Low velocity perforation design of metal plates

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Abstract

This article examines some recent experimental test data on the perforation of mild steel plates having thicknesses $2 \leq H \leq 8$ mm and struck by relatively heavy masses travelling up to about 13 m/s. The plates are fully clamped around circular, square and rectangular boundaries and struck by projectiles having blunt, conical and hemispherical impact faces. It transpires that the dimensionless perforation energies are smallest for the plates struck by the blunt-faced projectiles and largest for the hemispherical ones. The perforation energies are greatest at the plate centre and are smaller near to the supporting boundaries. These latter effects are captured in an empirical equation for the dimensionless perforation energy. This equation provides a lower bound to almost all of the test data on the different plate geometries and impactor shapes and is, therefore, a useful tool for design purposes.
Keywords: perforation, impact, circular plate, rectangular plate, blunt, conical, hemispherical impactors.

1 Introduction

Many empirical equations for the impact perforation of ductile metal plates have been developed over the years since Robins studied the problem in 1742. However, most of these equations have been obtained using experimental data from high velocity tests with relatively light missiles which are of particular interest for military engineers. Nevertheless, there is a large class of practical industrial impact problems which involve heavy masses travelling at relatively low velocities. These impact loadings produce global deformations (e.g., large transverse displacements of the plating) prior to perforation which contrasts with the local shear failures, which often occur at the high impact velocities associated with the existing empirical equations.

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Several well-known empirical equations were compared by Wen and Jones [1] with some experimental data recorded on fully clamped circular mild steel plates, which were impacted by blunt-ended projectiles at the plate centre. The experimental results of Wen and Jones [2] revealed a significant reduction in the perforation energy for impacts near to the supporting boundary of a circular plate. Wen and Jones [2] incorporated this phenomenon into a modification of the new empirical equation which was developed by Wen and Jones [1] for central impacts.

Recently, some experimental results were reported by Jones and Birch [3-5] for the impact perforation of circular, square and rectangular plates subjected to relatively heavy indenters having blunt, conical and hemispherical impact faces. The plates were made from mild steel with thicknesses between 2 mm and 8 mm and were fully clamped around the outer boundaries and struck normally by masses travelling up to about 13 m/s.

It is the objective of this paper to compare some of the experimental results with the predictions of the empirical perforation equation developed by Wen and Jones [1] for the central impact of circular plates by blunt-faced projectiles and with the modification of this equation by Wen and Jones [2] for non-central impacts. Comparisons are also made with the experimental results for the perforation energies of square and rectangular plates together with some observations on the perforation energies of plates struck by masses having conical and hemispherical impact faces.

2 Experimental details

The experimental arrangement for the perforation tests used by Jones and Birch [3-5] is similar to that described by Wen and Jones [1-2]. Suffice it to say that the plates were fully clamped around the outer boundaries of the plate span, which is characterised by a diameter 2R for circular plates and dimensions 2L x 2B (L > B) for rectangular plates. The plate thicknesses (H) are 2, 4, 6 and 8 mm, while the projectiles (mass G) have cylindrical bodies of diameter d with blunt, conical (90° included angle) or hemispherical impact faces. The plates are impacted in a drop hammer apparatus with velocities up to about 13 m/s.

For a given impact scenario (i.e., given plate geometry and striker characteristics), the drop height is increased for each successive test until a transition from wholly ductile deformations to cracking and then complete perforation is achieved. Each individual test is performed on a virgin plate so that four to six plate specimens are used for each impact scenario. The threshold energy for perforation is estimated as the average between the maximum energy, which does not cause perforation, and the minimum impact energy that does.

The mechanical properties of the plates are given in Tables 1 by Jones and Birch [3-5], while the plate geometries, impactor details and experimental results are presented in the remaining tables of these references.

3 Empirical equations

The dimensionless perforation energy is defined as

$$\Omega_p = \frac{GV_p^2/2}{\sigma_y H^3}, \tag{1}$$

where $GV_p^2/2$ is the perforation energy discussed in section 2, V_p is the perforation velocity and G is the striker mass. σ_y is the yield stress for a plate material having a thickness H.

The dimensionless impact location for a circular plate is

$$\xi = r_i/R \tag{2}$$

where r_i is the radial location of the impact position measured from the plate centre and R is the radius of the support.

The dimensionless impact location for rectangular plates is

$$\xi = \left(L^2\,\xi_x^2 + B^2\,\xi_y^2\right)^{1/2} / \left(L^2 + B^2\right)^{1/2}, \tag{3}$$

where $\xi_x = x_i/L$, $\xi_y = y_i/B$ and x_i and y_i are the coordinates of an impact location measured from the plate centre along the length (x) and breadth (y) axes, respectively. 2L is the length of a rectangular plate and 2B is the breadth ($B < L$).

The dimensionless empirical equation (8) (Wen and Jones [1]), which was developed for the perforation of mild steel plates fully clamped around a circular boundary and struck by blunt-faced impactors at the centre, may be written in the present notation as

$$\Omega_p = (\pi/2)(d/H) + 2(d/H)^{1.53}\,(S/d)^{0.21} \tag{4}$$

where S is the plate span. The span is taken as $S = 2R$ for a circular plate and in Reference [4] as $S = 2B$ for square and rectangular plates.

Equation (4) was modified Wen and Jones [2]) to predict the dimensionless perforation energy of a circular plate struck at any impact position characterised by ξ, given by equation (2), and may be written in the dimensionless form

$$\Omega_p = (\pi/2)(d/H) + 2(d/H)^{1.53}\,\{S(1-\xi)/d\}^{0.21}\ . \tag{5}$$

Equation (5) reduces to equation (4) for central impact ($\xi = 0$) and again was developed for blunt-faced impactors striking circular mild steel plates. However, it is used by Birch and Jones [4] for predicting the perforation energy of square and rectangular plates when substituting $S = 2B$.

4 Experimental results

The predictions of equation (5) are compared in Figure 1 with the experimental perforation energies (Jones and Birch [3]) which were obtained on 8 mm thick circular plates with 2R = 203.2 mm and struck by blunt impactors (O). It is evident that equation (5) follows the trend of the experimental data, but predicts dimensionless perforation energies which are about 10 per cent larger.

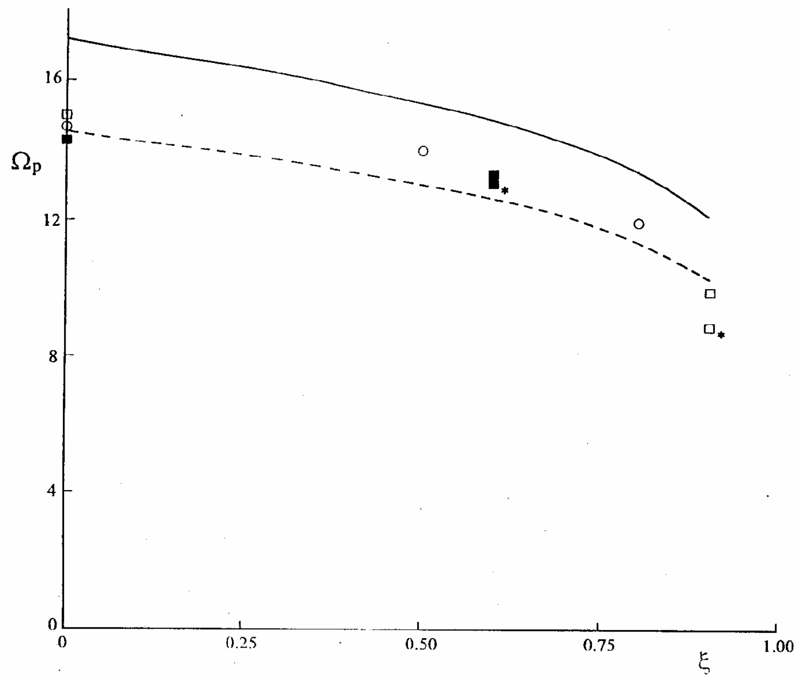

Figure 1: Dimensionless perforation energies for 8 mm thick circular and square smild steel plates fully clamped around the boundaries and struck at several positions across the span by blunt impactors.

——————: equation (5), S/d = 10, d/H = 2.5

- - - - - - - - - - -: 0.85 x equation (5), S/d = 10, d/H = 2.5

experimental results: O; circular plates, 2R = 203.2 mm
S/d = 2R/d = 10, d/H = 2.54 [3]

□; square plates, 2L = 2B = 200 mm
S/d = 2B/d = 10, d/H = 2.5 [4].

■; square plates, 2L = 2B = 200 mm
S/d = 2B/d = 9.84, d/H = 2.54 [4]
$*\xi_x = \xi_y$

Also shown in Figure 1 are data reported in Reference [4] for two sets of tests of 8 mm thick square plates with 2L = 2B = 200 mm (□, ■). It is observed that the dimensionless perforation energies of the circular and square plates having similar values of S, H and d are virtually indistinguishable from a practical perspective. Thus, Figure 1 suggests that equation (5) could be used to predict the dimensionless perforation energies for both circular and square fully clamped plates which have the same values of d/H and S/d. The results in Figure 1 and in Wen and Jones [2], Jones and Birch [4-5], as well as equation (5), illustrate the importance of catering for the significant reduction in the dimensionless perforation energy near to a support or a ‘hard point’.

The comparison in Figure 2 between equation (5) and the experimental data recorded on 4 mm thick circular mild steel plates with 2R = 101.6 mm struck by blunt impactors (Jones and Birch [5]) (■) is similar to that observed in Figure 1. Figure 2 also contains experimental results on rectangular plates (□) with 2B = 100 mm having the largest aspect ratio (L/B = 2.5) studied in Reference [4]. It transpires that the perforation energies of the rectangular plates are closer to the predictions of equation (5) for the larger values of ξ.

It is evident from a practical viewpoint that the comparisons in Figures 1 and 2 suggest that the dimensionless perforation energies are independent of the actual plate shape and depend only on the dimensionless span, S/d, for given values of the remaining parameters d/H and ξ.

Figure 2 also contains the dimensionless perforation energies for fully clamped circular plates subjected to impactors having conical (90^o included angle) and hemispherical impact faces designated by the symbols ▼and ◆, respectively. Similar experimental values are also presented for the impact perforation of rectangular plates (▽, ◇). It is observed that the experimental results for the conical impactors are similar for the circular and rectangular plates with S = 2R ≅ 2B. However, there is a noticeable difference between the two sets of results for the hemispherical shaped impactors.

It is evident from the experimental results presented in Figure 2 that a blunt-faced impactor perforates a plate with the least dimensionless energy, while a hemispherical one requires the greatest energy. The dimensionless perforation energy associated with a conical impactor is somewhat less than that required by a hemispherical one; but it is greater than that associated with a blunt-faced impactor.

Thus, the results in Figure 2 and those reported by Jones and Birch [3-4] reveal that, over the range of parameters studied, a blunt-faced impactor produces the most critical design requirement for fully clamped mild steel plates with thicknesses $2 \leq H \leq 8$ mm and subjected to impact velocities up to about 13 m/s. In this circumstance, equation (5) could be used for critical safety designs and if multiplied by a factor of 0.85 would produce a lower bound to the dimensionless perforation energies of almost all the experimental data reported in References [3] and [4] for circular, square and rectangular plates struck by blunt, conical and hemispherical impactors.

It should be noted that the predictions of several other well-known empirical equations (SRI, BRL, Neilson, Jowett) have been examined by Wen and Jones [1] and Jones and Birch [3-4], for the relatively large mass-low velocity impact perforation of interest in this manuscript. It transpires that equation (5) provided the most consistent results over the entire range of parameters studied and for impact velocities up to about 13 m/s. Further details and observations on the experimental programme from which the data in this article is taken are offered by Birch and Jones [3-5].

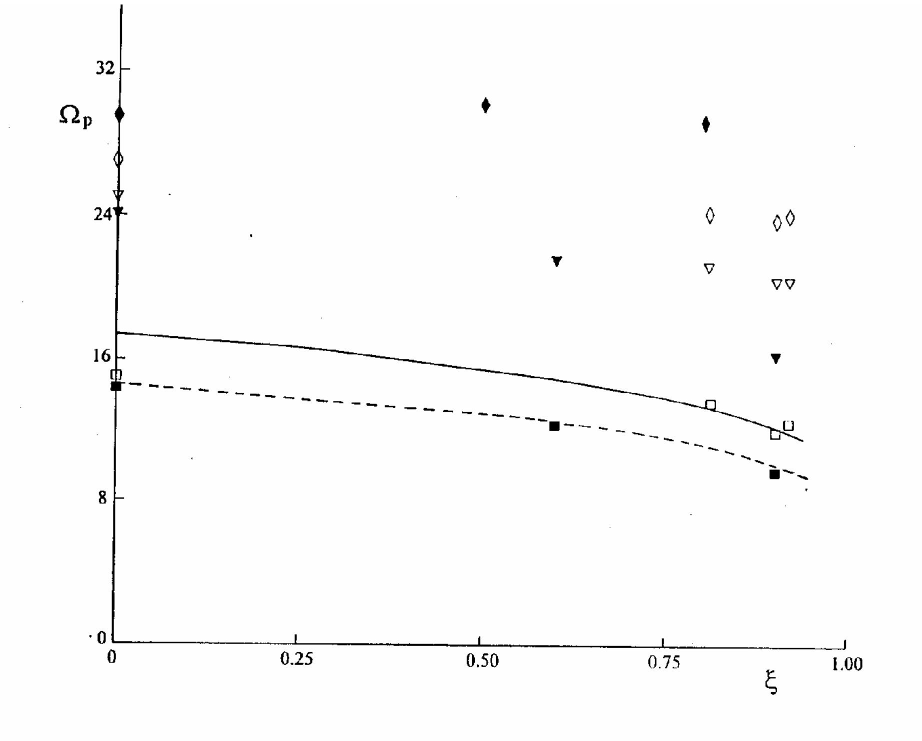

Figure 2: Dimensionless perforation energies for 4 mm thick circular and rectangular mild steel plates fully clamped around the boundaries and struck at several positions across the span by impactors having blunt, conical and hemispherical impact faces.

————————: equation (5), S/d = 9.84, d/H = 2.54

- - - - - - - - - - -: 0.85 x equation (5), S/d = 9.84, d/H = 2.54

experimental results: □, ▽, ◇; rectangular plates (2L = 250 mm, 2B = 100 mm) struck by blunt, conical and hemispherical impactors, respectively. S/d = 9.84, d/H = 2.54 [4].

■, ▼, ◆; circular plates (2R = 101.6 mm) struck by blunt, conical and hemispherical impactors, respectively. S/d = 10, d/H = 2.54 [3, 5].

5 Conclusions

This article examines the low-velocity perforation of mild steel plates caused by masses which are heavy relative to the corresponding plate mass and travelling at impact velocities up to about 13 m/s. It transpires, for plates between 2 and 8 mm thick, that a projectile having a cylindrical body and a hemispherical impact face requires the greatest energy for perforation, while a blunt-faced missile perforates a plate with the least energy. A conical-faced indenter requires somewhat less energy than a hemispherical one, but more than a blunt-faced projectile. It was observed that important global displacements were produced before perforation in these low-velocity tests. Moreover, the dimensionless perforation energy was independent of the shape of the external boundaries studied (circular, square and rectangular) and it was observed that the minimum span, S, could be used to characterise the perforation energy of the different plate shapes.

An empirical equation (equation (5) multiplied by 0.85) was shown to provide a lower bound prediction for the perforation energy of almost all the present experimental data for all plate geometries and indenter shapes. Thus, this formula appears suitable for the design of mild steel plating subjected to heavy projectiles which cause perforation at low velocities. The formula also captures the reduction of perforation energy of impacts near to a supporting boundary.

Notation

d	diameter of projectile
r_i	radial distance of impact location from centre of a circular plate
x_i, y_i	coordinates of impact location in a rectangular plate
$2B$	breadth of rectangular plate
G	projectile mass
H	plate thickness
$2L$	length of a rectangular plate ($L > B$)
R	outside radius of a circular plate
S	span
V_p	perforation velocity
ξ	dimensionless impact location defined by equations (2) and (3) for circular and rectangular plates, respectively
ξ_x, ξ_y	x_i/L and y_i/B, respectively
σ_y	yield stress of plate material
Ω_p	dimensionless perforation energy defined by equation (1)

Acknowledgments

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