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Resistance of high strength concrete plates to hard projectiles impact

Dancygier, A.N., Yankelevsky, D.Z., Ben-Menashe, Y.
National Building Research Institute, Haifa, Israel

ABSTRACT: The response of Regular and High Strength Concrete (RSC and HSC) plate specimens with a variable reinforcement ratio to an impacting projectile was studied experimentally and analytically. The experimental part of the study included a comparison of the response of 40 x 40 cm plate specimens to a local impact of a projectile. The effect of the concrete strength and of the reinforcement ratio was studied. The cylindrical steel projectile, weighed 165 gr (including the sabot), and had a sharp conical nose with a 1.4 aspect ratio. It was accelerated by a gas gun to velocities that ranged from ~150 to ~250 m/sec, measured by an electro-optical device. The results are compared with the theoretical values predicted by the classical perforation NDRC formula. The influence of the reinforcement ratio is also examined analytically by incorporating this parameter as a variable in this formula.

1 INTRODUCTION

Nuclear power plants structures and protective structures are commonly designed to impact loading caused by projectiles or missiles travelling at velocities ranging from ~200 m/sec in the first case, to over 1000 m/sec in the second case (e.g. US NRC 1977; HDA 1986). Under these conditions reinforced concrete elements are subjected to scabbing at the rear face, which reduces their effectiveness as protective structures. A common recommendation to improve the plate response is to use closely spaced reinforcement bars near the rear face of the element (e.g. HDA 1986), where reflected tension waves developed and generate scabbing. The steel bars reinforcement is not expected to prevent scabbing, and its major contribution is to limit the damaged zone depth and the size of the concrete fragments. The element performance against perforation may be influenced, however, by both the concrete strength and amount of reinforcement. The current penetration equations consider concrete strength, based on experimental data with Regular Strength Concrete (RSC) only. The reinforcement ratio is assumed to have a small effect and is commonly disregarded (e.g. Slitter 1980).

In the current study a series of comparative penetration tests were conducted, where RSC and High Strength Concrete (HSC) plates with different reinforcement ratios were subjected to an impact of a hard accelerated projectile. The influence of concrete strength and reinforcement ratio on the elements response was studied.

2 EXPERIMENTAL STUDY

2.1 *Experimental Setup*

The tests were conducted in a laboratory setup, shown in Fig. 1. The impact load was generated by 25 mm diameter steel projectiles, that were accelerated by a gas gun system, with a 50 mm diameter barrel. The projectiles were set inside the gun's barrel by a sabot made of two hard plastic rings that weighed 40 ~ 45 gr. The cylindrical heat treated steel projectiles, weighed 165 gr (including the sabot), and had a sharp conical nose with a 1.4 aspect ratio. Measurements of the projectiles' velocities were taken by an electro-optical device, which consisted of two infra-red light emitting diodes (LED) and two matching receivers, located at a fixed distance from each other. The target was mounted on a stationary fixture in front of the gun, and all the plates were simply supported against lateral displacements.

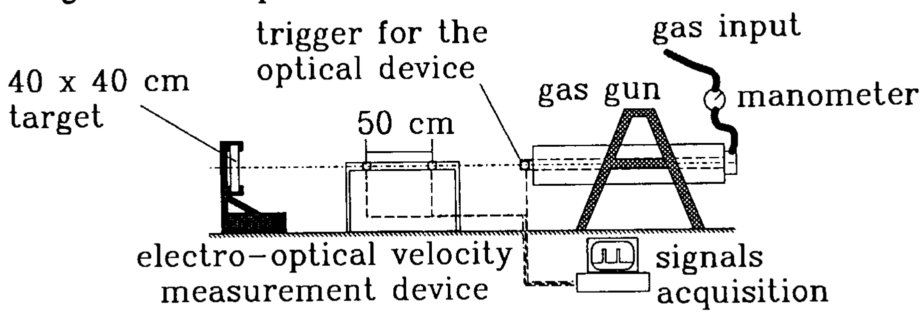

Figure 1: Scheme of the test set-up

2.2 *Test Plan*

The tested specimens were 5x40x40 cm plates, made of two types of concrete: RSC with an average compressive strength of 35-39 MPa (measured in uniaxial compression tests of 7x7x7 cm cubes) and tensile strength of 3 MPa (measured in splitting tests of 10x25 cm cylinders), and HSC with an average compressive strength of 112 MPa and tensile strength of 6 MPa. The reinforcement consisted of fence meshes and conventional re-bar meshes, with diameters of 0.5 to 5 mm, and variable spacings, yielding reinforcement ratios that varied from 0.16% to 1.82% (in each direction), and are detailed in Table 1. After being impacted by the projectile, the plates were examined visually. The crater dimensions and type of the damage (perforation or scabbing), were documented. *Perforation* was defined as the case when the projectile fully penetrated the specimen. When the projectile was stuck in the punched plate it was considered as a *perforation limit*.

2.3 *Results*

All the plates were scabbed, but some were also perforated. The tests results, which are summarized in Table 1, show the influence of the different parameters on plates perforation resistance: The *effect of concrete strength* is demonstrated by the higher velocities required to cause full penetration of the projectile through the HSC specimens (e.g. compare A3-5-R and A2-5-H). However, larger craters and more transverse cracks were observed in the HSC specimens, indicating a more brittle behavior.

Table 1. Specimens details and response.

Plate	Reinforcement: Mesh details (each way)	Mesh type	ρ (%)	Yield stress (MPa)	Concrete strength (MPa)	Projectile velocity (m/sec)	RESPONSE OF THE PLATE: Perfo-ration	Crater dimensions (mm)	Radial cracks	Transv-erse cracks
A4-5-R	$2\phi 0.5@7$	W1	0.16	183	35	158	P	190x200	2	4
A4-5-H	$2\phi 0.5@7$	W1	0.16	183	112	206	P	180x220	-	5*
A3-5-R	$\phi 2.5@34$	W2	0.36	382	35	165	PL	170x190	[2]	[3]
A2-5-H	$\phi 2.5@34$	W2	0.36	382	112	215	PL	180x200	-	7
A8-5-R	$\phi 2@16$	W2	0.49	316	39	160	-	180x200	[5]	[3]
A8-5-H	$\phi 2@16$	W2	0.49	316	112	208	-	200x200	-	4
A2-5-R	$\phi 3@25$	W2	0.71	382	35	204	P	160x160	-	[1]
A7-5-R	$\phi 4@34$	W2	0.92	316	39	171	-	160x170	[3]	[1]
A7-5-H	$\phi 4@34$	W2	0.92	316	112	170	-	170x200	[3]	[3]
A5-5-R	$\phi 5@27$	W3	1.82	534	39	221	P	150x180	[1]	[3]
A5-5-H	$\phi 5@27$	W3	1.82	534	112	246	-	160x220	1	3
A6-5-R	$\phi 5@27$	W4	1.82	473	35	191	P	160x190	-	-
A6-5-H	$\phi 5@27$	W4	1.82	473	112	225	PL	190x220	-	-

Mesh type: W1 - woven smooth wires in two layers, 10 mm apart; W2 - woven fence mesh; W3 - non-woven, non-welded, cold-worked bars; W4 - same as W3 but deformed bars.
Perforation: P - full penetration of the projectile through the plate;
PL - perforation limit.
Cracks: number of observed cracks; [#] - fine cracks (less than 1/2 mm thick).
* the specimen was broken into 5 pieces

The specimens perforation velocities were also influenced by the *amount of reinforcement*: higher velocities were required to perforate plates with higher reinforcement ratios (compare A2-5-R and A7-5-R with A3-5-R). The effects of concrete strength and reinforcement ratio on perforation velocities is shown in Fig. 2.

The relatively larger number of transverse cracks in the specimens with the woven meshes indicates that a larger area of the plate was mobilized by this type of reinforcement to resist the impact. This *effect of the reinforcement type*, was also shown by the response of reinforcement: in comparison to the non-woven A5 and A6 specimens, the woven meshes were symmetrically deformed, indicating a development of a membrane. Finally, since the A5 and A6 plates differ only in the steel properties, it was noted that the specimens with the higher reinforcement strength (A5) yielded higher perforation velocities, although it was not deformed.

3 COMPARISON WITH ANALYTICAL PREDICTIONS

The current tests data were compared with the *perforation limit*, as predicted by the NDRC equation (1946), a classical equation which is commonly found to yield predictions, which are in good agreement with experimental results (e.g. Haldar 1984, Williams 1994). However, although the NDRC equation accounts for the concrete strength, its predictions for HSC extrapolate the experimental basis on which it was developed. Furthermore, this equation (as well as most of the well known penetration equations) does not account for the influence of the reinforcement. To include this parameter in the expression, the NDRC equation was modified, as suggested by Riera (1989), based on the following assumptions: The material parameter affecting the plate response, is more likely to be its tensile strength rather than its compressive strength (Riera 1989). Hence, the concrete strength parameter, which appears in the equation was converted from *compressive* strength to *tensile* strength, using the EC-2 (1992) relation, $f_{ct}=0.3\cdot f_{ck}^{2/3}$, where f_{ct}, and f_{ck} are the average concrete tensile and compressive strength, respectively (f_{ck} is the strength of a cylindrical specimen, which is considered to be ~20% less than the strength of a cubical specimen).

When *perforation* is considered, the influence of the reinforcing mesh will be introduced in the ultimate mode of deformation, after a failure surface (crack) occurs, and activates a dowel action of the reinforcement. In this case, the tensile strength of the material, $f_{ct,eq}$ at ultimate conditions, would be equal to f_{ct} for a relatively low reinforcement ratio, and when the amount of reinforcement is relatively high, $f_{ct,eq} = f_{sy,eq}$, where $f_{sy,eq}$ is the effective tensile strength, determined by the reinforcement, and is equal to $f_{sy}\cdot(A_s/A)$. A_s is the area of the steel, which is perpendicular to the failure surface (the reinforcement cross sectional area, according to the above assumptions), A is the area of the failure surface, and f_{sy} is the steel (or reinforcement) tensile yielding stress.

Assuming a conical failure surface as described in Fig. 3, with a reinforcement ratio ρ in each direction, it can be shown that $f_{sy,eq}$ is given by:

$$f_{sy,eq} = f_{sy}\,\rho\left(\frac{d_s}{h}\right)\frac{\left(\frac{d}{h}+2\left(\frac{d_s}{h}-\frac{x}{h}\right)\tan\alpha\right)\cos\alpha}{\left(1-\frac{x}{h}\right)\left(\frac{d}{h}+\left(1-\frac{x}{h}\right)\tan\alpha\right)} \tag{1}$$

where d is the projectile diameter, x is the penetration depth, and the other parameters are shown on Fig. 3. Note that the above modification may be applied also in other penetration equations that use the material strength as a parameter. For a conical failure surface with $\tan(\alpha)=2$, the NDRC equation, modified according to the procedure described above, was plotted in Fig. 4 and 5, and together with the tests results in figure 2. It can be seen that the prediction of the equation is conservative, but the modification yields a trend that agrees with the tests results. Figures 4 and 5 show the influence of the reinforcement ratio on the perforation depth: For RSC, a reinforcement ratio below ~1% does not affect the resistance, however, a higher amount of reinforcement enhances its performance against perforation.

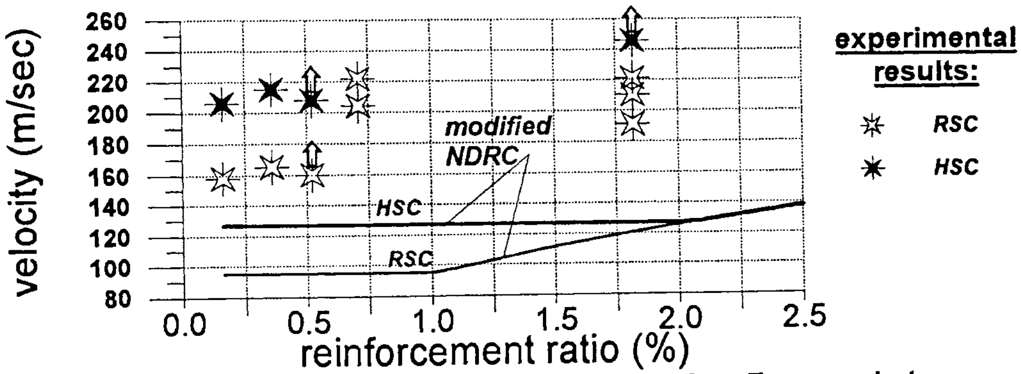

Figure 2: Perforation velocities for 5 cm plates (projectile weight including sabot = 165 gr)

4 DISCUSSION AND CONCLUSIONS

Regular strength and high strength concrete plates with different reinforcement ratios, that were subjected to an impact of a projectile, showed some patterns of response that indicate the behavior of these composite elements. High strength concrete contributes to the enhanced resistance of the plate against dynamic punching action due to impact, but in a brittle manner. It appears that there is an influence of the reinforcement amount, and of the reinforcement mesh type on the resistance of the structural element against perforation.

Comparison of the current tests results with the NDRC predictions for the perforation limit, shows that, for the tested projectile and velocity range, the formula's predictions are conservative, for both concrete strengths. A modification to the formula, which takes into account the influence of the reinforcement ratio is suggested, and shows a trend similar to that observed in the tests. However, this preliminary modification is based on some simplistic assumptions, and needs more refinement.

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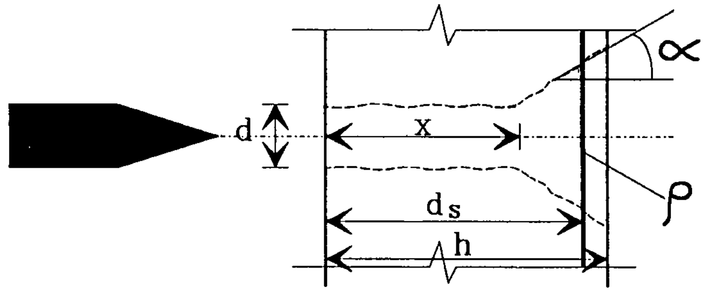

Figure 3: Failure surface at preforation

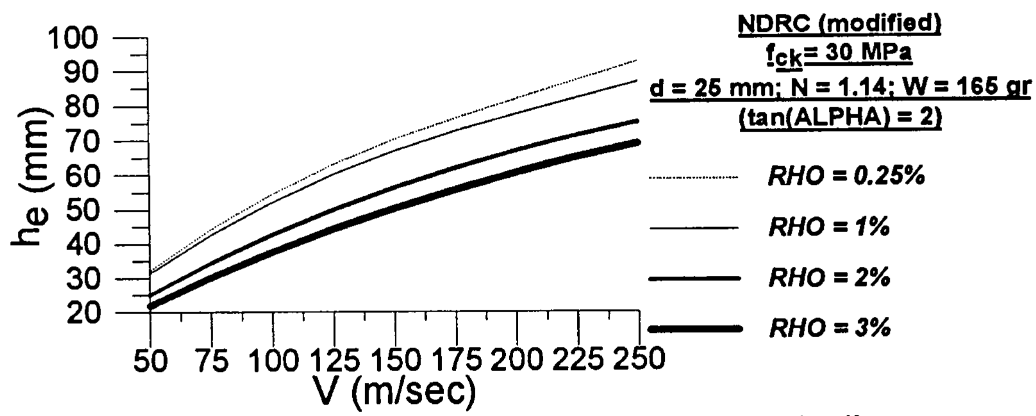

Figure 4: Perforation limit for different reinforcement ratios

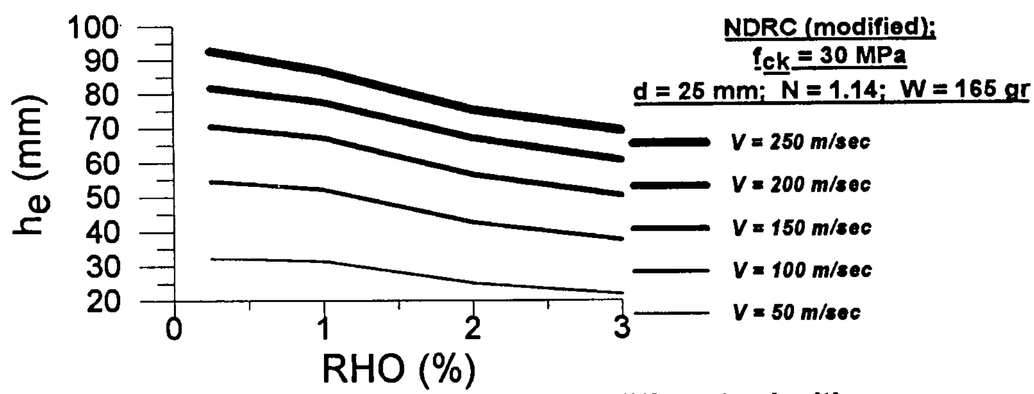

Figure 5: Perforation limit for different velocities