BEHAVIOR OF COUPLING BEAMS STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER SHEETS

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Abstract In this research, using the results of 6 tests, the effect of Carbon Fiber Reinforced Polymer (CFRP) sheets on the behavior of reinforced concrete coupling beams of shear walls is studied. First, in the experimental part of the study, four coupling beams with different reinforcements were manufactured and tested. Then, after the failure of the specimens, two of them were rehabilitated and strengthened with CFRP sheets, and retested. Four specimens were constrained longitudinally in order to evaluate the effect of the slab diaphragm on the coupling beam behavior. In each test, the applied load and the displacement of the coupling beam were measured. Test results show that the CFRP sheets can increase the shear strength of the conventional reinforced coupling beams. The Canadian Institute ISIS equations are in agreement with the test results of the strengthened beams. The assumption of a major diagonal crack instead of 45 degrees inclined cracks due to shear forces results in a better prediction of the strength of coupling beams. Based on the results of this study, the effect of longitudinal constraint may not be remarkable for the strength of coupling beams with conventional reinforcements. The rehabilitated and strengthened coupling beams with CFRP sheets can achieve appropriate strengths even larger than those of original beams. However, their stiffness decreases.

Keywords Coupling Beam, Concrete Wall, Reinforced Concrete, Shear Wall

چکیده در این مقاله با استفاده از نتایج ٦ آزمایش، اثر ورق های پوششی پلیمری CFRP بر تیرهای پیوند بتنی دیوارهای برشی بررسی می‌گردد. ابتدا، در بخش آزمایشگاهی تحقیق، ٤ تیر پیوند با آرماتورگذاری متفاوت ساخته و آزمایش شدند. سپس بعد از شکست نمونه ها، دو عدد از نمونه ها تعمیر و توسط ورق های CFRP تقویت و آزمایش شدند. ٤ عدد از نمونه ها در جهت طولی مقید شدند تا اثر دیافراگم دال کف ساختمان بر رفتار تیرهای پیوند ارزیابی شود. در هر آزمایش بار وارده و تغییر مکان تیر پیوند اندازه گیری شد. نتایج آزمایش نشان می‌دهند که ورق های CFRP می‌توانند مقاومت برشی تیرهای پیوند با آرماتورگذاری معمولی را افزایش دهند. همچنین روابط طراحی کمیته ISIS کانادا برای محاسبه مقاومت تیرهای پیوند با نتایج آزمایش مطابقت خوبی دارد. فرض یک ترک قطری در طول تیر پیوند بجای ترک های ٤٥ درجه که ناشی از نیروهای برشی می‌باشد، به نتایج بهتری از پیش بینی مقاومت برشی می‌انجامد. بر اساس نتایج این تحقیق، قید طولی اثر قابل ملاحظه ای در مقاومت تیر پیوند با آرماتورگذاری معمولی ندارد. تیر های تعمیر و تقویت شده توسط ورق های CFRP به مقاومت های مناسب و حتی بیشتر از تیرهای پیوند اولیه رسیدند. البته سختی این تیرها نسبت به تیرهای اولیه کاهش یافت.

1. INTRODUCTION

The behavior of coupled shear walls is influenced by the stiffness, strength and ductility of coupling beams. Paulay [1,2] showed that the failure of coupling beams with small length to depth ratios and conventional reinforcements is almost brittle. To improve the ductility of the coupling beams, using diagonal reinforcement in the beams [3] has been suggested. However, diagonal reinforcement may increase the construction problems due to the congestion of reinforcement in some parts of the beams. Studies have been conducted in order to propose an appropriate reinforcement layout [4-6].

In some researches, the use of steel plates or profiles has been performed [7,8]. In the present study, the effect of CFRP sheets on the strengthening of coupling beams is investigated. The use of external CFRP sheets can be useful because of their high strength and good performance. The efficiency of these materials in the improvement of seismic characteristics of coupling beams is not yet known. In most experimental studies, the effect of slab diaphragm on constraining the coupling beams has not been taken into account [9,10]. The longitudinal constraint may influence the strength and ductility of coupling beams [10]. In this study, four specimens have been longitudinally constrained in order to evaluate the constraining effect of the slab diaphragm on the strength and ductility of coupling beams.

2. TEST PROGRAM

2.1. Specimens The present test program is the first part of an experimental study on the behavior of coupling beams. First, four coupling beams were manufactured and tested. After the testing of the specimens, two were rehabilitated and strengthened by CFRP sheets and retested. Four specimens were longitudinally constrained. Before the casting of each constrained specimen, one PVC pipe with a diameter of 30 mm was installed at the middle of the beam (Figure 1). The dimensions of specimens and reinforcement are shown in Figure 1.

Figure 2 shows the specimens that have been strengthened with CFRP sheets. The details of the specimens including longitudinal and transverse reinforcing bars, concrete and steel strengths and longitudinal constraint are presented in Table 1.

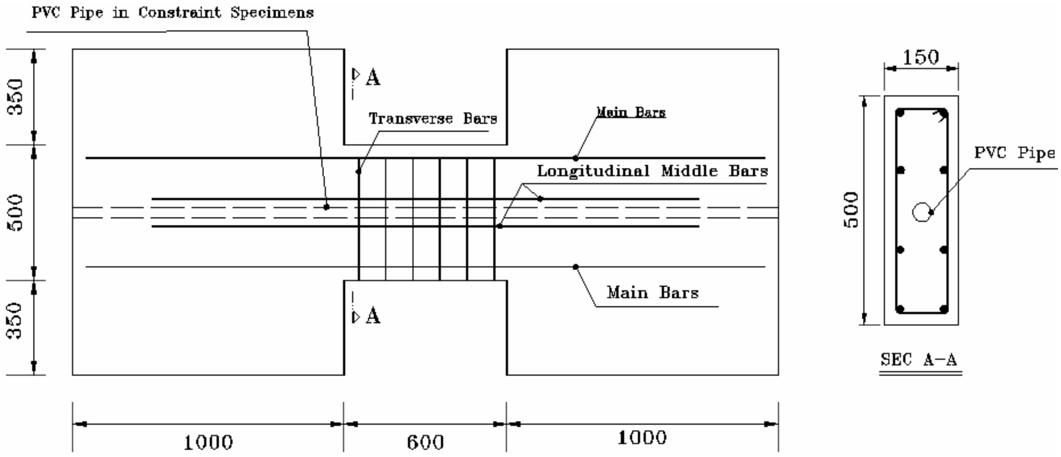

Figure 1. Dimensions of specimens and reinforcement.

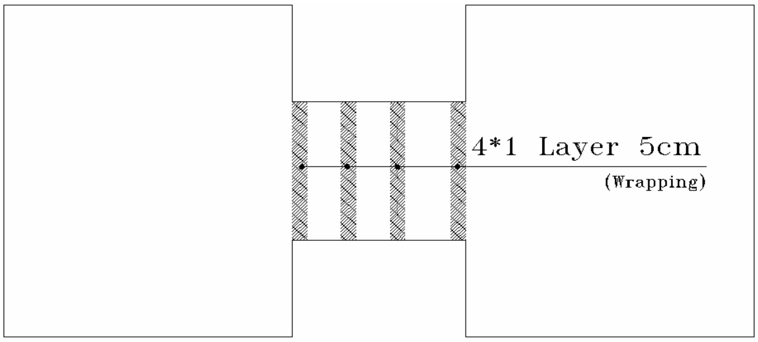

Figure 2. Specimens strengthened with CFRP sheets.

The thickness of all of specimens was 150 mm. The type of CFRP sheets was C-sheet 240 with 3800 MPa ultimate strength and 240 GPa modulus of elasticity. The thickness of one layer of CFRP sheet was 0.176 mm and its ultimate strain was 1.55 percent. As shown in Figure 2, each strengthened specimen had 4 CFRP strips with a total width of 20 cm and 70.4 mm^2 section area. Specimens P1, P3 and P4 had similar reinforcements except that P1 and P4 had 6 and P3 had 4 stirrups along the beam length. The main difference between specimens P1, P3 and P4 was the constraining condition (i.e. Specimen P1 was free and Specimen P3 and P4 were longitudinally constrained). Specimens P1 and P3 were rehabilitated and strengthened with CFRP Sheets after testing. The rehabilitated specimens were named P1-RE and P3-RE as shown in Table 1. Specimen S2 was strengthened with CFRP strips to study the effect of CFRP sheets on the strength of coupling beams. The amount of shear reinforcement in Specimen S2 was half of that in Specimens P1 and P4. Four specimens of P1, P3, P4 and S2, the steel bars and CFRP sheets were designed in order to have similar shear strength. The difference between the strengths of the specimens (as seen in Table 2) is due to the actual concrete strength and yield strength of reinforcing bars in different specimens. The methods used for shear strength calculation will be given in Section 4.

2.2. Test Setup A Test setup is shown in Figure 3. As shown in Figure 3, one side of the specimens was free and the other side was fixed to the strong floor by steel bars. A steel beam was fixed to the free end of the specimens in order to transfer the applied load from a displacement control hydraulic jack to the specimens. The axis of the applied load passed through the middle of each specimen. Therefore, the middle of the coupling beams was the point of inflection and two asymmetric moments were produced at the beam ends. These conditions are similar to the conditions of real coupling beams. Lateral movements of the specimens were prevented by appropriate facilities. Loads and displacements were measured using a computer aided data acquisition system. Before the casting of each constrained specimen, one PVC pipe with a 30 mm diameter was installed at the middle of the beam. By placing a high strength steel bar with a 20 mm diameter in the PVC pipe and anchoring its ends, the free elongation of the specimens was prevented. According to the previous studies [9,10], the specimens would expand longitudinally under loads, therefore the steel bar should always be in tensile. The load in the steel bar was measured using a load cell attached to one side of the bar (Figure 3).

3. TEST RESULTS

3.1. Load-Displacement Relationship Figure 4 shows the load-displacement relationships of different coupling beams. Also, the measured and calculated strengths are compared in Table 2. Shear and bending strengths of specimens were calculated according to the proposed equations by ACI318-05 [11]. The proposed equations by the Canadian Institute ISIS were used for the calculation of specimens strengthened with CFRP sheets [12]. The maximum compressive strain of concrete was considered equal to 0.003, and all of the strength reduction factors were considered equal to 1.

3.2. Failure Modes The crack pattern and failure mode of specimens are shown in Figure 5. As shown in Figure 5, diagonal cracks occurred in all of the specimens. Diagonal cracks opened widely before shear failure in all specimens. However, the crack distribution is not the same in different coupling beams.

Failure of Specimen S2 occurred suddenly with only one deep diagonal crack. All of the CFRP strips used for shear strengthening, fractured at beam failure.

4. ANALYSIS OF TEST RESULTS

4.1. Shear Strength of Coupling Beams According to ISIS [12], the shear strength of CFRP strips can be calculated by Equation 1 as follows:

$$V_{frp} = \frac{E_{frp}\varepsilon_{frpe}A_{frp}d_{frp}}{S_{frp}} \quad (1)$$

where E_{frp} is the modulus of elasticity of CFRP sheets, A_{frp} is the section area of one strip, d_{frp} is the height of the beams, S_{frp} is the spacing between strips, and ε_{frpe} is the effective strain of FRP sheets. The value of ε_{frpe} is considered equal to 0.004 for sections that are wrapped.

Equation 1 is based on the assumption of 45 degrees incline cracking due to shear forces. This assumption may only be appropriate for normal beams. However, as seen in the present study and observed by other researchers, in a coupling beam with small length to depth ratios, diagonal cracking occurs along the beam length. Therefore, it should be more appropriate to consider the effect of all

TABLE 1. Details of Specimens.

Specimen	f'_c (MPa)	Long. constraint	Main Long. bar	Middle long. bar	Transverse bar
			f_y (MPa)	f_y (MPa)	f_y (MPa)
P1	20	Free	16 Φ 2 × 2	12 Φ 4	8 Φ 6
			510	461	516
P3	20	constrained	16 Φ 2 × 2	12 Φ 4	8 Φ 4
			510	461	516
P4	20	constrained	16 Φ 2 × 2	12 Φ 4	8 Φ 6
			510	445	427
S2	32	constrained	16 Φ 2 × 2	8 Φ 4	8 Φ 3
			510	427	427
P1-RE	25	Free	16 Φ 2 × 2	12 Φ 4	8 Φ 6
			510	461	516
P3-RE	25	constrained	16 Φ 2 × 2	12 Φ 4	8 Φ 4
			510	461	516

TABLE 2. Comparison Between Beam Strengths.

Beam	(1) V_c	(2) V_s	(3) V'_s	(4) V_{frp}	(5) V'_{frp}	(6) V_b	(7) V_{cal}	(8) V_{test}	V_{test}/V_{cal}
P1	49.1	233.4	311.2	-	-	389.5	$V_c + V_s = 282.5$ $V_c + V'_s = 348.4$	333.1	1.18 0.92
P3	49.1	155.6	207.5	-	-	389.5	$V_c + V_s = 204.7$ $V_c + V'_s = 255.6$	256.0	1.25 1.00
P4	49.1	193.2	257.6	-	-	387.1	$V_c + V_s = 242.3$ $V_c + V'_s = 306.7$	315.7	1.30 1.03
S2	62.4	96.6	128.8	50.7	67.6	332.0	$V_c + V_s + V_{frp} = 209.7$ $V_c + V'_s + V'_{frp} = 258.8$	248.7	1.19 0.96
P1-RE	49.4	224.5	299.3	50.7	67.6	389.5	$V_c + V_s + V_{frp} = 324.6$ $V_c + V'_s + V'_{frp} = 416.3$	353.0	1.09 0.85
P3-RE	49.4	149.7	199.5	50.7	67.6	389.5	$V_c + V_s + V_{frp} = 249.8$ $V_c + V'_s + V'_{frp} = 316.5$	313.9	1.26 0.99

1. Shear strength of concrete, kN, 2. Shear strength of transverse reinforcement according to ACI, kN, 3. Shear strength that would be sustained across major diagonal by all stirrups at yield, kN, 4. Shear strength of CFRP sheets, kN
5. Shear strength that would be sustained across major diagonal by all CFRP strips
6. Maximum shear force related to bending strength, kN, 7. Calculated shear strength, kN, 8. Measured shear strength in a test, kN.

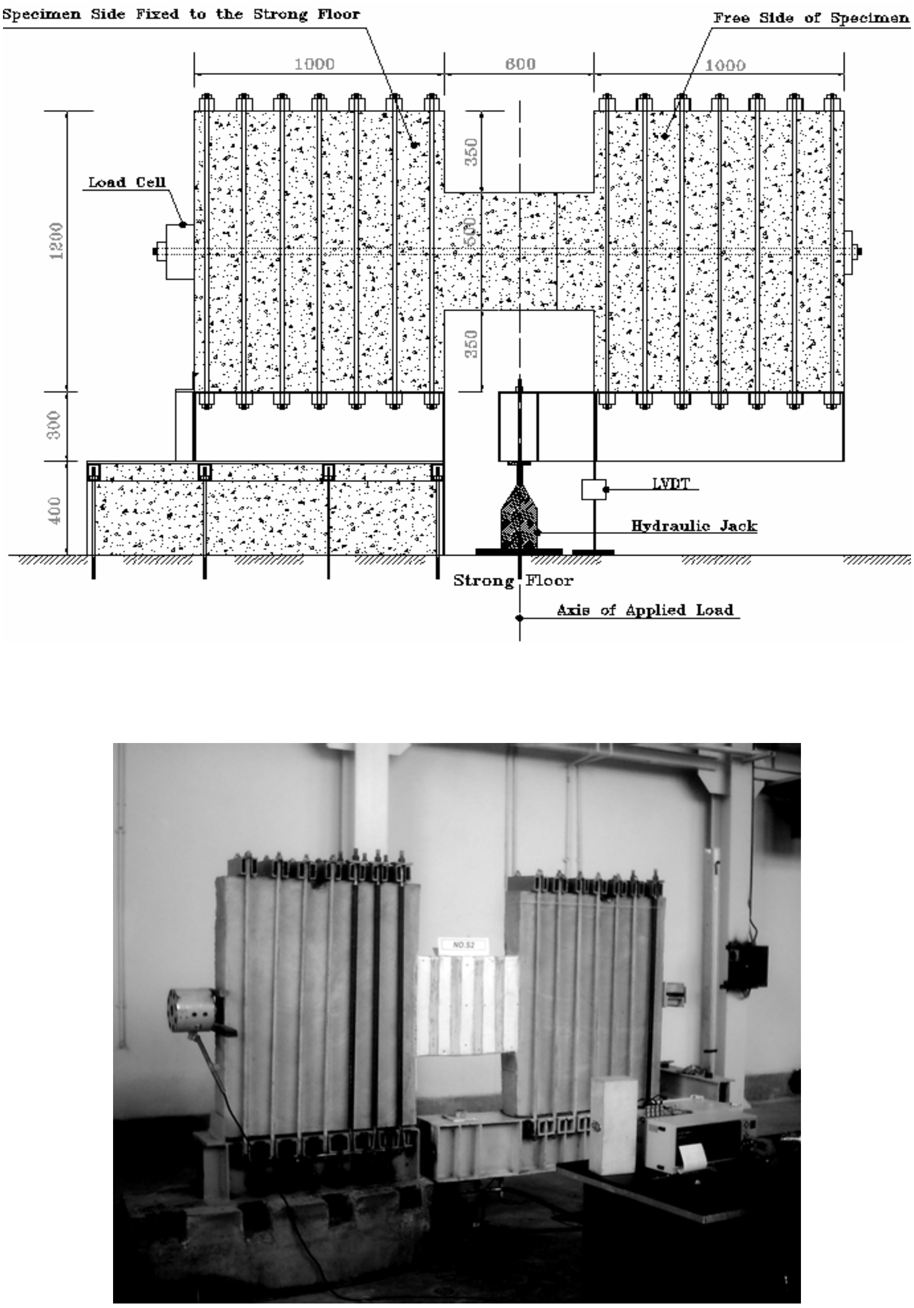

Figure 3. Test setup.

CFRP strips in the calculation of the beam shear strength. To account for the effect of all CFRP strips in shear strength, Equation 1 is modified as follows:

$$V'_{frp} = E_{frp}\varepsilon_{frpe}A_{frp}.n \qquad (2)$$

where n is the number of strips cut by the major diagonal crack.

For the values of the $V_{test}/V_{cal.}$ ratio in Table 2, the average of the $V_{test}/V_{cal.}$ values using Equation 1 is 1.21 with a standard deviation of 0.07. If Equation 2 is used in the calculation of $V_{cal.}$, the

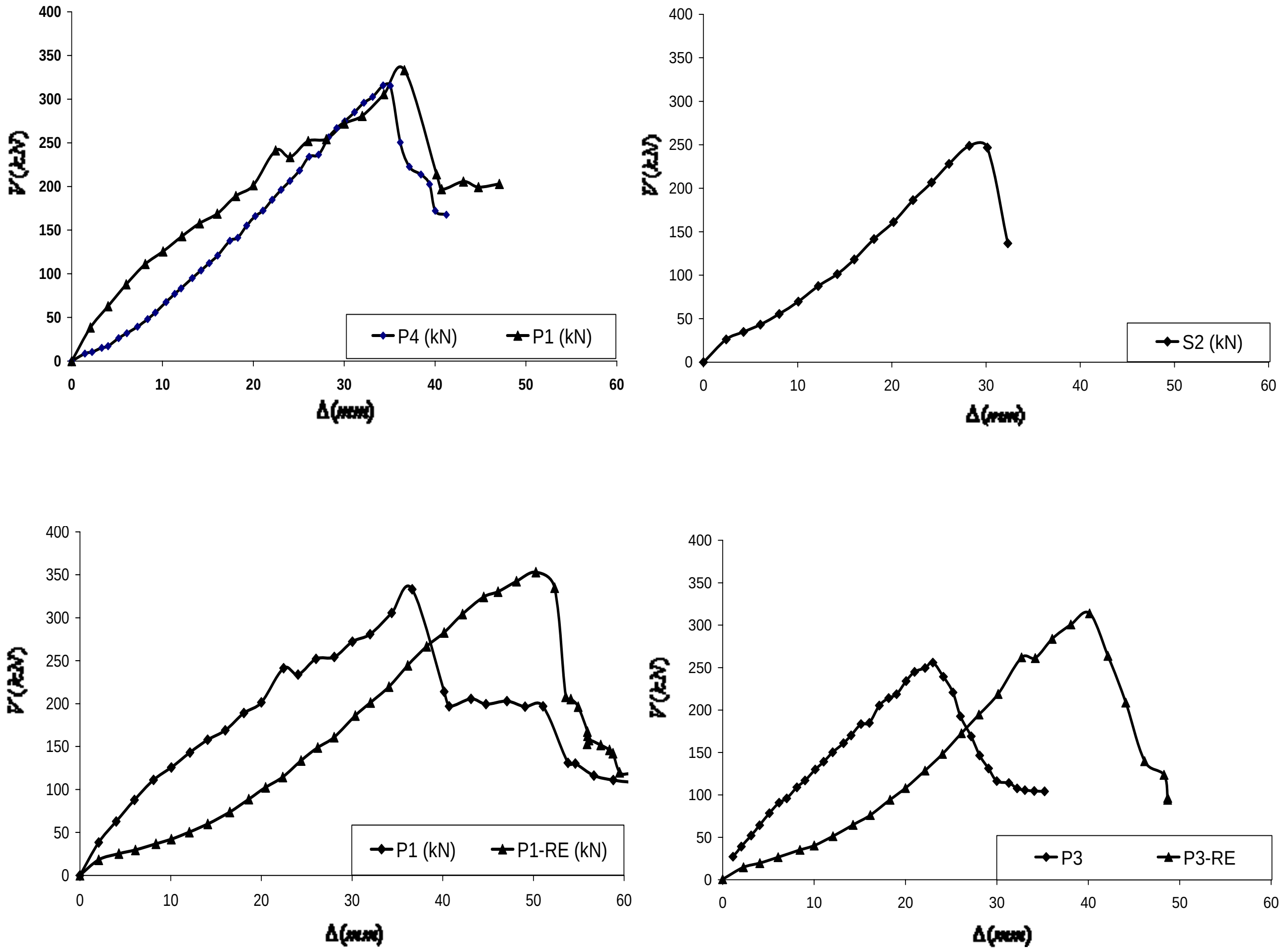

Figure 4. Load-displacement relationships.

average of the $V_{test}/V_{cal.}$ values is 0.96 with a standard deviation of 0.06. Therefore, the assumption of diagonal cracks instead of 45 degrees incline cracks due to shear forces (i.e. accounting for all transverse reinforcement and CFRP sheets in the calculation of V_{cal}) results in a better prediction of the strength of coupling beams.

To prevent bending failure in specimens, adequate longitudinal reinforcement should be provided in coupling beams. The bending moment capacity M_s due to the longitudinal reinforcement results in a shear force V_b as shown in Figure 6. The value of V_b is calculated by the following equation:

$$V_b = \frac{2M_s}{L} \qquad (3)$$

where M_s is the bending strength according to ACI318-05, and L is the length of the coupling beam. Shear failure occurs in a specimen if shear strength V_{cal} (Table 2) is less than V_b. As seen in Table 2, the value of V_b is larger than V_{cal} in all specimens. Test results also showed shear failure in all specimens. For calculating the bending strength of specimens, the effect of all longitudinal bars distributed over the height of the sections was considered.

As shown in Table 2, the calculated shear

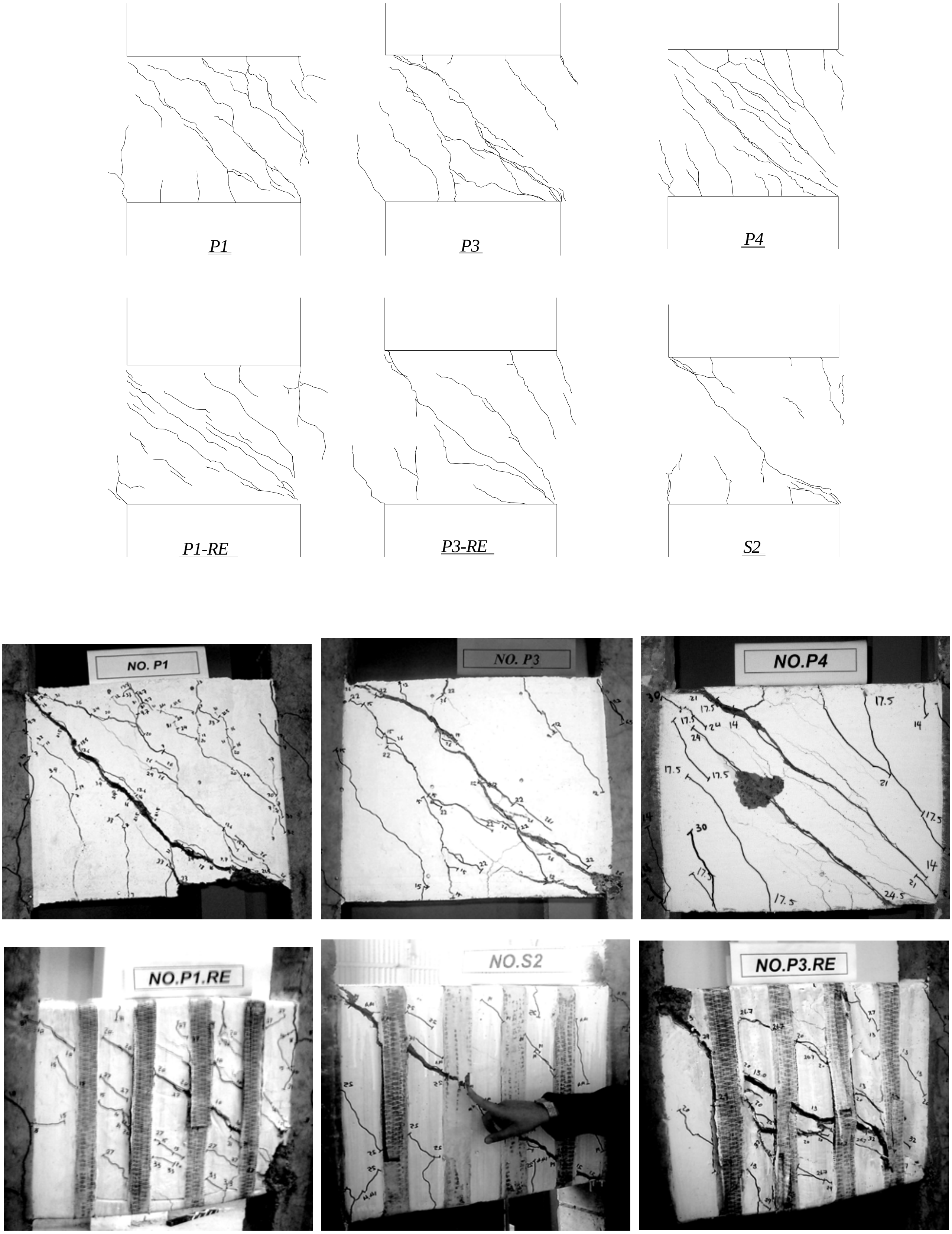

Figure 5. Crack pattern and failure mode of specimens.

strengths using V'_s and V'_{frp} have more agreement with the test results in most cases. The main reason may be that in beams with diagonal cracks, all of the stirrups have participated in carrying the load. The values of V_{test}/V_{cal} in Table 2 show that with the exception of specimen P1-RE, the correlation between test results and calculated values is more appropriate when V'_s is used instead of V_s. In specimen P1-RE a complete diagonal crack did not take place and one CFRP strip did not fracture at beam failure (Figure 7).

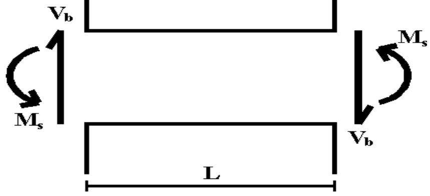

Figure 6. Equilibrium condition in a coupling beam.

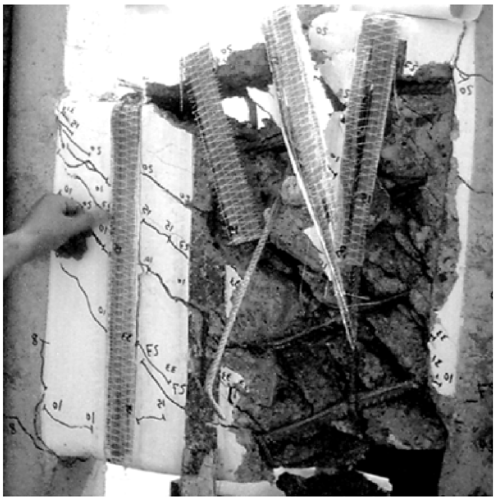

Figure 7. Crack pattern in Specimen P1-RE after complete failure.

4.2. Constraining Effect Some experimental researches have shown that coupling beams longitudinally expand under loads in tests [9,10]. However, in real structures, this may not take place because of the constraining effect of slab diaphragm and high rigidity of shear walls. In the present research, the expansions of some specimens were prevented using a longitudinal bar to account for the effect of the slab diaphragm. The longitudinal bar was installed in PVC pipes located at the middle of the specimens and anchored at their two ends using two nuts. To eliminate the spacing between the nuts and the specimens, an initial tensile force was applied to the bar by fixing the nuts. Due to elongation of the specimens during loading, tensile forces were applied to the bar. These forces were recorded by a load cell.

Table 3 shows the measured axial loads in the constraint specimens before and during loading. Also, this table presents vertical displacements of one end of the beams related to the other end at maximum shear and axial forces.

Specimens P1 and P4 were similar except that Specimen P4 was constrained against expansion. As shown in Table 2 and Figure 4, the behavior of these two specimens is not very different. Also, the results in Table 3 show that the longitudinal constraint loads are not significant. Therefore, the effect of longitudinal constraint may not be remarkable for the strength of coupling beams with conventional reinforcement. The effect of the longitudinal constraint may be significant in coupling beams with diagonal reinforcement. Another test program is needed to be able to reach a conclusion on the effect of longitudinal constraint on the behavior of coupling beams. In the second part of the study, it is planned to manufacture and test specimens with diagonal reinforcement for further investigation on the effect of longitudinal constraints.

4.3. Rehabilitated Specimens As mentioned earlier, Specimens P1 and P3 were rehabilitated and strengthened by CFRP sheets in order to study the effects of rehabilitation of damaged specimens due to excessive loads. The results of the rehabilitated specimens P1-RE and P3-RE are given in Table 2. Figure 4 compares the behavior of the original and rehabilitated specimens under loading until their failure. As seen in Figure 4, the rehabilitated specimens have achieved the strength of the original specimens. However, the stiffness of these specimens has decreased. The reduction of the stiffness of the rehabilitated specimens can be due to the formation of gaps between the first and second concretes in the rehabilitation process.

TABLE 3. Axial Forces of Tensile Bars and Vertical Displacements of on End of the Coupling Beams.

Specimen	Primary axial force F_0 (kN)	Maximum axial force F_{max} (kN)	Disp. at F_{max} (mm)	Disp. At V_{test} (mm)
P3	Not recorded	Not recorded	Not recorded	23
P4	18	42.61	35.09	34.286
S2	18	32.71	30.145	28.217
P3-RE	18	45.62	40.145	40.145

5. CONCLUSIONS

In the present research, the behavior of coupling beams in coupled shear walls was studied. Based on the test results and the comparison between measured and calculated values, the following conclusions can be drawn.

- The assumption of a major diagonal crack instead of 45 degrees incline cracks due to shear forces results in a better prediction of the strength of coupling beams. In this case all transverse reinforcement and CFRP sheets along the beam length are accounting for in the calculation of shear strength.
- Based on the results of this study, the effect of longitudinal constraint may not be remarkable for the strength of coupling beams with conventional reinforcement.
- In shear strengthening with CFRP strips, Canadian Institute ISIS equations are in agreement with the test results.
- The rehabilitated and strengthened coupling beams with CFRP sheets can achieve appropriate strengths even larger than those of the original beams. However, their stiffness decreases.

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