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The Johnson-Holmquist Ceramic Model as used in LS-DYNA2D

by

G. McIntosh

December/décembre 1998

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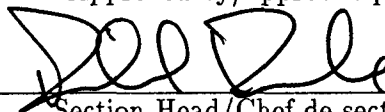
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Approved by/approuvé par



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ABSTRACT

A constitutive model for ceramics by Johnson and Holmquist has been incorporated and validated in the finite element computer program LS-DYNA2D. Using experimental data acquired at DREV, parameters for high density ceramics (around 98% theoretical maximum density) have been established. The effect of varying some of the parameters on the calculated depths of penetration into semi-infinite targets and the ballistic limits of armour has been investigated.

RÉSUMÉ

Le modèle de céramique de Johnson et Holmquist a été utilisé et vérifié dans le programme d'éléments finis LS-DYNA2D. Utilisant des données expérimentales du CRDV, les paramètres pour des céramiques de haute densité (environ 98 % de densité maximale) ont été établis. L'effet des variations de ces paramètres sur les profondeurs de pénétration dans des cibles semi-infinies et sur les limites balistiques a été étudié.

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TABLE I

EXECUTIVE SUMMARY

Current emphasis in numerical simulations is on accurate modelling of material behaviour. Modelling is cheaper, safer and more flexible than doing many series of experiments. However, the computational description of a material must be as accurate as possible before simulations of it are considered reliable. Ceramics and other brittle materials are difficult to model and characterize because damage and fracture mechanisms are not easily definable.

This memorandum describes one model, the Johnson-Holmquist model, which was incorporated into a finite element hydrodynamic computer program called LS-DYNA2D. The incorporation was verified against previously reported work and was found to be correctly incorporated. Simulations of impacts of projectiles (SLAP, APM-2) onto high density ceramic tiles covering aluminum were performed. Various thicknesses of ceramic were used, corresponding to those used in depth of penetration and ballistic limit tests at DREV. By adjusting the values of key parameters in the model, these simulations were fitted to agree with experimental data.

With the model and these fitted values, DREV is in a better position to simulate ceramic behaviour at high strain rates. Such simulations will be of special importance in the ballistic protection area, for both personnel and vehicles (LAV, tanks) where full scale tests are very expensive.

LIST OF SYMBOLS

a	intact material strength parameter
b	damaged material strength parameter
c	strain rate influence parameter
d_1, d_2	damage parameters
f_s	failure strain
G	shear modulus
k_1, k_2, k_3	elastic constants for Johnson-Holmquist model
m	damaged material strength parameter
n	intact material strength parameter
P	Pressure (may be subscripted)
T	tensile strength
β	fraction of damage energy to convert to internal pressure
ϵ	strain
μ	$\rho/\rho_o - 1$
ρ	density (may be subscripted)
σ	stress
*	superscript indicating a normalised quantity
DOP	depth of penetration
HEL	Hugoniot elastic limit
LAV	light armoured vehicle
LSTC	Livermore Software Technology Corporation
RHA	rolled homogenous armour
SLAP	saboted light armour piercing
TMD	theoretical maximum density

The above list is not exhaustive but does include most of the symbols used in this document.

1.0 INTRODUCTION

One of the current activities in numerical simulations is the modelling of material behaviour under high velocity impact since it is cheaper, safer and more flexible than doing many series of experiments. However, the computational description of a material must be as accurate as possible before simulations of it can be considered reliable. One type of material which is of current interest, especially for armour applications, is ceramics. A ceramic material has a complicated response to high strain rates, with damage and fracture being very important. One semi-empirical model to describe the behaviour of brittle materials such as ceramics under high dynamic loads is called the Johnson-Holmquist model (Ref. 1,2). In this memorandum, this model will be described and its implementation and validation in the finite element hydrodynamic computer program called DYNA2D (Ref. 3) will be given.

This work was performed at DREV between October 1996 and April 1998 under Work Unit 2bb15, Numerical Modelling of Ballistic Events.

2.0 MODEL DESCRIPTION AND INCORPORATION TESTS

The Johnson-Holmquist model was originally formulated (Ref.1) to consider the behaviour of brittle materials and then further refined (Ref. 2) to be more flexible and less parameter sensitive. The constitutive behaviour described by this model is as follows.

There is an initial elastic regime which continues until yield occurs (the plastic strain starts at this point). Damage starts to accumulate and the material weakens. The material then behaves along the weakened material curve. The rate at which the material moves from undamaged to damaged and the strength of the the weakened material are all variables the user must establish but unfortunately, they are not directly measurable. Hence, simulations with various parameters are necessary to establish a self-consistent set useful for describing the material's behaviour.

The model will now be described in some detail. In the following equations, the stresses and pressures are normalized as follows. Normalized quantities are indicated by an asterix superscript. Given the Hugoniot elastic limit (HEL) and the shear modulus (G), $\mu(= \rho/\rho_o - 1)$ at the HEL, μ_{HEL} , is found by solving

$$HEL = k_1\mu_{HEL} + k_2\mu_{HEL}^2 + k_3\mu_{HEL}^3 + \frac{4}{3}G \frac{\mu_{HEL}}{1 + \mu_{HEL}}$$

where k_1, k_2, k_3 are model elastic constants. Next, the pressure at the HEL, P_{HEL} , is found via

$$P_{HEL} = k_1\mu_{HEL} + k_2\mu_{HEL}^2 + k_3\mu_{HEL}^3$$

and the stress at the HEL, σ_{HEL} , from

$$\sigma_{HEL} = \frac{3}{2}(HEL - P_{HEL}).$$

Then, the normalized pressure, P^* , is given by

$$P^* = P/P_{HEL}$$

where P is the real pressure. Any normalised stress, σ^* , is given by

$$\sigma^* = \sigma / \sigma_{HEL}$$

where σ is the real stress. The description of the model can now begin. In a brittle material subjected to damage, the equivalent stress is

$$\sigma^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*)$$

where the strength envelope for the intact material is

$$\sigma_i^* = a(P^* + T^*)^n(1 + c \ln \dot{\epsilon}),$$

the strength of the damaged material is

$$\sigma_f^* = b(P^*)^m(1 + c \ln \dot{\epsilon}),$$

and the damage parameter is

$$D = \sum \Delta \epsilon^P / \epsilon_f^P,$$

which depends upon the plastic strain to fracture:

$$\epsilon_f^P = d_1(P^* + T^*)^{d_2}$$

and the incremental plastic strain in a given computational cycle, $\Delta \epsilon^P$. In the above, a, n, c, b, m, d_1, d_2 are all material constants, T^* is the normalised tensile strength and $\dot{\epsilon}$ is the normalised strain rate. As for the pressure, it is given by

$$P = k_1\mu + k_2\mu^2 + k_3\mu^3 + \Delta P$$

(in compression) or by

$$P = k_1 \mu$$

(in tension) where ΔP is a pressure increment due to the conversion of energy loss (due to damage) into internal energy (pressure). Note that, in this model, any frictional energy loss is considered negligible.

The Johnson-Holmquist model was incorporated into LS-DYNA2D (Ref. 3) by the company Livermore Software Technology Corporation (LSTC) and corrected at DREV. A test case (described in Ref. 2) was simulated. It consists of a controlled compression at a constant rate followed by a constrained release at the same rate (opposite direction). The resulting stress-pressure curve is shown in Fig. 1 as the solid curve. Various features of the model are visible in this figure. There is an initial linear, elastic behaviour until the σ_i^* curve (solid circle symbols) is reached. Damage starts at this point and continues to increase until it reaches the σ_f^* curve (solid square symbols). As the applied force direction is reversed, elastic release occurs. As the system goes through its initial position, the elastic force starts to rise again (due to the internal pressure resulting from damage) and reaches the limiting σ_f^* curve which it follows again. This behaviour matches the results given in Ref. 2 and were reproduced with only one parameter change: our d_1 was 0.00815 instead of original 0.005. This gives one confidence that the model is incorporated correctly. The plastic strain as calculated in LS-DYNA2D may be different to that of Ref. 2 in which the finite element program EPIC was used. EPIC uses triangular finite elements and must therefore handle the strains differently. Thus, the damage may accumulate differently as

TABLE IJohnson-Holmquist parameters for an around 98%-TMD ceramic

Parameter	Value
ρ	3.89 g cm^{-3}
G	1.5196 MBar
k_1	2.30974 MBar
k_2	-1.60027 MBar
k_3	23.7376 MBar
$\dot{\epsilon}_o$	$10^{-6} \mu s^{-1}$
HEL	0.0657 MBar
T	0.00262 MBar
a	0.88
n	0.64
c	0.07
b	0.28
m	0.6
σ_{max}^*	1.0
β	1.0
d_1	0.01
d_2	0.7
f_s	1.5

well. If this is indeed the case and d_1 being a damage parameter, it follows that d_1 would have to be "code-dependent" and thus different in the two cases.

For all subsequent simulations, a different set of parameters was used which described better the around 98% theoretical maximum density (TMD) ceramic material that was used experimentally. These parameters are given in Table I and were originally found in the code EPIC. In the parameter variation studies which follow, these parameters were unchanged except where specifically noted. In general, only b and f_s were changed.

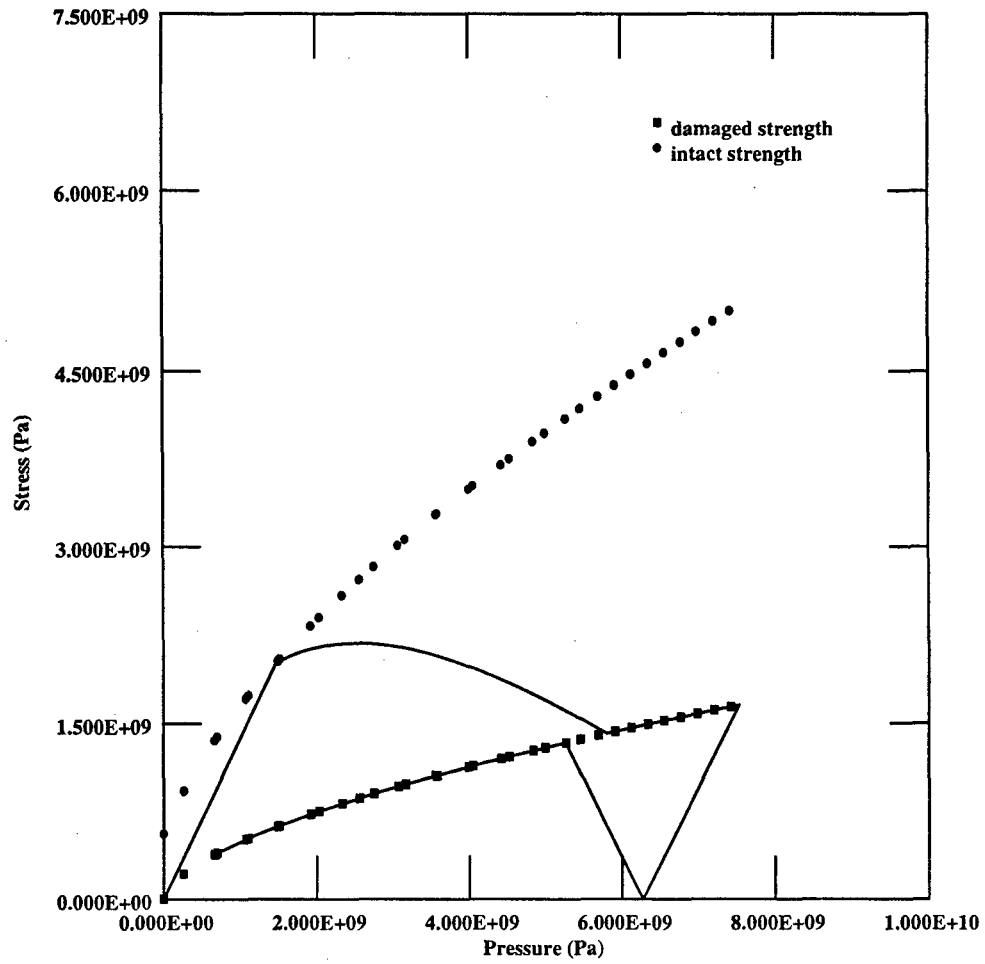


FIGURE 1 – Ceramic material response to compression and release, after Ref. 2 with $d_1=0.00815$. The solid line is generated by the application and release of a load.

3.0 VALUES FOR JOHNSON-HOLMQUIST MODEL PARAMETERS

An isolated model is not worth very much in the absence of values for the parameters within it. To determine these values, comparisons of simulations with experimental results are used, the values being varied until good agreement between simulation and experiment is reached. At DREV, two types of experimental results are available for comparison: depth of penetration tests and ballistic limit tests. The methods used and results obtained from these tests will be described briefly in the following subsections.

A depth of penetration (DOP) test is one in which a sample of a material is affixed to a large block of backing material such as aluminum or rolled homogeneous armour (RHA) and a projectile strikes the top surface of the combined face plate-backing. The resulting hole or depression in the backing material is then measured, usually as a function of sample material thickness. For comparison purposes, the experimental depths of penetration obtained at DREV were 5.63 cm for the 0.82 cm thick ceramic, 1.68 cm for the 1.27 cm thick ceramic and 0.83 cm for the 2.54 cm thick ceramic. By varying certain material parameters in the simulations, the calculated depth of the hole can be adjusted to match the experimental results. In these simulations, the projectile was a sabot light armour piercing (SLAP) tungsten core and the backing material was 6061-T6 aluminum, thick enough (usually 7 cm) so that rear surface or boundary effects did not affect the results ("semi-infinite"). The overlying ceramic facing was one of three possible thicknesses: 0.82 cm, 1.27 cm or 2.54 cm. The meshing was uniform in the vertical directions within each

material and variable horizontally, with finer meshing at the center and coarser meshing in the outer regions away from the projectile's point of impact. Finer meshing is used to resolve better the interaction between the small tip of the projectile and the much larger target.

In a ballistic limit test, a plate of potential armour material is affixed to a backing plate of finite thickness. The velocity of the impacting projectile is adjusted so that the projectile is just stopped (or barely perforates the target). This velocity is called the ballistic limit and is closely related to the experimental V_{50} , the velocity at which 50% of the projectiles will perforate the target. Experimentally, random variations from shot to shot (e.g. in yaw, velocity, alignment, material properties, etc.) cause variable results, hence a probabilistic velocity is usually reported. In the present simulations, the projectile was an APM-2 0.50 caliber Mo-Mn steel core and the backing material was 2024-T3 aluminum 0.7225 cm thick while the ceramic face plate was 0.8 cm thick. Uniform meshing was used vertically and variable meshing horizontally, with finer meshing near the projectile's impact point and coarser meshing further out radially.

There are many parameters in the Johnson-Holmquist model (see Table I) and it is not wise to try to fit them all. That would take too much time and tends to detract from the underlying question of which parameters are important and which are not. The following philosophy was adopted in this document. As far as the material properties of the ceramic are concerned, it is assumed that the properties of the undamaged ceramic are

known best and hence, can be used without modification directly as found in the literature (e.g. in the code EPIC) or can be determined experimentally. However, for the damaged material, freedom is allowed and the different values can be tried. Upon examination of the equations describing the ceramic model, various critical parameters are noted. For damage production, the critical parameter is d_1 . For the strength of the damaged materials, one parameter, namely b , is of great importance. These are the main parameters which will be examined in the following sections.

3.1 Failure Criteria

In a penetration problem, since there are no available fracture models, there must be some mechanism for removing material for penetration to occur. Otherwise, the material will simply be stretched, sometimes beyond physical limits and worse, penetration will never occur. In this section, two items will be addressed. First, the most common erosion criterion, a critical failure strain, will be discussed with a view to finding a rational approach to selecting an appropriate failure strain. This is the criterion used for most of the subsequent simulations in this document. Second, a more physical criterion is strongly desirable and thus other possible failure criteria are outlined.

One common erosion criterion used in hydrocodes is based upon a failure strain parameter (f_s): an element is eroded if the plastic strain in it exceeds a user-specified limit. However, a rational approach to determining a failure strain cannot be done independently

of other parameters as the strains generated within a material depend upon them. One critical parameter for the J-H model is b , which determines the strength of the damaged material and it should be determined first. One starts with preliminary values for all the parameters, taken, for example, from Table I and uses a large failure strain (for example, 10), far above any plastic strain generated in the material (and hence erosion is suppressed). A simulation of a DOP test is done and the magnitudes of the resulting strains are noted. A new, lower failure strain, one that ensures erosion, is then chosen and the simulation is rerun. The DOP is noted and b is varied to get agreement between experiment and simulation. At this point, one should have a 'good' set of parameters which characterize the material according to the constitutive model described earlier. The ballistic limit tests are then simulated with this set of parameters. The failure strain is adjusted so that with the experimental ballistic limit velocity, a projectile will barely perforate the target. The transition to penetration is quite sensitive to the value of f_s . In Fig. 2, the residual velocity (either perforation or rebound) is shown as a function of f_s for two different b 's. As can be seen, there is a steep slope around a critical f_s . With the new critical failure strain (usually lower), the DOP is reconfirmed. In effect, what one is doing is iterating to fit both the DOP and ballistic limit tests by adjusting two parameters, b and f_s . The net result must be a reasonable agreement between experiment and simulations in both cases.

Other erosion criteria can be envisaged. For example, one is a damaged strength model in which a fully damaged material in tension beyond its (intact) tensile strength is eroded. This is relatively easy to implement and was done so by eroding any element

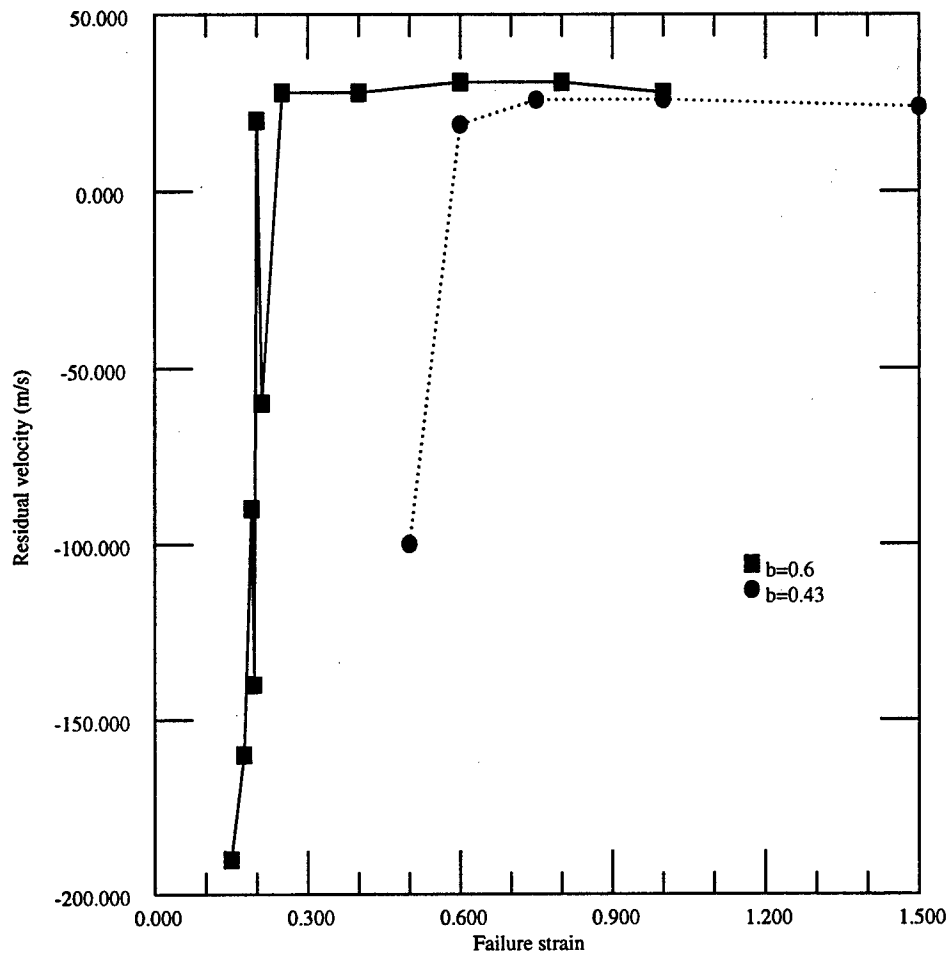


FIGURE 2 – Variation of residual velocity with failure strain for an impact velocity of 400 m/s onto a ceramic-aluminum sandwich

with $P^* + T^*$ less than 0 and for which the damage parameter was 1 (fully damaged). The results indicate that, without changing other parameters of the model, the material tends to erode too quickly and hence DOP and ballistic limit results vary significantly from experiments. As in the failure strain case, varying the strength of the damaged material by changing b results in better agreement. This was done and the resulting DOP versus b for various thicknesses of ceramic are shown in Fig. 3. As the strength of the damaged material increases (larger b), the DOP decreases. The experimental results cannot be reproduced exactly but using a b around 0.75 yields acceptable results. For comparison, the undamaged material has a strength parameter (a) of 0.88 and thus, it is seen that to reproduce the experiments, with this erosion criterion, the material cannot lose a lot of strength when damaged, something which is not the case in reality. For this reason, further investigation of this criterion was not pursued.

3.2 Depth of Penetration

For these simulations, the failure strain erosion criterion was used. Various failure strains were tried, keeping the damaged material strength parameter constant ($b=0.43$). In Fig. 4, the DOP is shown as a function of failure strain and for 3 different thicknesses of ceramic. As expected, as the failure strain limit is raised, the DOP decreases. This occurs because the ceramic material resists the penetration longer at higher failure strains and hence slows the projectile more and a slower projectile does not penetrate as far into the infinite backing material. A failure strain of 1.5 yields results close to the experimental

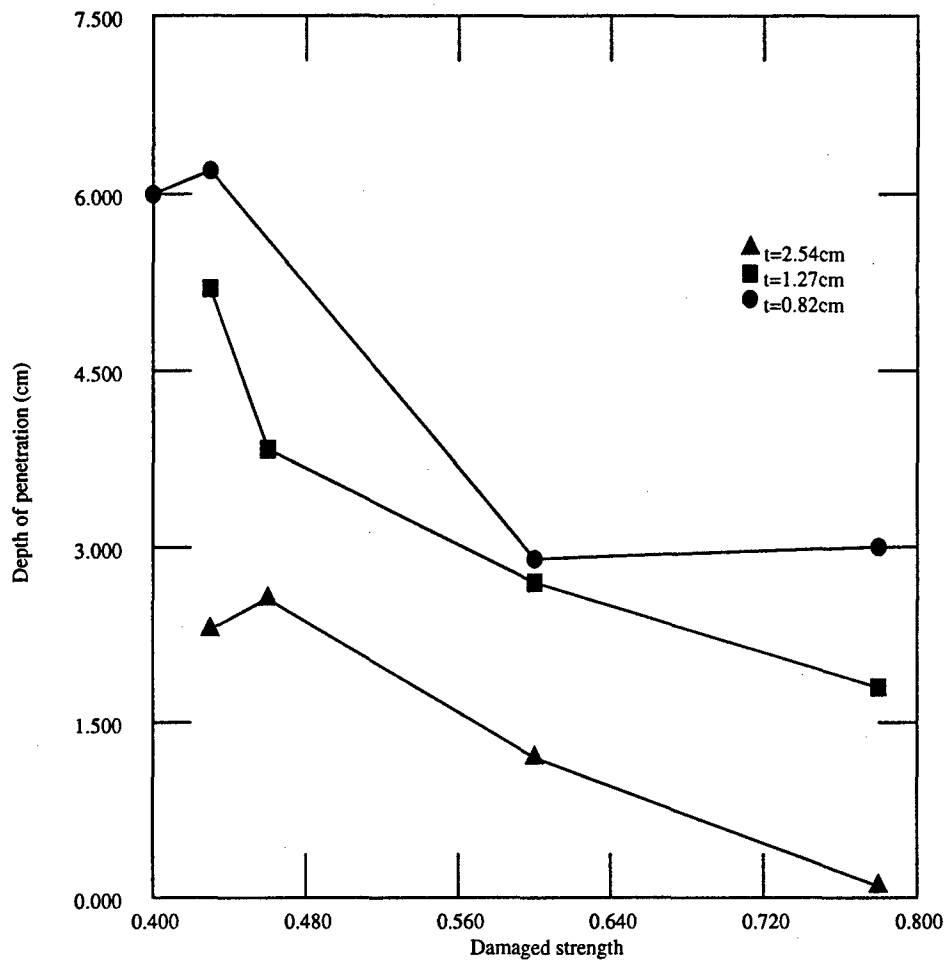


FIGURE 3 – Variation of depth of penetration with strength of damaged material using a pressure-based erosion criterion

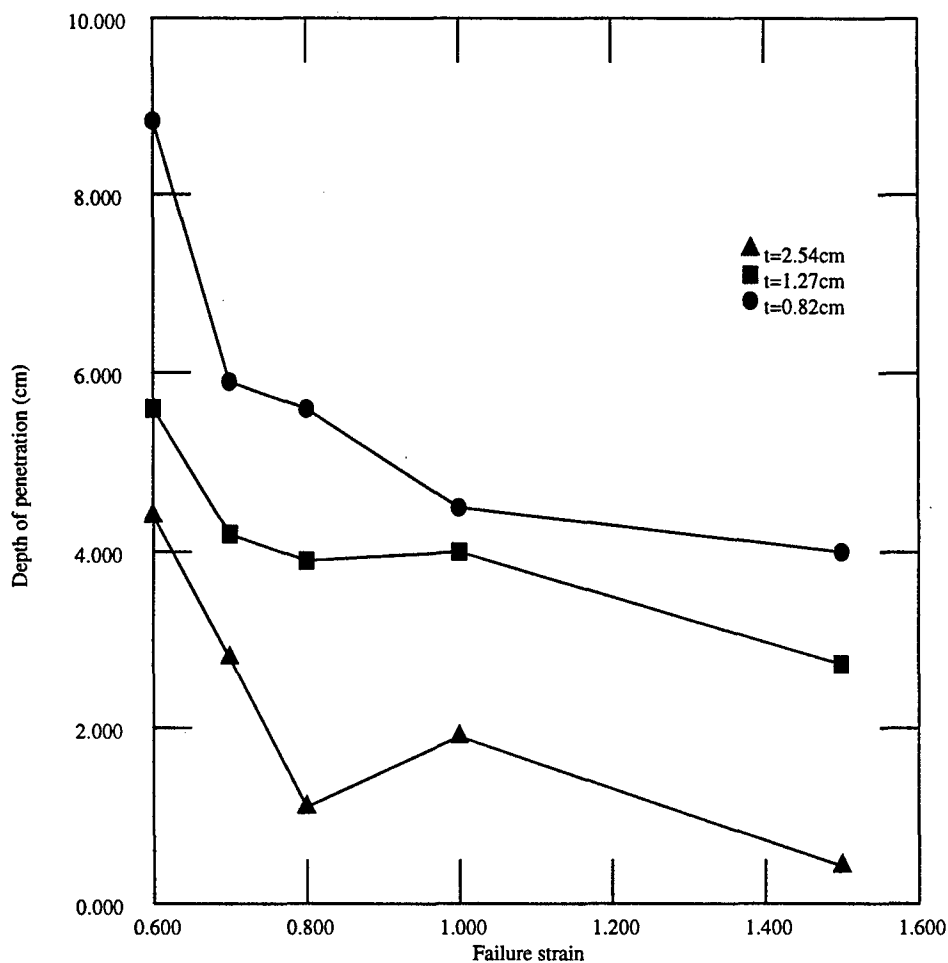


FIGURE 4 - Depth of penetration into aluminum behind ceramic plates of various thicknesses as a function of assumed failure strain and for $b=0.43$

values but it is impossible to find a f_s for which all are reproduced. Near f_s of 0.7 ± 0.1 , a sharp rise in the DOP is noted. This value of f_s is suggestive as it is near the f_s needed to reproduce the ballistic limit results as discussed in the previous section.

Using the failure strain determined above (1.5), variations of the damaged material strength parameter (b) were tried. These results are shown in Fig. 5 where they are compared with experimental data (dashed line). The experimental results are bracketed

by these variations (less than $\pm 10\%$). However, none of the three b 's reproduced the experimental results exactly. The b of 0.43 is a reasonable compromise.

The final set of simulations was done with $f_s=1.5$ and $b=0.43$, but the damage parameter d_1 was varied. This parameter controls the rate at which damage accumulates. If d_1 is zero, the damage is 'instantaneous'. These were done for the three different ceramic thicknesses and the results are plotted in Fig. 6. Once again, substantial variations were observed but the experimental results could not be reproduced. The original damage parameter of 0.01 gives reasonable results but using 0.0125 would give better agreement.

3.3 Ballistic Limit Simulations

For these simulations, the failure strain erosion criterion was used. Ballistic limits are determined in simulations by plotting the residual velocity (velocity with which a projectile exits the target) versus the impact velocity. This was done for three b - f_s combinations and the curves are given in Fig. 7 along with the experimental results. For $b=0.43$ and $f_s=1.5$, the combination which gave the compromise results in the DOP penetration case, there is a significant difference between the experimental and numerical results. By using $f_s=0.6$ (determined to be the best for the ballistic limit velocity), excellent agreement is obtained at all impact velocities. An intermediate result is obtained with $f_s=1.5$ and $b=0.40$, a combination which gives an upper limit to the results in the DOP case. The need for two quite different f_s 's to reproduce the results from two different experiments suggests

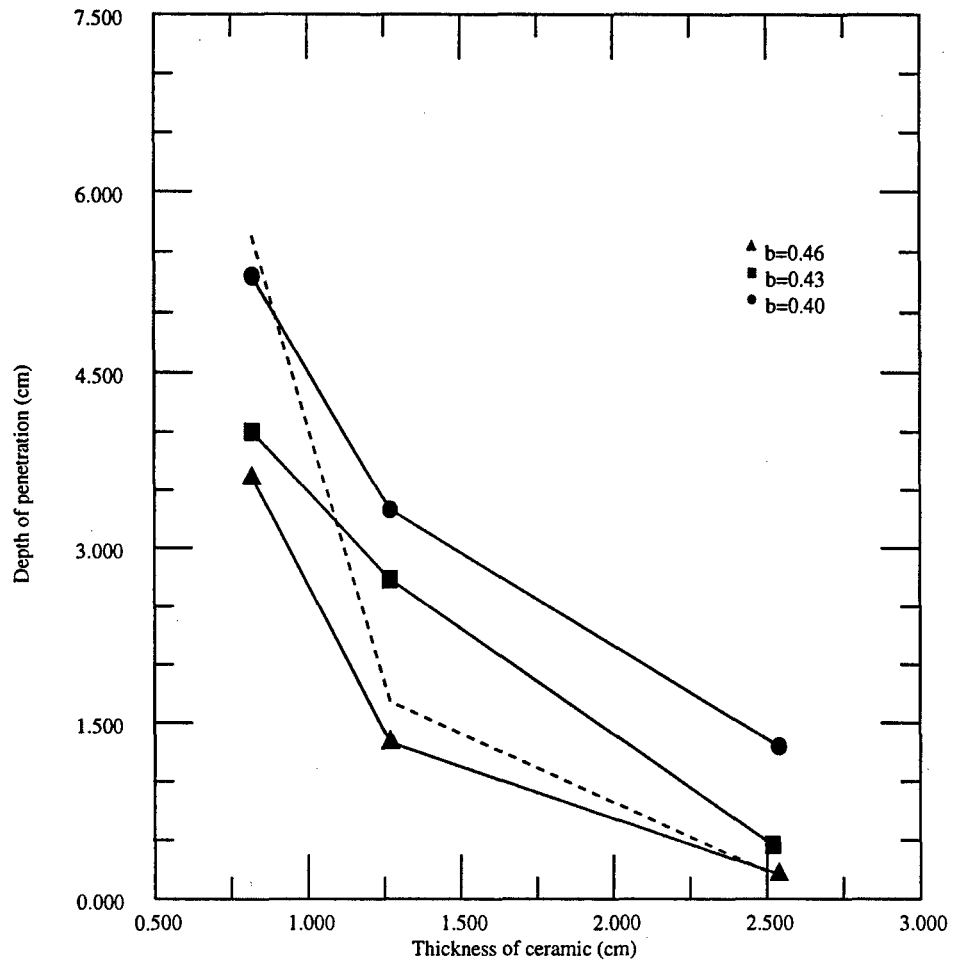


FIGURE 5 – Depth of penetration into aluminum versus thickness of ceramic facing for various damaged material strengths. A failure strain of 1.5 was used. The dashed line is the experimental data.

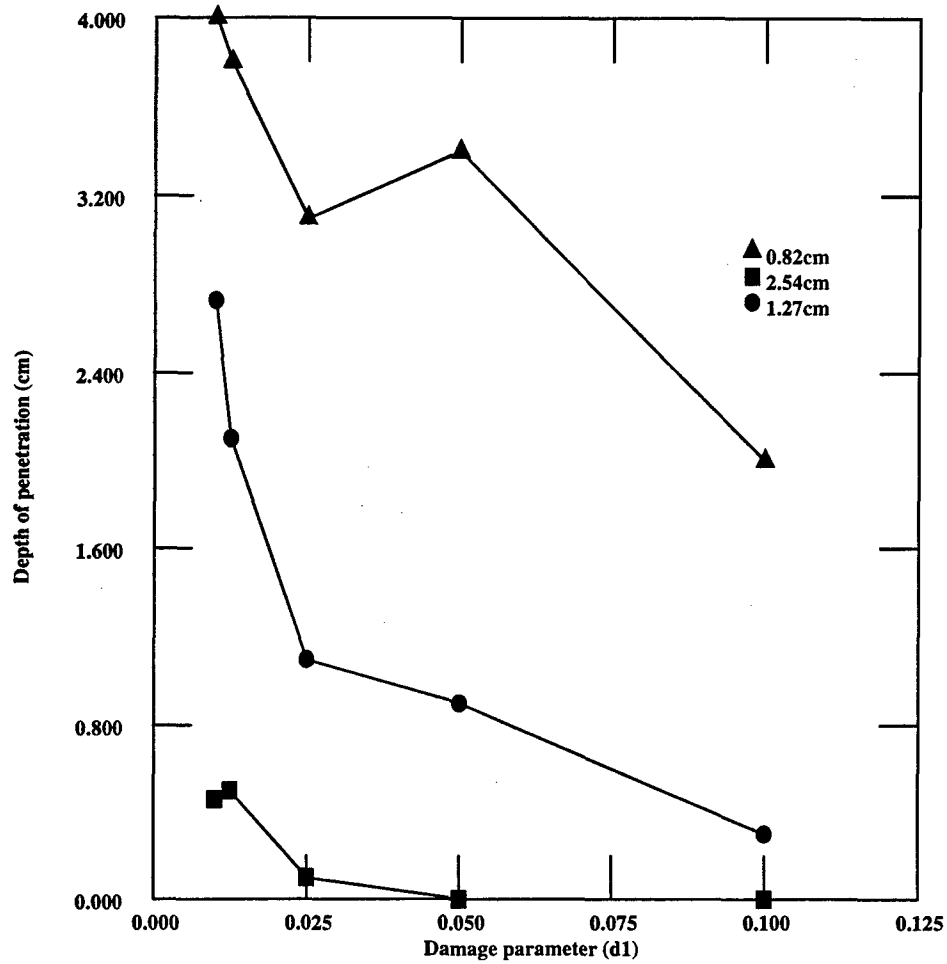


FIGURE 6 - Depth of penetration into aluminum versus the damage parameter, d_1 for three different ceramic thicknesses

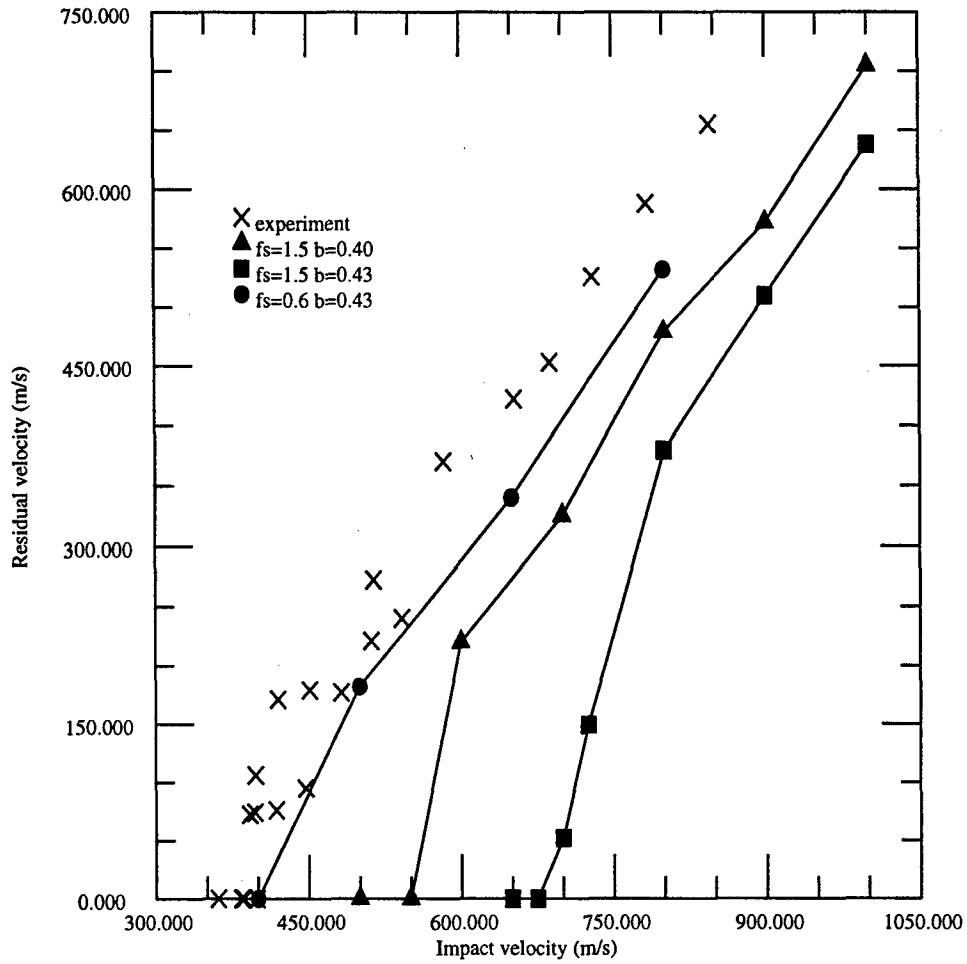


FIGURE 7 – Comparison of calculated ballistic limits with experimental data

that the failure strain criterion is not the best criterion for determining erosion. Further study is needed here.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Two sets of parameters were found which can be used to model around 98% TMD ceramics in depth of penetration tests (Table I with $f_s=1.5$ and $b=0.43$) and ballistic limit

tests (Table I with $f_s=0.6$ and $b=0.43$). More work is needed to derive a better erosion criterion and to be able to use one set of parameters (perhaps Table I with $f_s=0.8$ and $b=0.43$) for all simulations involving this ceramic material.

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A constitutive model for ceramics by Johnson and Holmquist has been incorporated and validated in the finite element computer program LS-DYNA2D. Using experimental data acquired at DREV, parameters for high density ceramics (around 98% theoretical maximum density) have been established. The effect of varying some of the parameters on the calculated depths of penetration into semi-infinite targets and the ballistic limits of armour has been investigated.

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