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Equivalent concrete thickness for perforation of mild steel plates

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ABSTRACT

Estimating experimentally the equivalent concrete thickness for perforation of mild steel plate targets subjected to hard projectiles (regardless the steel plate will be used as steel linear or not) was the aim of this study. The paper presents the experimental results on perforation of plain concrete panel targets of different thicknesses (100–600 mm) in addition to experimental results on perforation of mild steel plate targets tested under the same circumstances. Twenty-seven shots of hard projectiles perforation test on plain concrete and mild steel plates were conducted (some of these experiments have been presented before). Two formulae relating the perforation resistance of mild steel plate to an equivalent concrete thickness are proposed; one for converting a thin steel liner to an equivalent concrete thickness, and the other for replacing a steel plate target with an equivalent concrete target (and vice versa). Both formulae are influenced by the concrete strength, mass and diameter of projectile.

1. Introduction

An important aspect in the design of concrete barriers against missiles is to minimize the concrete barrier thickness, spalling and scabbing phenomena at the faces of its walls. One way to solve this design aspect is to replace the concrete barrier with steel barrier. To do so, estimating the equivalent concrete thickness for perforation of mild steel plate targets subjected to hard projectiles is a demand. To the best of authors' knowledge, there is no published formulae intended to relate the perforation resistance of plain concrete target with that of steel plate target (and vice versa) each standalone against missile impact. The only available formulae are relating the perforation resistance of a thin steel plate liner to an equivalent concrete thickness.

Second way to minimize the concrete barrier thickness is to attach protective plates, commonly made of steel, to the rear faces of protective walls. Lining the rear face of walls by a steel plate can efficiently help blocking the scabbing fragment and protecting the inner human and equipment from injury or damage under the impact of projectiles. Based on many experimental and analytical studies, UKAEA [1] reported that rear steel plates attached to a concrete wall improve its perforation and scabbing resistance. These steel plates apparently have a restraining effect on the projectile due to several factors. First, the rear steel plate acts as an additional tension membrane on the back face, stiffening the wall. Its presence retains concrete pieces which retard the passage of the missile. Finally, the rear steel plate provides an amount of resistance by itself. Therefore, a measure of this resistance was required [2]. Front steel plate acts, if it is thick enough, as an additional compression membrane on the front face and its presence can efficiently help restraining the front face damages and blocking the spalling fragment. Perforation tests for concrete barriers with steel plate liners, [2–8] showed that the rear steel liner can restrain the rear face damage and improve the perforation resistance of the composite target efficiently.

There are many empirical and analytical equations to calculate the required concrete barrier thickness to prevent local failure due to missile impact. To apply these equations to concrete barriers with a steel plate liner, some recommend converting the thickness of steel plates to equivalent thickness of concrete [1,2,4,9–11].

It can be noted from all the above studies and others, that the attention was focused toward the equivalent concrete thickness for perforation of a steel plate as a liner and not as a separate target.

This study presents an attempt to experimentally determine the equivalent concrete thickness for perforation of mild steel plate targets subjected to hard projectiles, regardless the steel plate will be used as a steel linear or not. The paper presents the experimental results on perforation of plain concrete panel targets of different thicknesses (100–600 mm) in addition to experimental results on perforation of mild steel plate targets of total thickness up to 60 mm tested under the same circumstances. Also, an attempt to propose a formula relating the perforation resistance of a mild steel plate to an equivalent concrete thickness is presented.

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Table 1
Mechanical properties of the projectile [12].

Weight (g)	Brinell hardness number (HB)	Yield strength (MPa)	Ultimate strength (MPa)	Strain at fracture (%)
175	475	1726	1900	7

2. Experiments

Comparative tests were conducted on mild steel and concrete panel specimens that were subjected to an impact of similar hard steel projectiles, accelerated to different velocities. The projectile, with a blunt-nose, was 23 mm in diameter, 64 mm long and weighed 175 g. The use of the same projectile in all the experiments (plain concrete panel and steel plate targets) at velocities that were controlled enabled comparison of their response, which was evaluated according to their perforation resistance, the response of panels under impact load was indicated through if the perforation had happened or not.

All the mild steel plate targets (specimens) were with dimensions of 500 × 500 mm^2 of 30, 50 and 60 mm thicknesses. The steel plate targets of thickness 60 mm was either two steel plates of 30 mm thickness (30 + 30) or one steel plate of 50 mm thickness and the other of 10 mm thickness (50 + 10). It should be noted that the experimental data for mild steel plates has been presented before [12], and is therefore mainly given for comparison. The tested concrete targets were plain concrete panels with the same dimensions of steel plate targets (500 × 500 mm^2) and of 100, 150, 200, 250, 350, 400, 500, and 600 mm thicknesses.

2.1. Setup

The impact penetration tests were conducted in the laboratory setup [7]. The projectiles were launched from a 23 mm powder gun that was mounted on a rigid mount. The gun can launch projectiles with velocities of about 980 m/s or less. The projectile impact velocity was measured with electro optical velocity measurement device. Test specimens (concrete and steel) were mounted on stationary stiff steel frame at distance of 50 m in front of the gun and rigidly clamped around the periphery, such that a square of dimensions 400 × 400 mm^2 was exposed.

2.2. Materials

The projectile was made of hard-steel alloy with a blunt-nose. The mechanical properties of the used projectile and mild steel plates are shown in Tables 1 and 2, respectively.

All plain concrete panels were made of concrete of a specified nominal compressive strength, f_{cu} of 26 MPa ($f_c = 0.8 f_{cu} = 20.8$ MPa [7]), slump of 85 mm and coarse crushed dolomite aggregates of 10 mm maximum size. The cement was type I Portland cement conforming to ASTM C150-89, and its content was about 350 kg/m^3 and the water/cement ratio was about 0.57. The concrete was cast in the same way in all specimen types in horizontal forms. Mix proportion and mechanical properties of the concrete for the panels are shown in Table 3.

Table 2
Mechanical properties of mild steel plates [12].

Density (kg/m^3)	Brinell hardness number (HB)	Yield strength (MPa)	Ultimate strength (MPa)	Strain at fracture (%)
7850	102	240	360	20

Table 3
Mix proportions and mechanical properties of the concrete.

Cement (OPC) (kg/m^3)	Coarse aggregate (dolomite) (kg/m^3)	Fine aggregate (sand) (kg/m^3)	Water (liter/m^3)	Slump (mm)	Compressive strength[a] (MPa)	Flexural strength[a] (MPa)
350	1100	760	200	85	26	4.6

[a] Compressive and flexural strength was the test results of 150 × 150 × 150 mm^3 cubic and 100 × 100 × 500 mm^3 beam specimens after 28-day, curing (20 ± 5 °C, R.H. 95%).

3. Experimental results and discussion

3.1. Steel plates and assessment of test results with the commonly used formulae

Experimental results (impact velocity, failure state; perforated or not and the damage after impact) of 30, 50 and 60 mm thickness steel plates are shown in Table 4, it can be seen that the projectile did not perforated the 30 mm thick steel plate (specimen S30A) at impact velocity of 355 m/s while perforation occurred at impact velocity of 604 m/s for specimen S30B. The impact velocity of 955 m/s could perforate the 50 mm thick plate. The double layer 60 mm thick plates (S60A and S60B) did not perforated at impact velocity of 960 and 962 m/s. The impact velocities against the steel plate thicknesses are shown in Fig. 1; the cases where the plate stopped the projectile (no perforation) are drawn as red circles, the green circles are drawn for perforation cases.

To estimate the perforation velocities (perforation limits) of steel plates, a number of commonly used formulae have been used. These formulae are listed below [12].

1. Taylor [13,14]

$$V_P = \sqrt{\frac{2.66\pi\ r_p^2 h_o \sigma_y}{m}} \tag{1}$$

2. Ballistic Research Laboratory (BRL) [9,15]

$$V_P = \sqrt{\frac{2.88 \times 10^9\ h_o^{1.5} d^{1.5}}{m}} \tag{2}$$

3. Bethe [13,16]

$$V_P = \sqrt{\frac{4\pi\ r_p^2 h_o \sigma_y}{m}} \tag{3}$$

4. Woodward [17]

$$V_P = \sqrt{\frac{2}{m}} \sqrt{\frac{\pi}{2} r_p h_o \sigma_y \left(r_p + \frac{\pi}{2} h_o \right) + 1.42\pi \sigma_y h_o \left(\frac{h_o}{1.81} \right)^2} \tag{4}$$

5. Gupta and Madhu [18]

$$V_P = K h_o^2 \tag{5}$$

6. Gupta et al. [19]

$$V_P = \sqrt{\frac{kdY}{m}}\, h_o^n \tag{6}$$

7. Chen and sLi [20], for intermediate thick plates