.1 Experimental Results

Several observations can be made on the results presented in Table I. The first concerns the effect of the total yaw on the residual DOP. The firings performed into the bare aluminium backing produced rather consistent results in all cases (including that of a 3.8° angle). Comparable observations on the yaw effect can be made for the results with the ceramic tiles (Table I). Surprisingly, in several occurrences the penetration obtained was significantly better when the total yaw was higher than the initial 3° limit. A limited set of results (including some not presented in Table I) are illustrated at Fig. 1. A possible lead is related to the projectile's nose shape. Past studies have demonstrated that pointed projectiles are generally much more sensitive to ceramic armours than blunt projectiles. This effect is not yet explained and shall require further investigation.

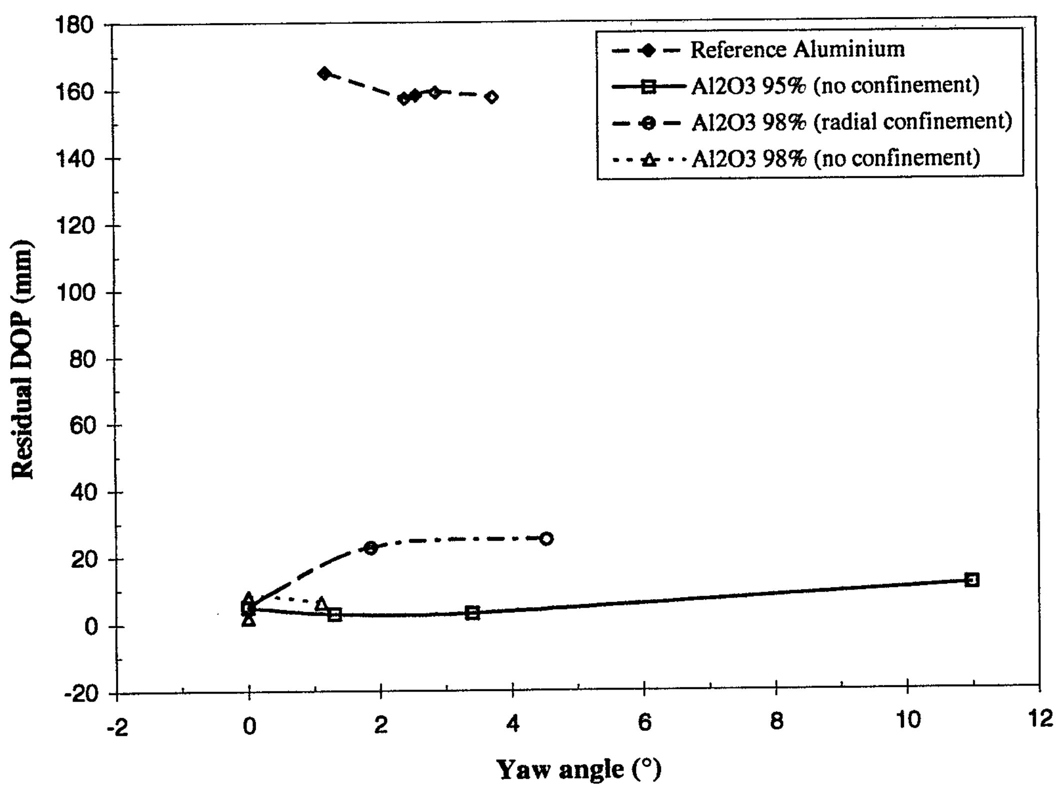


FIGURE 1 - Effect of the yaw angle at impact on the DOP

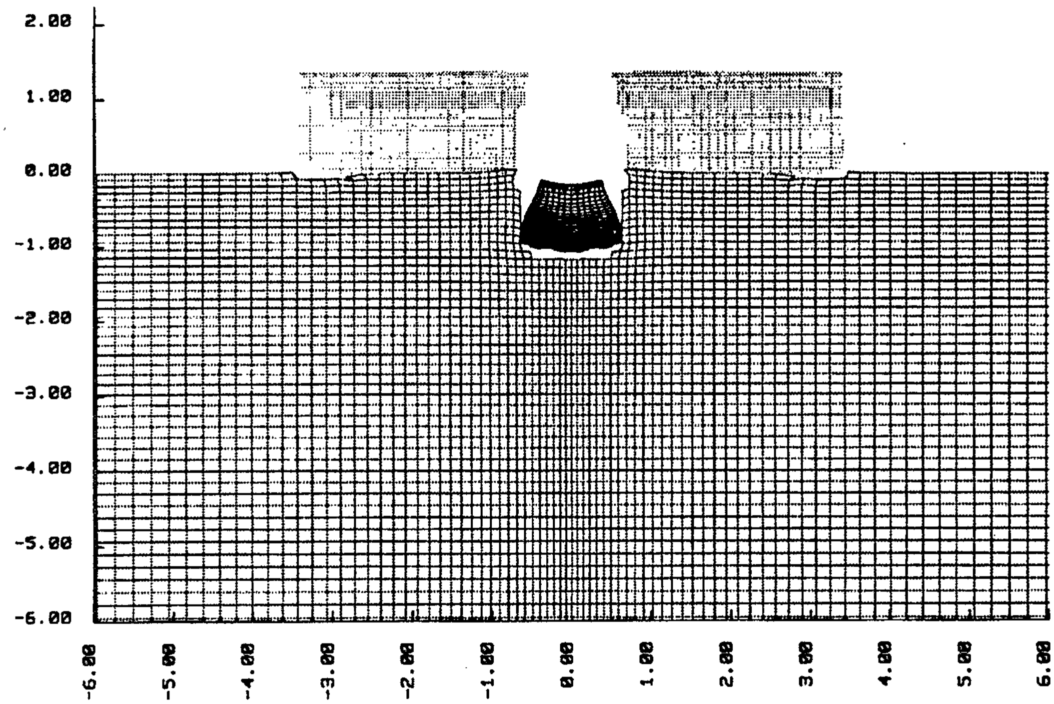
The main observation concerns the large scatter in the penetration results obtained from firings performed under very similar conditions. In some occasions, the largest residual DOP is 4 to 5 times larger than the lowest residual DOP (e.g. 25.0 and 5.1 for the Al_2O_3 98% tile), raising some questions on the test validity. A possible explanation is related to the inherent variation in the ceramic properties themselves. This hypothesis forms the basis of the numerical study reported here.

5.2 Computational Results

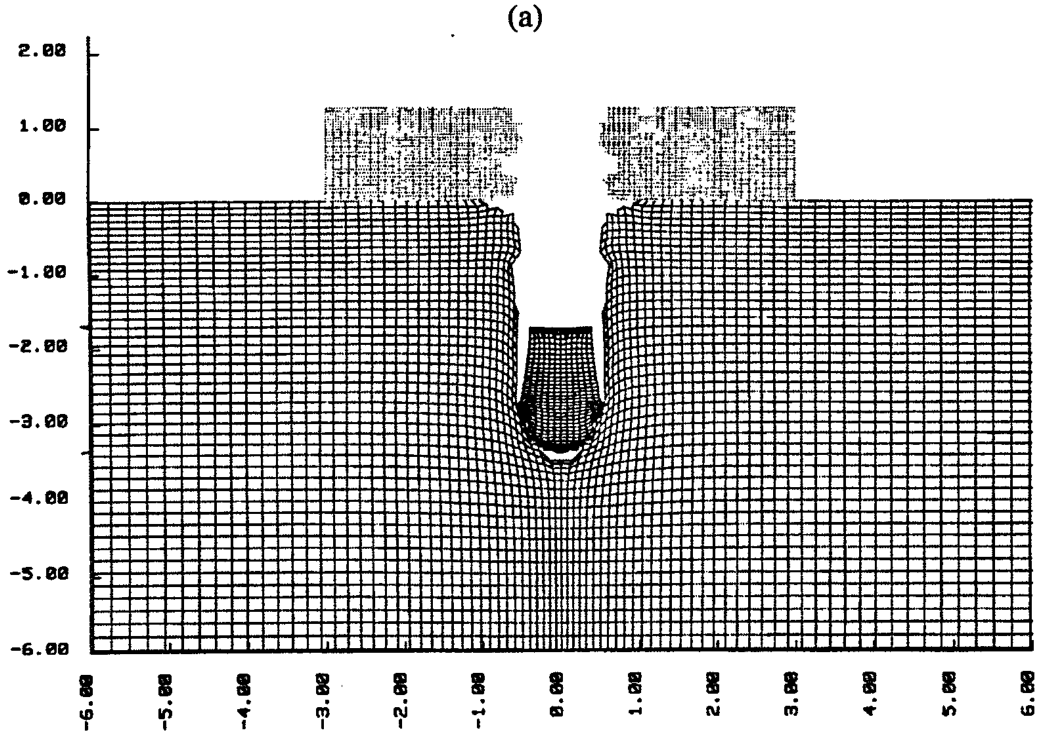
All simulations of the penetration problem were performed at an impact velocity of 990 m/s. A simulation was first performed with just the aluminium target and a DOP of 157 mm was obtained. This value compared quite well with the experimental value (159 mm). Subsequent simulations were performed with the ceramic tile in place. Using a variance of ±25%, simulations were performed with the ceramic modelled using the J-H constitutive model and a randomised tensile hydrostatic pressure, T^*. Figure 2a shows a profile of the penetration through the ceramic and the DOP in the aluminium target. A DOP of 11.5 mm was obtained. Figure 2b shows the penetration of the same simulation but using a different seed number for the random number generator. In this case, however, the DOP obtained was 30.1 mm. Figure 3 shows the penetration profile using another random number sequence, but with a variance of ±40%. In this case the DOP obtained is 24 mm with the ceramic damaged in the usual conical form. The results presented compare quite well with the experimental variation observed.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The number of samples tested in each configuration is too limited (generally 3), and the scatter in the penetration results too large to draw any firm conclusion from the analysis performed herein. The large scatter observed in the penetration results requires further study to identify the experimental factors contributing to these large discrepancies. A thorough analysis of the targets might lead to the identification of some clues to explain these phenomena. Particular attention should be given on the target preparation to ensure that variations observed are not induced by the test method and the set-up used.



(a)



(b)

FIGURE 2 - DYNA 2D simulation using two different random number sequences for T^{*}=0.3167 and a variance of ±25%

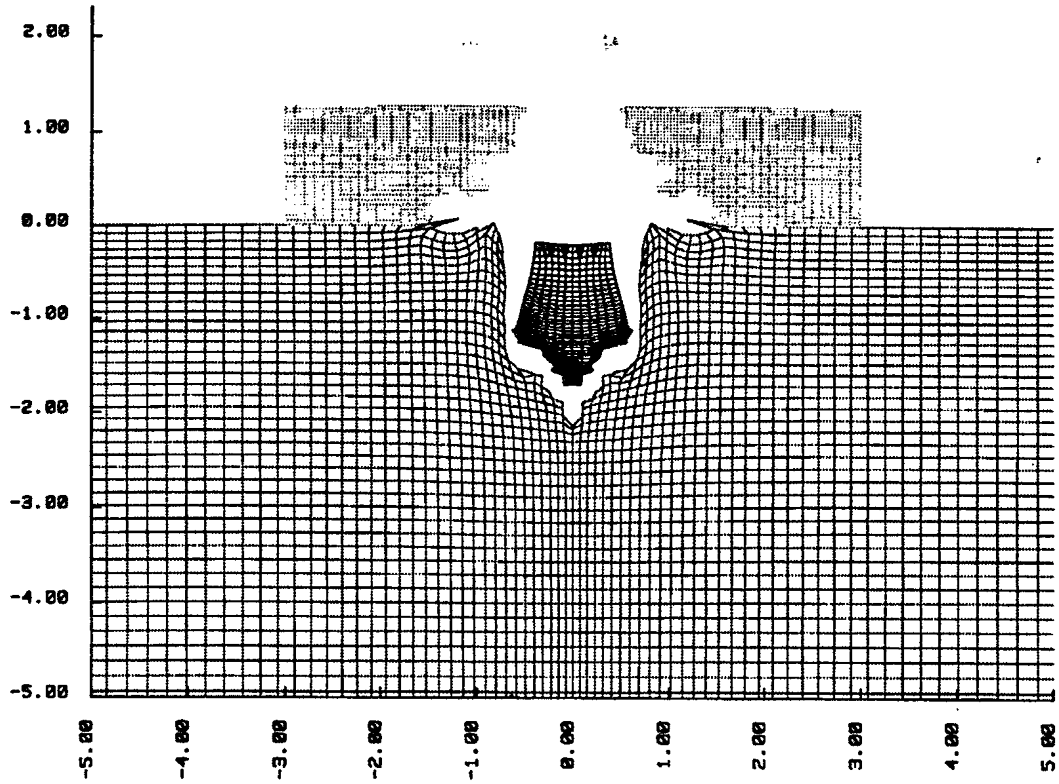


FIGURE 3 - DYNA 2D simulation using T^*=0.3167 and a variance of ±40%

The simulations conducted in this preliminary study reproduced the large variance in the depth of penetration results. These results seem to suggest that the penetration of the ceramic is quite sensitive to the tensile hydrostatic pressure T^*. Even though the simulations compare quite well with the experimental results, it is not possible at this stage to conclude that the variance of T^* is the only factor causing the scatter observed. More in depth studies are currently being performed in order to examine the physical meaning of randomising the tensile hydrostatic pressure and to relate this parameter to a physical quantity of the ceramic such as flaw size or porosity.

7.0 ACKNOWLEDGEMENTS

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