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A FIRST APPROACH TO PENETRATION OF TANDEM CHARGES INTO CONCRETE

TELAND Jan Arild

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Director of Research

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8) ABSTRACT

As a first approach to the penetration of tandem charges, we consider the penetration of rigid projectiles into concrete targets containing pre–drilled cavities. An analytical model based on a modification of cavity expansion theory is developed. It is compared with other semi–empirical models and two sets of experimental data. However, due to lack of triaxial concrete data from the experiments, the concrete properties had to be estimated from an empirical relation. Despite this, the model is seen to give qualitative agreement with experiments, but further research and experiments are needed to examine the quantitative predictions of the analytical model.

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CONTENTS

A FIRST APPROACH TO PENETRATION OF TANDEM CHARGES INTO CONCRETE

1 INTRODUCTION

An important problem in penetration mechanics is to determine the effect of having a weakened target, maybe because the first stage of a tandem charge has damaged the target before impact of the main projectile.

As a first approach to the general problem, it might be interesting to consider a situation of a projectile penetrating a target containing a pre–drilled cylindrical cavity. Previous work on this topic has mainly been based on empirical and numerical studies. Here we attempt to model the problem analytically, using the penetration theory based on cavity expansion. The theory should be valid for all cases of "hard" projectiles impacting "soft" targets, but here we will mostly be concerned with concrete targets.

This report is an extended version of a paper (1) that has been submitted for presentation at the 19th International Symposium on Ballistics.

2 OVERVIEW OF THE PROBLEM

Our situation is illustrated in Figure 2.1. A projectile with radius a is impacting a target with a predrilled cavity of radius b. It will be convenient to define the relative cavity radius (or diameter) by $R=b/a$. In the special case $R=0$ we then have no initial cavity, while for $R=1$ the projectile fits exactly inside the cavity, and should be able to penetrate a semi–infinite target indefinitely.

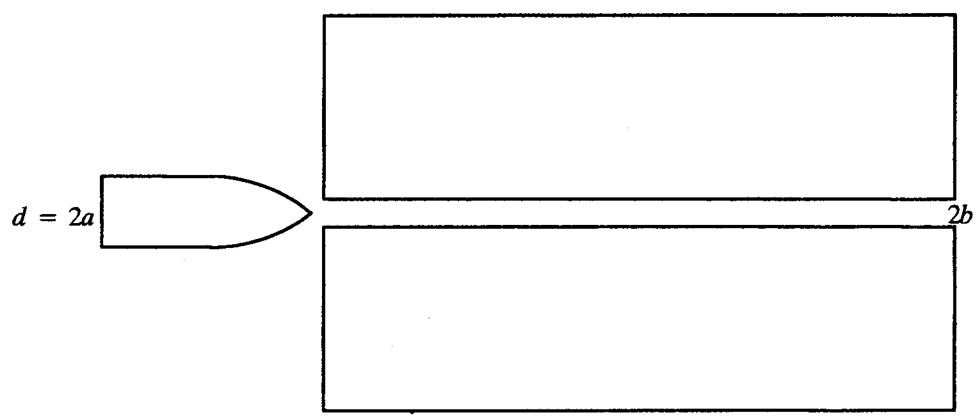

Figure 2.1 Penetration of a projectile with radius a into a target containing a predrilled cavity of radius b.

It is now necessary to say a few words about how to present equations for penetration of targets with pre–drilled cavities. Formulas can either be given in terms of absolute penetration depth x (as a function of the variables describing the problem), or as relative penetration depth $X = \frac{x(R)}{x(R = 0)}$, i.e. the penetration depth with a cavity divided by penetration with no cavity. In this paper we will denote relative (dimensionless) quantities by capital letters, and absolute quantities by small letters.

If one has a theory that agrees exactly with experiment, it does not matter whether comparisons are presented in terms of relative or absolute penetration depth. However, let us imagine a theory that consistently underpredicts the absolute penetration depth by 50%. Agreement would then be exact for the relative penetration depth, which shows that the formula predicts the R–dependence of the penetration depth correctly, even though the absolute results are wrong. Thus, both points of view are of interest, so when comparing theory with experiment, we will do this both in terms of absolute and relative quantities.

3 PREVIOUS WORK

The problem of having a concrete target with predrilled cavity was first examined by Murphy (2) . His approach was based on Bernard's empirical equation (3) for penetration into rock, which was modified in the following way:

$$\left(\frac{x}{d}\right)_{Murphy} = \frac{1}{1 - R^2}\left(0.0254\frac{mv_0}{d^3\sqrt{\rho\sigma_c}}\right) \tag{3.1}$$

where d=$2a$ is the projectile diameter, m is the mass, v_0 the impact velocity, ρ is the concrete density and σ_c is the compressive strength. However, the relative penetration depth X is easily seen to take on a much simpler form:

$$X_{Murphy} = \frac{1}{1 - R^2} \tag{3.2}$$

Using some simple semi–analytical models, Murphy also estimated the maximum penetration depth from a tandem charge with shaped charge in the first stage.

Expanding on the work of Murphy, Folsom (4) examined the same problem in his Master's thesis. He started with a modified version of the ACE empirical equation (5) containing two unknown constants that were empirically determined according to his experiments. His final result became quite complicated, but can be written on the following form:

$$\left(\frac{x}{d}\right)_{Folsom} = \frac{1 - 0.38R^2}{1 - R^2}\left(5.47 \cdot 10^{-4}\frac{mv^{1.5}}{\sigma_c^{0.5}d^{2.785}}\right) - \frac{4}{1 - R^2}f(\psi, R) + \sqrt{\psi - \frac{1}{4}}$$

$$f(\psi, R) = -\frac{g^3}{3} + \left(\frac{1 - R^2}{4} - \psi + 2\psi^2\right)g + \frac{(1 - 2\psi)}{2}\left(g\sqrt{\psi^2 - g^2} + \psi^2 \arcsin\left(\frac{g}{\psi}\right)\right)$$

$$g(\psi, R) = \sqrt{\psi(1 - R) - \frac{(1 - R)^2}{4}} \tag{3.3}$$

For sufficiently large velocities, the first term dominates over the two other terms, and the relative penetration depth is easily seen to reduce to the following quite simple expression:

$$X_{Folsom} = \frac{1 - 0.38R^2}{1 - R^2} \tag{3.4}$$

The same problem was later examined by Mostert (6), who used a combination of numerical and experimental observations to independently rederive Equation (3.2).

4 CAVITY EXPANSION THEORY

Cavity expansion theory has been widely applied to the penetration of rigid projectiles. In this paper we slightly modify this theory to make it applicable to penetration of targets containing pre–drilled cavities. A similar approach has recently been suggested independently by Szendrei (7).

4.1 Regular cavity expansion theory

The idea behind penetration theories based on cavity expansion is to use stresses that develop when a cavity is forced to expand inside a material to estimate the force on the projectile during penetration. This is done by calculating the stresses on the boundary of a cavity that is expanding at a given velocity, and relating them to stresses on the surface area of the projectile. On integrating these stresses over the surface area, an estimate for the total force F on the projectile is obtained. A review of cavity expansion theories is given in Teland (8).

In regular penetration theories, the force on the projectile (parallell to the symmetry axis) is calculated according to the following integral over the projectile surface:

$$F_0 = -2\pi s^2 \int_{\phi_0}^{\pi/2} p_r(v,\phi)\left(\sin\phi - \sin\phi_0\right)\cos\phi d\phi \tag{4.1}$$

where s is the curvature radius, ϕ defines the position on the projectile nose and ϕ_0 is defined in Figure 4.1. The function p_r is an estimate of the radial stress on the projectile nose during penetration. It is found from cavity expansion theory by first calculating the radial stress during expansion of a cavity and then applying a specific procedure to estimate the angular dependence of the stress along the projectile nose.

In many cases, the result takes the following simple form (at least approximatively):

$$p_r = A + Bv^2\cos^2\phi \tag{4.2}$$

where A and B are constants depending on properties of the target material, v is the projectile velocity and the angle ϕ defines the position on the projectile surface.

For a given material model, it is possible to calculate A and B analytically or numerically directly from cavity expansion theory. However, if a complete concrete description is unavailable, one can instead use an empirical expression for A and B derived by Forrestal et.al. (9)–(10):

$$A = S\sigma_c \ , \quad S = 82.6\left(\frac{\sigma_c}{10^6}\right)^{-0.544} \ , \quad B = \rho \tag{4.3}$$

Using Equation (4.3) we can obtain an estimate for A and B by only knowing the concrete compressive strength and density.

Assuming Equation (4.2) and performing the integration in Equation (4.1), then gives us the following expression for the force:

$$F_0 = -\left(\alpha_0 + \beta_0 v^2\right) = -\pi a^2\left(A + N_0 B v^2\right) \tag{4.4}$$

where N_0 is a function of the projectile nose shape. For an ogive nose, we have:

$$N_0 = \frac{8\psi - 1}{24\psi^2} \ , \quad \psi = \frac{s}{2a} \tag{4.5}$$

4.2 Modified cavity expansion theory

When an initial cavity of radius b is present in the target, the force on the projectile will obviously be reduced. Instead of integrating over the whole projectile surface to find the force, we now only have to integrate over the part of the surface that will be in contact with the target.

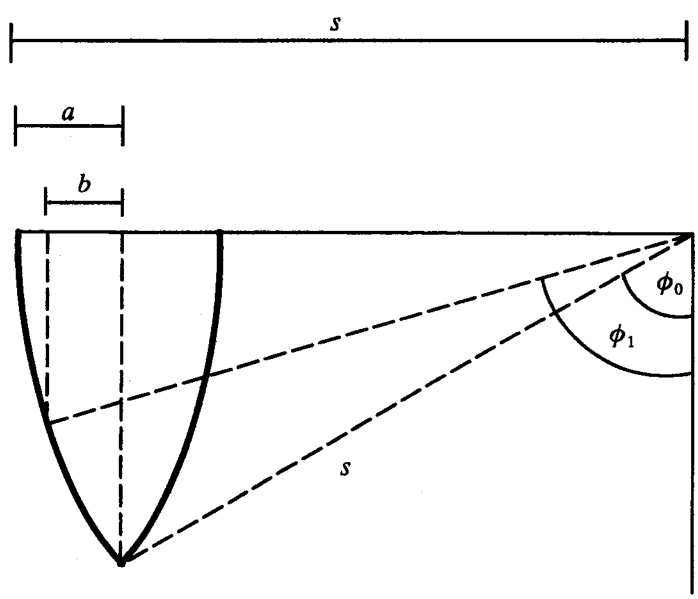

Figure 4.1: The projectile and initial cavity geometry.

This amounts to only integrating from ϕ_1 to $\pi/2$ instead of from ϕ_0 to $\pi/2$, where the angles ϕ_1 and ϕ_0 are defined in Figure 4.1. Some simple geometry shows them to be given by:

$$\sin\phi_0 = \left(\frac{s-a}{s}\right) \quad , \quad \sin\phi_1 = \left(\frac{s+b-a}{s}\right) \tag{4.6}$$

The expression for the force can thus be written as:

$$F = -2\pi s^2 \int_{\phi_1}^{\pi/2} p_r(v,\phi)\left(\sin\phi - \sin\phi_0\right)\cos\phi d\phi \tag{4.7}$$

After inserting Equations (4.2) and (4.6) into Equation (4.7), it only remains to do the actual calculations. This is straightforward, although slightly cumbersome. In the end we obtain the following result:

$$F = -\left(\alpha + \beta v^2\right) \tag{4.8}$$

$$\alpha = \pi a^2 A\left(1 - R^2\right) \tag{4.9}$$

$$\beta = \frac{\pi a^2 B}{24\psi^2}\left((8\psi - 1) - R^2\left(6(4\psi - 1) + 8R(1 - 2\psi) - 3R^2\right)\right) \tag{4.10}$$

We see that both coefficients now turn out to be functions of the normalised cavity radius R.

Let us examine some special cases of Equations (4.9)–(4.10). We easily see that for $R = 0$, the familiar result of normal cavity expansion theory is retrieved. The case of a hemispherical nose ($\psi = 1/2$) is also interesting, as β takes the following simple form:

$$\beta = \frac{1}{2}\pi a^2 B\left(1 - R^2\right)^2 \tag{4.11}$$

5 PENETRATION DEPTH

The penetration process can now be divided into two phases.

5.1 Initial penetration phase

The presence of an initial cavity in the target enables the projectile nose to enter the target without interacting with it. Only after having travelled a distance x_{init} will the nose first come into contact with the target material. This gives an extra geometrical contribution to the penetration depth, which is easily seen to be given by:

$$x_{init} = \sqrt{s^2 - (s-a)^2} - \sqrt{s^2 - (s-a+b)^2} = s\left(\cos\phi_0 - \cos\phi_1\right) \tag{5.1}$$

Further, when the projectile first interacts with the target, only a part of the nose is in direct contact with the material. Our Equations (4.8)–(4.10) for the force is therefore not valid until the projectile has penetrated deeply enough for the nose to be completely surrounded by target material. This phase could in principle be implemented analytically by making replacing ϕ_1 in Equation (4.7) with a function $\phi(x)$, so that integration would only be over the part of the nose that has entered the target. Unfortunately, this would make it impossible to obtain an analytical solution. In the comparison with experimental data below we will instead find a numerical solution (11) in the initial penetration phase.

5.2 Cavity expansion phase

After the initial penetration phase, Equations (4.8)–(4.10) for the total force on the projectile should be valid. Since the penetrator is assumed to remain rigid, this enables us to use Newton's 2nd law to calculate the projectile deceleration and eventually penetration depth. In general the final penetration depth is found to be:

$$x_1 = \frac{m}{2\beta}\ln\left(1 + \frac{\beta}{\alpha}v_1^2\right) \tag{5.2}$$

where v_1 is the velocity of the projectile after the initial penetration phase. In cases where the initial phase can be neglected, we can put $v_1 = v_0$. Assuming this, we have the following expression for the normalised penetration depth X:

$$X = \frac{x_1(R) + x_{init}}{x_1(R = 0)} \tag{5.3}$$

We see that this equation becomes quite complicated in the general case:

$$X = \frac{\beta_0}{\beta}\frac{\ln\left(1 + \frac{\beta}{\alpha}v_0^2\right)}{\ln\left(1 + \frac{\beta_0}{\alpha_0}v_0^2\right)} + \frac{2s\beta_0\left(\cos\phi_0 - \cos\phi_1\right)}{m\ln\left(1 + \frac{\beta_0}{\alpha_0}v_0^2\right)} \tag{5.4}$$

However, for a hemispherical nose, it simplifies somewhat:

$$X = \frac{1}{(1 - R^2)^2}\frac{\ln\left(1 + \frac{B}{2A}(1 - R^2)v_0^2\right)}{\ln\left(1 + \frac{B}{2A}v_0^2\right)} + \frac{x_{init}}{x_1(R = 0)} \tag{5.5}$$

For low velocities, and ignoring the contribution from x_{init}, Equation (5.4) is easily seen to approach the result of Equation (3.2). This holds true for all nose shapes in the low velocity range.

6 COMPARISON WITH EXPERIMENTAL DATA

Both Folsom and Mostert have performed penetration experiments into concrete targets with pre–drilled cavities of various diameters. In this section we will compare our analytical theory with their experimental data.

However, in order to obtain results from our analytical model, we need to calculate the material constants A and B. These constants will typically depend on the elastic parameters, yield curve and other properties of the corresponding target material. Unfortunately, from both experimental series, the compressive strength σ_c of the concrete is the only target parameter that was measured. Therefore we will use Forrestal's empirical relation (4.3) to estimate A and B for these experiments .

6.1 Experimental data from Folsom

Folsom performed two experimental series, one with 88.7g projectiles of diameter 22 mm, and one with 5.93 kg projectiles of diameter 88.6 mm, both having nose curvature $\psi = 1.25$. Only the experiments with the larger projectiles were performed at roughly the same impact velocity, so we will only compare our analytical theory with them. In this case, the concrete had a compressive strength of 48.5 MPa, a density of 2370 kg/m^3 and the impact velocity was approximately 206 m/s.

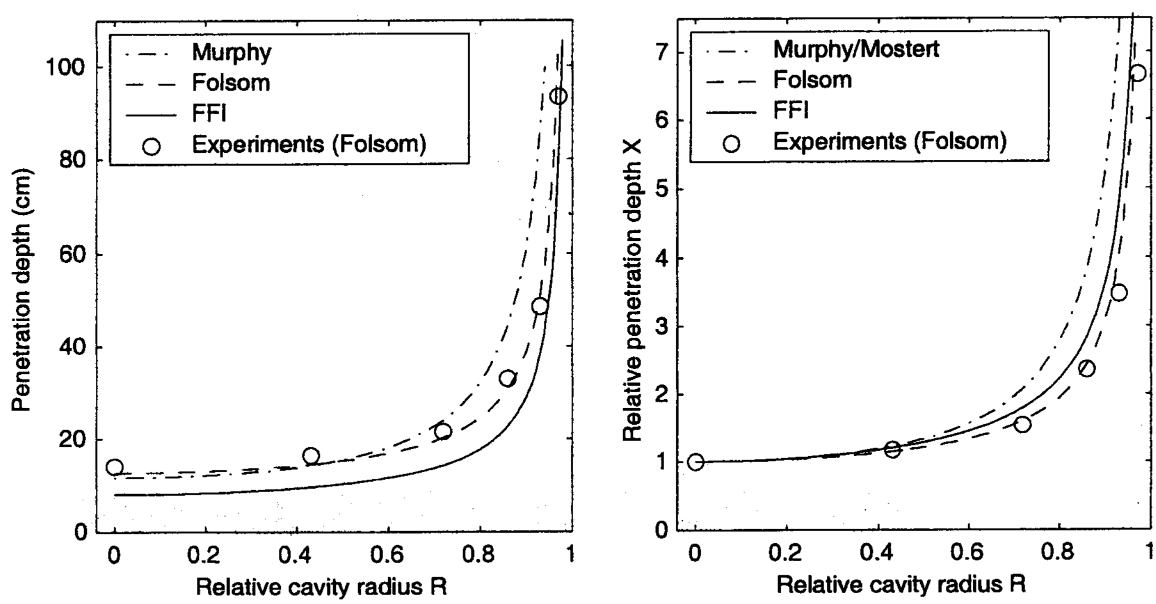

Figure 6.1: Penetration depth as a function of relative cavity radius for an 88.6 mm projectile impacting 48.5 MPa concrete targets.

The diameter of the concrete targets was 40.64 cm, which gives a ratio between target and projectile diameter of only 4.59. This was probably insufficient to stop boundary effects from increasing the penetration depth (12) .

In Figure 6.1 we have plotted the absolute and relative penetration depth as a function of the relative cavity radius R. Murphy's formula is seen to overestimate the penetration depth for large R in both cases, whereas Folsom's formula seems to be pretty accurate, especially for large initial cavities. This is not surprising as Folsom's formula was created on the basis of curve fitting to exactly these experimental data. The cavity expansion approach is seen to consistently underestimate the absolute penetration depth, which is however to be expected if boundary effects were present. It overpredicts the relative penetration depth, which is related to the underprediction of $x(R = 0)$.

6.2 Experimental data from Mostert

Mostert has also performed several experiments with projectiles impacting reinforced concrete targets containing initial cavities of various diameters. According to Mostert (13), the mass of the projectile was $m = 141.6$ g, diameter 20 mm and $\psi = 2.11$. The concrete had a compressive strength of 20 MPa and we have used an estimated density of $2000\ kg/m^3$.

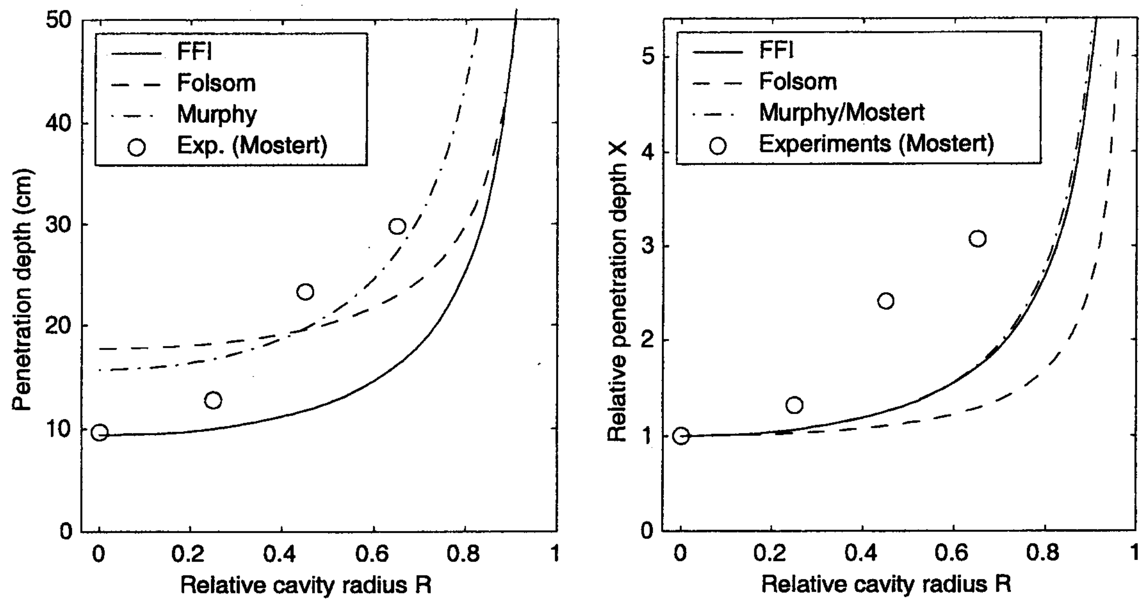

Figure 6.2: Relative penetration depth as a function of relative cavity radius for a 20 mm projectile impacting 20 MPa concrete targets.

His targets were 30 cm thick in all cases. In one of the test series the initial cavity depth was 15 cm, while in the other series the cavity was 30 cm deep, i.e. went right through the target. The targets were rectangular with a front face of 30 × 30 cm. This gives a target/projectile diameter ratio of minimum 15. Boundary effects should therefore not be present in the experiments, except perhaps for large initial cavities when the projectile almost perforated the target.

Mostert fired two shots for each initial cavity diameter, but the same velocity of 350 m/s was not always obtained. In our comparison we have used the data points which were closest to 350 m/s.

In Figure 6.3 we have plotted the results for penetration depth as a function of R. It is seen that none of the formulas agree very well with all the experimental data. The cavity expansion approach, however, is seen to give good result for $R=0$, but underpredicts penetration in the other cases. This could be due our applied concrete model being inaccurate and possible boundary effects at the rear of the target. Folsom's equation is seen to very much underestimate the relative penetration depth.

In Figure 6.4, we have plotted the relative penetration depth as a function of cavity radius, and the picture is slightly different. The cavity expansion theory and Murphy/Mostert's formulas are almost exactly the same, except at very large cavities, while Folsom's equation very much underpredicts penetration depth. Agreement is still not very good, though.

Mostert also performed experiments with 15 cm deep cavities. The cavity expansion based theory can easily be applied to this case as well. If the projectile penetrates deeper than 15 cm, all of the projectile nose will suddenly start interacting with the target. Thus, we can no longer use the modified cavity expansion theory and have to switch to normal theory ($R = 0$).

From Equations (7.14) and (7.16) in (8), we are able to express the projectile velocity as a function of the penetration depth:

$$v(x) = \sqrt{\frac{\alpha}{\beta}}\exp\left(-\frac{\beta x}{m}\right)\sqrt{1 + \frac{\beta}{\alpha}v_1^2 - \exp\left(\frac{2\beta x}{m}\right)} \qquad (6.1)$$

By putting x equal to 15 cm, we can determine the remaining projectile velocity $v(x = 15\ cm)$ when it reaches the bottom of the initial cavity. Calculating the final penetration depth is now equivalent to using the velocity obtained from Equation (6.1) as initial velocity for a projectile penetrating a target with no initial cavity.

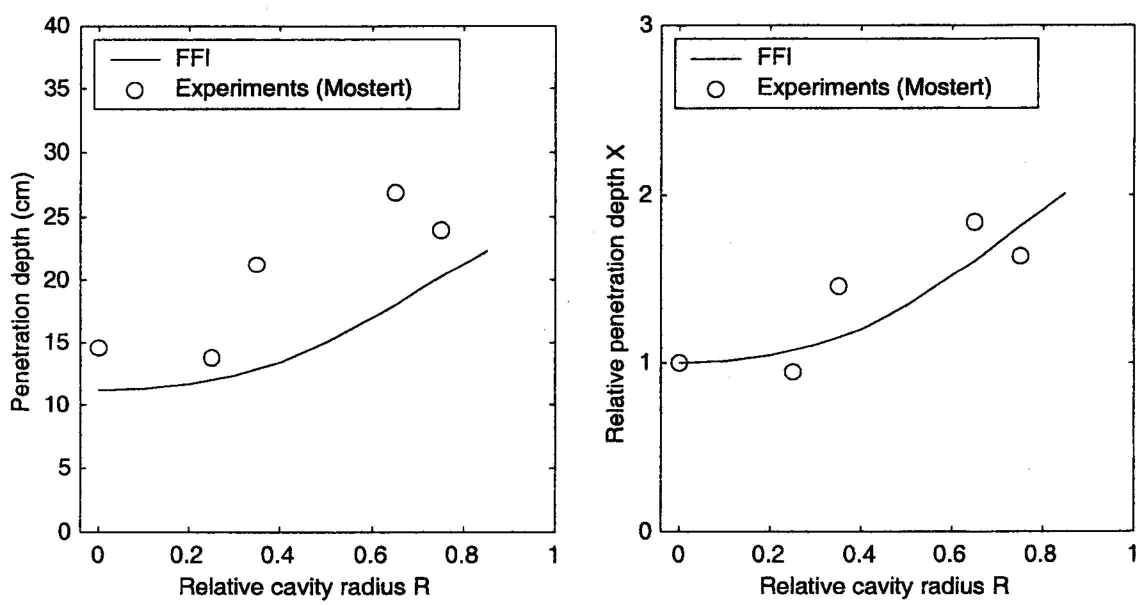

Figure 6.3: Penetration depth as a function of cavity radius for an initial cavity 15 cm deep and a 20 mm projectile impacting 20 MPa concrete targets.

In Figures 6.3 we have plotted the absolute and relative penetration depth as a function of cavity radius compared to Mostert's experimental data. The other formulas were not applicable to this case. It is seen that for the absolute penetration depth, the formula underestimates penetration (which again could be due to boundary effects in the experiments), while the relative penetration depth seems to fit the data quite well. Again this might be explained by the applied concrete model being inaccurate.

7 SUMMARY

We have presented an analytical method for calculating penetration into a target containing a pre–drilled cavity. This should be considered as a first approximation to the full problem of penetration of a tandem charge.

The model has been compared with two sets of experimental data and the results so far indicate that it might be able to predict the penetration depth when an initial cavity is present. However, the accuracy of the model is uncertain since the complete triaxial properties of the concrete used in the experiments were not known, and the material constants of the model therefore had to be estimated through an empirical relation. Also, boundary effects might have been present in some of the experiments, which again makes it difficult to compare the experimental results with the predictions of the model. It is clear that further research and experiments are needed on this topic.

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