Scientific paper

Effects of Fiber Type on Blast Resistance of Slurry-Infiltrated Fiber Concrete Under Contact Detonation

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Abstract

When designing blast-resistant concrete members that are subject to contact detonation, it is necessary to reduce the spall damage due to tensile stress waves reflected from the back sides of the members. In a previous study, the authors confirmed the good spall-reducing performance under contact detonation of slurry-infiltrated fiber concrete (SIFCON), which is manufactured by first placing fibers into an empty mold and then infiltrating them with grout. In this study, to obtain SIFCON with further improved spall reduction, experimental investigations were conducted regarding the effects of different fiber types on the blast resistance of SIFCON slabs against contact detonation. Five types of steel fibers and four types of synthetic fibers were employed as reinforcing fibers. The thickness of the SIFCON slabs was fixed at 80 mm, and contact detonation tests were conducted using two amounts of SEP explosives. All of the SIFCON samples investigated reduced the spall damage due to contact detonation more effectively than normal concrete and other conventional fiber reinforced cementitious composites. Furthermore, by using SIFCON with fine straight steel fibers, the spall-limit thickness of the slab could be reduced by 54% or more.

1. Introduction

When designing important structures such as industrial plants and public facilities, it is necessary to ensure their robustness against accidental or intentional explosions, which rarely occur but can cause severe damage. In particular, the fracture modes of reinforced concrete (RC) slabs subjected to contact detonation are characterized by spalling due to reflection of the tensile stress waves from the back sides of the slabs (McVay 1988; Morishita *et al.* 2000). To protect the lives of humans inside structures under such conditions, it is necessary to prevent the launch of concrete fragments that accompany spalling. Therefore, reducing spall damage is an impor-

tant issue faced by designers of blast-resistant concrete structures.

In recent years, experimental investigations have been conducted with the objective of improving the blast-resistant performance of concrete slabs, without increasing the concrete strength or the number of reinforcement bars (Morishita *et al.* 2004), and several researchers have reported the good performance of fiber-reinforced cementitious composites (FRCC) (Banthia *et al.* 2004; Lan *et al.* 2005; Coughlin *et al.* 2010; Foglar and Kovar 2013; Ellis *et al.* 2014; Pantelides *et al.* 2014; Castedo *et al.* 2015; Li *et al.* 2016; Luccioni *et al.* 2017).

In general, it is necessary to raise both the aspect ratio and the volume content of fibers to achieve a high level of flexural toughness from FRCCs. However, these factors considerably increase the consistency of the FRCC in its fresh state. On the other hand, slurry-infiltrated fiber concrete (SIFCON), which is manufactured by first placing steel fibers into an empty mold and then infiltrating them with grout, was introduced by Lankard (1984) as one type of FRCC. Although the upper limit of the fiber volume fraction is currently about 3% in conventional FRCC, SIFCON can achieve a value of more than 10%. Regarding the blast resistance of SIFCON, Sun *et al.* (1999) and Chun *et al.* (2013) showed that SIFCON slabs or blocks subjected to contact detonation are excellent at reducing damage. Their conclusions were derived from experimental data in which the entire bottom surface of a SIFCON specimen was supported by a steel sheet or soil, but because stress waves may penetrate steel sheets or soil under such conditions, the spall-reducing performance of SIFCON, which directly leads to secondary injury, was not evaluated in those studies.

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Table 1 Materials used in SIFCON.

Cement	High-early strength Portland cement	Density: 3.14 g/cm ³
Admixture	Blast furnace slag	Density: 2.91 g/cm ³ , specific surface area: 5960 cm ² /g
Fine aggregates	Silica sand No. 7 (S7)	Bone-dry density: 2.63 g/cm ³ , particle size: 1.2 mm or less
	Silica sand No. 8 (S8)	Bone-dry density: 2.40 g/cm ³ , particle size: 0.3 mm or less
Chemical admixtures	Superplasticizer	Poly-carboxylic acid type
	Thickener	Methyl-cellulose based
	Antifoaming agent	Polyether based

Table 2 Mixture proportions and characteristic values of grout.

ID	Batch	W/B [%]	W/P [%]	Sg/B [%]	S/B [%]	Unit weight [grams per 20 kilogram can of the solids]					T_w [°C]	T [°C]	0-Flow (JASS)	0-Flow (JIS)	J14 [s]	JP [s]	M [g/cm ³]	γ [kN/m ³]	σ_B [MPa]	Applied fiber type
						W	C	Sg	S7	S8										
S7-0.8	A	36	20	50	80	4000	5550	5550	8900	—	19.3	23.8	327	391	9.5	15.8	2.172	21.5	99.1	S_3DM, S_3DL, S_4DL, S_5DL, PP_L
	B	36	20	50	80	4000	5550	5550	8900	—	20.5	24.5	326	394	8.6	13.3	2.163	21.5	111	PET_M, PET_L
	C	36	20	50	80	4000	5550	5550	8900	—	20.1	24.4	320	393	9.9	16.0	2.171	21.5	110	PP_M
S8-0.4	—	35	25	50	40	5000	7150	7150	—	5700	20.1	25.5	330	399	11.2	18.4	2.057	20.7	106	S_F

Notes:

- 1) W/B is the water-to-binder ratio, W/P is the water-to-powder ratio, Sg/B is the replacement ratio of cement by blast furnace slag, S/B is the sand-to-binder ratio, P (= C + Sg + S) is the amount of powder, B (= C + Sg) is the amount of binder, W is the amount of water, C is the amount of cement, Sg is the amount of blast furnace slag, S is the amount of fine aggregates, T_w is the kneading water temperature, and T is the kneading completion temperature.
- 2) "0-Flow" means a flow value measured without impacting the flow table.
- 3) J14 is the J14 funnel flow time, JP is the JP funnel flow time, M is the unit weight of fresh grout, γ is the unit weight of the dried state, and σ_B is the compressive strength.
- 4) Three $\phi 50 \times 100$ mm cylindrical specimens were prepared for compressive strength test, which were cured in wet conditions for 28 days, followed by curing in air for 14 days until testing.

However, subsequent studies (Yamaguchi *et al.* 2007, 2008, 2010, 2012, 2015, 2017) focusing on the fracture properties of spall proved that SIFCON using steel fiber reduces spall better than other FRCCs. Furthermore, the authors developed mortar-preparation grout that can fill the narrow gaps of the fibers in SIFCON to reduce the matrix contraction as well as the environmental burden associated with SIFCON production. SIFCON with mortar-preparation grout was found to have the same blast resistance as SIFCON with paste-preparation grout. However, under severely corrosive conditions, synthetic fibers may be effective replacements for the steel fibers in SIFCON due to the superior corrosion resistance of the former. However, the blast resistance of SIFCON with synthetic fibers has not been investigated to date.

This study was conducted to investigate the possibility of improving the spall-reducing performance of SIFCON. SIFCON was manufactured using nine types of reinforcing fibers: five types of steel fibers and four types of synthetic fibers. In addition, experimental investigations were performed to study the effects of the fiber types on the blast resistance of SIFCON slabs against contact detonation. Contact detonation tests were conducted on SIFCON slabs using 100 g and 130 g of explosives and a

fixed slab thickness of 80 mm. The slab specimens were supported at two parallel sides by wooden jigs. After the tests, the fracture behaviors of each specimen were observed in detail, and the size of the local damage created in each specimen was measured and compared with those in normal concrete and various other FRCC slabs treated in previous studies.

2. Experimental method

2.1 Materials and mix proportions

Tables 1 and 2 summarize the grout materials and mixture proportions. Blast-furnace slag and high early strength Portland cement were used for the binder. Silica sand Nos. 7 and 8 were used for the fine aggregates. In accordance with a previous study (Morishima *et al.* 2018), S7-0.8 (fine aggregate: silica sand No. 7; water-to-binder ratio W/B = 36%; sand-to-binder ratio S/B = 80%) was used as the basic grout in this study. Meanwhile, S8-0.4 (fine aggregate: silica sand No. 8; W/B = 35%; S/B = 40%) was used in the S_F fiber case, because it was considered difficult to inject the S7-0.4 grout into the narrow fiber gaps during the test.

Table 3 shows the characteristics of the reinforcement

Table 3 Characteristics of reinforcement fibers.

	S_3DM	S_3DL	S_4DL	S_5DL	S_F
Appearance
Material	Notes: 1) In the above photographs, a single memory of the scale bar is 1 mm. 2) In the steel fibers with both ends hooked (S_3DM, S_3DL, S_4DL, and S_5DL), the hook portions of are shown surrounded by dashed line.				
	Steel	Steel	Steel	Steel	Steel
Density	7.85 g/cm ³	7.85 g/cm ³	7.85 g/cm ³	7.85 g/cm ³	7.85 g/cm ³
Diameter × length	0.62 × 30 mm	0.75 × 60 mm	0.75 × 60 mm	0.90 × 60 mm	0.20 × 13 mm
Shape	Ends-hooked	Ends-hooked	Ends-hooked	Ends-hooked	Small diameter and straight
Tensile strength	1080 MPa	1225 MPa	1800 MPa	2300 MPa	2000 MPa
Tensile elastic modulus	205 GPa	205 GPa	205 GPa	205 GPa	205 GPa
Fiber volume fraction	11.5%	8.5%	8.5%	10.0%	10.0%
	PP_M	PP_L	PET_M	PET_L	
Appearance					Note: In the photographs at left, a single memory of the scale bar is 1 mm.
Material	Polypropylene	Polypropylene	Polyethylene terephthalate	Polyethylene terephthalate	
Density	0.91 g/cm ³	0.91 g/cm ³	1.32 g/cm ³	1.32 g/cm ³	
Diameter × length	0.53 × 30 mm	0.68 × 48 mm	0.70 × 30 mm	0.70 × 40 mm	
Shape	X-shaped cross-section and embossed surface	X-shaped cross-section and embossed surface	Indented surface	Indented surface	
Tensile strength	500 MPa	500 MPa	450 MPa	450 MPa	
Tensile elastic modulus	7 GPa	7 GPa	20 GPa	20 GPa	
Fiber volume fraction	10.5%	9.0%	15.0%	14.0%	

fibers. The five types of steel fibers and four types of synthetic fibers can be described as follows.

- (1) S_3DM, S_3DL, S_4DL, and S_5DL were steel fibers with both ends hooked. Each fiber had a different hook shape and aspect ratio.
- (2) S_F was a straight and small-diameter steel fiber (diameter: 0.2 mm, length: 13 mm).
- (3) PP_M and PP_L were poly-propylene fibers with X-shaped cross-sections and embossed surfaces. Each fiber had a different aspect ratio.
- (4) PET_M and PET_L were poly-ethylene-terephthalate fibers with indented surfaces. The length was 30 mm for PET_M and 40 mm for PET_L.

The fiber volume fraction was changed depending on the fiber shape. Thus, the fiber volume fraction was determined after the amounts of fibers in three columns were averaged, where each fiber was manually pre-packed into a steel formwork (100 mm × 100 mm × 400 mm) containing three columns. The resulting values are

shown in **Table 3**.

2.2 Manufacturing method of SIFCON

Figure 1 illustrates the SIFCON manufacturing process. The fiber packing and grouting were performed from the explosion side of the specimen. Firstly, the predetermined amount of fiber was measured and manually packed into a mold. In the packing phase, it was important not to force the fibers into a certain direction, except for the part that was forcibly directed by the mold. However, because the fibers tend to be oriented in a direction parallel to the ground surface, it is considered that the fibers were actually two-dimensionally oriented in a plane parallel to the explosion side. After that, the grout was injected from the upper surface of the framework. When manufacturing the grout, powder and water were mixed simultaneously using a high-speed hand-mixer (rotation frequency: 1100 rpm) for 4 minutes. When filling the grout, no vibration was applied to the

Table 4 SIFCON material test results.

Fiber type	F_g [%]	γ [kN/m ³]	σ_B [MPa]	E [GPa]	σ_f [MPa]	$\bar{\sigma}_B$ [MPa]
S_3DM	99.5	27.7	132	17.2	42.4	36.8
S_3DL	99.9	26.2	65.6	29.2	62.6	53.0
S_4DL	99.8	26.2	62.4	32.9	63.8	52.3
S_5DL	99.7	27.0	82.3	33.5	71.0	58.3
S_F	99.0	26.1	171	21.5	44.9	28.7
PP_M	98.4	19.8	44.3	19.5	21.5	17.3
PP_L	98.7	20.1	39.5	19.9	19.0	15.4
PET_M	99.5	20.1	59.1	18.5	25.8	21.0
PET_L	99.6	20.2	65.2	17.6	28.9	23.3

Notes:

- 1) F_g is the filling rate of grout, γ is the unit weight in the dried state, σ_B is the compressive strength, E is the Young's modulus, σ_f is the bending strength, and $\bar{\sigma}_B$ is the flexural toughness coefficient.
- 2) F_g was calculated based on the grout and fiber density as the ratio of the measured density to the theoretical density. The reference displacement for the calculation of $\bar{\sigma}_B$ was 4 mm.

framework, because the grout could be filled in due to its own weight.

2.3 Material characteristics

Three $\phi 100 \times 200$ mm cylindrical specimens and three $100 \times 100 \times 400$ mm prism specimens were prepared for compressive and flexural tests, respectively. These specimens were cured in wet conditions for 28 days, followed by curing in air for 14 days. In this study, a three-point bending test (span length: 300 mm) was conducted as a bending test method. The flexural toughness coefficient was calculated using the following equation:

$$\bar{\sigma}_B = \frac{3}{2} \cdot \frac{T_b}{\delta_{tb}} \cdot \frac{l}{bd^2} \quad (1)$$

where T_b is the area under the load-displacement curve until the displacement reaches 4.0 mm [N·mm], δ_{tb} is the displacement of 4.0 mm, l is the span length [mm], and b

and d are the width and depth, respectively, of the column specimen [mm]. The value of the limit displacement for calculating flexural toughness is specified as 2.0 mm in the standard of the Japan Concrete Institute (JCI 1984). However, the value was assumed to be 4.0 mm in this experiment, because the load-carrying capacity of all the SIFCON specimens reached its peak within the range from 2.0 to 4.0 mm in the displacement.

Table 4 shows the material characteristics of SIFCON. It was confirmed that the filling property was good and that the filling rate of the grout was 98% or more. However, the filling rate slightly declined in S_F and PP_M, which had relatively small diameters.

For SIFCON with steel fiber, the flexural toughness increases when the fiber is longer and the volume fraction is larger. For the S_5DL fiber, the highest flexural strength was 70 MPa or more in this study. However, the effect of the end hook shape on the flexural property was considered to be small.

2.4 Specimen configuration

Figure 2 shows the bar arrangement and specimen shape. Each specimen was a square with side lengths of 500 mm and a constant thickness of 80 mm. To prevent the slabs from breaking, a reinforcing bar (SD295A D10), which had a lattice shape with vertical and horizontal pitch of

Fig. 1 Example of the manufacturing process.

Fig. 2 Bar arrangement and specimen shape.

120 mm, was arranged at the center of slab thickness. The curing conditions were the same as for the test specimens.

2.5 Contact detonation test method

Figure 3 shows the specimen setup for the contact detonation test. Each specimen was supported by two wooden jigs with an inside span of 410 mm. The SEP explosives (penthrate: 65%, paraffin: 35%; density: 1.30 g/cm³) were installed at the center of the upper surface of each specimen, and blasting was initiated using an electric detonator. The explosives were cylindrical, with the diameter equal to the height, and weighed 100 g or 130 g. In accordance with previous studies (Morishita *et al.* 2004), the spall limits and perforation limits of the normal RC slabs can be expressed using the scaled concrete thickness ($T/W_m^{1/3}$) as follows:

$$\frac{T}{W_m^{1/3}} = \frac{T}{W^{1/3}} \cdot \left(\frac{K_{TNT}}{K} \right)^{1/3} = \begin{cases} 3.6; \text{spall limit value} \\ 2.0; \text{perforation limit value} \end{cases} \quad (2)$$

[unit: cm/g^{1/3}]

where T is the slab thickness [cm], W_m is the tri-nitro-toluene (TNT) equivalent amount of explosives [g], W is the amount of explosives used [g], K_{TNT} is the Chapman-Jouguet (C-J) detonation energy of the TNT [= 4.29 MJ/kg], and K is the C-J detonation energy of the explosives used [= 3.71 MJ/kg]. In this study, $T/W_m^{1/3}$ was calculated to be 1.81 cm/g^{1/3} and 1.66 cm/g^{1/3} for 100 g and 130 g, respectively. Both values indicate the perforation fracture mode for a normal RC slab.

2.6 Measurement of external damage method

After the contact detonation test, the local damage was measured along the four lines shown in Fig. 4 and averaged, because its shape was asymmetric. The damage depth of the crater and spall was defined as the distance from the end of the explosion surface and the surface to the deepest point in each case. Finally, the specimen was cut along line 1 in Fig. 4, and the internal damage was observed.

Fig. 3 Specimen setup for the contact detonation test.

3. Results and discussion

3.1 Fracture behaviors of the specimens

3.1.1 100 g of explosives

Table 5 shows the fracture behavior of SIFCON with 100 g of explosives. The spall characteristics in order of increasing damage were as follows.

- (1) In SIFCON with S_F fibers, concentric cracks originating from around the center of the back side were observed on the cut surface. However, these did not extend to a fatal opening due to the bridging effect of the S_F fibers, and the scattering of the small pieces was completely restrained. Radial cracks originating from the explosion point also occurred on the back side.
- (2) In SIFCON using S_3DM fibers, spall was slightly observed near the top, and swelling occurred near the center of the back side, although the scattering of the main spall fractures was substantially restrained. Observation of the cut surface confirmed that the matrix was crushed near the center of the back side, but the fragments of the crushed matrix were captured by the densely arranged S_3DM fibers.
- (3) In SIFCON using PP_M fibers, the spall fracture extent on the outside of the back side was similar to that in the case of S-3DM fibers, but the damage situation inside the slab was somewhat different. Specifically, spherical cracks originating from around the center of the back side occurred inside, and the spall pieces below this point were restrained from falling off by the bridging effect of the PP_M fibers.
- (4) In the other SIFCON, although spall of different scales depending on the fiber type was clearly observed in each case, perforation was not evident in this experimental configuration. However, the fracture mode was spall for all specimens even though the fracture mode is perforation in a normal RC slab.

Radial cracks centered on the spalling point were also observed in all specimens, and the number of cracks tended to increase when synthetic fibers were used. In addition, in SIFCON using synthetic fibers, cracking parallel to the side face of the slab was observed, due to the tensile stress wave reflected from the side face.

<Measurement items>

C is the crater diameter, S is the spall diameter, H is the perforation hole diameter, C_d is the crater depth and S_d is the spall depth.

Fig. 4 Definition of local damage measurement.

Table 5 Fracture characteristics of SIFCON with 100 g of explosives.

	S_3DM		S_3DL		S_4DL	
Left: Explosion side
Right: Back side						
Section
	S_5DL		S_F		PP_M	
Left: Explosion side
Right: Back side						
Section
	PP_L		PET_M		PET_L	
Left: Explosion side
Right: Back side						
Section

Notes:

- 1) The bearing position was at both the left and right ends.
- 2) The cracks that can be observed visually are emphasized on the explosion side and the back side.

3.1.2 130 g of explosives

Table 6 shows the fracture characteristics of SIFCON with 130 g of explosives. Spall clearly occurred in most specimens, and the scale was larger than in the test with 100 g of explosives. Even in this case, holes were not observed through any of the SIFCON samples. On the other hand, in SIFCON with S_F fibers, only circular cracks around the center of the back side and radial cracks were observed, but spall was not evident even with 130 g of explosives.

3.2 Local fracture dimensions

3.2.1 Crater dimensions

Figure 5 shows the measured crater diameters and depths. With 100 g of explosives, the diameter range is roughly 110 to 130 mm. Although the diameter is slightly larger for SIFCON with PET_M fibers, differences in the reinforcing fibers do not affect the diameter. With 130 g of explosives, the diameter range is roughly 120 to 140 mm in general, although it is slightly smaller for SIFCON with S_F fibers. For both amounts of explosives, the depth has a slight tendency to be reduced by SIFCON with S_F fibers. Accordingly, it can be inferred that the bottom embrittlement of the crater tends to be reduced by the constraining effect of closely-spaced fine fibers. However, except for slight deviations for SIFCON with

other fibers, the crater is almost the same with the same amount of explosives.

3.2.2 Spall dimensions

Figure 6 shows the measured crater diameters and depths. For SIFCON with S_F fibers, spall did not occur with either amount of explosives, and the best spall-reducing performance was achieved among the fibers for this examination object. For SIFCON with steel fibers with both ends hooked, when using S_3DM fibers, which have the smallest diameter and fewer ends hooked, the spall diameter and depth are the smallest and tend to increase. The following two factors are presumed to be the reasons for this behavior.

By analogy to a previous study (Morishita *et al.* 2004), reinforcement bars have little effect in terms of the spall reduction of normal RC slabs. It is expected that restraint is impaired by the macro reinforcement effect with larger fiber diameters. Thus, it is possible that the spall fraction part was weakened where multiple cracks densely occurred.

When fibers leave the matrix, local bearing pressure occurs due to snubbing, a phenomenon in which the stiffness increases due to fibers getting caught in the matrix when they obliquely bridge the cracked surface, in the matrix near the fiber exit port. The flexural stiff-

Table 6 Fracture characteristics of SIFCON with 130 g of explosives.

	S_3DM		S_3DL		S_4DL	
Left: Explosion side
Right: Back side
Section
	S_5DL		S_F		PP_M	
Left: Explosion side
Right: Back side
Section
	PP_L		PET_M		PET_L	
Left: Explosion side
Right: Back side
Section

Notes:

- 1) The bearing position was at both the left and right ends.
- 2) The cracks that can be observed visually are emphasized on the explosion side and the back side.

ness of the fiber increases with increasing fiber diameter. The matrix is broken near the fiber exit port due to the bearing pressure, possibly causing the spall size to increase.

In addition, comparing the S_3DL and S_4DL fibers with equal diameters, lengths, and volume fractions, the spall diameter and depth tend to increase when using S_4DL fibers with many ends hook steps. Thus, even if the number of end hook steps is increased to increase the pulling resistance of the fiber, the matrix is easily broken because the bearing pressure increases at the hooked part, so it is difficult to improve the spall reduction effect.

In SIFCON with synthetic fibers, the spall diameter and depth tend to be larger than those in SIFCON with steel fibers. In a previous study (Yamaguchi *et al.* 2007), one of the authors showed that the spall-reducing performance of FRCC tended to be raised with increasing in its flexural toughness; because the values of the flexural toughness coefficient of SIFCON with synthetic fibers were significantly lower than those of SIFCON with steel fibers as shown in **Table 4**, it is inferred that the spall diameter and depth of the former tended to be enlarged. However, in SIFCON with PP_M fibers, the spall is quite small with 100 g of explosives as compared to SIFCON with other synthetic fibers. Therefore, even with synthetic fibers, it may be possible to improve the spall prevention performance further by decreasing the fiber

diameter.

Also, comparing PET_M and PET_L fibers, even if the fiber diameter is the same, the spall size can obviously be reduced due to the increase in fiber pulling resistance by using long fibers.

3.3 Correspondence to damage evaluation formula for a normal RC slab

3.3.1 Comparison of damage with normal RC slabs

The contact detonation tests on normal RC slabs was not conducted in this study, this section was established for the purpose of comparing the damage with normal RC slabs using the existing damage evaluation formula. As described in Section 2.5, this experiment was performed under conditions where perforation would occur with normal RC slabs. Therefore, it is necessary to compare this experimental data with the calculations of perforation case in normal RC slabs.

3.3.2 Crater shape

Figure 7 shows the relation between crater depth and crater diameter, including the values calculated according to the following damage evaluation formulas (Morishita *et al.* 2004) on a normal RC slab:

$$\frac{C}{T} = 5.0 \frac{C_d}{T} \quad ; \text{ without perforation} \quad (3)$$

$$\frac{C}{T} = 62.5 \frac{C_d}{T} - 18.8 \quad ; \text{ with perforation} \quad (4)$$

where C is the crater diameter [cm], C_d is the crater depth [cm], and T is the slab thickness [cm].

In addition, **Fig. 7** as well as **Figs. 8, 10, and 11** include the experimental data (Yamaguchi *et al.* 2007, 2008) obtained when general FRCC (with a fiber volume

fraction of 5.0% or less) was mixed with the fibers during kneading.

In **Fig. 7**, for SIFCON with S_F fibers and 130 g of explosives, although a slight deviation is observable due to the crater depth becoming slightly smaller, the other data lie almost within the range $\pm 25\%$, which is the standard prediction accuracy of the above equations. Therefore, the crater shapes generated in various FRCC slabs including SIFCON are equivalent to those in normal concrete.

Note: V_f is the fiber volume fraction, d_f is the fiber diameter, and l_f is the fiber length.

Fig. 5 Measurements of crater diameter and depth.

Note: V_f is the fiber volume fraction, d_f is the fiber diameter, and l_f is the fiber length.

Fig. 6 Measurements of spall diameter and depth.

Fig. 7 Relationship between crater diameter and crater depth.

Fig. 8 Relationship between spall diameter and spall depth.

3.3.3 Spall shape

Figure 8 shows the relation between the spall depth and spall diameter, including the values calculated according to the following damage evaluation formulas (Morishita *et al.* 2004) on a normal RC slab:

$$\frac{S}{T} = 6.7 \frac{S_d}{T} \quad ; \text{ without perforation} \quad (5)$$

Fig. 9 Schematic diagram of the influence of fiber orientation on spall.

Fig. 10 Normalized crater depth according to modified-scaled concrete thickness.

Fig. 11 Normalized total damage depth according to modified-scaled concrete thickness.

$$\frac{S}{T} = -58.8 \frac{S_d}{T} + 41.8 \quad ; \text{ with perforation} \quad (6)$$

where S is the spall diameter [cm], S_d is the spall depth [cm], and T is the slab thickness [cm].

In **Fig. 8**, when perforation does not occur, the measured values of various FRCCs including SIFCON differ from the values calculated using Eq. (5). Thus, when the spall depth is constant in various FRCCs including SIFCON, the spall diameter tends to be reduced more than in normal concrete.

As mentioned in Section 2.2, in SIFCON manufacturing, the fibers are oriented two-dimensionally in a plane parallel to the casting surface (i.e., explosion surface) of the fiber. Also, in various FRCCs other than SIFCON, although the placement is performed so that the casting surface becomes the explosion surface, it is generally known that fibers are two-dimensionally oriented in a plane parallel to the casting surface. Therefore, as shown in **Fig. 9**, on the top of the spall fracture surface, although the number of fibers bridging the spall fracture surface decreases, it is considered difficult for the spall fragments to fall down because of the bridging effect due to the large number of fibers on the sides. Consequently, the spall fragments fall down within a relatively narrow range just below the explosives and the spall fragments on the periphery remain in the plate; thus, the spall diameter tends to be smaller than in normal concrete.

3.3.4 Crater and damage depths

Figures 10 and **11** show the crater and damage depths (where the damage depth is the sum of the crater and spall depths) as functions of $T/W_m^{1/3}$, including the values calculated according to the following damage evaluation formulas (Morishita *et al.* 2004) on a normal concrete slab:

$$\frac{C_d}{T} = -0.046 \frac{T}{W_m^{1/3}} + 0.42 \quad (7)$$

$$\frac{C_d + S_d}{T} = \frac{C_d}{T} \left(3.6 < \frac{T}{W_m^{1/3}} \right) \quad (8)$$

$$\frac{C_d + S_d}{T} = -0.49 \frac{T}{W_m^{1/3}} + 2.0 \quad \left(2.0 \leq \frac{T}{W_m^{1/3}} \leq 3.6 \right) \quad (9)$$

$$\frac{C_d + S_d}{T} = 1.0 \quad \left(\frac{T}{W_m^{1/3}} < 2.0 \right) \quad (10)$$

Although the measured crater depths for various FRCCs including SIFCON vary slightly in **Fig. 10**, the results agree well with the values calculated using Eq. (7) overall. Thus, even if various FRCCs including SIFCON are applied, the crater depth cannot be reduced substantially.

Meanwhile, focusing on the data for $T/W_m^{1/3} = 1.81$ cm/g^{1/3} in **Fig. 11**, the damage depth is approximately

70% or more of the slab thickness in various FRCCs other than SIFCON, whereas it is less than that in most of the SIFCON data. In SIFCON with S_F, S_3DM, and PP_M fibers, the damage depth is 20% to 40% of the slab thickness; thus, the spall-reducing performance is good. At this point, the spall limit in a normal RC slab is $T/W_m^{1/3} = 3.6 \text{ cm/g}^{1/3}$, so it is possible to reduce $T/W_m^{1/3}$, which can become the spall limit, by about 50% by replacing normal concrete with SIFCON with S_3DM and PP_M fibers for reinforcement.

When $T/W_m^{1/3} = 1.66 \text{ cm/g}^{1/3}$, this value is about 46% of the spall limit in a normal RC slab, and all of the SIFCON samples were restrained from perforation. However, the damage depth is increased to 60% or more of the plate thickness in most of the SIFCON samples. The line segment connecting the $T/W_m^{1/3} = 1.81 \text{ cm/g}^{1/3}$ and $1.66 \text{ cm/g}^{1/3}$ data tends to have a steep gradient compared with Eq. (8). On the other hand, in SIFCON with S_F fibers and $T/W_m^{1/3} = 1.66 \text{ cm/g}^{1/3}$, the damage depth remains at about 25% of the slab thickness. Thus, SIFCON achieved good spall reduction and is expected to be usable for constructing blast-resistant structural members.

4. Conclusions

In this study, to obtain SIFCON with better spall reduction, experimental investigations were conducted regarding the effects of different types of fibers on the blast resistance of SIFCON slabs against contact detonation. The conclusions can be summarized as follows.

- (1) All of the SIFCON samples in this study restrained perforation under contact explosion conditions that would cause perforation on a normal RC slab.
- (2) In SIFCON with small-diameter straight steel fibers, the spall reduction limit is approximately 54% or more. It is possible to construct blast-resistant structural members with good spall suppression by using SIFCON.
- (3) In SIFCON with steel fibers hooked at both ends, the thicker the fiber and the more end hook steps, the greater the spall size.
- (4) In SIFCON with synthetic fibers, the spall size tends to increase compared with when steel fibers are used. However, with $T/W_m^{1/3} = 1.81 \text{ cm/g}^{1/3}$, in SIFCON using polypropylene fibers of relatively small diameter, spall can be reduced successfully. Thus, it is possible to improve the blast resistance further by applying small-diameter fibers, even if they are synthetic.
- (5) The spall diameter tends to be smaller in FRCC including SIFCON than in normal concrete with the same spall depth, which is considered to be due to the influence of the fiber orientation.
- (6) The crater size in FRCC including SIFCON does not differ much from that in normal concrete, and significant crater reduction cannot be expected even by employing FRCC.

In this study, the parameter of fiber such as material, cross-sectional shape and hook shape are different, respectively. Also, fiber volume fraction changes according to these parameters. Therefore, the effect of fiber type could not be quantitatively evaluated in this study. We would like to consider this matter in the future.

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