Punching shear strength of RC slabs with AFRPm and PVA short-fiber-mixed shotcrete

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ABSTRACT: Static loading tests were performed to study the increase in load capacity of reinforced concrete (RC) slabs afforded by applying aramid-fiber-reinforced plastic mesh (AFRPm) and polyvinyl-alcohol (PVA) short-fiber-mixed shotcrete reinforcement to the bottom surface of the slabs. The reinforcement method was found to improve the punching shear strength of the RC slab. It was also found that the punching shear strength of the slab after reinforcement can be roughly estimated by applying the calculation method for RC slabs reinforced with FRP sheet at the bottom surface.

1 INTRODUCTION

In recent years, many reinforced concrete (RC) structures have been repaired and reinforced.

Here the authors propose a reinforcing method in which AFRPm and shotcrete mixed with PVA short-fibers are applied. Since this method is easy to apply and does not require steel plates or special cement, it is believed to solve the shortcomings of conventional reinforcing methods. To study increase in load bearing capacity of RC slabs that are reinforced with this method, static loading tests were performed, as explained in the following section.

2 OUTLINE OF THE TEST

2.1 *Outline of the specimen*

Table 1 lists the five specimens. Various combinations of reinforcement were applied to four of the slabs, by varying the combinations of shotcrete and the number of AFRPm layers. In Table 1, Specimen N is the non-reinforced specimen. Specimen SN has shotcrete without short-fiber. Specimen S has shotcrete mixed with short- fiber. Suffixes 0, 1, and 2, indicate the numbers of AFRPm layers. S-0 has no AFRPm layer.

Table 1. Reinforcements

Specimen	Shotcrete	AFRPm (nominal tensile strength)
N	-	-
SN-0	No short-fiber	-
S-0	Short-fiber	-
S-1		1 layer (200 kN/m)
S-2		1 layers (400 kN/m)

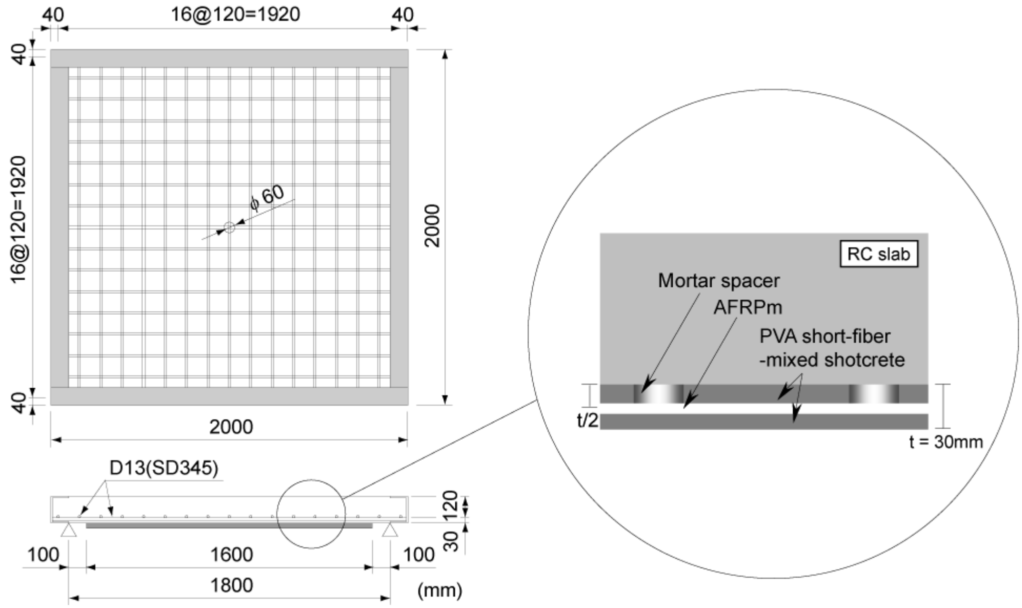


Figure 1. Specimen configuration (left) and reinforcement (right)

Figure 1 shows the dimensions and rebar layout of the specimens, and the configuration of the reinforcements. The punching shear test was performed with the specimen simply supported at the four edges with a clear span of 1.8 m. A 60-mm-diameter × 200-mm-long steel cylinder was placed at the center of the slab, and loading was applied with a hydraulic jack. At the time of the test, the compressive strength of the concrete was 24.3 MPa at a material age of 48 days, and the yield strength of the rebar was 392 MPa. The measured items were applied load P and displacement δ (displacement at the loading point). After the test, the specimens were sectioned longitudinally for crack observation.

The reinforcement is applied to the bottom surface of the specimen, except for a 10 cm border at the support (Figure 1). The application procedure is as follows: 1) The concrete surface is sandblasted to remove exfoliated concrete and to increase the bond with the shotcrete. 2) The AFRPm, supported by mortar spacers, is fixed 15 mm from the concrete surface, i.e., at the midpoint of the 30-mm shotcrete thickness. 3) After shotcreting, the surface is finished with a trowel.

2.2 *Properties of the materials used for reinforcement*

Table 2 lists the mix ratios of the shotcrete, and Table 3 shows their mechanical properties. Table 4 lists the properties of the PVA short-fiber and AFRPm. The AFRPm interval was 80 mm, sufficiently longer than the PVA short-fiber length of 30 mm.

Table 2. Shotcrete mix ratio

V_f (vol. %)	W/B (%)	Unit weight (kg/m^3)					SP (C × %)	Slump (cm)	Air content (%)
		W	C	SF	S	G			
0	43	185	387	43	1365	340	0.5	3.6	6.5
1.5	43	185	387	43	1365	340	2.0	5.8	6.0

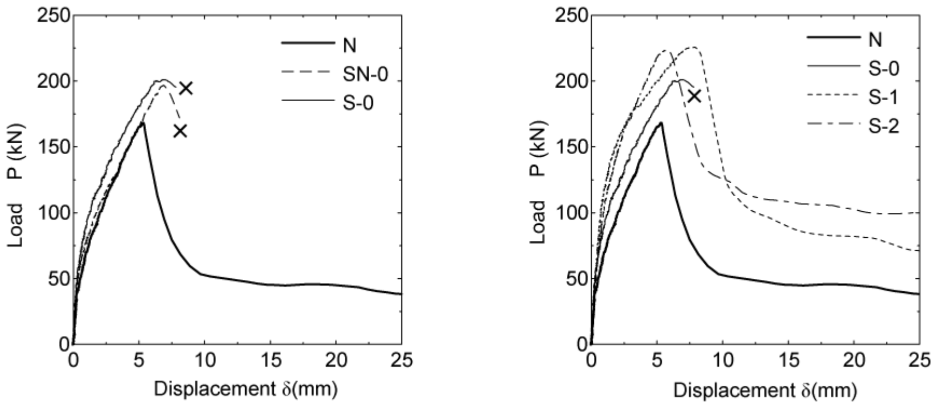
B = C + SF, V_f: short-fiber mix ratio per volume, SP: high-range water-reducing agent

Table 3. Mechanical properties of shotcrete

V_f (%)	Compressive strength (MPa)	Elastic coefficient (GPa)	Flexural strength (MPa)	Flexural ductility index (MPa)
0	76.1	36.6	7.9	0.2
1.5	95.8	36.6	8.4	2.6

Table 4. Properties of PVA short-fiber and AFRPm

PVA short-fiber					AFRPm			
Diameter (mm)	Length (mm)	Elastic coefficient (GPa)	Tensile strength (GPa)	Breaking strain (%)	Nominal tensile strength (kN/m)	Elastic coefficient (GPa)	Tensile strength (GPa)	Breaking strain (%)
0.66	30	29.4	0.88	7.0	100, 200	118	2.06	1.75



(a) varied parameter: short-fiber content (b) varied parameter: number of AFRPm layers

Figure 2. Load-displacement curves

3 TEST RESULTS

3.1 *Load-displacement curve*

Figures 2(a) and 2(b) show load-displacement curves for the various specimens. Figure 2(a) shows curves for three types of specimens: with shotcrete including PVA short-fiber but no AFRPm (S-0), with shotcrete not including PVA short-fiber but no AFRPm (SN-0), and with neither shotcrete nor AFRPm (N). Figure 2(b) shows specimens with different numbers of AFRPm layers (S-0, -1, -2), and the specimen with neither shotcrete nor AFRPm (N).

In Figure 2(a), Specimen N, with neither shotcrete nor AFRPm, shows that the rate of increase in load bearing capacity slows at about P=50 kN from cracking that begins at that load. After a linear increase in load bearing capacity, there is a sudden drop at a load of about P=160 kN, as the slab reaches the ultimate state. For Specimen SN-0, with shotcrete not including short-fibers but no AFRPm, the load bearing capacity up to about P=160 kN is almost the same as that of specimen N. Specimen SN-0 reaches the ultimate state at about P=200 kN.

For Specimen S-0, with short-fiber-mixed shotcrete but no AFRPm, the rate of increase in load bearing capacity does not slow even at P=50 kN; it gradually slow at about P=80 kN. Then, from P=100 kN, the load bearing capacity shows a linear increase, with a rate similar to those of Specimens N and SN-0. Specimen S-0 reaches the ultimate state at a slightly higher load than for Specimen SN-0. This clarifies that shotcrete increases the load bearing capacity of the RC slab, and that shotcrete with short-fiber further increases the load at which cracks occur and the maximum load.

In Figure 2(b), for Specimen S-1, with short-fiber-mixed shotcrete and one layer of AFRPm, the rate of increase in load bearing capacity does not slow until about P=130 kN, then it slightly slows, and the specimen reaches the ultimate state at P=220 kN. In contrast, for Specimen S-2, with short-fiber-mixed shotcrete and two layers of AFRPm, the initial rate of increase in load bearing capacity is slightly less than that of Specimen S-1, but the rate of increase in load bearing capacity after the initial increase is greater for S-2 than for S-1. It reaches the ultimate state at a slightly lower load than that of Specimen S-1.

These comparisons clarify that installing AFRPm hinders reductions in load bearing capacity by restraining cracking, and that it increases the punching shear strength. The test also shows that increasing the number of AFRPm layers does not increase the load bearing capacity. Therefore, it is thought that there is an upper limit in improving the punching shear strength of RC slabs with this method.

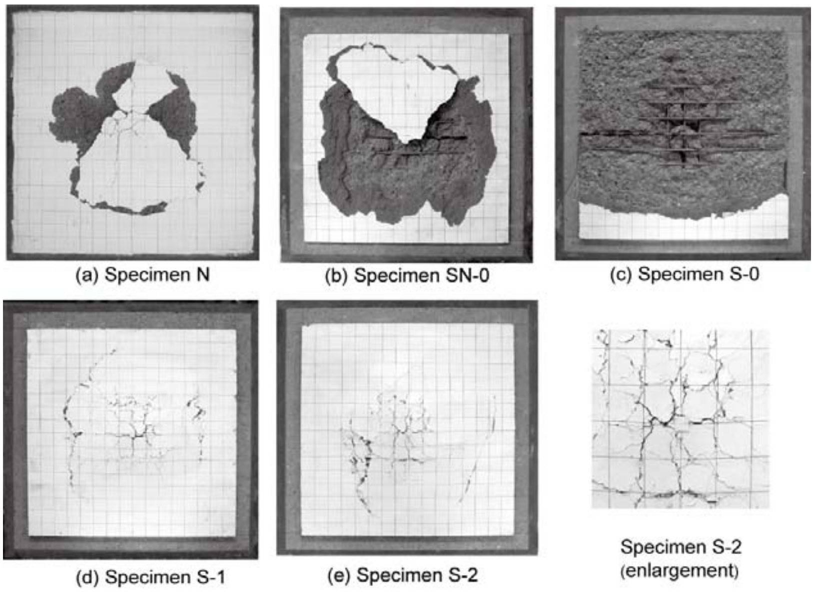


Photo 1. Bottom surface of RC slabs after the test

3.2 *Failure characteristics*

Photo 1 shows the failure at the bottom surface of the RC slabs after the test. For Specimen N (no shotcrete, no AFRPm), an almost round portion of the concrete at the center of the slab has been punched out, and in some portions, large pieces of concrete cover have spalled. For Specimen SN-0 (shotcrete, no short-fiber, no AFRPm), an almost round portion of the shotcrete and concrete has been punched out at the center of the RC slab, similar to Specimen N. In this case, the punching shear cracks have propagated into the concrete cover, and the concrete cover has spalled in a wider area than in Specimen N.

For Specimen S-0 (short-fiber-mixed shotcrete, no AFRPm), the shotcrete has been punched out with RC slab concrete in a wide area. From this, it appears that the bonding strength between the shotcrete and the RC slab concrete exceeds the tensile strength of the RC slab concrete. In the test, the shotcrete and the RC slab concrete spalled when a cone formed by punching shear (hereinafter: punching-shear cone) after the sudden drop in load. The punching shear cracks in the RC slab seem to have propagated horizontally along the lower border of the RC slab, but not into the shotcrete layer because of shear strength resulting from the action of the PVA short-fiber in the shotcrete in restraining crack widening (called “the bridging effect”).

In contrast, for Specimens S-1 and 2 (short-fiber-mixed shotcrete, one or two layers of AFRPm) there were many microcracks at the center of the slab, with radial cracks around the center point. However, the concrete did not spall. This clarifies that mixing PVA short-fiber into the shotcrete and adding AFRPm restrains the spalling of concrete even after punching shear failure.

Photo 2 shows the five specimens sectioned longitudinally through the center of the slab. From the photo, Specimen N shows punching shear cracks from the loading point extending toward the supports and spalling in some portions of the shotcrete. Specimen SN-0 shows a punching-shear cone that extends continuously from the slab concrete to the shotcrete layer where substantial spalling occurred. Specimen S-0 shows a punching-shear cone that is similar to that in Specimen SN-0. The shotcrete layer has not punched out, but wide areas ~~had~~ have spalled.

In contrast, for Specimens S-1 and S-2, the cone from the punching shear could be observed, but the shotcrete layer and AFRPm has not punched out. The punching-shear cone is smaller than those for Specimens N, SN or S-0. This is attributed to improvements in flexural rigidity of the slab by the AFRPm and steepening of the cone. A similar phenomenon was observed when the bottom surface of the RC slab was reinforced with FRP sheet and subject to static loading

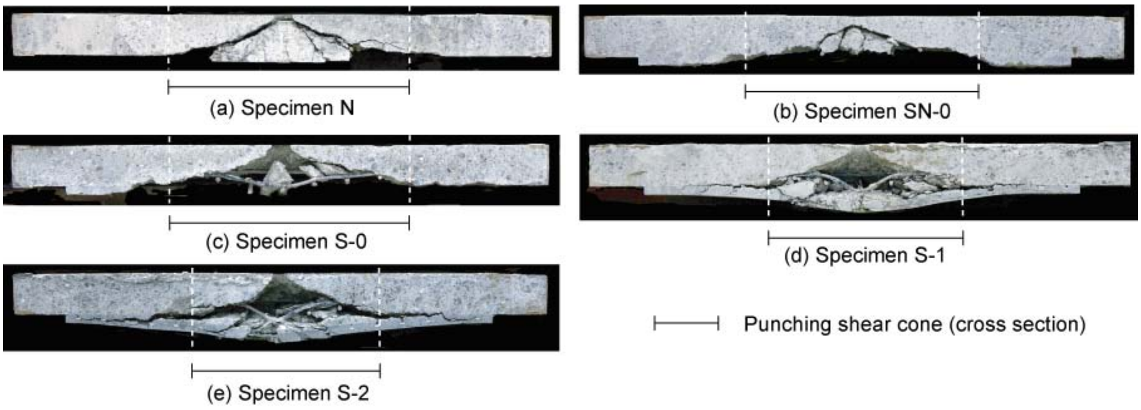


Photo 2. Cracks at the cross section of the slab

tests. It is also believed that the shotcrete layer with AFRP sheet reinforcement was prevented from spalling completely because of the small area of the cone.

3.3 *Increase in punching shear strength*

As mentioned earlier, the AFRPm prevented the shotcrete and concrete cover from spalling even at the ultimate state. Therefore, it is believed that the AFRPm increased punching shear strength by strengthening the concrete cover. In previous research the authors proposed an equation, based on this finding, for calculating the strength contribution of the concrete cover (hereinafter: “strength increment”) to the strength of an RC slab reinforced with FRP sheet. Equation (1) calculates the strength increment of RC slabs reinforced with AFRPm and PVA short-fiber-mixed shotcrete. This equation was developed from an equation used to calculate strength increment of RC slabs reinforced by FRP sheets:

$$V_{pcd} = \beta_d \cdot \beta_p \cdot \beta_r \cdot f_{pcd} \cdot u_p \cdot d \tag{1}$$

$$f_{pcd} = 0.20\sqrt{f'_{cd}}\ ,\ \ \beta_d = \sqrt[4]{1/d}\ ,\ \ \beta_d = \sqrt[3]{100p}\ ,\ \ \beta_p = 1 + 1/(1 + 0.25u/d)$$

Where:

f'_{cd} : Compressive strength of concrete
u : Perimeter length of the punching-shear cone at the lower rebar (hereinafter: perimeter length of loading plate)
u_p : Perimeter length of the punching-shear cone at $d/2$
d : Distance between rebar and AFRPm
p : ($=n_f A_f/(b \cdot d)$), ratio of rebar reinforcement (AFRPm reinforcement converted to rebar reinforcement)
A_f : Cross-sectional area of AFRPm
n_f : ($=E_f/E_s$), elastic coefficient ratio (AFRPm / rebar)

In Figure 3: 1) u is perimeter length of the punching-shear cone at the lower rebar assuming a punching shear crack angle of $\alpha 1$=45°; 2) the crack angle at the concrete cover is $\alpha 2$, as revealed in the test, and it is assumed that the shotcrete forms the punched out portion of the concrete cover; 3) u_p is the perimeter length of the punching-shear cone at $d/2$; and 4) the strength increment of the shotcrete, therefore, can be calculated using the equation used for calculating the punching shear strength of an RC slab. In this calculation, reinforcement afforded by the AFRPm at the bottom of the slab is converted to the reinforcement afforded by rebars, using the cross-sectional area of AFRPm and elastic coefficient ratio (AFRPm / rebar).

Table 5 compares strength increments and punching shear strengths obtained from the test to those obtained from the calculation, for Specimens N, S-1 and S-2. The calculated punching

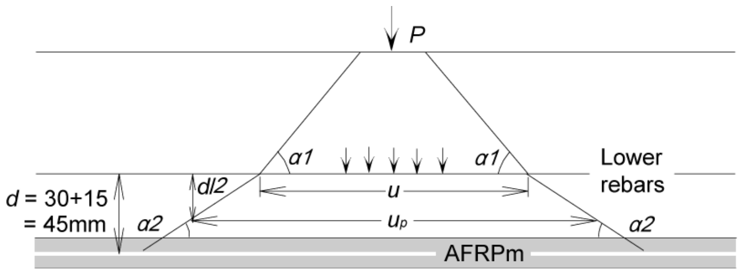


Figure 3. Punching shear (schematic)

Table 5. Angle of crack, strength increment and punching shear strength

Specimen	Angle of crack		Strength increment		(i)/(ii)	Punching shear strength		(iii)/(iv)
	α1 (deg.)	*α2* (deg.)	Measured (i) (kN)	Calculated (ii) (kN)		Measured (iii) (kN)	Calculated (iv) (kN)	
N	26	10	-	-	-	168.3	161.3	1.04
S-1	26	17	57.4	53.7	1.07	225.7	215.0	1.05
S-2	29	19	55.7	65.1	0.86	224.0	226.4	0.99

shear strength (iv in Table 5) is the sum of the punching shear strength of the RC slab without reinforcement specified in the *Standard Specification for Concrete Structures of the Japan Society of Civil Engineers* and the strength increment (ii in Table 5) calculated for the different reinforced specimens.

In this table, the calculated values for strength increment and punching shear strength for Specimen S-1 (one layer of AFRPm) agree with the measured values. For Specimen S-2 (two layers of AFRPm), the calculated values are slightly higher than the measured values. This is because there appears to be an upper limit to improvements in strengths with this method, and the improvement in Specimen S-2 seems to be near this limit.

The findings clarify that the punching shear strengths of RC slabs reinforced with the proposed method can be calculated by using the same equation used for calculating the strengths of RC slabs reinforced with FRP sheet at the bottom surface.

4 SUMMARY AND CONCLUSION

Static loading tests demonstrated the effectiveness of AFRPm and short-fiber-mixed shotcrete reinforcement applied to the bottom surface of an RC slab in increasing the load capacity of the slab. The findings from the tests are as follows:

- The method increases the punching shear strength of RC slabs while restraining the spalling of concrete covers.
- The bonding strength between the shotcrete and the RC concrete surface exceeds the tensile strength of the RC concrete.
- It is possible to roughly estimate the punching shear strength of RC slabs reinforced with this method by using a method for calculating the strengths of RC slabs reinforced with FRP sheet at the bottom surface.

5 REFERENCES

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