論 文

[2178] ON PERFORATION OF CONCRETE SLABS PRODUCED BY IMPACTS

Wojciech RADOMSKI* and Hiroshi MASUYA**

1. INTRODUCTION

It is known that many of various concrete structures are subjected to impact or impulsive loads, particularly, in most cases these types of loads may occur accidentally. However, the investigations of dynamic behaviours of concrete structural members are rather limited compared to research on their static behaviours, thereby the knowledge on the dynamic problems concerning these members is so far incomplete.

The phenomena produced by the impact loads in the structural concrete elements are very complex. They may be in general characterized as wave and local effects. In this paper the study is focused on the local effects.

The most important local impact effects produced by the missiles in concrete structural elements are the following: *penetration* , *perforation* , *scabbing* and *spalling* .

Penetration is the displacement of missile into the element. It is measured by the depth of the crater formed at the zone of impact.
Perforation means "full penetration". The missile passes through the element with or without exit velocity.
Scabbing is the peeling off from the back face of the element opposite to the impact face.
Spalling is the ejection of material elements from the front face of the element(i.e. the face on which the missile hits).

The paper deals with some problems concerning the perforation of the concrete slabs produced by impact loads. It requires to define so called perforation thickness of a structural element.

Perforation thickness is the maximum thickness of a structural element which a missile with a given impact velocity will completely penetrate. Theoretically, the exit velocity of the missile is equal to zero. For concrete, the perforation thickness is considerably greater than the penetration depth due to scabbing of concrete from the back face of the element. Determination of the perforation thickness for the concrete structural elements is very important for the safety design of many structures in which the impact loads may occur. The perforation thickness

* Department of Civil Engineering, Kanazawa University
(Warsaw University of Technology, Poland)
** Department of Civil Engineering, Kanazawa University

of the concrete structural elements has been determined experimentally so far by various authors and several empirical formulae for prediction of this thickness have been formulated, as discussed below.

2. EMPIRICAL FORMULAE FOR PREDICTING THE PERFORATION THICKNESS OF CONCRETE ELEMENTS

Because of very complex phenomena produced by impacts in the structural concrete elements a theory concerning dynamic behaviour of these elements is not well developed so far ([1],[2]). It particularly concerns the determination of the perforation thickness. The thickness has been mostly determined experimentally. A theoretical approach to this problem has been presented in a few papers only (e.g. [3]).

The missile impacts on the structural elements can be classified as "hard" or "soft" depending on whether the missile deformability is small or large relative to the element deformability [4]. So far majority of experiments performed for the determination of perforation thickness of the concrete elements deals with "hard" impact. All of the empirical formulae based on these experiments are formulated for the case of normal impact, i.e. when the impacting missile strikes normal to the element face. Some of major empirical formulae for the prediction of perforation thicknesses of concrete elements are listed in Table 1. The formulae A-D have been formulated many years ago but they have been analyzed and verified during the last decade in the several papers, e.g. in [5], [6] and [7], where detailed information on limitations concerning the applicability

Table 1 Empirical formulae for prediction of perforation of concrete elements

Ⓐ Modified Petry formula

$$e = 2x \; ; \quad x = 12 K_p A_p \log_{10}\left(1 + \frac{V^2}{215000}\right)$$

Ⓑ Army Corps of Engineers (ACE) formula

$$\frac{e}{d} = 1{,}32 + 1{,}24\,\frac{x}{d} \quad \text{for } 3 \leq \frac{e}{d} \leq 18 \; ; \qquad \frac{x}{d} = \frac{282\,D\,d^{0{,}215}}{(f_c')^{1/2}} \left(\frac{V}{1000}\right)^{1{,}5} + 0{,}5$$

Ⓒ Modified National Defence Research Committee (NDRC) formula

$$\frac{e}{d} = 3{,}19\left(\frac{x}{d}\right) - 0{,}718\left(\frac{x}{d}\right)^2 \quad \text{for } \frac{x}{d} < 1{,}35 \text{ or } \frac{e}{d} \leq 3 \; ;$$

$$G_{\left(\frac{x}{d}\right)} = K N d^{0{,}2} D \left(\frac{V}{1000}\right)^{1{,}80} ; \qquad G_{\left(\frac{x}{d}\right)} = \begin{cases} \left(\frac{x}{2d}\right)^2 & \text{for } \frac{x}{d} \leq 2{,}0 \\ \left(\frac{x}{d} - 1\right) & \text{for } \frac{x}{d} > 2{,}0 \end{cases}$$

Ⓓ Modified Ballistic Research Laboratory (BRL) formula

$$\frac{e}{d} = \frac{427\,D\,d^{0{,}2}}{(f_c')^{1/2}} \left(\frac{V}{1000}\right)^{1{,}33}$$

Ⓔ Commissariat á l'Energie Atomique – Electricité de France (CEA–EDF) formula

$$e = 0{,}82 R_c^{-3/8} \rho^{-1/8} \left(\frac{M}{\phi}\right)^{1/2} V_c^{3/4}$$

Symbols used:

e=perforation thickness; x=penetration depth (crater depth); K_p=coefficient depending on the nature of the concrete (K_p=0,00799 for massive concrete, =0,00426 for normal reinforced concrete, =0,00284 for specially reinforced concrete); A_p=weight of missile/unit projected area, [lb/ft^2]; V=impact velocity of missile, [ft/s]; D=W/d^3; W=missile weight, [lb]; d=missile diameter, [in]; f_c'=ultimate compressive strenght of concrete, [lb/in^2]; $K = \frac{180}{(f_c')^{1/2}}$; N=missile shape factor (N=0,72 for flat nosed bodies, =0,84 for blunt nosed bodies, =1,00 for average bullet nose, spherical end, =1,14 for very sharp nose); R_b= ultimate compressive strenght of concrete [MPa]; ρ=density of concrete [kg/m^3]; M=missile mass [kg]; ϕ=missile diameter [m]; V_c=impact velocity of missile [m/s].

Note: formulae Ⓐ÷Ⓓ = U.S. Customary units; formula Ⓔ = SI units of these formulae, are given.

To the best of the authors' knowledge, the formula E is the newest empirical formula for the prediction of perforation thickness of the reinforced concrete slabs subjected to the impact loads. It has been formulated [8] on the base of the tests covering the following range of variables: ultimate compressive strength of concrete 30-50 MPa, mass of missile 20-300kg, missile velocity 25-200m/s, slab thickness versus diameter of missile 0.34-4.2, percentage of reinforcement μ = 0.8%-1.5%. The density of reinforced concrete has been taken as 2500 kg/m^3 . The missiles with the flat noses have been used. The relationship between the impact missile velocity and the perforation thickness of the reinforced concrete slab according to the formula E is shown in Fig.1 for the following numerical data: mass of missile 50kg and 200kg, ultimate compressive strength of concrete 30MPa, 40MPa and 50MPa, diameter of missile 0.25m. It should be emphasized that since perforation thickness is more dependent on the amount of reinforcing than scabbing or penetration effects, the formula E should not be applied to slabs with much lighter or heavier reinforcing than mentioned above (i.e. 0.8%-1.5%).

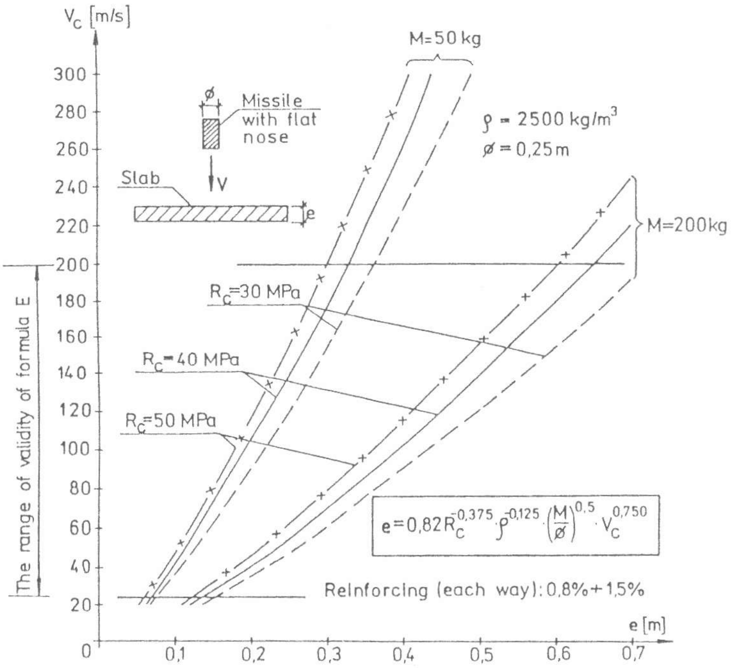

Fig.1 The relationship between the impact velocity and perforation thickness

3. INFLUENCE OF STEEL FIBRE ADDITION ON PERFORATION OF CONCRETE SLABS SUBJECTED TO IMPACT LOADS

There is no doubt that steel fibre reinforced concrete (SFRC) is a particularly appropriate material for applications in the various structures subjected to impact loads. It has been confirmed by the development of such applications during the last few years. However, the tests of the SFRC elements (e.g. the SFRC slabs) under the impact loads are seldom performed. Moreover, it should be emphasized that the results of dynamic tests and theoretical analysis concerning the plain concrete structural members cannot be in general extended to the SFRC members because of the different properties of these materials.

A very interesting test concerning the comparison between dynamic behaviour of the conventionally reinforced concrete (RC) slabs and SFRC slabs subjected to the impact load has been performed by e.g. T.Uchida, H.Tsubata and T.Yamada [9]. They found out that the addition of steel fibres to the concrete slabs with conventional reinforcement for bending is very effective in decreasing the formation of cracks under impact loading.

They also found out that the ratio of energies absorbed in the slabs under impact and static loading reaches almost 2 in the case of RC slabs and is more than 4 when steel fibres are used.

It should be emphasized, however, that no formulae for prediction the perforation thickness of SFRC slabs under the impact loads have not been formulated except for a formula presented in the paper[10].

The perforation problem concerning SFRC slabs has been studied by the one of the authors and M. A. Glinicki. Square slabs of 0.50 × 0.50 m with variable thicknesses from 5 to 25 mm were centrally loaded by steel cylinders with a hemispherical nose of radius 25 mm and masses of 1.495, 2.610 and 4.175 kg. The impact velocity was the same throughout the tests and equal to 7 m/s. Straight, smooth, steel fibres 0.4 × 40 mm were used of 0.5% (15 slabs) and 1.0% (15 slabs) volume fractions. Structural and geometrical parameters of the tested slabs as well as the impact parameters provided a variety of failure modes of the slabs, i.e. from almost "pure" perforation to the perforation accompanied by extensive cracking over the whole surface of the slab. The analytical consideration based on the test results and on the conservation of energy for penetrating missiles has led to the following original formula for the prediction of perforation thickness (h) of SFRC slabs:

$$h_p^{SFRC} = \frac{U}{D[(\pi/\sqrt{3})\lambda f_{fl} u_0 + \eta V_f l \{k_1 (l/d)\tau_f + k_2 f_y\}]} , \qquad (1)$$

where $V = 0.5mv^2$ denotes the kinetic energy of a missile with mass m and impact velocity v. The dimensionless parameters k_1, k_2, p are as indicated follows:

$$k_1 = 1 + (2/\pi), \qquad k_2 = 0.25(\pi + p), \qquad p = S/lD$$

The other symbols are: D, diameter of missile; λ, strain rate factor, equal to 1.2 - 1.3 [11]; f_{fl}, static flexural strength of concrete matrix; u_0, depth of crater formed in the impact zone; η, coefficient of fibres effectiveness, equal to 0.637 for random plane distribution of fibres [12]; V_f volume content of fibres (%); l, d, length and diameter of respectively; τ_f, fibre pull-out strength; f_y, yield stress of steel fibres; S, surface of structural cracks, i.e. product of crack length summed for all the cracks in slab [12].

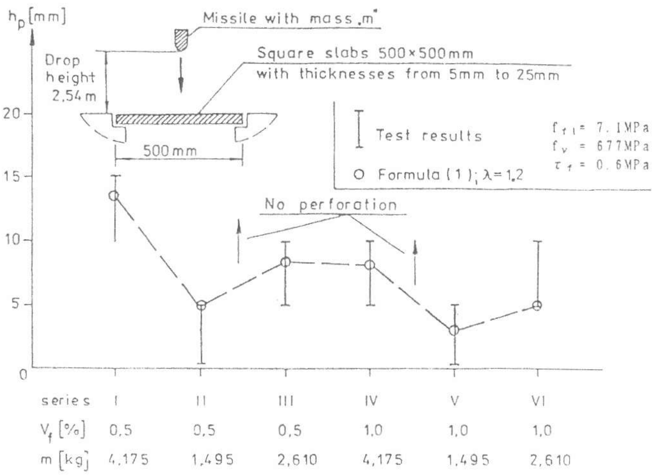

Fig.2 Comparison of calculations and experimental values of perforation thickness

The results of the calculations and experiments are summarized in Fig.2. A good correlation between the test observations and the calculations performed according to formula (1) is obtained. However, the presented formula should be confirmed and verified by further investigation to be valid in many other cases.

The calculations performed by the authors according to CEA-EDF formula (formula E in Table 1) and formula (1) indicate that the perforation thickness of an RC slab is greater than the thickness of an SFRC slab when they both are subjected to impacts with the same energy. This conclusion seems to be very important for both technology and economy, however, it should be confirmed by further investigation.

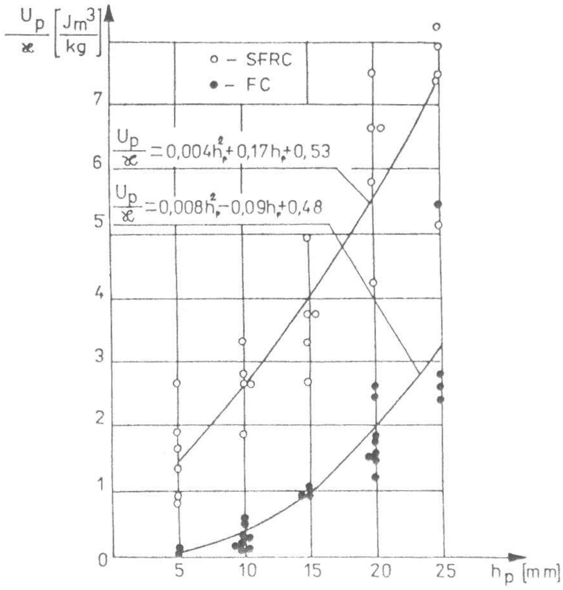

Fig.3 The relationship between the impact energy and perforation thickness

An experimental and analytical comparison between the perforation thicknesses of SFRC and ferrocement (FC) slabs has been performed by one of the authors and J.Grabowski [13]. The geometrical parameters of the slabs and the impact parameters were the same as described previously. Therefore the test results may are directly comparable. However, the different nature of both materials demanded the application of a common and simple base to conduct a comparison between the dynamic behaviour of two kinds of tested slabs. It was assumed that the mass of steel used for reinforcing the slab per cubic meter of this member, i.e. the ratio κ in kg/m^3, was used for such a base. The values of κ corresponding to FC slabs varied from 96 kg/m^3 to 480 kg/m^3 and corresponding to SFRC slabs varied from 39.2 kg/m^3 to 78.4 kg/m^3. It is evident that the values of κ corresponding to FC slabs were much higher than in the case of SFRC slabs. The test results concerning the both kinds of slabs are summarized in Fig.3. The value of the impact energy producing the perforation of slabs (U_p) divided by the ratio κ is plotted versus their perforation thickness (h_p). The results shown in Fig.3 imply rather unexpected. Namely, the effectiveness of used fibres seems to be higher than that of meshes. This results from the fact that the points corresponding to SFRC slabs are plotted in the figure above the points corresponding to FC slabs. This information seems to be very interesting from both technical and economical points of view. However, this problem requires further investigation and more detailed analysis.

4. CONCLUSION

The research problems concerning the perforation of concrete slabs under the impact loads are not well developed, especially in the theory. It is due to the very complex phenomena produced by impacts in these members and due to heterogeneity of the material, particularly in the case of SFRC elements. On the base of the results presented above, the following conclusions can be drawn.

1) The empirical formulae for the prediction of perforation thickness of

the concrete and reinforced concrete slabs have been verified during the last decade and may be useful for applications.
2) In spite of SFRC is a very appropriate material for applications in the various structures subjected to the impact loads, the lack of the formulae for the prediction of perforation thickness of SFRC slabs can be noticed.
3) The author's original formula for the prediction of perforation thickness of SFRC slabs seems to be very promising but requires further experimental verification.
4) As not expected, the steel fibres seem to be more effective than meshes with respect to the perforation toughness of the slabs. However, this observation requires further investigation.

REFERENCES

1) Radomski, W.,"Behaviour of SFRC slabs under dynamic loads," Proceedings of the 5th International Conference on Composite Structures, Ed. I.H.Marshall, Elsevier Applied Science, 1989, pp. 755-768.
2) King, M. W., Miyamoto, A. and Masui, H.: "Failure Criteria and Nonlinear Dynamic Analysis of Concrete Slabs Under Impulsive Loads," Proceedings of JCI Vol.12.2, June 1990, pp.859-864.
3) Berraud, C., Millard, A., Nahos, G., "Perforation of a concrete slab by a missile: finite element approach," Trans.pf the 7th Int.Conf. on Structural Mechanics in Reactor Technology, Chicago, Vol.J, 1983, pp. 373-378.
4) Kennedy, R.P., "A review of procedures for the analysis and design of concrete structures to resist missile impact effects," Nuclear Engineering and Design, Vol.37, No 2, May 1976, pp. 183-201.
5) Chang, W.S., "Impact of solid missiles on concrete barriers," Journal of the Structural Division. ASCE, vol. 107, No ST2, February 1981, pp. 257-271.
6) Degen, P. P., "Perforation of reinforced concrete slabs by rigid missiles," Journal of the Structural Division, ASCE, vol. 106 , No ST7, July 1980, pp. 1623-1642.
7) Sliter, G. E., "Assessment of empirical concrete impact formulas," Journal of the Structural Division, ASCE, vol. 106, No ST5, May 1980, pp. 1023-1045.
8) Berraud, C. et al., "Local behaviour of reinforeced concrete walls under missile impact," Nuclear Engineering and Design, 45(1978), pp.457-469, (in French).
9) Uchida, T., Tsubata, H., and Yamada, T., " Experimental investigation reinforced concrete slabs subjected to impact loading," Trans. of the Int. Conf. on Structural Mechanics in Reactor Technology, Brussels, Vol.J, 1985, pp.173-178.
10) Glinicki M. A. and Radomski, W., "Fracture of steel fibre reinforced concrete slabs produced by impact loads," Proc. of the RILEM Symp. on Development in Fibre Reinforced Concrete, Sheffield, Vol.2, paper6.6, 1986.
11) Hughes, G., "Hard missile impact on reinforced concrete," Nuclear Engineering and Design, vol.77, 1984, pp. 23-35.
12) Brandt, A. M.,"On the optimization of the fibre orientation in cement-based composite materials," Fiber Reinforced Concrete-International Symposium. ed. G. C. Hoff, ACI SP-81, Detroit, 1984, pp. 23-28.
13) Grabowski, J. and Radomski. W."Behaviour of steel fibre reinforced concrete and ferrocement slabs under impact loads," Proc. of the Third International Conf. on Ferrocement, New Delhi, 1988, pp.282-289.