FRACTURE OF STEEL FIBRE REINFORCED CONCRETE SLABS PRODUCED BY IMPACT LOADS

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Synopsis. The paper presents results of impact tests of steel fibre reinforced concrete slabs and an attempt of theoretical analysis of observed phenomena. The influence of fibre content, slab thickness and impact energy upon the structural performance of slabs was investigated. An observed failure pattern involved the formation and movement of cone shaped plug of material. The number and the width of cracks in slabs were found to be fibre content sensitive. An increase of fibre content from 0.5% to 1.0% by volume resulted in an increase of 1.3 to 1.8 times in the number of impacts to failure. Presented attempt of theoretical analysis was based on energy considerations. A simplified model of fracture mechanism provided an expression for the perforation thickness of SFRC slabs that well fitted the test results.

INTRODUCTION

It is known that steel fibre reinforced concrete (SFRC) is a particularly appropriate material for applications in the constructions subjected to dynamic loads, especially to impacts. On the other hand, however, the knowledge on the behaviour of SFRC under impact loads is incomplete up to now due to relatively few studies of this problem compared to research on static properties of the material. The majority of investigations carried out so far has been limited to determination of only one dynamic characteristic of SFRC - its impact resistance. Some aspects concerning the resistance determined by means of different experimental method have been discussed by one of the authors in the previous paper [1].

It should be emphasized that the impact resistance is a very important material characteristic but it is not sufficient for full estimation of the behaviour of SFRC in constructions subjected to impact loads. There is a necessity for it to know the other dynamic properties concerning first of all the dynamic effects produced in the material by blows, such as e.g. waves and local phenomena, dissipation of the impact energy, fracture. Investigations of these problems are not too developed so far. However, during last few years it may be noticed an increase of research interests in this field [2], [3], [4], [5].

Determination of dynamic properties of SFRC requires fundamental investigations, first of all experiments, due to very complicated physical phenomena connected with the action of impact loads and heterogeneity of the material. For that reason the theoretical analysis should be based on the results of tests. Investigations of the forms of the slab fracture produced by impacts are of prime interest in several constructions, like nuclear reactors, bridges, storm barriers and other marine or industrial structures. One of the most important problems concerning the effect of impact loads on slabs is their perforation. This problem has been studied up to now relative to reinforced concrete slabs [6], [7] but the results of these investigations are not in aggreement with test results for SFRC slabs due to different properties of both materials.

The paper presents some results of the experiments performed on SFRC slabs of various thicknesses and steel fibre contents. There is also presented an attempt of theoretical interpretation of the observed phenomena with the aid of fracture mechanics of composite materials.

PROGRAMME OF INVESTIGATIONS

The scope of experiments was to investigate failure mode of SFRC slabs due to impact load as a function of slab thickness and changes of impact energy as well as steel fibre reinforcement.

All specimens were nominally 0.50x0.50 m square slabs of variable thickness h=0.005 m, 0.010 m, 0.015 m, 0.020 m, 0.025 m . The concrete mix proportions by weight based on cement were: cement, 1; sand, 3; water, 0.5. Straihgt smooth steel fibres 0.004x0.04 m were used in volume fractions of 0.5% and 1%. Fiveteen slabs were prepared with concrete mix containing V_f = 0.5% of fibres by volume and another fiveteen slabs were prepared with fibre content V_f = 1.0%. The slabs were tested at the age of seven months. Accompanying control concrete cubes 0.08x0.08x0.08 m as well as beams 0.04x0.04x0.16 m were made to give tha static compressive and flexural strength respectively. The compressive strength f_c and flexural strength f_{fl} values are given in table 1.

The slabs were placed on a square steel frame with a continuous ledge providing about 0.01 m width of support. A tube with an inside diameter of about 0.05 m was used to guide a falling projectile so as to strike the slab

Table 1. Test Results

Series no	Slab thickness	Fibre content	Projectile mass	Impact energy	No. of impacts to failure	Strength compr.	flex.
	h	V_f	m	U	n	f_c	f_{fl}
	m	%	kg	J		MPa	
I	0.005 0.010 0.015 0.020 0.025	0.5	4.175	104	1 1 - - -	43.2	8.0
II	0.005 0.010 0.015 0.020 0.025	0.5	1.495	37	2 3 4 8 8	42.2	6.9
III	0.005 0.010 0.015 0.020 0.025	0.5	2.610	65	1 2 3 4 5	32.6	7.1
IV	0.005 0.010 0.015 0.020 0.025	1.0	4.175	104	1 2 2 5 6	32.6	7.1
V	0.005 0.010 0.015 0.020 0.025	1.0	1.495	37	2 4 8 9 11	32.6	7.1
VI	0.005 0.015 0.020 0.025	1.0	2.610	65	1 4 7 9	32.6	7.1

centre. An available drop height of 2.54 m provided the maximum impact velocity of about 7 m/s. Three steal cylinders with a hemispherical nose of radius of 0.025 m were used as projectiles. The projectiles had masses of 1.495 kg, 2.610 kg and 4.175 kg so as to allow the changes of impact energy. Table 1 shows which projectile was used for each series of slabs tested.

The slabs of series I were subjected to single impact while slabs of other series were impacted repeatedly until failure, i.e. complete perforation, occurred. The number of impact to failure was recorded. Dial gauges were used to measure the crater depth and the width of cracks visible on slab surfaces.

TEST RESULTS

Repeated Impact

The relationship between the slab thickness

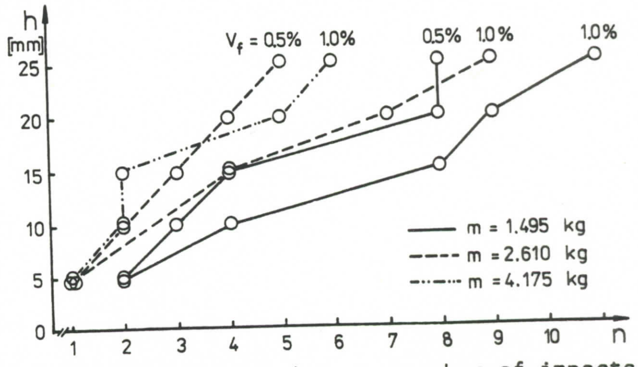


Fig.1 Relationship between number of impacts to failure n and slab thickness h for different fibre contents V_f and projectile masses m .

h and the number of impacts to failure n is illustrated in Fig.1. As expected the influence of slab thickness upon the number

Fig. 2 Failure modes of slabs
a/ series no V, h = 0.025 m, V_f = 1.0%; rear face
b/ series no III, h = 0.025 m, V_f = 0.5% ; front face
c/ series no I, h = 0.005 m, V_f = 0.5%; front face

of impacts to failure was significant. Differences of shapes of each n-h plot were supposed to be due to material non-homogenity, especially due to random distribution of fibres in slabs. A significant influence of fibre content on the number of impacts to failure was found too. The two-fold increase of fibre content, from 0.5% to 1.0%, resulted in the increase of 1.3 to 1.8 times of number of impacts to failure, provided that the same projectiles were used. A more precise evaluation of fibre content influence on the number of impacts to failure can be obtained using X-ray photographs of actual fibre distribution. This analysis is actually being conducted by the authors.

Structural and geometrical parameters of slabs and impact parameters chosen in test provided a variety of failure modes of slabs, i.e. from almost "pure" perforation to perforation accompanied by extensive cracking over the whole surface of slab. Some characteristic exemples are shown in Fig. 2.

In the case of slab thicknesss of 0.020 m and 0.025 m, and fibre content of 1.0% it was observed that formation of a cone-shaped plug of material in the vicinity of impact was followed by its movement and crushing as a consequence of repeated impacts. As far as the thinner slabs of the same V_f are considered it was found that the formation and movement of similar cone-shaped plug was accompanied by circular cracking around the point of impact in a fan pattern. This suggests that a complex failure mechanism, being a result of punching shear stress conditions as well as bending stress conditions, was activated/Fig.2b/.

A similar failure pattern, with circular cracks in a fan form was observed for slabs of V_f = 0.5% irrespective of their thickness. The extent of circular cracks was the greatest for the thinnest slabs, even up to 1/3 of the span /Fig.2c/. Therefore it is difficult to conclude whether this effect should be included in local or rather in global effects.

An overall structural response of slabs resulted in cracks extending towards edges of slabs. A significant contribution of fibres to impede development and progress of cracks was noticed. The cracking was visibly smaller in the case of slabs of V_f = 1.0% in comparison to slabs of V_f = 0,5%. An increase of slab thickness also resulted in smaller and shorter cracks.

The scabbing and spalling phenomena were not observed, although small pieces of concrete of a size of aggregate particles ejected from the rear face were found. The material fracture was due to pulling out of fibres.

Single Impact

Effects of single impact were investigated for projectile masses of 4.175 kg and 2.610 kg Slabs of thickness of 0.005 m and a slab of thickness of 0.010 m were perforated. In the other cases the following effects of single impact were observed:

- formation of a crater of hemispherical shape corresponding to the shape of projectile nose,
- cracking visible on the rear surface of slab in the form of cracks along the diagonals and a circular crack around the impact point, indicating an initial stage of formation of cone-shaped plug of material.

A tendency of decreasing of crater depth /z_c/ with increasing of slab thickness /h/ was noticed /Fig. 3/. A greater crater depth was found to correspond to a greater mass of projectile. However, a significant influence of fibre content on the crater depth was not distinguished. This observation is in an agreement with expectation that effectiveness of fibres should be pronounced only after extensive cracking.

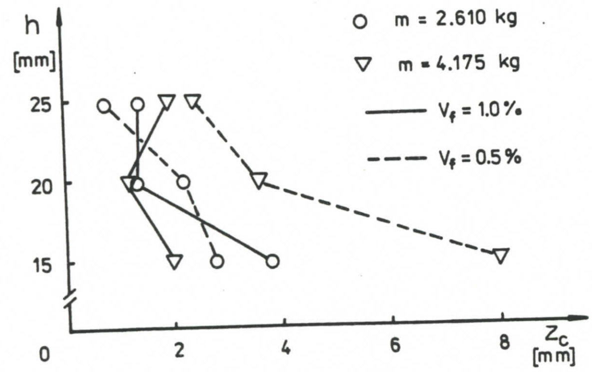


Fig. 3 Relationship between slab thickness /h/ and crater depth/z_c/ due to single impact.

THEORETICAL ANALYSIS OF THE EFFECTS OF SINGLE IMPACT

The perforation thickness of slab subjected to certain impact load is an important parameter in many applications. From among a variety of formulas for perforation thickness of conventionally reinforced concrete slabs /e.g. 8 , 9 / none seems to be directly applicable for SFRC slabs. This is because of differences of material properties and also because none of mentioned formulas includes directly the reinforcement ratio.

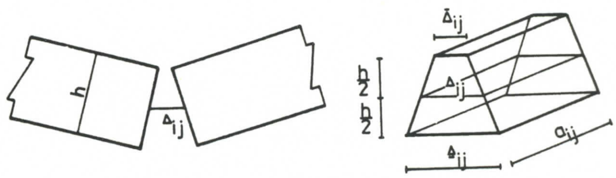
The following attempt to create such formula for SFRC slabs was based on the conservation of energy for penetrating projectille impact. Fracture energy of a SFRC slab was supposed to consist of two parts, namely:

- local fracture energy /W_L/,
- global fracture energy /W_G/.

Static tests of fibre reinforced concrete elements / 10 , 11 / showed that the most important fracture mechanism involved in cracking process is fibre pull-out. Adopting the formulas developed in 11 the following formula for global fracture energy W_G is obtained:

$$W_G = \frac{1}{\pi}\eta V_f\left(2\frac{l}{d}\tau_f + \theta f_y\right)hS_r \,, \qquad /1/$$

where:
η - coefficient of fibre effectiveness, equal to 0.637 for random plane distribution of fibres,
V_f - fibre content by volume,
l, d - fibre length and diameter respectively,
τ_f - fibre pull out strength,
θ - average angle of fibre inclination in relation to a crack,
S_r - surface of structural cracks, i.e. a product of crack length summed for all cracks in slab, f_y - yield stress of steel,
The derivation of this formula was based on the assumption that a real crack in slab can be approximated by a model crack of flat surfaces shown in Fig. 4.



$$S_r = \sum_{j=1}^{r}\sum_{i=1}^{t}\Delta_{ij}a_{ij} \qquad \Delta_{ij} = \frac{1}{2}(\bar{\Delta}_{ij} + \Delta_{ij})$$

Fig. 4 Model of crack in slab section

The local failure energy was evaluated as a summ of energies corresponding to the following mechanisms:

- formation of a cone-shaped plug of material /W_1/,
- movement of the cone-shaped plug relative to the remainder of slab /W_2/.

The model of local failure zone is shown in Fig. 5.

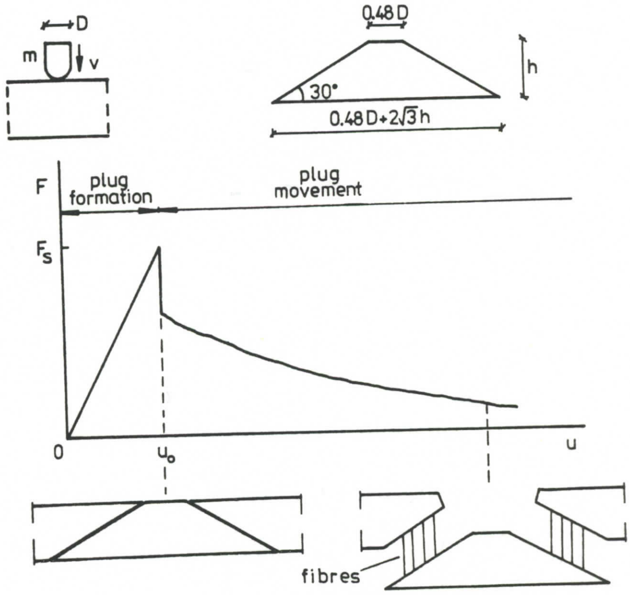


Fig. 5 Model of local failure zone

The zone is assumed to be linearly elastic until formation of a cone-shaped plug of material is completed. The corresponding maximum vertical component of resultant force F_s acting over a surface of cone-shaped plug is obtained:

$$F_s = \frac{2}{\sqrt{3}}f_t S \,, \qquad /2/$$

where:
f_t - concrete tensile strength,
S - lateral surface of cone.
According to 9 the concrete tensile strength can be calculated as follows:

$$f_t = 0.5\lambda f_{fl} \,, \qquad /3/$$

where: λ - strain rate factor, f_{fl} - static flexural strength of concrete.
On the basis of experimental observations the cone shaped plug is modelled as a cone shown in Fig. 5, whose lateral surface is given:

$$S = 2\pi hD(0.48+1.73\frac{h}{D}) \quad , \qquad /4/$$

where D denotes the projectile diameter.
The fracture energy relative to a complete formation of plug equals to the triangular area under the F-u diagram, in which u denotes a vertical displacement of the plug, i.e.:

$$W_1 = \frac{2}{\sqrt{3}}\pi hD(0.48 + 1.73\frac{h}{D}) f_t u_0 \ . \qquad /5/$$

Due to an assumption of nondeformable plug the process of its movement is treated as the process of propagation of diagonal circural crack. Perforation of slab is supposed to occur when all the fibres bridging this diagonal crack are pulled out of the matrix, therefore a movement over an average distance of 1/4 l is required. The following formula for W_2, similar to formula /1/, is obtained:

$$W_2 = \frac{1}{2}\pi hDl(0.48+1.73\frac{h}{D})\eta V_f(\frac{2l}{\pi d}\tau_f + 0.5f_y) \qquad /6/$$

Thus:

$$W_L = \pi hD(0.48+1.73\frac{h}{D})\{\frac{1}{\sqrt{3}}\lambda f_{fl}u_0 + \frac{1}{2}\eta V_f l(\frac{2l}{\pi d}\tau_f + 0.5f_y)\} \ . \qquad /7/$$

Comparing the impact energy to the fracture energy of SFRC slab results in a formula for perforation thickness h_p, which for the sake of simplicity is given in the following linear form:

$$h_p = \frac{U}{D\{\frac{\pi}{\sqrt{3}}\lambda f_{fl}u_0 + \eta V_f l(\kappa_1\frac{l}{d}\tau_f + \kappa_2 f_y)\}} \quad , \qquad /8/$$

where $U = 0.5\ m\ v^2$ denotes the kinetic energy of projectile of mass m and impact velocity v, while the dimensionless parameters are as follows:

$$\kappa_1 = 1+\frac{2}{\pi}p \ ; \quad \kappa_2 = \frac{1}{4}(\pi+p) \ ; \quad p = \frac{S_r}{lD} \ . /9/$$

The parameter p is dependent on the surface of structural cracks in slab, therefore h_p can be estimated for an assumed extent of global effects.

For the calculations according to formula /8/ following numerical values were taken: f_{fl}, V_f and U as given in table 1, $l = 0.04$ m, $d = 0.004$ m, $D = 0.05$ m, $f_y = 677$ MPa, $\lambda = 1.6$, $S_r = 0.0025$ m, $u_o = 0.0025$ m, $\eta = 0.637$, $\theta = 0.25\pi$, $\tau_f = 0.6$ MPa.
The results of calculations were checked against experimental results and a good correlation was obtained /Fig 6/.

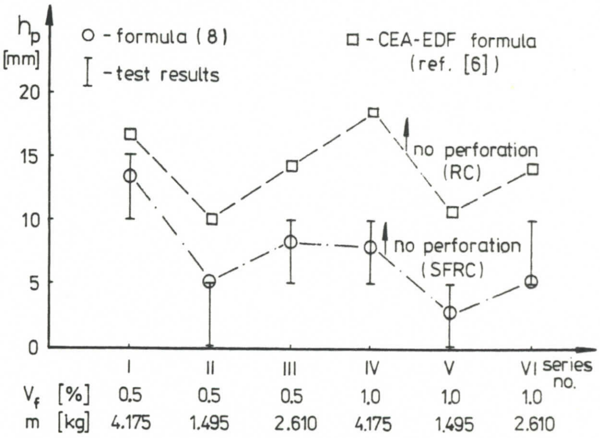


Fig. 6 Comparison of theoretical and experimental values of perforation thickness h_p for all series of tested slabs.

The outlined attempt of analysis of impact effects was based on several assumptions and simplifications. More research is necessary for full understanding of the influence of slab geometry, material properties and impact conditions upon the response of SFRC slabs to impact loads.

CONCLUSIONS

The following conclusions can be drawn.
1. An observed failure pattern involved the formation of localized crater followed by the formation and movement of a cone-shaped plug of material. The failure of slabs of fibre content of 0.5% was additionally accompanied by circural cracking around the impact point in a fan pattern. Scabbing and spalling phenomena were not observed.
2. The number and the width of structural cracks extending from the centre of slab to its edges were found to be fibre content sensitive.
3. The two-fold increase of fibre content, from 0,5% to 1.0%, resulted in the increase of 1.3 to 1.8 times of number of impacts to failure.
4. Following effects of a single impact were recorded:
- formation of a crater of shape corresponding to the shape of projectile nose,
- cracking visible on the rear face of slab in the form of crack along the diagonals and a circular crack around the impact point indicating formation of cone-shaped plug.

5. A tendency of decreasing of crater depth with increasing of slab thickness was noticed. However, a significant influence of fibre content on the crater depth was not observed.
6. Predictions of the perforation thickness of SFRC slab according to proposed formula were in a good agreement with the test results.

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