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CONFINED REINFORCED CONCRETE VERTICAL ELEMENT DUCTILITY UNDER LATERAL LOAD: INFERENCE FROM TEST RESULTS

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Vertical elements fail during earthquakes due to lateral load. Carbon-fiber-reinforced polymer (CFRP) can play a significant role in preventing sudden collapse due to lateral load. Confinement provided by transverse shear reinforcement and polymer sheets increases both the compressive and lateral strength of concrete. To test the effect of CFRP confinement on concrete columns, seven square and four circular vertical specimens were tested and results were compared with theoretical predictions at Bangladesh University of Engineering and Technology. The specimens were wrapped at the vertical portion on an intermittent basis so that CFRP strips fell at the gap of horizontal reinforcements of the specimens' vertical portion. Cyclic shear test was performed while maintaining axial compression. The test results were close to the theoretical predictions. The results thus suggest that CFRP wraps can contribute increased shear strength and ductility of vertical elements. High-strength concrete specimens did not reach their maximum strength due to the testing facility's limitations, but they provided the expected results in the lower bound.

Keywords: CFRP, Cyclic shear, Dilation, Shear strength.

1 INTRODUCTION

In the early days, the vertical elements (i.e., columns) of bridges and buildings were constructed using low-strength concrete that had low seismic performance. The main ingredients of concrete were burned clay and broken stone aggregate. Columns' seismic performance can be improved by increasing their ductility, which affects the concrete's strength (Yang *et al*. 2018, Kabir *et al*. 2020). Confining pressure such as fiber reinforced polymer (FRP) wrapping can enhance the ductility behavior of concrete columns (Choudhury *et al.* 2016). In this research, to test the effects of carbon-fiber-reinforced polymer (CFRP) wrapping on columns, three burned clay and four broken stone aggregate specimens square in shape and two burned clay aggregate and two broken stone aggregate specimens circular in shape, were tested. Initially, the plan was to begin the study from 10 MPa and increase to 30 MPa. However, during the test, it was not possible to break the 30-MPa concrete sample due to the inadequate capacity of the testing facility. A 20-MPa concrete sample was subsequently introduced. Specimens of vertical elements were examined using Eq. 10.2 to Eq. 10.5 of ACI 440.2R-02 (ACI Committee 440 2002) and Eq. 3.4.1 to Eq. 3.4.3 provided in HBRI-UTOKYO guidelines (2022). The authors previously indicated through theoretical predictions in Nuruzzaman *et al.* (2020) that use of FRP showed greater contribution to increasing shear strength for low-strength concrete compared to high-strength concrete. This paper aims to verify the effects of CFRP wrapping on columns by presenting a comparison of test outcomes and theoretical predictions.

2 CFRP, CONCRETE, AND REINFORCEMENT PROPERTIES

CFRP sheet thickness was 0.167 mm. The tensile strength of sheets was 3,400 N/mm^2, and the modulus of elasticity (E) was 245 N/mm^2. The effective strain of confined concrete was 0.0104. Well-graded, burned clay aggregates and broken stone aggregates were used in making the concrete (AASHTO M80). Fine aggregate consisted of natural sand. Normal Portland cement (AASHTO M85 type 1) was used in making concrete. Ten MPa, 20 MPa, and 30 MPa concrete was used in the specimens. The transverse reinforcement or tie bar was of 473 MPa yield strength and longitudinal bars were of 498 MPa.

3 THE SCHEMATIC DIAGRAM OF THE RIG

Reinforcement of specimens is shown in Figure 1 and in Figure 2. In Figure 3, the specimen is placed in the loading set up. The testing was conducted using a computer-controlled jack system with cyclic shear loading. Displacement recording set-up is shown schematically in red. Shear strength (V_n, Q_{su}) was calculated following ACI Code 440.2R (ACI Committee 440 2002) and HBRI-UTOKYO (2022) seismic evaluation guidelines. The height-to-width ratio of each specimen was kept at 2 (480:240), thus meeting the criteria of a short column (Matsukawa *et al.* 2023). All specimens were wrapped with CFRP at regular intervals between the transverse reinforcements.

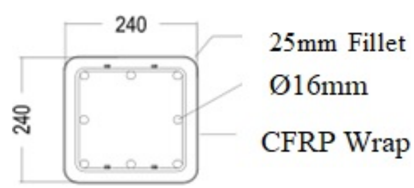
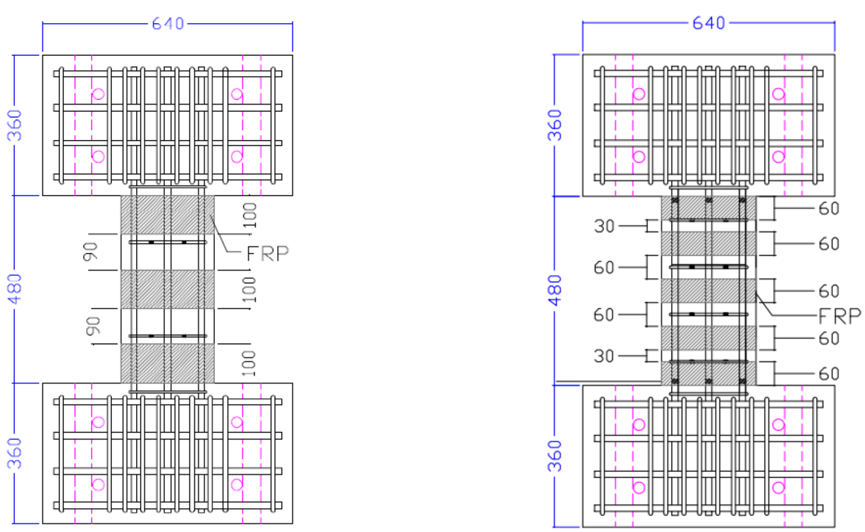


Figure 1. Cross-section of column.



(a) (b)

Figure 2. CFRP and reinforcement of specimens: (a) 0.1% @ 240mm, (b) 0.2% @ 120mm.

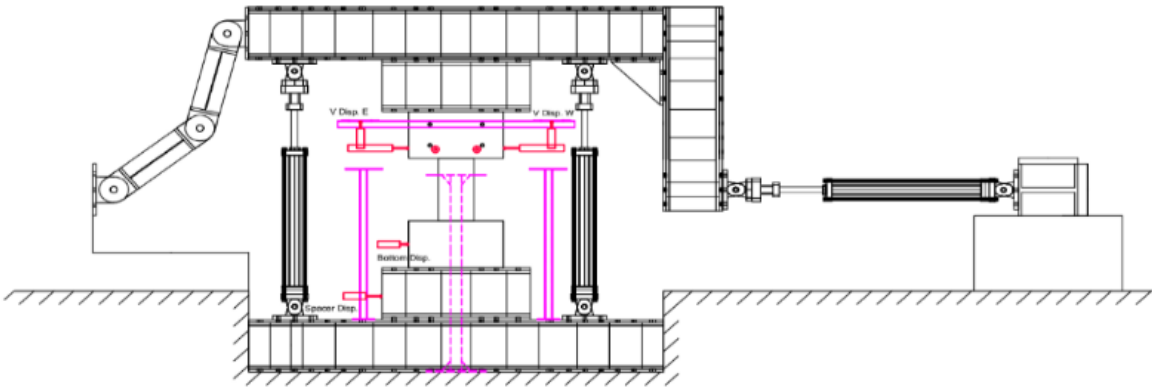


Figure 3. The specimen is placed in the loading setup.

4 THEORETICAL ESTIMATIONS OF THE SHEAR CAPACITIES

Theoretical estimations of shear capacity were done by the equations from ACI Code 440.2R, which were as follow (ACI Committee 440 2002):

Shear capacity (Eq. 1),

$$\phi V_n = \phi V_c + V_s + \psi_f V_f \tag{1}$$

Shear strength of concrete (from ACI 318-02) (Eq. 2),

$$V_c = 0.17\left(1 + \frac{N_u}{13.8A_g}\right) f_c' bd \tag{2}$$

Shear strength contribution for the rectangular hoop (Eq. 3),

$$V_s = \frac{A_s f_{yd}}{S} \tag{3}$$

Shear contribution of CFRP (Eq. 4),

$$V_f = \frac{2t_f W_f F_{fe} d_f}{S_f} \tag{4}$$

$$f_{fe} = \varepsilon_{fe} E_f \tag{5}$$

where; N_u: axial load, A_g: gross concrete area, f_c': concrete's strength, b: width, A_s: horizontal reinforcement area, S: horizontal reinforcement spacing, d: distance of the outer most fiber from the neutral axis of considered section, f_{yd}: yield strength of steel, t_f: thickness, W_f: width, f_{fe}: effective stress of the CFRP (Eq. 5), S_f: spacing of CFRP, ε_{fe}: effective level in CFRP, E_f: elasticity modulus of CFRP.

5 TESTS ON SQUARE AND CIRCULAR VERTICAL ELEMENTS

Square and vertical elements were cast for testing. Figure 4 shows the crushing of the square sample specimen and cracks in the circular specimen.

Figure 4. Test specimens: (a) crushed square sample with stone aggregate, (b) cracks in the circular sample.

6 DESCRIPTION AND TEST RESULTS OF SPECIMENS

Seven square vertical specimens and four circular specimens were tested, and the following tables and graphs represent the results. Tables 1 and 2 show the test results of the seven square vertical and four circular specimens, respectively.

Table 1. Summary of square sample test result (axial load 340 kN for all specimens).

Specimen	Aggregate	Transverse Reinforcement	Hoop Details	Target Strength [MPa]	Testing Strength [MPa]	Cyl. Str. with CFRP [MPa]	Max. Shear Load	Specimen Condition
CFRP SP-01	Stone	0.2%@120mm	Welding	10	11	50	148	Broken
CFRP SP-02	Brick	0.2%@120mm	Welding	10	12	42	150	Broken
CFRP SP-03	Stone	0.1%@240mm	Welding	30	32	72.5	160	Not Broken
CFRP SP-04	Stone	0.1%@240mm	Welding	10	12.5	54	177.123	Broken
CFRP SP-05	Brick	0.1%@240mm	Welding	10	11	40	159.44	Broken
CFRP SP-06	Brick	0.1%@240mm	Welding	20	22	57	177.273	Not Broken
CFRP SP-07	Stone	0.1%@240mm	Welding	20	17	60	184.465	Not Broken

Table 2. Summary of circular sample specimen test results.

Specimen	Aggregate	Transverse Reinforcement	Hoop Details	Target Strength [MPa]	Testing Strength [MPa]	Axial Load [kN]	Maximum Shear Load
CFRP SP-01	Stone	0.2%@120mm	Welding	10	10.5	340	141.16
CFRP SP-02	Stone	0.2%@240mm	Welding	10	11.7	340	156.89
CFRP SP-03	Brick	0.1%@240mm	Welding	10	9.7	340	155.54
CFRP SP-04	Brick	0.2%@120mm	Welding	10	10.1	340	198.85

7 THEORITICAL EVALUATION AND COMPARISON WITH RESULTS

Jacketing of the vertical element with CFRP changes shear strength (Q_{su}). Thus, CFRP wrapping can be used for retrofitting work. The change can be evaluated using Eqs. 6 and 7 (Eq. 3.4.1 to Eq. 3.4.3 provided in HBRI-UTOKYO (2022)). The equations are as shown in Eq. (6) and Eq. (7):

$$Q_{su} = \left\{ \frac{0.053 p_t^{0.23}(F_c + 18)}{\frac{M}{Qd} + 0.12} + \alpha_L \sqrt{p_w \sigma_{wy} + P_{wf}\sigma_{fd}} + 0.1\sigma_0 \right\} bj \tag{6}$$

$$\alpha_L = 0.038 F_c \leq 0.85 \quad 1.0 \leq M/Qd \leq 3.0$$

$$\sigma_{fd} = \min\left(E_{fd}\varepsilon_{fd}, \frac{2}{3}\sigma_f\right) \tag{7}$$

where; p_t: tensile reinforcement ratio (%), F_c: concrete compressive strength, d: effective depth of column, D: depth of column (D=50 mm), b: width of column, σ_0: axial stress in column (<7.8 MPa), h_0: clear height of column, M: flexural strength, σ_f: nominal tensile strength of CFRP, M/Q: shear span length (h_0/2 shall be applied), j: distance between centroids of forces (0.8D), p_w: transverse reinforcement ratio, σ_{wy}: yield strength of transverse bars, P_{wf}: transverse reinforcement ratio of CFRP, σ_{fd}: design tensile strength of carbon fiber sheet, E_{fd}: nominal elastic modulus of carbon fiber sheet, ε_{fd}: effective strain of carbon fiber sheet (0.70%), α_L: reduction factor for low strength concrete.

Flexural strength (Mu) was calculated in the same way as existing RC columns (Matsukawa *et al*. 2023). Comparison of maximum shear loads for square specimens with different concrete strengths are shown in Figure 5. Specimens with and without CFRP were compared against the test result. In this figure, theoretical predictions vary linearly. At low strength, test results were clustered, and at midrange, they have a nonlinear formation. In Figure 6, circular column test results are compared with theoretical predictions for different concrete strengths. In both figures, theoretical predictions are lower than the test results.

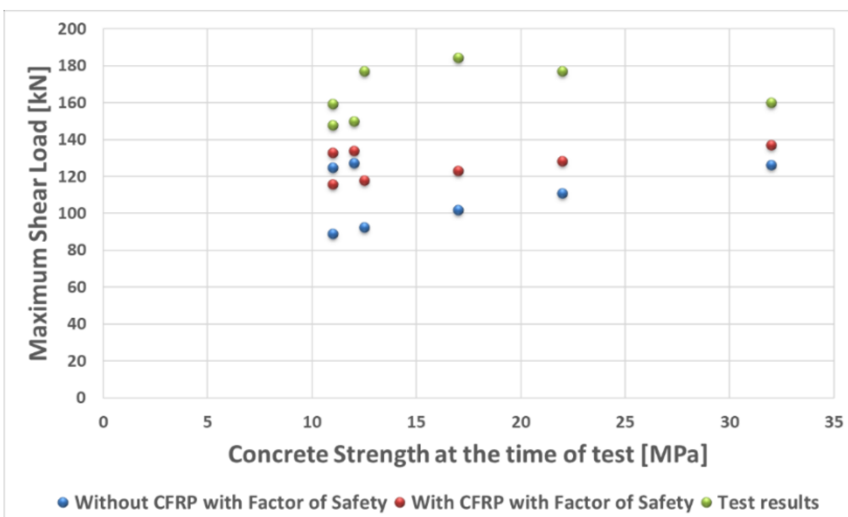


Figure 5. Comparison of square column's theoretical predictions and test results.

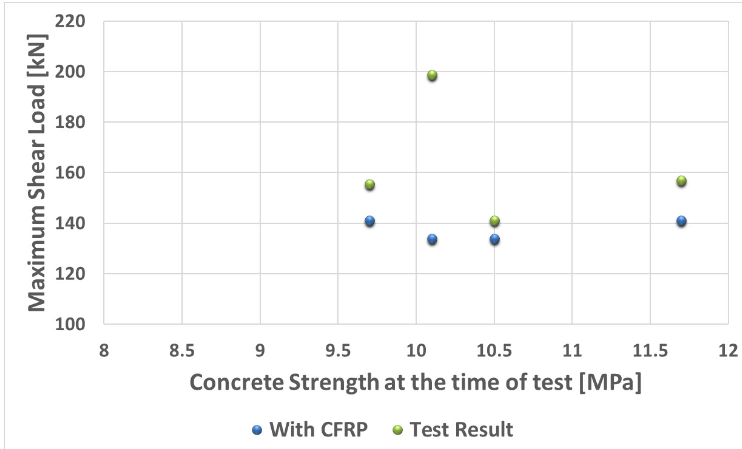


Figure 6. Comparison of circular column's theoretical and test results with.

8 CONCLUSIONS

A comparison was presented between theoretical predictions and test results of the shear capacity of CFRP jacketing of square and circular columns according to ACI Code 440.2R (ACI Committee 440 2002) and equations provided by the University of Tokyo and the Housing and Building Research Institute, Dhaka, Bangladesh (HBRI-UTOKYO 2022). The comparisons showed that the test results were close to ACI Code ACI-440.2R (ACI Committee 440 2002) and that the equations provided in HBRI-UTOKYO (2022) can be used in practice in Bangladesh with an assured safety factor. This was verified by the theoretical predictions and sufficient test results. In a structure such as a bridge or building, CFRP's contribution to self-weight is small in shear force but improves ductility. CFRP helps increase ductility and shear strength and is effective in low-ductile vertical elements.

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