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Confined reinforced concrete bridge pier ductility under lateral load: Theoretical predictions

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ABSTRACT: Bridge piers - a column element connecting bridge girders with the bridge foundation—often fail under lateral load during earthquakes. To prevent this type of catastrophic collapse, improving the lateral load-carrying capacities of such columns is important. Increasing the compressive strength of concrete is possible through confinement, with an aim to enhance not only the axial load-carrying capacity but also the lateral load-carrying capacity when a column has to act under simultaneous shear and axial forces. To this end, theoretical calculations for a few prototype reinforced concrete columns were examined based on the ACI 440.2R-02 provisions. In addition to confinement obtained from transverse steel reinforcements, attaching fiber-reinforced polymer wraps at regular intervals between each of the transverse steel reinforcements is considered. Calculations suggest that fiber-reinforced polymer wraps can contribute 47–65% of the total shear capacity of the eight strengthened specimens we considered. Experiments are needed to confirm such shear capacity and ductility behavior enhancements for various grades of concrete, confinement ratios, and types of coarse aggregate used in the concrete.

1 INTRODUCTION

Bangladesh has a risk of earthquakes due to several semi-actives to presently-dormant plate boundaries within her vicinity. Recent surveys revealed that many old and dilapidated reinforced concrete (RC) bridges have poor performance predictions in future earthquakes due to low strength concrete, high axial load ratio on piers, insufficient transverse reinforcements, and lack of seismic detailing. Furthermore, brick aggregate was often used in old RC bridge piers, particularly in rural areas of Bangladesh. In RC buildings, the use of brick aggregate is still common. Nevertheless, older bridge piers or building columns often do not meet the current seismic code requirements. Yang et al. (2018) and Kabir et al. (2020) indicated the strength of concrete has a strong dependence on the ductility behavior of RC columns. Low-strength concretes and concretes from brick aggregate show unique ductility behaviors when compared to high-strength concretes or concretes from stone aggregates. In this theoretical study, four prototypes of brick and four prototypes of stones qu are columns of similar types were assessed for shear capacities under high axial loads. Concrete strengths of 10 MPa and 30 MPa are considered. Transverse reinforcement ratios are 0.10% to 0.20%. Welded 90° hooks used as transverse reinforcements, for 0.10% and 0.20% reinforcement ratios, are considered. All specimens were wrapped with fiber-reinforced polymer (FRP) at regular intervals between the transverse reinforcements. Even though the calculation following ACI 440.2R-02 shows the FRP confinement increases the ductility in all cases proportionate to the applied confinement irrespective of the aggregates used, it is important to consider unique dilation behavior of brick aggregate concretes observed earlier in confined concrete (Islam et al. 2015; Choudhury et al. 2016) to see whether the dilation behavior has an effect on the ductility behavior as well. The analysis of dilation behavior should shed light on the effectiveness of FRP wraps for enhancing the ductility behaviors of bridge piers and building piers for use as a potential method of retrofitting in the context of Bangladesh.

2 DILATION PHENOMENON OF STONE AGGREGATE CONCRETE AND BRICK

In a confined column, the dilation phenomenon and the geometry of the column cross-section govern the magnitude of the confining pressure and confining pressure distribution, respectively under axial compression. High-definition videos in the past have shown rapid post-peak failure events occur in columns experiencing either large dilation or large confining pressure displaying a characteristically different composite action in concretes made from stone aggregate under confinement (Chowdhury et al. 2016). Under axial load, stress–strain responses of confined concrete columns with larger dilation, for example low strength concrete, can have increased initial stiffness and markedly decreased final stiffness. Chowdhury et al. (2016) mentions about early mobilization in the FRP confinement in brick aggregate columns compared to columns of stone aggregate concrete with insignificant dilation properties. The uniformity of the confining pressure distribution of circular columns was credited with more effectively restraining dilation-induced phenomena compared to square confined columns in earlier works. Thus, though brick aggregate concrete can have low strength, it has better dilation performance in terms of mobilizing the FRP confinement when subjected to high axial compression.

Nevertheless, if the axial load of a shear-damaged RC column and pier with a significantly deteriorated axial capacity cannot be distributed to the neighboring columns or piers by the surrounding beams, slabs, and girders, then axial collapse may occur. In certain severe cases, the axial collapse of a column or pier may trigger partial or global building and bridge collapse, which can result in catastrophic damage to property and loss of life. To reduce serious losses caused by shear-damaged RC columns or piers, proper evaluation of residual axial capacities is necessary so that the seismic resistance evaluations and seismic retrofit designs of old RC buildings and old bridges can be rationally conducted. In this paper, theoretical calculations lead to eventual test plans for a direct assessment of FRP-confined bridge pier ductility under lateral load. In the FRP confinement technique, installation is faster and the floor-space reduction is less compared to the reinforced concrete jacketing technique. Nevertheless, enhanced axial capacity, which is the desired result of FRP confinement, is only achieved when the core concrete dilates under axial compression and induces hoop strain in the installed FRP wrap.

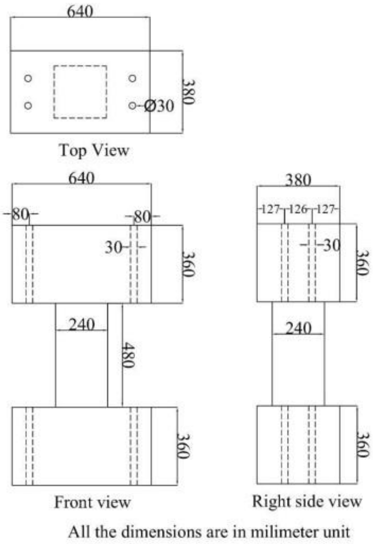


Figure 1. Top, front and right side view of a prototype column.

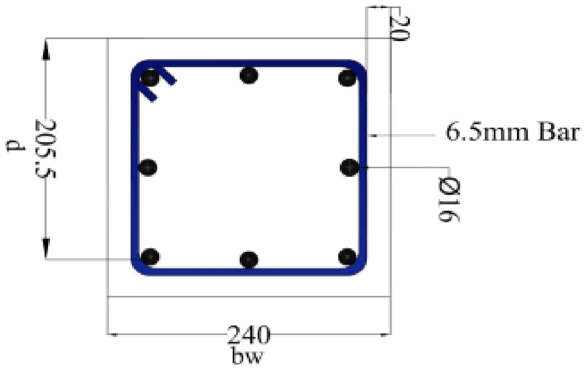


Figure 2. Cross-section of a prototype column.

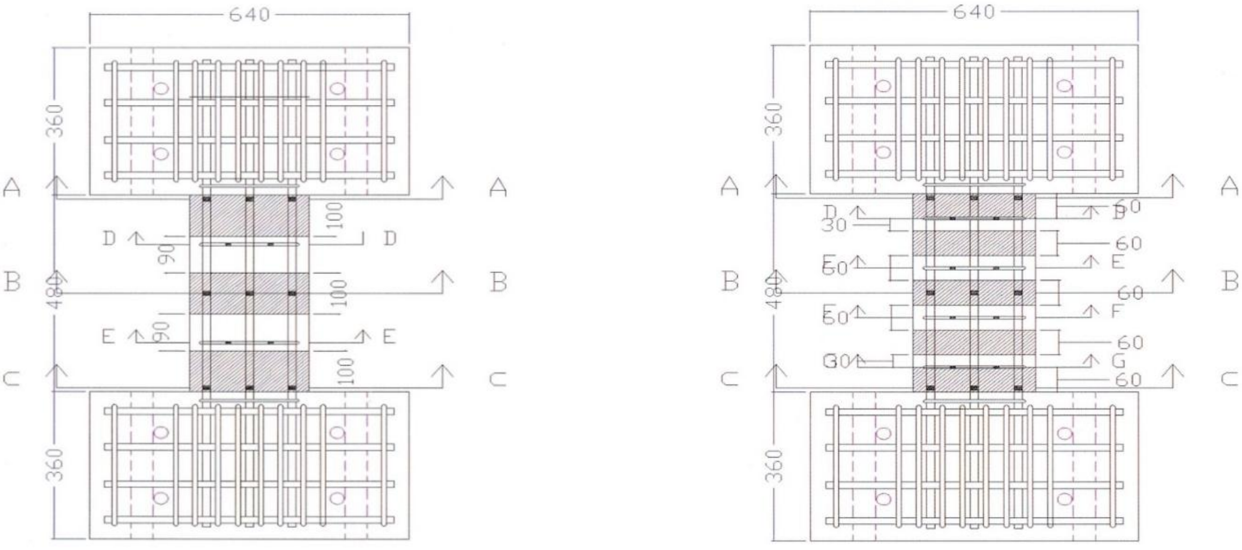
3 DETAILS OF REINFORCED CONCRETES AND FRP

Normal Portland cement conforming to AASHTO Standard Specification M 85 Type 1 requirements will be used to prepare concrete. Well-graded brick aggregates and stone aggregates meeting AASHTO Standard Specification M 80 produced from crushing the bricks and stone boulders will be used. Fine aggregate shall consist of natural sand and fine aggregates from different sources of supply shall not be mixed or stored in the same pile. The amounts of deleterious substance when tested in accordance with STP 3.4 shall not exceed the following limits. Any other deleterious materials shall not cause a strength reduction of the concrete of more than 5% in relation to the strength of concrete free of the concerned deleterious material. Salinity and fines free potable water is recommended for concrete making. Mix design exercises and trial mixes are needed to forecast achieving the predicted concrete strengths before actual castings. Deformed steel bars and tie bars supplied by the local market are proposed for longitudinal and transverse reinforcement of all four columns. The average yield strength of the #5 longitudinal bars was 498 MPa, and the yield strength of tie bars was 473 MPa respectively.

FRP wrap of 0.167 mm nominal thickness, 3,400 N/mm^2 tensile strength, 245 N/mm^2 elastic modulus, and 0.0104 effective strain is considered for confining concrete having theoretical strengths of 10 MPa and 30 MPa.

4 DETAILING OF PROTOTYPES AND THE SCHEMATIC OF THE RIG FOR TESTING

This paper provides details of the theoretical investigation of the behavior of low-strength, isolated bridge piers subjected to axial and lateral loads, which can be subjected to experiments in future to confirm the unknown material phenomena in shear due to the effects of local aggregates. To this end, all experimental details are described. The boundary conditions in such an experiment can be maintained by using a computer-controlled jack system to keep the system as close as possible to real situations. The experimental program thus includes construction and testing of eight columns with different concrete grades, aggregates, strengths and transverse reinforcement ratios under various combinations of lateral and axial loads. The columns were rigidly connected to the top and bottom beams and tested in double curvature. Figures 1-3 show the specimen details, whereas Figure 4 shows the testing rig capable of delivering in-plane cyclic lateral loads under high axial loads.



0.1% @ 240mm **0.2% @ 120mm**

Figure 3. Cross-section showing reinforcement detailing of the prototype column confined with FRP wraps.

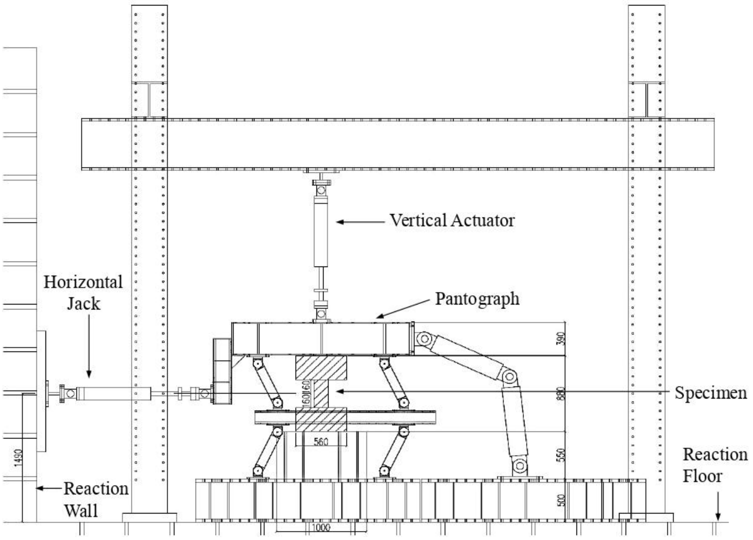


Figure 4. Probable loading setup to produce the desired effect on the specimen.

5 THEORETICAL ESTIMATION OF THE SHEAR CAPACITIES

The shear capacities for prototype columns attached with FRP strips (Figure 4) are presented in Table 1.Estimations are based on Equations 1 and 2, where according to the ACI Code (ACI 440.2R), nominal shear strength V_n of FRP-strengthened columns can be obtained from three components: shear strength provided by concrete, V_c, shear strength provided by steel reinforcement, V_s, and shear strength provided by FRP, V_f; where ϕ and ψ_f are the strength reduction factor and additional FRP strength-reduction factor, respectively.

$$\phi V_n = \phi(V_c + V_s + \psi_f V_f) \qquad (1)$$

Where,

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

N_u is the axial load, A_g is the gross concrete area, f_c' is the concrete strength, b is the width, and d is distance from extreme compression fiber to the neutral axis of the section.
Shear contribution for rectangular hoop, V_s, from ACI 318-02 is given by Equation 3:

$$Vs = \frac{Asfyd}{s} \qquad (3)$$

Where, A_s is the transverse reinforcement spacing, f_y is the yield strength of steel, and d is the distance from extreme compression fiber to the neutral axis.
Shear contribution of FRP, V_f:

$$V_f = \frac{2t_f W_f f_{f_e} d_{f_v}}{S_f}; \qquad (4)$$

$$f_{f_e} = \varepsilon_{f_e} E_f \qquad (5)$$

where t_f is the thickness, W_f is the width, f_{f_e} is the effective stress in the FRP (i.e., the stress level attained at section failure),d_{f_v} is the depth of FRP, S_f is the spacing of FRP, ε_{f_e} is the effective strain level in FRP reinforcement (i.e., the strain level attained at section failure), and E_f is the tensilemodulus of elasticity of FRP. Table 1 shows the estimated shear capacities and contributions of each component for the eight prototypes with two types of transverse spacing.

Table 1. Estimated shear capacities.

ID	Types of Aggregate	f_c' (MPa)	V_c (kN)	V_s (kN)	V_f (kN)	ϕV_n (kN)	$\frac{V_f \times 100}{V_n}$
CB2	Brick	10	37.95	22.96	102.20	118.50	64.69
CB4	Brick	30	65.73	22.96	102.20	139.33	55.02
CB6	Stone	10	37.95	22.96	102.20	118.50	64.69
CB8	Stone	30	65.73	22.96	102.20	135.71	55.02
CB10	Brick	10	37.95	45.91	102.20	156.55	56.48
CB12	Brick	30	65.73	45.91	102.20	135.71	48.96
CB14	Stone	10	37.95	45.91	102.20	135.71	56.48
CB16	Stone	30	65.73	45.91	102.20	156.55	48.96

Note: CB2, CB4, CB6, CB8: s is 240 mm. CB10, CB12, CB14, CB16: s is 120 mm.

Total shear capacity in 10 MPa concrete is always lower than 30 MPa concrete. However, a comparison between the specimens' values in the last column of Table 1 clearly shows that the relative contribution of FRP to total shear capacity of a strengthened column is larger for 10 MPa concrete compared to 30 MPa concrete. FRP is more effective at increasing shear capacity for columns with larger transverse reinforcement spacings, possibly indicating better mobilization of confinement by FRP in unconfined zones. Further tests are required to substantiate this hypothesis and its comparative extents between brick and stone aggregate concretes having different dilational behaviors (Islam et al. 2015; Chowdhury et al. 2016).

6 CONCLUSIONS

This paper proposes an experimental study to compare the improvement of shear capacity and ductility of bridge piers(RC columns) by incorporating FRP wraps in form of strips at different intervals for brick and stone aggregate concretes with a range of dilational behaviors. The calculations are expected to result in optimized ductility and comparisons of the shear capacity equation between brick and stone by adding FRP wrap at different intervals of RC bridge piers. From the theoretical calculation, FRP seems to provide higher shear capacity, leading to increased ductility.

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