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Experimental investigation of the use of CFRP grid for shear strengthening of RC beams

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Abstract: Carbon fiber reinforced polymer (CFRP) sheet and grid have been widely applied to improve both shear and flexural strength of reinforced concrete (RC) beams. Compared to CFRP sheet, CFRP grid and sprayed mortar have advantages in dealing with the damaged concrete surface. This work examined the effectiveness of CFRP grid and sprayed mortar in enhancing the shear capacity of RC beams. Three RC beams were fabricated and two of them were strengthened by CFRP grid and sprayed mortar. Then four-points bending test was carried out to collect the data on the behavior of CFRP grid and stirrups in the three beams. The results are presented and discussed in this paper. This study evaluated the strengthening effectiveness of CFRP grid and sprayed mortar and the behavior of stirrups and CFRP grid. The difference in behaviors between stirrups and CFRP grid was analyzed.

Keywords: CFRP grid, sprayed mortar, stirrup, shear strengthening, RC beam.

1. Introduction

After a period of rapid economic growth, repairing and retrofitting of existing infrastructures that have been aging rapidly, such as buildings, bridges, and tunnels, have been among the most important civil engineering challenges all over the world. For example, in Japan, the percentage of highway bridges that are more than 50 years old was approximately 18% in 2013 and will be 43% in 2023. For tunnels, this percentage is 20% and 34%, respectively [1]. The other reason for the demand for strengthening and rehabilitation of structures is the upgrading of their load carrying capacity and resistance to withstand underestimated loads, to ameliorate the increased perceived risk from earthquakes. Since 1990s, carbon fiber reinforced polymer (CFRP) has been used in civil infrastructures to increase the load carrying capacity due to the limited durability of traditional materials. Using CFRP has been considered as a very effective strengthening and rehabilitation method for such work. CFRP has many advantageous engineering characteristics such as high strength-to-weight ratio and stiffness-to-weight ratio, corrosion resistance, and ease of application and construction. CFRP currently plays a key role in strengthening and retrofitting concrete structures in Japan. The area of CFRP sheet used was 980,000 m^2 in 2006 and 1,310,000 m^2 in 2013 [2]. CFRP is usually used in the form of sheet. The consumption of CFRP in the form of grid was only about 5% of that of CFRP sheets in 2006. CFRP grid and sprayed mortar have advantages in dealing with damaged concrete surface. Scheme of CFRP grid application is shown in Fig. 1.

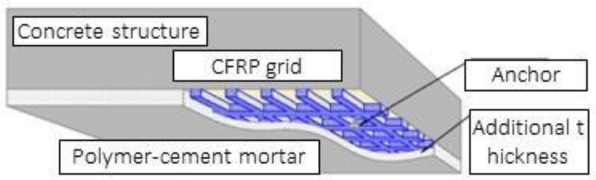

Fig. 1 – Schematics of CFRP grid reinforcement application

Many experimental studies have been conducted over the past decade to study the performance of concrete beams strengthened in shear with externally bonded FRP composites. Bukhari [3] reviewed the existing design guidelines for strengthening continuous beams in shear with CFRP sheets and proposed a modification to Concrete Society Technical Report. Chen [4] studied the shear behaviour of RC beams with FRP grid and concluded that RC beams strengthened with CFRP grid have good shear behaviour in terms of both increasing th

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Table 1 – Mix proportion of concrete

Gravel (mm)	Slump (mm)	W/C (%)	Air (%)	Weight (kg/m^3)				
				Water	Cement	Sand	Gravel	Admixture
20	120	55.6	4.5	158	284	792	1126	1.3

Table 2 – Properties of polymer and epoxy primer

Properties	Polymer	Epoxy primer
Main component	SBR synthetic rubber	vinyl acetate-ethylene copolymer
Solid content	45-46 (% by weight)	45-48 (% by weight)
Appearance	white milky liquid	white milky liquid
Viscosity	below 50 (mPa.s)	500-2000 (mPa.s)
pH	8.0-9.0	4.5-6.5
Density	1.0 (g/cm^3)	1.06 (g/cm^3)

Table 3 – Mechanical properties of concrete and mortar

Type	Compressive strength (N/mm^2)	Elastic modulus (kN/mm^2)	Tensile strength (N/mm^2)
Concrete	34.1	31.9	2.92
Mortar	36.7	31.0	2.87

Table 4 – Mechanical properties of reinforcing bars and CFRP

Type	Size	Area (mm^2)	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)
Rebar	D32	794.2	389	587	2×10^5
	D10	71.33	413	561	2×10^5
	D6	31.67	417	570	2×10^5
CFRP grid	CR8	26.5	*	1400**	1×10^5*

NOTE: * CFRP grid has no yield strength; ** manufacturer's data.

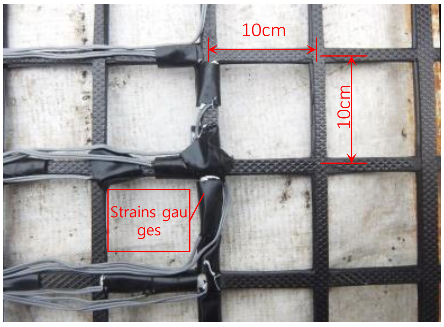


Fig. 2 – CFRP CR8

shear capacity and controlling of the crack width. Guo [5] examined the effect of shear capacity of RC beams reinforced with a haunch using the PCM shotcrete method with CFRP grid and investigated the adhesive properties of the reinforced interface between PCM and the existing concrete. Steffen [6] concluded that the use of CFRP grid could provide a quick, efficient method for providing corrosion resistant concrete deck reinforcement. CFRP grid reinforcement represents a suitable replacement for steel rebars in some concrete structural members subjected to aggressive environmental conditions that accelerate corrosion of the steel reinforcement and cause deterioration of the structures [7]. These studies have not focused on the difference in behaviours between stirrups and CFRP grid. The main purpose of this research was to study the capacity of CFRP grid and the behavior of stirrups and CFRP grid in shear strengthening. This paper illustrates the use of CFRP grid combined with sprayed mor tar to improve the shear strength of RC beams.

The existing guidelines are related to the application of CFRP sheet, and there are no specific guidelines for the application of CFRP grid. The material factor in calculating the effectiveness of CFRP grid in providing shear resistance capacity was evaluated. Based on the experimental result, the effectiveness of CFRP grid and sprayed mortar in enhancing the shear strength of RC beams was also evaluated. The difference in behavior between stirrups and CFRP grid was analyzed in detail.

2. Experimental Program

Three RC beams were fabricated and tested. The control RC beam was not strengthened while the two other beams were shear strengthened by CFRP grid and sprayed mortar. The three RC beams were designed such that their flexural strength was much higher than their shear strength to ensure that failure was controlled by the shear force.

2.1 Materials

The three RC beams were fabricated using ready-mixed concrete with a compressive strength of 34.1 N/mm^2 and maximum aggregate size of 20 mm. In the concrete mix, high-early-strength Portland cement was used and the water-cement ratio was 0.556 with the addition of water-reducing and air-entraining admixtures. The other parameters of the concrete mix are shown in Table 1. The mortar to be sprayed was made by mixing 25 kg premixed mortar, 1.21 kg polymer, and 4.1 kg water. In order to increase interface adhesion, epoxy primer was applied to the surface of concrete before spraying mortar. The properties of the polymer and epoxy primer are shown in Table 2.

D32 was used as the main reinforcing bar in the tension zone. D6 and D10 were used as the stirrup and reinforcing bar, respectively. The CFRP grid used in this test was CFRP-CR8 (The CR8 label is given by the manufacturer) with a grid spacing of 100 mm × 100 mm. The mechanical properties of concrete and mortar are given in Table 3. Mechanical properties of reinforcing bars and CFRP grid are listed in Table 4.

2.2 Test Specimens

The RC beams had the dimensions 200 mm × 500 mm × 2,750 mm. They were labelled RC beam 1 (control beam), RC beam 2, and RC beam 3. RC beam 1 and RC beam 2 were reinforced with 6D32 longitudinal rebars at the bottom and 2D10 longitudinal rebars on the top. The stirrup spacing was 200 mm (see Fig. 4). In RC beam 1, D10 bar was used for stirrups while, in RC beam 2, D6 bar was used as stirrups, which is smaller than the type used in the RC beam 1. With the assumption that the shear strength in this beam was lost due to corrosion, the cross-sectional area of the stirrups was reduced. RC beam 3 was reinforced with 6D32 longitudinal rebars at the bottom. RC beam 3 had no stirrups in order to evaluate the capacity of CFRP grid for enhancing shear resistance without stirrups. RC beam 2 and RC beam 3 were strengthened by CFRP grid and sprayed mortar. The CFRP grid was placed along the beam web and mortar was sprayed to create an additional 20 mm layer on both sides of the two beams.

Table 5 shows the total shear reinforcement area of each beam. Reinforcement area in RC beam 1 is the total of cross sections of D10, while, in RC beam 3, it is the total cross sections of CFRP grid (vertical grid only) and, in RC beam 2, it is the total of cross sections of D6 and CFRP grid in 200 mm beam length of each beam.

Fig. 3 – Reinforcing bars and stirrups

2.3 Casting RC Beams

First, the RC beams were cast in wooden formwork and cured by moisture-retaining cover (see Fig. 5). Eight days after the RC beam 2 and RC beam 3 were cast, their web's surface was sand blasted. The roughness of the beam surface after sand blasting was 0.15 mm. Four days later, CFRP grid was fixed on both sides of the beam by steel bolt anchors. On the next day, epoxy primer was applied. The roughness of the beam surface after applying epoxy was 0.13 mm. After the epoxy layer had dried, the repair mortar was sprayed (see Fig. 6). Finally, a curing compound was sprayed on the mortar surface. Tests of the RC beams were carried out at the age of 27th, 28th, and 29th day.

2.4 Instrumentation and Test method

Four-point-bending test was performed (see Fig. 7) on the three beams, with a span length (L) of 2,350 mm and a shear span (a) of 1,100 mm. The effective depth (d) was 423 mm. The shear span to effective depth (a/d) ratio was 2.6. During the test, when the first flexural crack and the first diagonal crack appeared, the specimens were unloaded to mark the cracks and take photographs. After that the load was continually increased until the beams failed. The failure processes were monitored by strain gauges installed on concrete, reinforcing bars and the CFRP grid, and by displacement transducers placed at mid-span and two end supports of each beam. Fig. 8 through Fig. 10 show locations of the displacement transducers and strain gauges installed on rebar, concrete, and CFRP grid in the three RC beams.

3. Results and Discussions

3.1 Load – displacement behavior, crack development and failure mode

Fig. 8 through 10 describe cracks generated during the test. The cracks shown in bold lines were the largest cracks at the ultimate state of each beam.

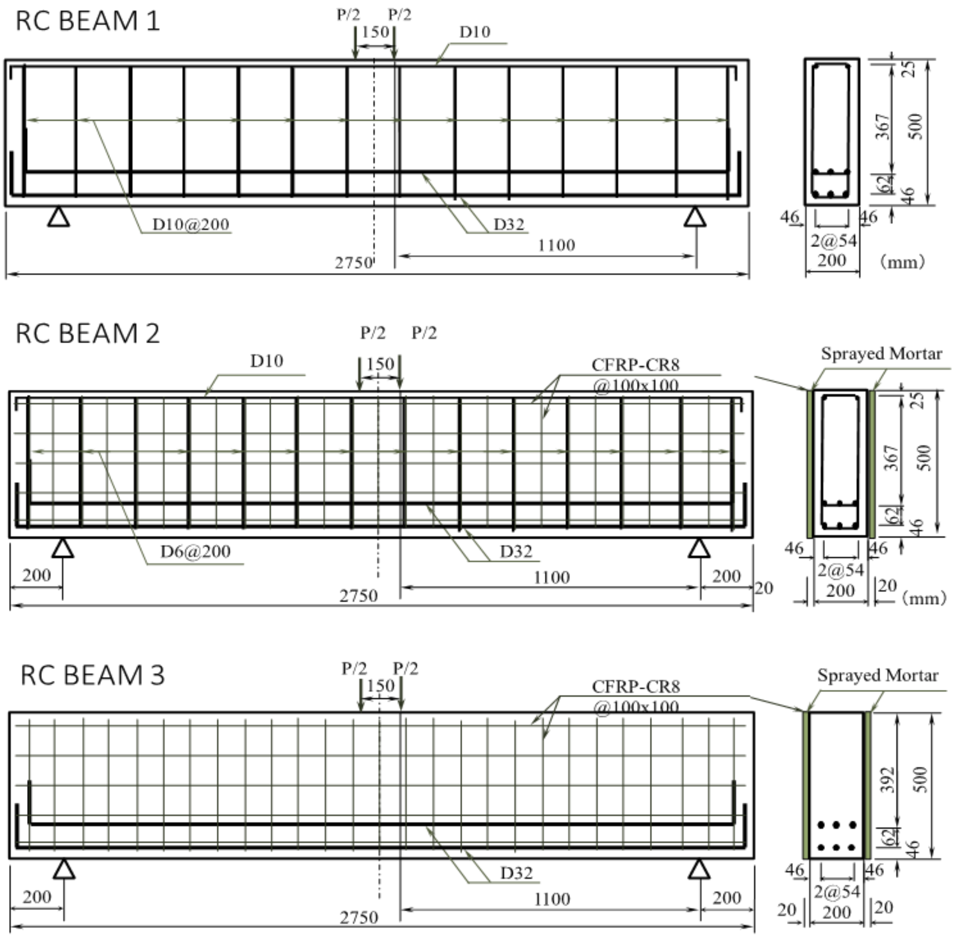


Fig. 4 – Longitudinal and transverse cross-sections of three RC beams and strengthening scheme using CFRP grid and sprayed mortar

Table 5 - Total cross-sectional area of shear reinforcement: CFRP grid and stirrups

No.	Shear reinforcement	Total reinforcement area (mm^2/200 mm length)	Ratio of shear reinforcement $p = \frac{A_s}{b \times s}$ (%)
RC beam 1	D10 @200 mm	142.66	0.37%
RC beam 2	D6 @200 mm and CFRP grid CR8 @100 mm	169.34	0.35%
RC beam 3	CFRP grid CR8 @100 mm	105.60	0.22%

NOTE: A_s - area of shear reinforcement (mm^2); b - beam width (b_{RC1} = 200 mm; $b_{RC2} = b_{RC3}$ = 240 mm); s - shear reinforcement spacing (mm).

Fig. 5 – RC beams fabrication

Fig. 6 – Fixing CFRP grid and spraying mortar

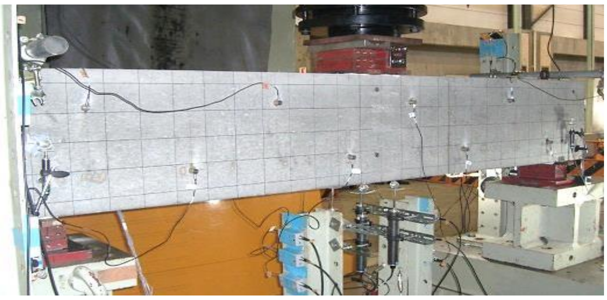


Fig. 7 – Beam loading

Based on the observation of cracks for the three beams, it is supposed that all beam failures were due to diagonal tension. The test results of all beams are summarized in Table 6. RC beam 2 exhibited the highest maximum load (757 kN) while RC beam 3 exhibited the lowest (617 kN) and RC beam 1 showed a value between the two extremes (690 kN). Compared to the control beam (RC beam 1), the maximum test load of RC beam 2 was higher by 9.7% while that of RC beam 3 was lower by 10.6%.

Table 6 – Summary of test results

Beam index	Cracking load (kN)	Maximum load (kN)		Max. mid-span displ. (mm)
		Design	Test	
RC beam 1	225	354	690	8.4
RC beam 2	300	697	757	7.4
RC beam 3	300	656	617	7.1

The total cross-sectional area of shear reinforcement placed in 200-mm beam length was 142.6 mm^2 (two bars of D10) in RC beam 1, while, in RC beam 2 and RC beam 3, it was 169.3 mm^2 (two rebars of D6 and four bars of CFRP CR8) and 105.6 mm^2 (four bars of CFRP CR8), equivalent to 118.7% and 74.3% of that of RC beam 1, respectively. The ratio of shear reinforcement of RC beam 1 was 0.37%, while, in RC beam 2 and RC beam 3, it was 0.35% and 0.22%, equivalent to 94.6% and 59.5%, respectively. The total cross-sectional areas of reinforcing bars and CFRP grid and the ratios of shear reinforcement are shown in Table 5**.** From test results, in two cases of strengthening, CFRP grid and sprayed mortar proved the effectiveness for enhancing the shear capacity. It could be concluded that concrete, rebar, mortar, and CFRP grid worked well together.

Fig. 11 shows the load versus mid-span displacement curves for the three beams. The maximum mid-span displacements of the three beams are listed in Table 6. RC beam 1 had the highest mid-span displacement of 8.4 mm while RC beam 2 and RC beam 3 had lower values of 7.4 mm and 7.1 mm (lower than 11.9% and 15.5% compared to RC beam 1), respectively. Each load versus mid-span displacement curve (see Fig. 11) could be divided into two stages. The first stage is before the cracking (225 kN for RC beam 1, 300 kN for RC beam 2 and RC beam 3). In this stage, RC beam 2 and RC beam 3 showed higher stiffness than RC beam 1 because their width was larger (240 mm) compared to that of RC beam 1 (200 mm). In the second stage after the cracking, there is a distinct difference between RC beam 1 and RC beam 3. The stiffness of RC beam 3 became lower than that of RC beam 1 due to cracks developed and the cross-section reduced. The Young's modulus of the stirrups is higher than that of CFRP grid (200,000 N/mm^2 versus 100,000 N/mm^2, respectively, in Table 4). RC beam 3 had CFRP grid but no stirrups. Therefore stirrups provide higher stiffness to the beam and result in smaller displacement value compared with the CFRP grid. In general, after strengthened by CFRP grid and sprayed mortar, both RC beam 2 and RC beam 3 had higher stiffness, ductility characteristic, and the cracking loads were also improved (except in the final period for RC beam 3, when the load was over 500 kN).

3.2 Behavior of stirrups in RC beam 1 and CFRP grid in RC beam 3

When the load increased, the RC beams deformed, cracks appeared and developed, and the beams failed. The behavior of the stirrups in RC beam 1 and that of the CFRP grid in RC beam 3 were different. Fig. 12 illustrates the load versus strain curves of stirrups in RC beam 1 and CFRP grid in RC beam 3. Strain gauges S3 and S4 with locations shown in Fig. 8 were installed on the stirrups in RC beam 1. Strain gauges G13 and G35 with locations shown in Fig. 10 were installed on the CFRP grid in RC beam 3. These strain gauges were near the cracks in each beam.

From Fig. 12, in general, strain values on CFRP grid in RC beam 3 are smaller than those on stirrups in RC beam 1. The strain recorded by G13 was the highest in RC beam 3 and the strain recorded by S3 was the highest in RC beam 1. These gauges were close to the ultimate cracks in each beam (see Fig. 8 and Fig. 10). The load versus strain curves consist of 3 stages: In the first stage, there are no cracks in each beam. Cracking load of RC beam 3 was around 300 kN while, for RC beam 1, it was around 225 kN (see Fig. 13). In this stage, at the same load levels, the strain of G35 was smaller than that of S4 and the slope of the experimental load-strain curves of RC beam 3 was higher

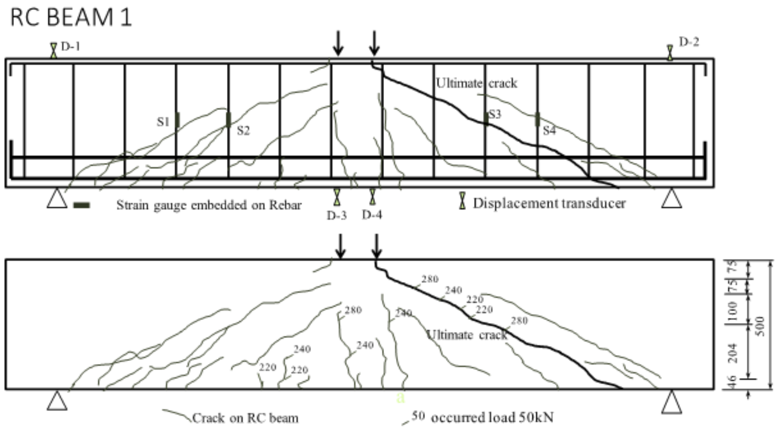


Fig. 8 – Locations of strain gauges on stirrups and experimental cracks in RC beam 1

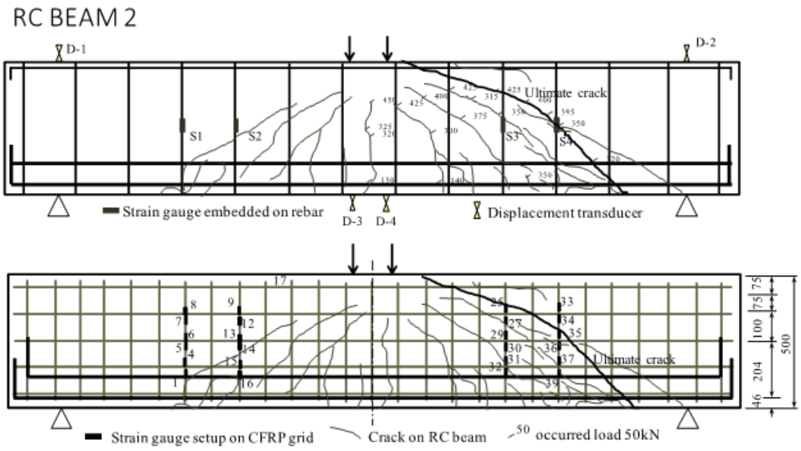


Fig. 9 – Locations of strain gauges on stirrups and experimental cracks in RC beam 2

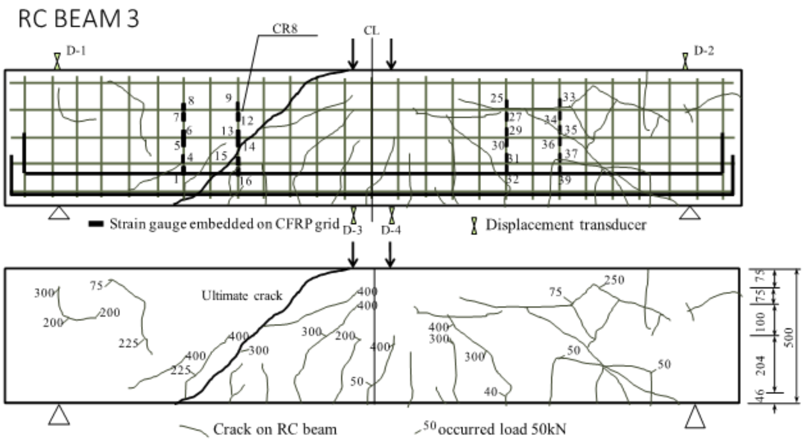


Fig. 10 – Locations of strain gauges on CFRP grid and experimental cracks in RC beam 3

than that of RC beam 1. The reason was the beam width of RC beam 3 was 240 mm (two layers of 20 mm including CFRP grid and sprayed mortar were applied on two sides of the RC beam) compared to the 200 mm width of RC beam 1. Thus, the bending stiffness of RC beam 3 increased by about 10%.

In the second stage, when the diagonal cracks appeared and developed, the length and the width of the cracks increased, the cross-sectional area reduced gradually, and the shear capacity of both beams provided by concrete and mortar reduced.

The shear strength of RC beam 1 was mainly provided by stirrups whereas that of RC beam 3 was mainly provided by CFRP grid. Moreover, the Young's modulus of CFRP grid (1×10^5 N/mm^2) is a half of that of the stirrup (2×10^5 N/mm^2) as shown in Table 4. Therefore, strains in RC beam 3 are higher than those in RC beam 1 as shown in Fig. 13 and Fig. 14.

In the third stage, when the load continued increasing, the stress on the stirrup reached the yield

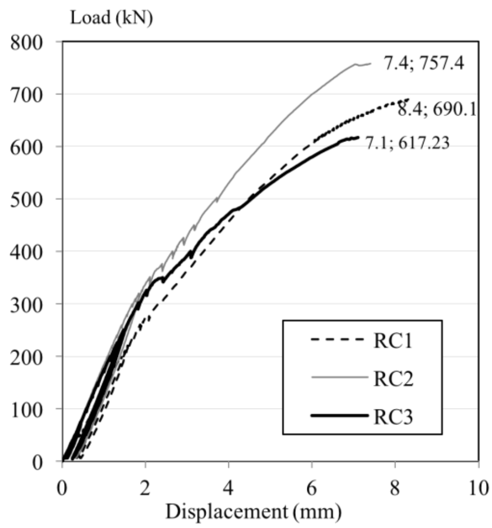


Fig. 11 – Load vs. mid-span displacement curves

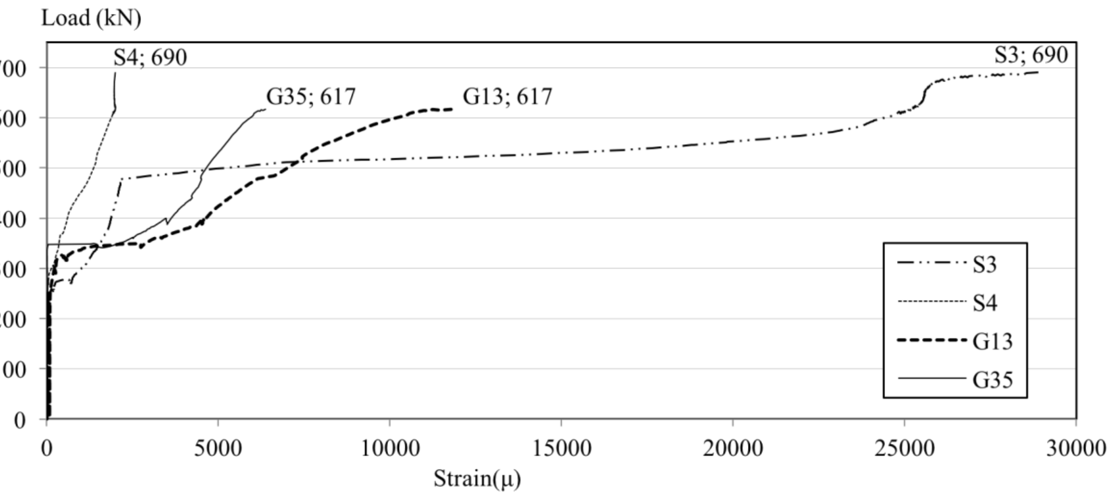


Fig. 12 – Load vs. strain curves of stirrups in RC beam 1 and CFRP grid in RC beam 3

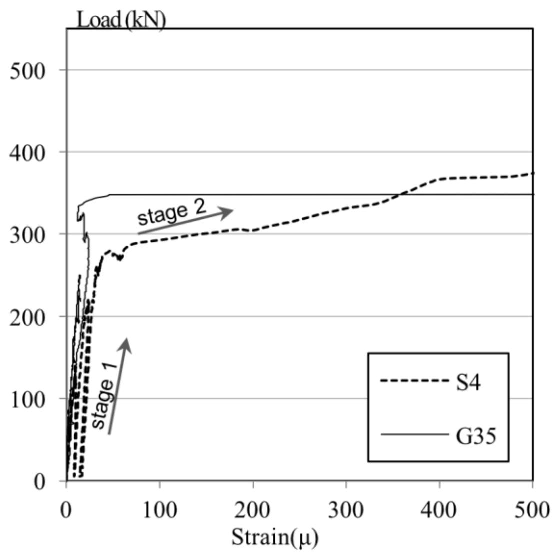


Fig. 13 – Load vs. strain curves of S4 (RC beam 1) and G35 (RC beam 3)

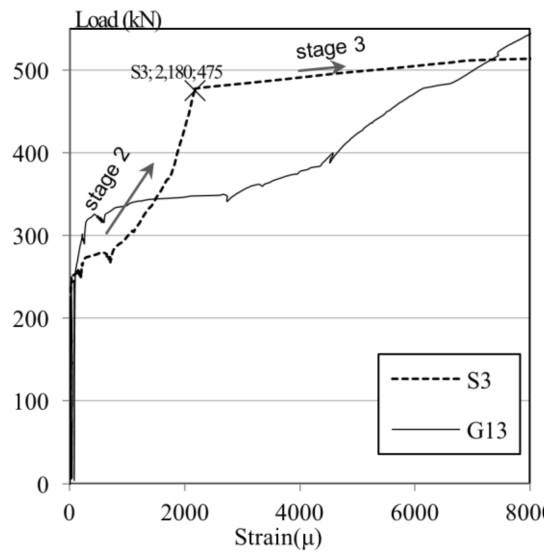


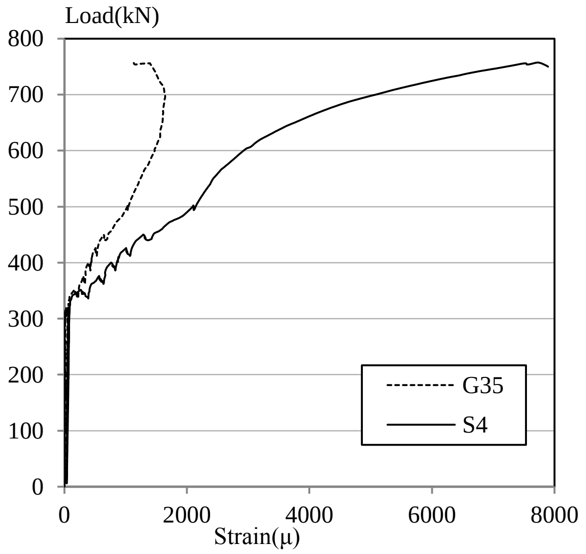
Fig. 14 – Load vs. strain curves of S3 (RC beam 1) and G13 (RC beam 3)

strength. From the values given in Table 4, the stirrup is expected to yield at a strain of $\varepsilon_{yield} = \frac{\sigma_{yield}}{E_s} = \frac{417}{2\times10^5}$ = 2,085 × 10^{-6}. In test, stirrup S3yielded at a strain of 2,180 × 10^{-6} equivalent to a load of 475 kN as shown in Fig. 14. When the stirrup yielded, the modulus of shear reinforcing bars reduced rapidly, whereas CFRP grid was elastic until fracture. This is the reason why strains in RC beam 3 were smaller than those in RC beam 1.

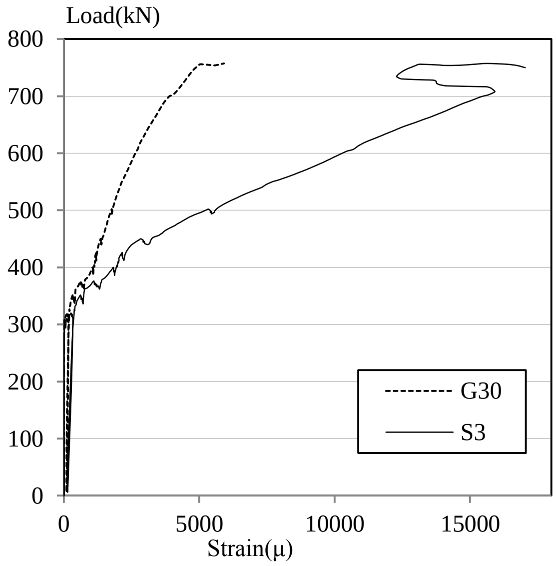
3.3 Difference in behavior between CFRP grid and stirrups in RC beam 2

Bonding between concrete and sprayed mortar is one of the most important factors that influence the effectiveness of reinforcement. The difference in behaviours between the stirrups and CFRP grid at the same positions in RC beam 2 may provide the information on the bonding between concrete and sprayed mortar. The strain gauges on CFRP grid G4, G14, G30, and G35 and those on the stirrups S1, S2, S3, and S4 were respectively at the same positions in RC beam 2. Locations of these strain gauges are shown in Fig. 9. The data of the bending test are listed in Table 7. Fig. 15 illustrates the load versus strain curves of the stirrups and CFRP grid in RC beam 2.

The strain curves for the load between 300 kN and 550 kN (see Table 7 and Fig. 15) show the following behaviour: When the load is greater than 350 kN, the strain values on the stirrup are higher than that on the CFRP grid (except stirrup S1), S3/G30 and S4/G35 are higher than S2/G14. At a load greater than 700 kN, the difference in strains between stirrup S4 and CFRP grid G35 becomes larger. At the ultimate stage, the strain recorded by S4 is about 5 times higher than that by G35 (4.9 times higher at a load of 750 kN). Thus, strain gauge readings at the same position differed significantly. This observation proved that, these materials (the CFRP grid and the stirrup) no longer worked together and the bonding between concrete and mortar was damaged. The possible reasons are as follows: First, when the strain on stirrups S2, S3, and S4 was greater than 2,085 × 10^{-6} (as calculated in section 3.2), the stirrups yielded and deformed rapidly after this point. Second, when the load was increased from 320 to 425 kN, cracks appeared and propagated towards the loading point, the compression area of the cross-section reduced. Most of these cracks were located on the same positions as S2, S3, and S4 (see Fig. 9). Once a crack crossed the locations of stirrups and CFRP grid, the adhesion of mortar to concrete surface was also damaged.



a) Stirrup S4 and CFRP grid G35



b) Stirrup S3 and CFRP grid G30

Fig. 15 – Load vs. strain curves of stirrup and CFRP grid in RC beam 2

3.4 Contribution of CFRP grid in shear strengthening of RC beams

Design shear capacity values were calculated for different values of shear strength as shown in Table 6. Flexural cracks appeared when the flexural cracking strength of concrete was exceeded by the applied stress. After that, if the stress reached the shear strength of concrete, diagonal cracks would occur. The design shear capacity of RC beam 1 is the sum of shear resistances contributed by concrete and reinforcement while those of RC beam 2 and RC beam 3 are the sums of shear resistances contributed by concrete, reinforcement, and CFRP grid. According to Eq. (9.2.3) of Ref [8], the design shear capacity was calculated using following equations:

$$V_{yd} = V_{cd} + V_{sd} \tag{1}$$

Table 7 – Comparison of strains on stirrups and CFRP grid in RC beam 2

Load (kN)	CFRP ( )				Stirrup – RC beam 2 ( )				Comparison			
	G6	G14	G30	G35	S1	S2	S3	S4	S1/G6	S2/G14	S3/G30	S4/G35
50	1.0	1.0	−2.0	3.0	2.0	2.0	1.5	1.5	2.0	2.0	−0.8	0.5
100	8.0	8.0	0.1	9.0	8.0	7.0	5.5	6.0	1.0	0.9	55.0	0.7
150	12.0	11.0	1.0	14.0	15.0	8.5	7.5	7.5	1.3	0.8	7.5	0.5
200	13.0	13.0	−3.0	15.0	17.0	8.5	6.0	7.0	1.3	0.7	−2.0	0.5
250	14.0	16.0	2.0	15.0	21.5	9.0	7.0	6.5	1.5	0.6	3.5	0.4
300	18.0	13.0	20.0	12.0	29.0	6.0	45.5	4.5	1.6	0.5	2.3	0.4
350	4.0	−14.0	418.0	154.0	32.5	5.0	592.0	247.5	8.1	−0.4	1.4	1.6
400	126.0	1111.0	1064.0	392.0	57.0	1248.0	1822.0	854.0	0.5	1.1	1.7	2.2
450	338.0	1785.0	1358.0	640.0	158.5	2264.0	3246.0	1443.5	0.5	1.3	2.4	2.3
500	636.0	2305.0	1789.0	1027.0	438.0	4046.5	5592.0	2091.0	0.7	1.8	3.1	2.0
550	864.0	2748.0	2126.0	1232.0	632.0	6475.0	7606.0	2417.5	0.7	2.4	3.6	2.0
600	1234.0	3273.0	2622.0	1467.0	782.0	9382.0	10198.5	2905.5	0.6	2.9	3.9	2.0
650	1451.0	3759.0	3168.0	1596.0	826.5	11489.5	12621.0	3714.0	0.6	3.1	4.0	2.3
700	1573.0	4243.0	3882.0	1645.0	864.5	13727.5	15415.5	5050.0	0.5	3.2	4.0	3.1

Design shear capacity in RC beam 1:

$$V_{yd1} = V_{cd1} + V_{sd1} \quad (2)$$

Design shear capacity in RC beam 2:

$$V_{yd2} = V_{cd2} + V_{sd2} + V_{CFRP} \quad (3)$$

Design shear capacity in RC beam 3:

$$V_{yd3} = V_{cd3} + V_{CFRP} \quad (4)$$

- V_{cd}: design shear capacity without shear reinforcement

$$V_{cd} = \beta_d \times \beta_p \times \beta_n \times f_{vcd} \times b_w \times d/\gamma_b \quad (5)$$

$f_{vcd} = 0.20\sqrt[3]{f'_{cd}}$ (N/mm^2) where $f_{vcd} \leq 0.72$ (N/mm^2)

$\beta_d = \sqrt[4]{1000/d}$ (d in mm) when $\beta_d > 1.5$, β_d is taken as 1.5

$\beta_p = \sqrt[3]{100 \times p_v}$ when $\beta_p > 1.5$, β_p is taken as 1.5

$\beta_n = 1$

b_w: web width

d: effective depth

$p_v = A_s/(b_w \times d)$

where, A_s - area of tension reinforcement (mm^2); f'_{cd} - design compressive strength of concrete (N/mm^2); f'_{cd} is taken as 34.1 N/mm^2 with concrete and 36.7 N/mm^2 with mortar (see Table 3); γ_b - member factor, may generally be taken as 1.3; V_{cd1} - shear resistance contributed by concrete; V_{cd2} - shear resistance contributed by concrete and sprayed mortar; V_{cd3} - shear resistance contributed by concrete and sprayed mortar.

- V_{sd}: design shear capacity of shear reinforcement, taken from Eq.(9.2.6) of Ref [8]

$$V_{sd} = A_w \times f_{wyd} \times z/S_s/\gamma_b \quad (6)$$

where, A_w - total area of shear reinforcement placed in S_s; f_{wvd} - design yield strength of shear reinforcement (yield strength of stirrup, D10 for RC beam 1 and D6 for RC beam 2, was taken, f_{wvd} of RC beam 1 is as 413 N/mm^2 and f_{wvd} of RC beam 2 is 417 N/mm^2 in Table 4); z - distance from location of compressive resultant to centroid of tension steel, which may be taken as d/1.15; S_s - spacing of shear reinforcement; γ_b - member factor, may generally be taken as 1.1.

- V_{CFRP}: design shear capacity of CFRP grid. In Japan, there is no standard specification for shear strengthening concrete structure using CFRP grid. In this case, the CFRP grid was taken as shear reinforcement.

According to Eq.(9.2.6) of Ref [8], the following equation was suggested for calculating V_{CFRP}.

$$V_{CFRP} = A_{CFRP} \times f_{CFRP} \times z/S_s/\gamma_b \quad (7)$$

where, A_w - total area of shear reinforcement placed in S_s; f_{CFRP} - design yield strength of shear reinforcement (In this experiment, there is no yield strength of CFRP and CFRP can be considered as a linear-elastic material. f_{CFRP} was taken as tensile strength, equal to 1,400 N/mm^2); γ_b - member factor of CFRP material (as there is no standard specification for CFRP grid, the safety ratio of 1.3 for CFRP sheet taken from "Guideline for repair and strengthening using CFRP sheet for concrete structure" [9] was used)

According to test results in Table 6, RC beam 1 and RC beam 2 showed the maximum test loads of 690 kN and 757 kN, respectively, much higher than design loads of 354 kN and 697 kN, respectively, due to the following reasons. First, the value of the design load is calculated for linear-elastic material, while at the load of 690 kN, the stirrup in RC beam 1 already yielded; second, there is safety ratio included in the formula in standard specifications. For RC beam 3, the design loads are higher than the experimental maximum load, due to the following reasons. First, applying the formula for stirrups to calculate shear strength of CFRP grid was not appropriate as some coefficients in the formula were not reasonable for CFRP grid, the stirrup has yield strength but CFRP grid does not. Second, when computing the design shear strength, it was assumed that the CFRP grid would work at full capacity. Actually, the maximum stress in CFRP grid was less than 1,400 N/mm^2 as shown in Table 4. At the ultimate state of strengthened beams, the maximum load of RC beam 3 was 617 kN and the maximum strain values of CFRP grid in RC beam 3 were recorded by strain gauges G13 and G35 (location of strain gauges are shown in Fig. 10). The maximum strains were $11{,}943 \times 10^{-6}$ and $6{,}377 \times 10^{-6}$ as shown in Fig. 16, respectively. The stress on the CFRP grid was calculated as follows.

$$\sigma_{CFRP}^{G13} = E_{CFRP}\varepsilon_{max}^{G13} = 1 \times 10^5 \times 11{,}943 \times 10^{-6} = 1194.3\ N/mm^2$$

$$\sigma_{CFRP}^{G35} = E_{CFRP}.\varepsilon_{max}^{G35} = 1 \times 10^5 \times 6{,}377 \times 10^{-6} = 637.7\ N/mm^2$$

The maximum stress values on the CFRP grid recorded by G13 and G35 were 85.3% and 45.5% of the tensile strength of CFRP grid (1,400 N/mm^2) as shown in Table 4. Guideline for repair and strengthening using CFRP sheet for concrete structure [9] suggests that the material factor for calculating CFRP sheet capacity is 1.3. There is no mention of the corresponding value for CFRP grid. Here, using material factor of 1.3, the shear design load of RC beam 3 would be 656 kN, which is not appropriate. In the present research work, a coefficient of 1.5 is proposed, indicating that the CFRP grid works at 66.7% of its tensile strength. Using the coefficient of 1.5, the design load will be 637 kN for RC beam 2 and 600 kN for RC beam 3.

4. Conclusions

Experiments were conducted to study the performance of CFRP grid and sprayed mortar for shear strengthening of RC beams. CFRP grid consists of vertical and horizontal components but this study only focused on researching the vertical component of the CFRP grid. Based on the collected data, the following conclusions were drawn.

(1) CFRP grid and sprayed mortar could be significantly effective in shear strengthening. In this experiment, RC beams strengthened with CFRP CR8 and sprayed mortar (RC beam 2 and RC beam 3) attained 110.7% and 89.4% of shear capacity compared with the ultimate load of the control beam (RC beam 1). The cross-sectional area of reinforcing materials in RC beam 2 and RC beam 3 were equivalent to 118.7% and 74.3%, respectively, of the cross-sectional area of stirrups in RC beam 1. In general, the stiffness, ductility characteristic, and the cracking load of the strengthened RC beams (RC beam 2 and RC beam 3) using CFRP grid and spayed mortar were improved.

(2) The behavior between the CFRP grid and the stirrups reflects the bonding between concrete and sprayed mortar. It is one of the most important factors that influences the reinforcement effectiveness. According to experimental results, when the load increased, variations of the stirrup strains and the CFRP grid strains at the same position in a strengthened RC beam had similar tendencies. After the stirrups yielded and the cracks developed in a strengthened RC beam, the bonding between concrete and sprayed mortar was considerably affected.

(3) In an application of CFRP grid and sprayed mortar, CFRP grid could not work at 100% of the tensile strength. Ref [9] reports the material factor of 1.3 for calculating CFRP sheet capacity, but the maximum stress of CFRP grid was 85.3% of the tensile strength in our experiments. Therefore, a material factor of 1.5 is proposed for the CFRP grid when applying the formula in Ref [8] to calculate the shear strength of a RC beam strengthened with CFRP grid and sprayed mortar. Using a coefficient of 1.5 means the CFRP grid works at 66.7% of its capacity.

It is concluded that the shear-strengthening of RC beams by CFRP grid and sprayed mortar is effective. CFRP grid and sprayed mortar are useful in strengthening and retrofitting of concrete structures. CFRP grid can support or replace stirrups in RC beams in providing shear strength. The availability of CFRP grid and sprayed mortar should be more intensively investigated and widely applied in concrete structures in the future.

References

1. White paper on land, infrastructure, transport and tourism in Japan (2014), 123 pp.
2. "CFRP Repair and Reinforcement Method Technology Research Association" http://tampoken.com/04.html (accessed on Dec. 5, 2016)
3. I.A. Bukhari, (2010) "Shear strengthening of reinforced concrete beams with CFRP," Magazine of Concrete Research, (1), pp. 62.
4. W.Y. Chen, (2010) "The shear behaviour of beams strengthened with FRP grid," Proceedings of the 5th International Conference on FRP Composites in Civil Engineering.
5. R. Guo, (2014) "Shearing Capacity and adhesive Properties of Reinforce Interface for RC beam with haunch retrofitted by CFRP grid with spraying PCM shotcrete," Memoirs of the Faculty of Engineering, Kyushu University.
6. R. Steffen, (2003) Design and Constructability of a CFRP Grid Reinforced Bridge Deck, High Performance Materials in Bridges, pp. 106-116.
7. B. Zhang, (2004) "Behaviour of one-way concrete slabs reinforced with CFRP grid reinforcements," Construction and Building Materials, 18(8), October 2004, pp. 625–635.
8. JSCE Guidelines for Concrete, N0.15. (2007) Standard Specifications for Concrete Structures, "Design," Japan Society of Civil Engineers, pp. 156.
9. JSCE – Concrete Committee (2000) Guideline for repair and strengthening using CFRP sheet for concrete structure.