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Flexural Strengthening of RC Beams with CFRP Sheets and U-Jackets

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ABSTRACT: This paper presents results obtained from an experimental program on the flexural strengthening performance of reinforced concrete (RC) beams strengthened with externally epoxy-bonded carbon fibre-reinforced plastic (CFRP) sheets. The parameters of study included level of loading and the type of CFRP sheets strengthening system. The test program consisted of four groups of beams. The first group was unstrengthened control group. The remaining three groups were divided into five series by the first CFRP sheet length and number of U-jackets. The first CFRP sheet layers, which were bonded directly to tension bottom concrete surfaces, had length of 640, 1080 and 1540 mm. CFRP sheets plus 50 mm in width strips of CFRP sheets (we called "U-jacket) wrapping up to 300 mm in full height of specimen to prevent debonding of the sheet layer. And the amount of U-jacket at a spacing 50 mm was made to change 0, 4, 8, 12 and 16 strips. These beams were tested in flexure and the experimental data on strength, deflection, strain on the CFRP sheet and rebar, and the modes of failure were investigated. The results show that in the case of RC beams with U-jackets of 16 strips, the maximum load of strengthened RC beams was almost the same regardless of the first CFRP sheet layer length, but the displacement at ultimate load increased with increase in number of U-jackets.

1 INTRODUCTION

A continuous fiber-reinforced sheet is thought to be effective for strengthening and rehabilitation of existing RC structures, and the number of existing concrete structures in which these reinforcing sheets are used has been increasing. Reinforcement of existing concrete structures with continuous fiber sheets is carried out mainly to increase flexural and shear strength of members. A large deflection capacity is also required for strengthening a bridge pier. A continuous fiber sheet, especially a CFRP sheet, is excellent in terms of tensile strength, lightness, and resistance to corrosion and chemical attack. In addition, a CFRP sheet can be handled easily because of its flexibility. Although many studies have been carried out to try to establish a rational retrofit design method (Takahashi & Sato 2006; Lei Zhao 2005), an appropriate reinforcement design method has not yet been established. Noticing the sheet length and number of U-jackets, the flexural behavior and strain of a CFRP sheet and rebar in the RC beam were examined experimentally by a static flexural loading test. The epoxy generally used for CFRP sheets was used as an impregnating adhesive resin.

2 OUTLINE OF EXPERIMENT

Sixteen reinforced concrete beams of 200×300 mm in cross section and 2200 mm in length were cast for the test program. Beam sketches, dimensions, and detailed reinforcement are shown in Figure 1. The reinforcement consisted of two D19 (deformed steel bar with a nominal diameter of 19.1 mm) rebars at the bottom with a total area of 573 mm^2, resulting in a reinforcement ratio of 1.146 percent, and two D6 (deformed steel bar with a nominal diameter of 6.35 mm) rebars at

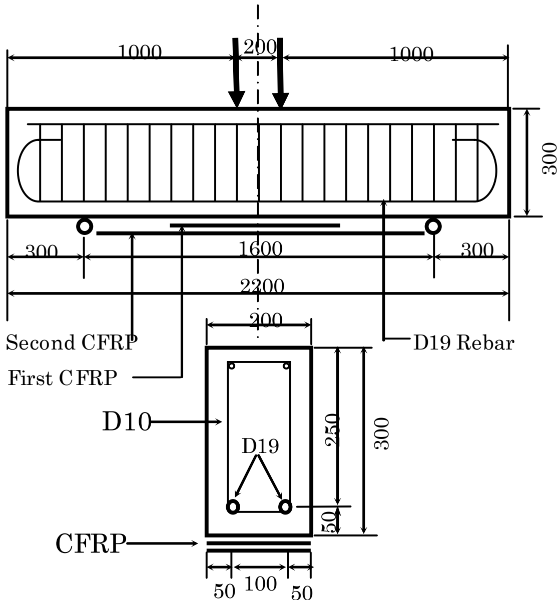


Figure 1 Test specimen detail

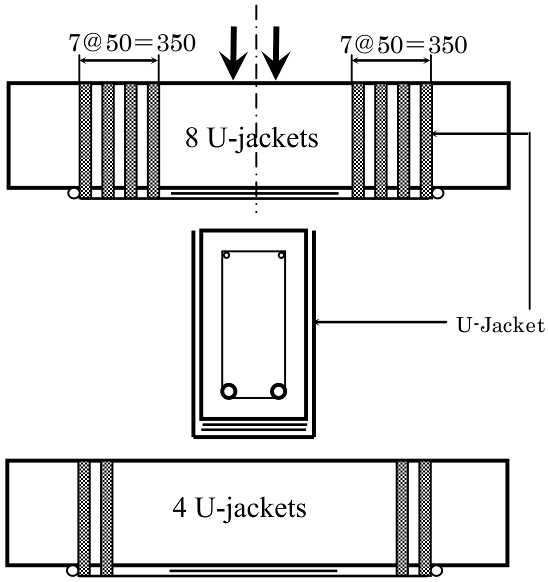


Figure 2 Test specimens with U-Jacket

the top. All specimens were reinforced for shear by closed stirrups with D10 (deformed steel bar with a nominal diameter of 9.53 mm) rebars equally spaced at 100 mm center-to-center throughout the span of the specimen. Details of the U-jacket are shown in Figure 2. All test specimens had two CFRP sheet layers. The lengths of the first CFRP sheet layer bonding directly to the concrete surface were 640, 1080 and 1540 mm, but the length of the second CFRP sheet layer was 1540 mm in all test specimens.

The test specimens were divided into four categories according to reinforcement schemes shown in Table 1. Specimen A00 was a control beam without CFRP sheets attached to the beam soffit (group A). The lengths of the first CFRP sheet layer were 640, 1080 and 1540 mm in groups B, C and D specimens, respectively. In groups B, C and D, U-jacket reinforcement quantity (the strip number) of each specimens was made to change with 0,4,8,12 and 16 strips. The first CFRP sheet layer length was set to 640 mm with reference to the spread at 45 degrees from the loading point, and the sheet length was increased in increments of 440 mm until 1540 mm. CFRP sheets were bonded to the beam soffit in the longitudinal direction on supporting-to-supporting points and at 30 mm ahead of the supporting points. And the points were supporting the specimen directly on its concrete bottom surface. All specimens were strengthened with CFRP sheets bonded to the tension surface and additionally by wrapping 50-mm-wide strips of CFRP sheets at a spacing of 50 mm up to 300 mm in height.

The experimental results are shown in Table 1 and the mechanical properties of the materials used for the test specimens are shown in Table 2.

In this study, the failure modes of test specimens were examined, and the strain of a tension steel rebar and CFRP sheet and the deflection just under the loading point were recorded using linear variable displacement transducers (LVDTs) at each load increment. Strain gauges of 5 mm in length were attached to the CFRP sheet from the center to both supports of the beam at a pitch of 100 mm, and strain gauges were also mounted on the tensile steel rebar.

The concrete was composed of high early-strength Portland cement, river sand and river gravel. The water-cement ratios and fine-coarse aggregate ratios were maintained at 45% and 38%, respectively.

The effects of length of the first CFRP sheet and number of U-jackets on failure mode, maximum load, deflection of the loading point, and strain of the rebar and CFRP sheet of the beam were examined experimentally.

Table 1 Experimental results

Group	Specimen No.	Sheet length (firtst+second) cm	Number of U-jackets	Concrete strength MPa	Ultimate Load kN	Failure Mode
A	00	No sheet	0	47.9	189.4	Flexural
B	01	64+154	0	40.2	233.4	Peeling
	02	64+154	4	46.3	239.3	Slippage peeling
	03	64+154	8	39.7	246.1	Slippage peeling
	04	64+154	12	41.3	256.0	Slippage peeling
	05	64+154	16	45.9	247.6	Slippage peeling
C	06	108+154	0	41.3	238.3	Peeling
	07	108+154	4	43.3	270.1	Slippage peeling
	08	108+154	8	46.9	284.4	Slippage peeling
	09	108+154	12	49.6	283.4	Slippage peeling
	10	108+154	16	41.8	273.6	Slippage peeling
D	11	154+154	0	40.2	244.0	Peeling
	12	154+154	4	41.5	272.6	Slippage peeling
	13	154+154	8	37.1	281.4	Slippage peeling
	14	154+154	12	43.3	279.5	Slippage peeling
	15	154+154	16	46.3	279.0	Slippage peeling

Table 2 CFRP sheet and steel rebar properties

CFRP sheet		Amount of fiber	300g/mm^2
		Thickness	0.167mm
		Elastic modulus	230GPa
		Tensile strength	3480MPa
		Strain of breakage	1530μ
Rebar	D19 (SD345)	Yield strength	371MPa
		Tensile strength	570MPa
	D10 (SD295A)	Yield strength	377MPa
		Tensile strength	537MPa

3 EXPERIMENTAL RESULTS

3.1 *Ultimate strength and failure modes*

As shown in Table 1, reinforcing with CFRP sheets increased the maximum ultimate strength of the specimens. Without U-jackets, the maximum load increases almost linearly with increase in the length of the first CFRP sheet. On the other hand, in the specimens with 16 U-jackets, an effect of the first CFRP sheet layer length is seldom observed at maximum load. If a span from the loading point with the spread of 45 degrees in the supporting point side is two CFRP sheet condition and in addition U-jacket reinforcement is sufficient for the span length, the effect of the first CFRP sheet length for the maximum load is seldom influenced. In the case of the ultimate strength to be decided by peeling of CFRP sheet, a peeling control effect by U-jacket is sufficiently shown. The test specimens without U-jacket reinforcement have reached to ultimate state in CFRP sheet peeling, but the specimens with U-jacket reinforcement have reached to ultimate state in interface slip movement between concrete surface and sheet (hereafter called "slippage peeling").

The relationships between maximum loads and numbers of U-jacket in all every group are shown in Figure 3, and the maximum load of control beam A00 without sheet reinforcement is also shown in this figure. As can be seen in this figure, in the case of length of 640 mm for the first CFRP sheet (Group B), the maximum load increases linearly with increase in number of U-jackets, but the maximum load does not increase like the rate of increase in number of U-jackets. On the other hand, the difference between the maximum load by the difference of the sheet length is seldom observed when CFRP sheet length was 1080 mm and 1540 mm. When the number of U-jackets was more than eight, the increase of the maximum load was seldom shown and maximum load became constant. These results indicate that the peeling was generated from the supporting point side to reach the ultimate state and that maximum load become constant by controlling the CFRP sheet peeling from the supporting point side. The ultimate state of test specimens without U-jackets has been reached in the rapid CFRP sheet peeling from which or other supporting point side. On the other hand, the ultimate state of test specimens with U-jackets has been reached in slippage peeling and some specimens failed due to horizontal breakage of the U-jacket in the corner of the wrapping after peeling of the CFRP sheets.

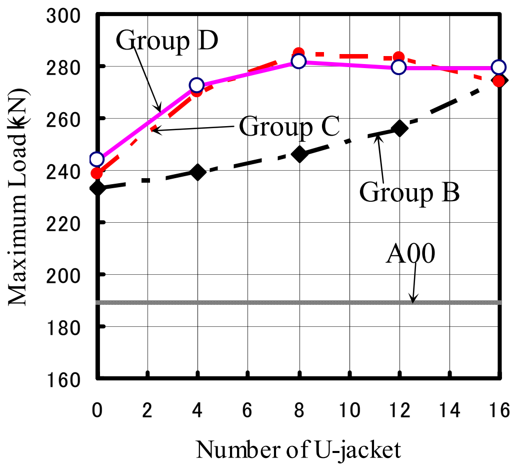


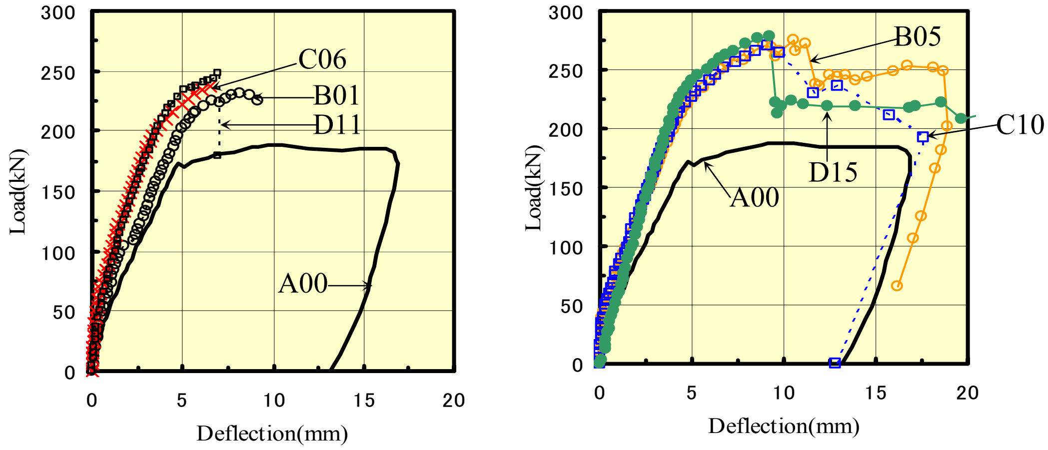
Figure 3 Maximum loads and numbers of U-jacket relationships

3.2 *Deflection behavior*

Load-deflection relationships at the loading point are shown in Figure 4. The deflection curve of control specimen A00 without a CFRP sheet is also shown in the figure. Figure 4(a) shows the relationships between load and deflections of the specimens without U-jackets according to the effect of first CFRP sheet length (640, 1080 and 1540 mm in length). Figure 4(b) shows the relationships between load and deflections of the specimens with 16 U-jackets according to the effect of first CFRP sheet length. As shown in Figure 4(a) and (b), the maximum load and fractural toughness behavior at the ultimate state were increased by using U-jacket reinforcement. Although deflection of specimens without U-jackets after CFRP sheet peeling approached the deflection of the control specimen and it can be confirmed that the load of specimens with U-jacket is kept to some extent and shifts to the ultimate state.

3.3 *Strain distribution in tension steel rebar and CFRP sheet*

Figure 5 shows the relationship between load and strain of reinforcement in the span center. The rebar strain was cut off at 5000 μ. Figure 5(a) shows the relationships between load and



(a) Without U-jacket (b) With 16 U-jackets

Figure 4 Load and Deflection relationships

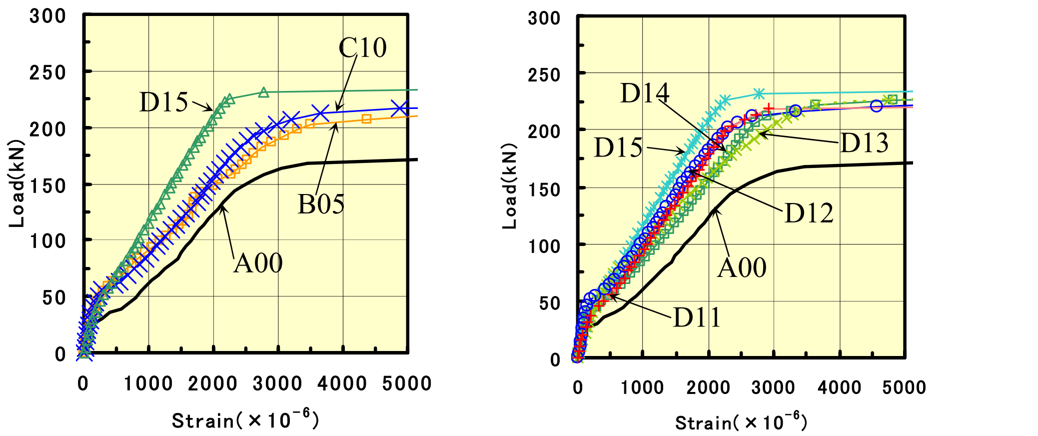
strain of the rebar in the case of 16 U-jackets and 640, 1080 and 1540 mm in first layer sheet length. Figure 5(b) shows the relationships between load and strain of the rebar in the case of increase in the number of U-jacket from zero to sixteen in increments of four U-jackets and with first sheet length fixed at 1540 mm.

Figure 5(a) shows that the cracking load increases from 30 to around 50 kN with increase in sheet length. The rebar strain gradient after cracking became steep with increase in first CFRP sheet layer length. This result indicates that apparent rebar rigidity increases.

Figure 5(b) shows that the apparent rebar rigidity also similarly increases with increase in number of U-jackets.

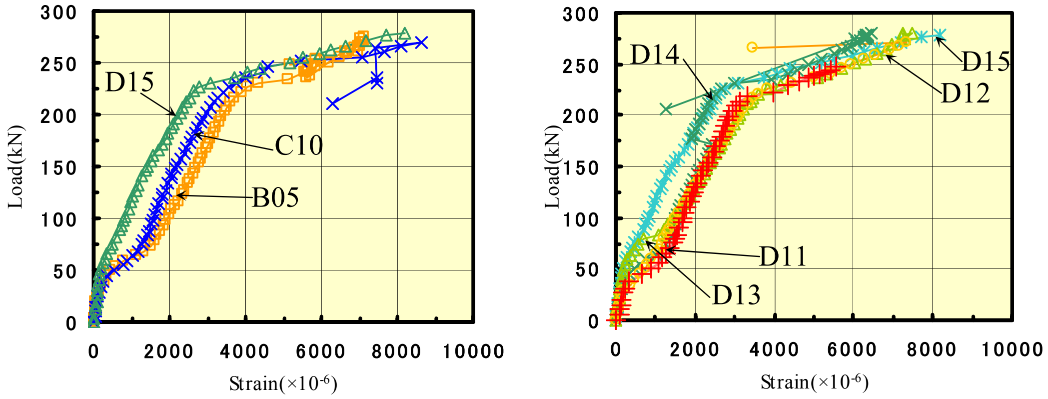
These results indicate that the apparent rebar rigidity also increases with both increase in first layer CFRP sheet length and U-jacket number.

Load-strain of CFRP sheet relationships at span center are shown in Figure 6. Figure 6(a) shows the relationships between load and strain of CFRP sheets in the case of 16 U-jackets and 640, 1080 and 1540 mm in first layer sheet length. Figure 6(b) shows the relationships between load and strain of CFRP sheets in the increase in the number of U-jackets from zero to sixteen in increments of four U-jackets with first sheet layer length fixed at 1540 mm.



(a) With 16 U-jackets (b) With first sheet length fixed at 1540mm

Figure 5 Load and steel rebar strain relationships



(a) With 16 U-jackets (b) With first sheet length fixed at 1540 mm

Figure 6 Load and CFRP sheet strain relationships

From Figure 6(a), the CFRP sheet strain values at the ultimate state were around 8000 μ, and the first point of inflection on the sheet strain curve with cracking becomes smooth with increase in sheet length. This means that the force applied to the sheet was smoothly transmitted.

Figure 6(b) shows that the apparent CFRP sheet rigidity (=gradient of sheet strain curves) increases with increase in the number of U-jackets.

These facts indicate that the increments of U-jacket is affected to increase the sheet strain. And it seems that a sharing of sufficient force in CFRP sheet by the U-jacket was carried out.

4 CONCLUSIONS

From the results of this study, the following conclusions can be drawn:

(1) The failure mode of beams without U-jackets was peeling of the CFRP sheet from the concrete. However, the failure mode of beams with U-jackets was interface slipping between the CFRP sheet and concrete. The ultimate load was increased by increase in the first CFRP sheet length in the case of no U-jackets. However, if the specimens have U-jackets and the first CFRP sheet length has been ensured to some extent, an increment of ultimate strength could not be seldom observed by the sheet length.
(2) Beam rigidity was increased by bonding a CFRP sheet on the tension surface. The maximum flexural strength was also increased and the fractural toughness behavior of the beam at the ultimate state was considerably improved by U-jackets.
(3) The cracking load of the beam was slightly increased, by increasing the sheet length, and apparent reinforcement rigidity after the cracking was also increased by increasing the CFRP sheet length.
(4) The sheet strain is around 8000 μ and it has not yet reached the sheet breakage strain. In the case of first CFRP sheet length being sufficient and the beam having U-jackets, the strain in the CFRP sheet increased and the transmission of force to the sheet became smooth.

5 REFERENCES

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