# Strengthening Short Concrete Columns Using Longitudinally Bonded CFRP Laminates

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**Synopsis:**

This paper investigates the behavior of short concrete columns strengthened with externally bonded longitudinal carbon fiber-reinforced polymer (CFRP) laminates combined with transverse basalt fiber-reinforced polymer (BFRP) wraps. A total of eighteen 500 mm-long [19.69 in-long] concrete column specimens with a square cross section (150 mm [5.91 in] width) were tested with different longitudinal and transverse reinforcement combinations under concentric and eccentric axial loadings. For eccentric loading, three end eccentricity to width ratios of 0.1, 0.2, and 0.3 were applied symmetrically at both ends of each simply supported column specimen to provide single curvature condition. The compressive longitudinal CFRP strips, in average, experienced 38% of their tensile rupture strain. The experimental results showed debonding of longitudinal CFRP laminates from concrete surface and buckling of bonded specimens as the dominant mode of failure, and revealed that transverse wrapping system is efficient in postponing the buckling/debonding failure.

**Keywords**: column, concrete, bonded, CFRP laminate, buckling, BFRP wrap, experimental.

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## 1. INTRODUCTION

The strengthening of reinforced concrete structures using fiber-reinforced polymer (FRP) composites have become popular due to their outstanding physical and mechanical characteristics including high-strength, low-weight, and high-corrosion resistance. Application of FRPs could be found in various forms such as applying them on the outer surface of concrete elements such as beams, slabs, and bridge decks in form of bonded laminates as well as near surface mounted (NSM) strips to increase their ultimate strength and stiffness, or in form of wraps to provide compressive structural members such as columns with confinement and increase their axial capacity. There have been many researches on the application of bonded laminates for strengthening of reinforced concrete beams [1, 2, 3], slabs [4, 5], bridge decks [6, 7, 8], and on the concrete columns wrapped with FRP [9, 10, 11]. In addition, some researchers have investigated columns strengthened with NSM technique using FRP composites [12, 13], however, very few researches have done on the application of concrete columns strengthened with longitudinally bonded FRP strips.

FRP wrapping have been known as a strong tool of strengthening for concrete columns, especially for concentrically loaded columns. Parvin and Wang [14] recognized that short columns under eccentric compressive loading can successfully increase the capacity. Hadi [15] found out that usage of FRP wraps is effective for eccentrically loaded columns up to a certain margin. Bisby and Ranger [16] showed that the effectiveness of FRP confinement for circular columns is reduced under combined axial and flexural loading. The other issue is the effect of cross-section on the effectiveness of wrapping system; wrapping for rectangular and square cross-sections is not as effective as for circular cross-sections due to the presence of sharp corners which transmit confining stresses to the concrete [17]. Although FRP wraps are very effective for uniaxial loading, longitudinal reinforcement might be needed, especially for slender columns, for combined axial and flexural loading systems to increase the stiffness of the reinforced concrete columns.

Sadeghian and Fam [18] investigated the effect of bonded longitudinal reinforcements analytically and found it more beneficial for eccentrically loaded slender columns than transverse wrapping, where large bending moments small axial loads exists. Shaat and Fam [19] examined carbon FRP (CFRP) plates for strengthening of slender steel columns experimentally and analytically whose result showed the effectiveness of the CFRP system in increasing the axial strength of steel columns as slenderness increased. Chaallal and Shahawy [20] figured out that the performance of bidirectional CFRP fabrics for strengthening of concrete beam-columns would improve their capacity, especially their flexural capacity. Sedeghian et al. [21] performed experimental study on the behavior of concrete columns longitudinally and transversely strengthened with CFRP laminates and realized that the application of longitudinal layers improves the bending stiffness and moment capacity of the columns, however, their longitudinal bonded elements were made of fabrics. In addition, Pham et al. [22] experimentally studied different wrapping arrangements on the confinement mechanism of circular column tested under axial loading and found the partial wrapping as an effective method to improve the axial capacity of the columns.

Due to lack of experimental data, the behavior of longitudinal unidirectional FRP laminates for strengthening concrete columns is not well-known, and there are some doubts about their performance under compression loads. The deboning of longitudinally bonded FRP strips to concrete columns as well as their buckling under compressive loads need an in depth understanding of the systems. Since an experimental program is needed to study the effect of bonded FRP strips on slender concrete columns, this research was designed to address the doubts and identify potential issues related to the application of CFRP bonded short concrete columns as a preparation phase for testing large scale slender columns. In this paper, CFRP and basalt FRP (BFRP) reinforcements opted as longitudinal and transverse reinforcing systems, respectively, to be attached externally on the surface of short concrete columns. The tests were conducted on pin-pin column specimens under different load eccentricities as well as combinations of transverse and longitudinal FRP reinforcements.

## 2. RESEARCH SIGNIFICANCE

This paper experimentally investigates the behavior of longitudinally bonded CFRP strips to short concrete column surfaces under eccentric loading, with and without transverse BFRP wrapping systems. Longitudinal CFRP strip reinforcement could be used as a strengthening method for slender columns with large eccentricity for which the knowledge of buckling of FRP strip is required as well as their debonding from concrete surface. Transverse FRP wraps as a modifier of buckling behavior by providing lateral support and limiting the length of buckling whose performance on longitudinal FRP strips attached to concrete columns is to be investigated in this study.

## 3. EXPERIMENTAL PROGRAM

A total of eighteen medium-scale plain concrete specimens with square cross-section were prepared and tested under concentric and eccentric loading up to failure. Thirteen of specimens were externally bonded with two CFRP laminates. Four of these specimens were partially and fully wrapped with unidirectional BFRP to decrease the buckling length of the longitudinal CFRP laminates. In this section, experimental test matrix, material properties, fabrication, and the test set up for CFRP strengthened concrete specimens as well as plain ones is explained.

### 3.1. Test matrix

A total of eighteen 500 mm [19.69 in] long concrete column specimens with a square cross-section (150×150 mm) [5.9×5.9 in] were tested under pure axial and combined axial and flexural loading. Five specimens were made of plain concrete, nine specimens were externally bonded with two symmetrically attached longitudinal CFRP strips (500×50×1.2 mm) [19.68×1.97×0.05 in] and epoxy adhesive. Four of the CFRP-bonded specimens were wrapped laterally with two layers of unidirectional basalt fabric and epoxy resin (BFRP); two of them with a narrow strip of 51 mm [2 in] wide BFRP, which is called partial wrap (WP) in this paper, and two of them with strips of 305 mm [12 in] width, which is called full wrap (WF), as presented in Table 1 and Fig 1. Four specimens were tested under pure axial load, including two plain concrete columns and two bonded specimens, while other specimens were tested under combined axial and flexural loads with eccentricities of 15, 30, and 45 mm [0.59, 1.18, and 1.77 in], which are 10, 20, and 30 percent of width of the specimens. The specimen ID that is presented in Table 1 is like “A-ex-y” for specimen without lateral reinforcement and “A-Wz-ex-y”; where A, x, y, and z are representatives of column type (“P” for plain or “B” for bonded), the eccentricity to width ratio (0, 10, 20, or 30), the specimen number (1, 2, or 3), and the type of lateral reinforcement (“P” for partial or “F” for full), respectively. For example, B-WF-e30-2 represents the second bonded specimen which is fully wrapped and was tested under eccentricity to width ratio of 30 percent.

### 3.2. Material properties

In this study, unidirectional CFRP laminate was used as the reinforcing material. The laminate was available in the form of 50 mm [1.97 in] wide and 1.2 mm [0.05] thick strips. The CFRP laminate was an old version of the commercial product. Per ASTM D3039/3039M-14 [23], five tensile CFRP coupons were tested to determine the tensile characteristic of longitudinal CFRP strips. All coupons showed a linear behavior up to a sudden rupture at their maximum tensile capacity. The average tensile modulus of elasticity, ultimate tensile strength, and ultimate tensile strain of the CFRP laminates derived from the tests were 180 GPa [26107 ksi], 3006 MPa [436 ksi], and 0.01668 mm/mm [0.01668 in/in], respectively. Furthermore, a compatible adhesive was used as the bonding material to attach the strips to the surface of the concrete specimens with a thickness of 1.5 mm [0.059 in]. The tensile strength, compressive modulus of elasticity, ultimate tensile strain, and the bond strength were 27.6 MPa [4003 psi], 3.06 GPa [444 ksi], 0.01 mm/mm [0.01 in/in], and 13.8 MPa [2002 psi], respectively, as reported by manufacturer. For wrapping, a unidirectional basalt fabric and epoxy resin were used. For resin, a mixture of epoxy resin and slow hardener was opted, which reported by manufacturer to have the tensile strength, tensile modulus, and maximum elongation of 50 MPa [7252 psi], 2.8 GPa [406 ksi], and 0.045 mm/mm [0.045 in/in], respectively. The epoxy resin was reinforced by a unidirectional basalt fabric with the areal weight of 300 g/m$^2$ [12.66 oz/ya$^2$] and nominal thickness of 0.115 mm [0.0045 in]. The tensile strength, tensile modulus, and ultimate tensile strain of basalt fibers were 2100 MPa [305 ksi], 105 GPa [15229 ksi], and 0.026 mm/mm [0.026 in/in], respectively, per manufacturer. Furthermore, the average rupture stress, rupture strain, and tensile modulus of elasticity of basalt fabric was reported by Fillmore and Sadeghian [24] as 624.1 MPa [90.5 ksi], 0.0279 mm/mm [0.0279 in/in], and 24.62 GPa [3570.8 ksi], respectively. Moreover, a ready-mix concrete with maximum aggregate size of 12.5 mm [0.5 in] was used. For concrete material, three cylinders (100 × 200 mm) [4 × 6 in] were tested at the time of testing, where the average compressive strength of 37 MPa were observed for the concrete material.

### 3.3. Fabrication

All concrete specimens were casted in one batch where the fresh concrete [Fig. 2(b)] poured in wooden formworks [Fig. 2(a)], and the specimens were cured in room temperature using plastic covers [Fig. 2(c)] to keep their moisture. Four column specimen types were fabricated in this experimental program whose schematic layout of longitudinal and transverse reinforcements are presented in Fig. 1. Due to the expectation of stress concentration and in turn occurrence of premature failure, the top and bottom of the specimens were transversely reinforced using two layers of 51 mm [2 in] wide unidirectional BFRP wraps [Fig. 2(d)], as shown in Fig. 1. After removing the formworks, the concrete side surfaces were polished to provide specimens with a better friction and bonding. Then a layer of 1.5 mm [0.059 in] tick adhesive was applied to both sides and two 500×50×1.2 mm [19.68×1.97×0.05 in] unidirectional CFRP strips were attached at the center of opposite concrete surfaces of column specimens to build the strengthening system [Fig. 1]. In addition, for partially and fully wrapped bonded specimens, two layers of epoxy reinforced with 50 mm [1.97 in] and 305 mm [12 in] wide unidirectional BFRP were applied transversely to the center of the bonded columns, respectively. At the end, the top and bottom surfaces of specimens were smoothened using grinder to vanish the imperfections of the surfaces, and two plastic bags filled with fresh quick set cement based grout were applied on the top and the bottom surfaces of the specimens to integrate the column specimen and the steel caps, which were used for applying eccentric loading [Fig. 3].

### 3.4. Test set-up and instrumentation

Two symmetric steel caps [Fig. 3], consisting of four adjustable angle steel profiles bolted to a wide steel plate on top of which a tick notched steel plate is welded, were tightened to the top and bottom of column specimens. Two steel rollers laid on the notch surface whose rotation ability provide the specimens with the simply supported boundary condition. The symmetricity of the steel caps and rollers, upon which load was applied, creates a single curvature deformation shape and a combined axial and flexural loading condition, as shown in Fig. 3. Load eccentricity and axial compressive loads at the top and the bottom of specimens are shown as “e” and “P”, respectively, in Fig.3. It is noticed that because of difficulties in providing loading condition in lab so that the column would be under double curvature and the fact that double curvature bending is sum of two single curvature but with different length, the test performed in single curvature as is usual in testing columns. To measure the strains of longitudinally bonded CFRP strips and lateral displacement, a data acquisition system including four linear variable differential transformers

(LVDTs) and two strain gauges obtained the data at a frequency of 10 Hz as shown in Fig. 3. Strain gauges where installed at the center of the CFRP strips on the outer surface as well as two vertical LVDTs (i.e. LVDT 1 and LVDT 2), with a gauge length of 100 mm [4 in], to measure the axial strain of the CFRP strips. Moreover, for measuring the lateral displacement of the specimens, two lateral LVDTs (i.e. LVDT 3 and LVDT 4) were pointed at the center of the tested specimens [Fig. 3]. All tests were performed using a displacement control approach with a displacement rate of 0.625 mm/min [0.025 in/min] by a 2 MN [450 kips] universal testing machine.

## 4. RESULTS AND DISCUSSION

In this section, the modes of failure discussed for plain and bonded specimens with or without transverse wrap. Then the effect of CFRP strips is discussed in terms of their influence in the load carrying capacity of the system and their impact in changing the mode of failure. The section eventually concluded with considering the effects of the load eccentricity on the behavior of the tested specimens.

### 4.1. Modes of failure

Overall, five modes of failure including concrete crushing (CC), concrete spalling (CS), concrete destruction (CD), debonding of CFRP stirps in compression side (DS), and buckling of CFRP strips in compression (BS) were observed during testing the column specimens, as mentioned in Table 2. The concrete crushing (CC) was considered as the mode of failure for a specimen when the extreme compressive strain reached 0.003 mm/mm [0.003 in/in] which was defined as the ultimate concrete strain in compression by ACI 318-14 [25]. The concrete spalling (CS) happened when a concrete segment in compression part separated from the column which had happened after concrete crushing occurred. All specimens built with plain concrete and tested under 10 percent eccentricity to width ratio (P-e10 group) were suddenly failed and split in half from, approximately, the mid-height of the columns which named as concrete destruction (CD). For all bonded specimen, whether with or without wrap, the debonding of CFRP strips in compression (DS) happened which immediately followed by the buckling of them (BS). For all bonded specimens, the buckling of strips in compression was simultaneously occurred at the peak load the bonded columns experienced.

The schematics of Fig. 4 illustrate the failure mode of failure for the bonded specimens. The shear stresses [Fig. 4(a)] created in the interface of the concrete and adhesive as well as the interface of adhesive and CFRP strips was increased as the load increased to a certain extend at which a debonding between one of these surfaces started and propagated through the length of the strip. As these debonding cracks spread along the compression strips, the strips functioned separately and tend to buckle due to the tendency of concrete column to bend and the compressive forces that they tolerated. The buckling of bonded columns without wrap happened with full unbraced length [Fig. 4(b) and Fig. 5(a)], or with a fraction of the unbraced length [Fig. 5(b)]. Moreover, the debonding happened between concrete and adhesive interface [Fig. 5(a)], between CFRP strip and adhesive [Fig. 5(b)], or both at the same time [Fig. 5(c)]. For some specimens, the occurrence of the buckling followed by crushing in compression concrete [Fig. 5(d)], however, for some of them the test stopped before observation of the crushing since the load dropped after buckling of CFRP strip in compression. For partially wrapped bonded specimens, the length of buckling was controlled with the transverse BFRP wrap at the middle of the column [Fig.4 (c)] which delayed the buckling and in turn gave a higher capacity in comparison to the bonded specimens without wrap. For these specimens, the buckling happened mostly in one side and followed by the crushing of the concrete [Fig.5 (e)]. The fully wrapped bonded specimens experienced buckling [Fig. 4(d)] although the unbraced length was very limited; the unbraced length was about 46.5 mm [1.83 in] in each side. However, the buckling for these specimens did not happen in that limited length and spread even inside the wrapped area [Fig. 5(f)]. Albeit the buckling spread inside the wrapped area, the capacity of these specimens was still more than the bonded ones due to stronger control of the buckling for these specimens provided by extended transverse BFRP wrap.

**4.2. Effect of eccentricity**

It is seen that as the load eccentricity increases, the bonded specimens experience more curvature since the displacement of these columns at the mid-height of specimen, corresponding to the peak load, tends to be increased as shown in Fig. 6(a). Moreover, it is observed that the slope of load-displacement curves, which is corresponding to the stiffness of the columns, as well as their peak loads decrease as the load eccentricity increases [Fig. 6(a)]. Furthermore, for bonded test specimens the ultimate displacement experienced is closer to the displacement corresponding to peak load for columns tested under higher eccentricity [Fig. 6(a)], which shows that a lower axial load and bending moment sustainability for specimens tested in higher eccentricities is achieved.

It is observed that as the load eccentricity increases, the strain corresponding to the peak load increases [Fig. 6(b)]. In addition, the strain experienced in compression side is higher than the ones experienced in the tensile side as presented in Table 2 for bonded specimens. Table 2 also provides the ratios of tensile and compressive strains at peak load to the ultimate tensile strain, or tensile rupture strain, derived from the material test. The average ratios of compressive and tensile strain of CFRP strips in compression to the rupture strain for all specimens at the peak load were 21% and 4%, respectively, while these values at the ultimate read strains were 24% and 7%, respectively [Table 2]. It is noticed that the values of strain at peak load are the corresponding strain at which buckling of CFRP compressive strips occurred. Moreover, Table 2 presents the axial load carrying capacity of specimens which reveals that for all bonded specimens, the capacity of bonded specimens was higher than plain specimens. In addition, the capacity even was more affected when the wrapping system used which is discussed in the following subsection.

### 4.3. Effect of wrapping

It was observed that all bonded specimens were capable of sustaining higher axial loads both in concentrically and eccentrically loaded specimens, as is shown in Table 2. In addition, the wrapping system which was used to control the unbraced length of compressive CFRP strips was quite effective and caused gain in the capacity of partially and fully wrapped specimens rather than bonded ones without lateral wraps. It is seen that the average axial capacity of specimens with partial wrap was even higher than the ones with full wrap whose reason could be explained as the degree of control over the unbraced length for the buckling of CFRP strip in compression. For partially wrapped specimens, the buckling length was exactly the complete length between the middle wrap and the end wrap while for the full wrapped case it was not determined. For B-WF-e30-2 specimen, the length of buckled CFRP strip in compression was 110 mm [4.33 in] and its axial capacity was 348.9 kN [87.4 kips] while for B-WF-e30-1, the same values were 190 mm [7.48 in] and 484.0 kN [108.8 kips], and for average of partially wrapped specimens these values are 173 mm [6.81 in] and 444.8 kN [100.0 kips], as shown in Fig. 7. It is noted that for two similar fully wrapped specimens, the length of buckling is different and the specimen with the lower length of buckling experienced lower loads. The justification for the latter is that buckling happened after the debonding, and for the specimen with longer buckling length more energy consumed to create a continuous debonding. Furthermore, the experimental program shows a more consistent axial capacity of partially wrapped specimens. Therefore, since the unbraced length is properly controlled using transverse wraps, the length of buckling can be reduced more appropriately using more strips instead of wrapping the full length of the column. Another result of the latter observation is that the longitudinal strips have more impact in the load capacity of the bonded specimens than the lateral wrapping since after buckling of CFRP strips in fully wrapped specimens the wrap still worked however a drop in the applied load observed.

It is seen that as the wrapping system added to the bonded specimens, the displacement of wrapped columns at the mid-height of specimen, corresponding to the peak load, increased as shown in Fig. 8(a). It is noted that in Fig. 8(b), the values of all strains were the ones recorded by strain gauges, but the ones for fully wrapped specimens are calculated based on the longitudinal LVDTs that had attached to specimens [Fig. 3] due to the loss of strain gauge data. It is observed that the slope of load-displacement curves decreases when the transverse wraps added to bonded specimens [Fig. 8(a)]. Moreover, by adding transverse wrapped specimens experienced higher values of ultimate displacement in comparison to bonded ones [Fig. 8(a)], particularly for fully wrapped columns. Moreover, for nearly all specimens, it is seen that the strain of CFRP strips at peak load for bonded specimens with and without wraps are similar in tension and compression, as presented in Fig. 8(b). In addition, the strain experienced in compression side was higher than the ones experienced in the tensile side for both discussed types of specimens. For specimens tested under 30 percent eccentricity to width ratio, the average ratios of compressive and tensile strain of CFRP strips for bonded specimens without wraps, partially wrapped, and fully wrapped specimens in compression to the rupture strain for all specimens at the peak load were 19%, 22%, and 26%, respectively, while these values at the ultimate read strains were 20%, 23% and 31%, respectively [Table 2].

The summary of test results is presented in Fig.9. Overall, plain specimens gained improvement in their load carrying capacity by adding the longitudinal CFRP strips. In addition, the combined application of longitudinal bonded CFRP and lateral wrapping was more efficient method than using just longitudinal CFRP strips, as shown in Fig.9. Therefore, for strengthening purposes the combined lateral and longitudinal system is suggested. It is noticed that lateral BFRP wraps were not initially considered in the test matrix and the specimens with wrapping added to the test matrix after observation of the results of bonded specimens to prevent the buckling of CFRP strips or limit the unbraced length of this strips. However, the plain specimens with just confinement were not examined due to limitation of specimen numbers. Thus, the contribution of longitudinal CFRP strips and lateral BFRP strips in strengthening of the specimens cannot be separated and another study is required to address this issue. On the other hand, since the cross section is square, the effect of confinement is limited due to the existence of the sharp corners. Also, it is observed that by using narrow BFRP strips, the capacity improved better than wider strips which implies that the gain in laterally reinforced specimens were mainly because of the lateral support that these wraps provided for longitudinal strips and to a lesser extend duo to their confinement effect.

The aim of this study was recognizing the behavior of short concrete columns strengthened using longitudinal CFRP strips, especially the compressive behavior of CFRP strips in compression where buckling of these strips is critical. However, the main beneficial application of this system is in slender columns in which the gain of stiffness provided by longitudinal CFRP strips alter the loading path of the column so that it intersects the axial load – bending moment interaction diagram of column in a higher axial load and cause gain in strength as numerically approved by Sadeghian and Fam [18]. Therefore, although the concrete crushing in compression would happen about 0.0035 mm/mm and the longitudinal strips cannot reach their ultimate crushing capacity, they are still advantageous in increasing the stiffness of column and in turn the capacity of the column.

## 5. CONCLUSION

In this study, the behavior of short concrete columns strengthened with longitudinal CFRP strips and transversely with BFRP wraps were examined experimentally. A total of eighteen simply supported column specimens consisting of five plain concrete, nine longitudinally CFRP bonded, and four longitudinally bonded and transversely wrapped specimens were tested under four load eccentricity to width ratios of 0, 0.1, 0.2, and 0.3. The following conclusions can be drawn from this study:

- Five modes of failure including concrete crushing, concrete spalling, concrete destruction, debonding of CFRP stirps in compression side, and buckling of CFRP strips in compression were observed. However, no crushing of CFRP strips in compression were observed. The ultimate capacity of each specimen occurred at the peak load for all specimen strengthened with CFRP strips which started by debonding and followed by compressive strip buckling of CFRP strip in compression.
- The average experimental compressive strain of CFRP strips in compression at the time of strip buckling, or peak load, was 21% of tensile rupture strain while the average of the ultimate recorded compressive strain was 24%.

- Test results showed that the performance of the longitudinally bonded specimens was improve by adding wrapping system. However, the debonding and buckling of compressive CFRP strips was not avoided even by wrapping nearly the whole length of the specimens. The experimental results showed that by using narrow transverse wraps, the unbraced length of longitudinal strips is determined and certain while wide wraps do not provide that preciseness and unbraced length could vary even in two specimens tested under the same condition.
- The effect of narrow transverse BFRP wraps in limiting the length of buckling of longitudinal CFRP bonded strips is similar to the effect of stirrups in restricting the unbraced length for rebars in concrete columns. Therefore, further studies on the behavior of lateral wraps in concrete columns strengthened with longitudinal bonded specimens is suggested.

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**Table 1** — Test specimen properties

| No. | Specimen ID | Eccentricity, e (mm) [in] | Eccentricity to width ratio, e/h | Longitudinal Reinforcement | Lateral Reinforcement |
|---|---|---|---|---|---|
| 1 | B-e0-1 | 0 [0] | 0 | 2 CFRP strip | None |
| 2 | B-e0-2 | 0 [0] | 0 | 2 CFRP strip | None |
| 3 | B-e10-1 | 15 [0.59] | 0.1 | 2 CFRP strip | None |
| 4 | B-e10-2 | 15 [0.59] | 0.1 | 2 CFRP strip | None |
| 5 | B-e10-3 | 15 [0.59] | 0.1 | 2 CFRP strip | None |
| 6 | B-e20-1 | 30 [1.18] | 0.2 | 2 CFRP strip | None |
| 7 | B-e20-2 | 30 [1.18] | 0.2 | 2 CFRP strip | None |
| 8 | B-e30-1 | 45 [1.77] | 0.3 | 2 CFRP strip | None |
| 9 | B-e30-2 | 45 [1.77] | 0.3 | 2 CFRP strip | None |
| 10 | B-WP-e30-1 | 45 [1.77] | 0.3 | 2 CFRP strip | 2” BFRP wrap |
| 11 | B-WP-e30-2 | 45 [1.77] | 0.3 | 2 CFRP strip | 2” BFRP wrap |
| 12 | B-WF-e30-1 | 45 [1.77] | 0.3 | 2 CFRP strip | 12” BFRP wrap |
| 13 | B-WF-e30-2 | 45 [1.77] | 0.3 | 2 CFRP strip | 12” BFRP wrap |
| 14 | P-e0-1 | 0 [0] | 0 | Plain | None |
| 15 | P-e0-2 | 0 [0] | 0 | Plain | None |
| 16 | P-e10-1 | 15 [0.59] | 0.1 | Plain | None |
| 17 | P-e10-2 | 15 [0.59] | 0.1 | Plain | None |
| 18 | P-e10-3 | 15 [0.59] | 0.1 | Plain | None |

**Table 2** — Summary of test results

| No. | Specimen ID | Peak Load, $P_u$ (kN) | Comp. strain of laminate at $P_u$ (mm/mm) | R1 | Tensile strain of laminate at $P_u$ (mm/mm) | R2 | Maximum comp. strain of laminate (mm/mm) | R3 | Maximum tensile strain of laminate (mm/mm) | R4 | Mode of Failure |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B-e0 | 835.0 | -0.0035 | 0.21 | -0.0017 | 0.10 | -0.0054 | 0.32 | -0.0022 | 0.13 | SD → SB |
| 2 | B-e10 | 667.9 | -0.0024 | 0.14 | -0.0002 | 0.01 | -0.0026 | 0.16 | -0.0003 | 0.02 | SD → SB |
| 3 | B-e20 | 553.4 | -0.0036 | 0.22 | 0.0007 | 0.04 | -0.0038 | 0.23 | 0.0025 | 0.015 | SD → SB → CC |
| 4 | B-e30 | 397.4 | -0.0032 | 0.19 | 0.0016 | 0.10 | -0.0033 | 0.20 | 0.0030 | 0.18 | SD → SB |
| 5 | B-WP-e30 | 444.8 | -0.0036 | 0.22 | 0.0017 | 0.10 | -0.0039 | 0.23 | 0.0026 | 0.16 | SD → SB |
| 6 | B-WF-e30 | 416.5 | -0.0043 | 0.26 | 0.0015 | 0.09 | -0.0051 | 0.31 | 0.0016 | 0.10 | SD → SB |
| 7 | P-e0 | 719.2 | - | - | - | - | - | - | - | - | CS |
| 8 | P-e10 | 596.3 | - | - | - | - | - | - | - | - | CS → CD |
| Average | | - | - | 0.21 | - | 0.04 | - | 0.24 | - | 0.07 | |

Note: CFRP strip strain recorded by SG2 (see Fig. 1) installed on the middle the strips at the extreme compressive layer; R1: the ratio of compressive strain of laminate at Pu to tensile rupture strain; R2: the ratio of tensile strain of laminate at Pu to tensile rupture strain; R3: the ratio of maximum compressive strain of laminate to tensile rupture strain; R4: the ratio of the maximum tensile strain of laminate to tensile rupture strain; CC: concrete crushing; CS: concrete spalling; CD: concrete destruction; SB: strip buckling; SD: strip debonding; the tensile rupture strain = 0.01668 mm/mm; Tensile strains are positive and compression ones are negative. [1 mm = 0.0394 in; 1 kN = 224.8201 lb]

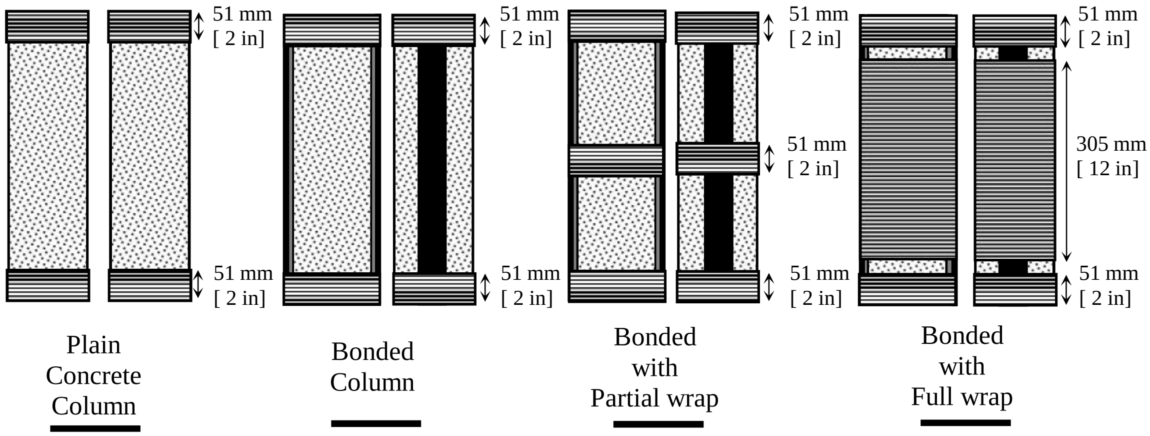



**Fig. 1**— Test specimen types and strengthening schemes.

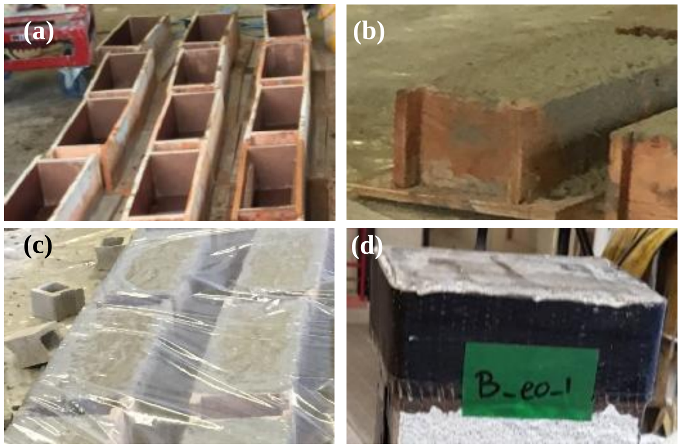



**Fig. 2**— Specimen preparation: (a) molds; (b) fresh concrete; (c) curing; (d) end wrap.

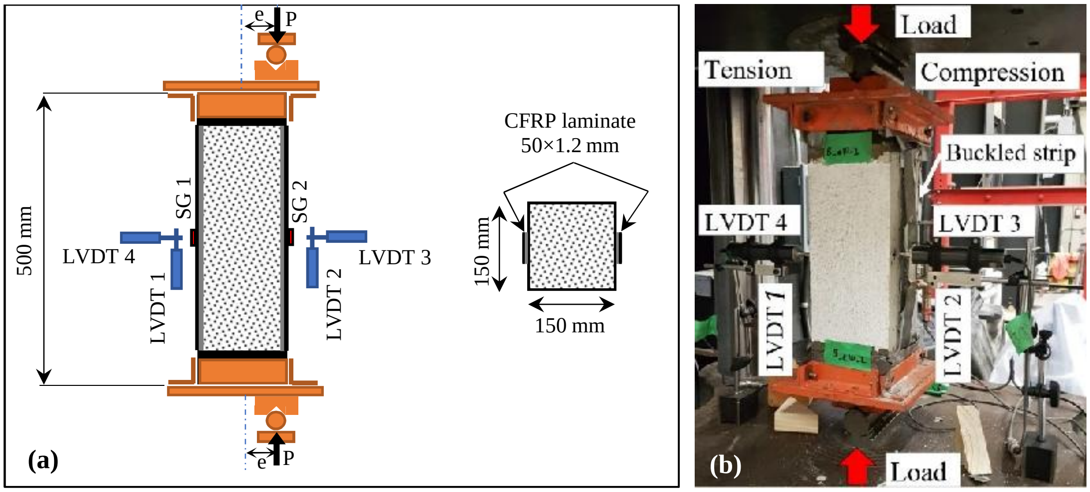



**Fig. 3**— Test set up and instrumentation: (a) schematic testing specimen and reinforcing layout; (b) testing machine and instrumentation.

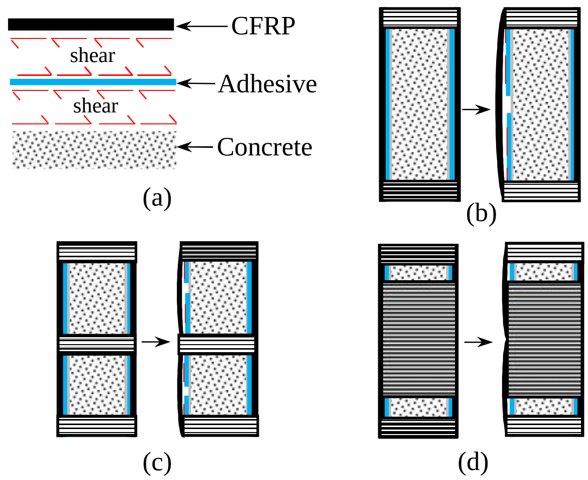



**Fig. 4**— Schematic failure modes: (a) shear flow in the interface of adhesive with CFRP and concrete; (b) buckling and debonding of bonded specimen; (c) buckling and debonding of partially wrapped specimens; (d) buckling and debonding of fully wrapped specimens.

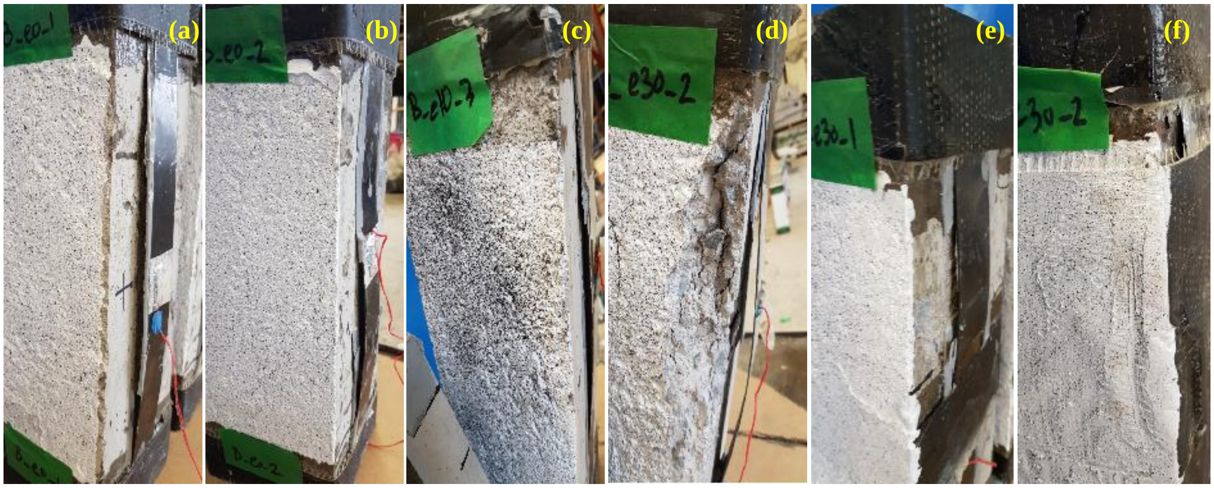



**Fig. 5**— Failure modes of reinforced specimens: (a) concrete and adhesive interface failure and buckling; (b) CFRP and adhesive interface failure and partial buckling; (c) combined adhesive and concrete plus adhesive and CFRP interface failure and buckling; (d) Concrete crushing and CFRP buckling; (e) buckling of partially wrapped CFRP strip; (f) buckling of fully wrapped CFRP strip.

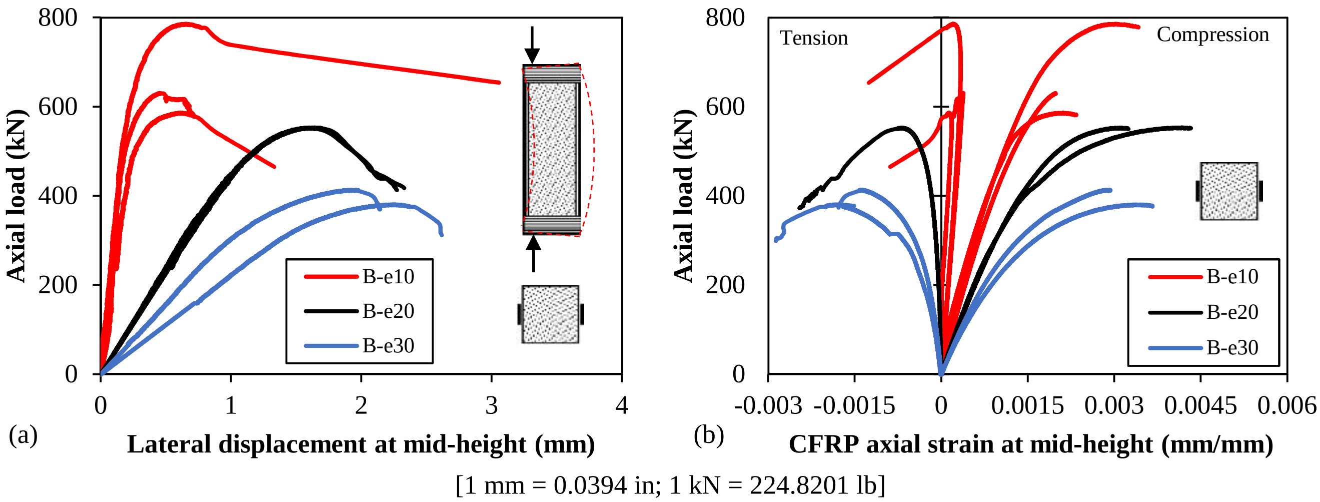



**Fig. 6**— Test results of the bonded specimens: (a) axial load vs. lateral displacement of bonded specimens; and (b) axial load vs. strain of compressive and tensile CFRP strips for bonded specimens.

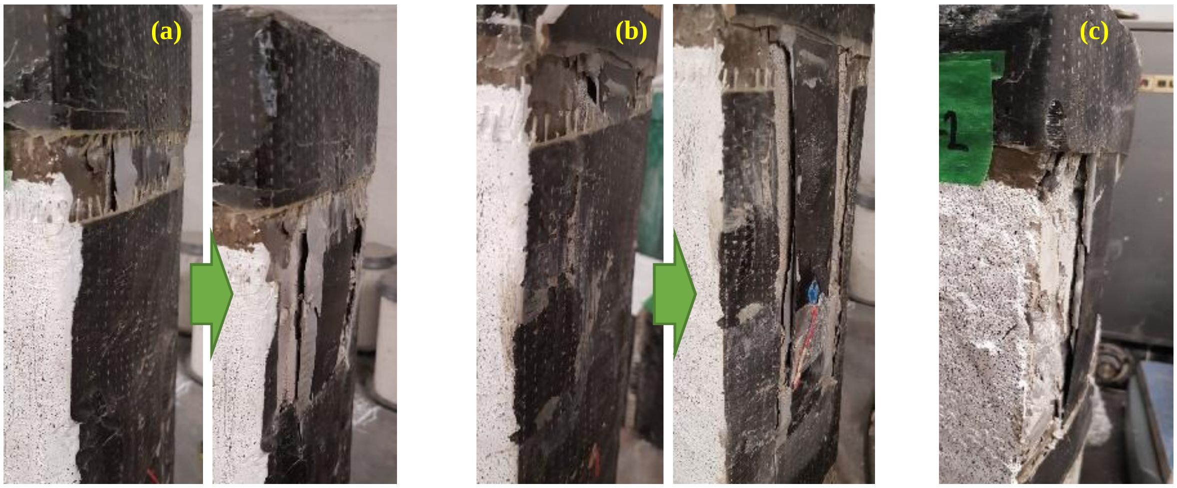
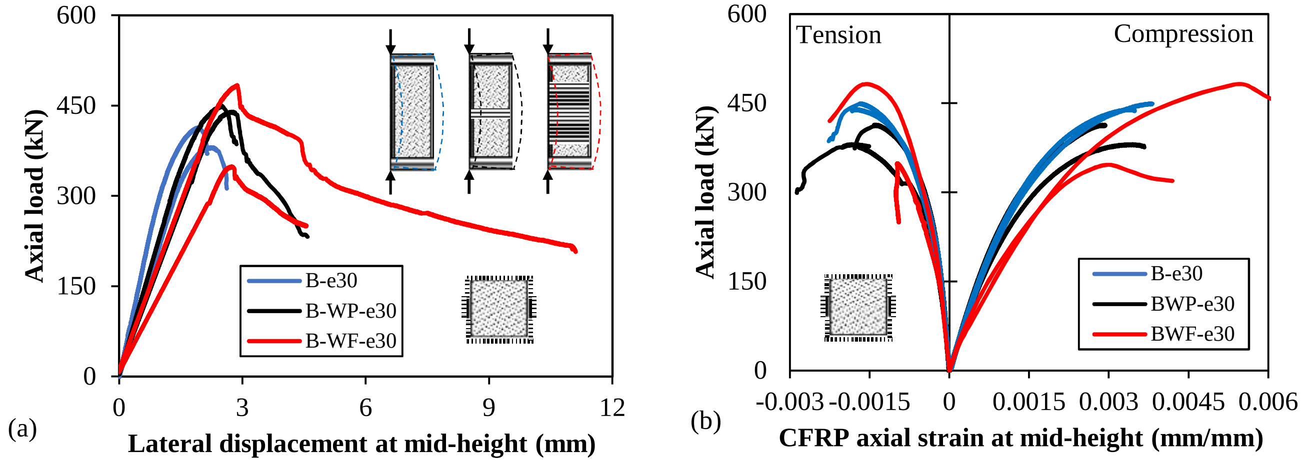



**Fig. 7**— Buckling length: (a) fully wrapped bonded column with 110 mm [4.33 in] buckling length and 348.9 kN [87.4 kips] axial capacity; (b) fully wrapped bonded column with 190 mm [7.48 in] buckling length and 484.0 kN [108.8 kips] axial capacity; (c) partially wrapped bonded column with 173 mm [6.81 in] buckling length and 444.8 kN [100.0 kips] axial capacity. Note: the full wraps were cut to show the buckling length.




[1 mm = 0.0394 in; 1 kN = 224.8201 lb]

**Fig. 8**— Test results of the wrapped bonded specimens: (a) axial load vs. lateral displacement of bonded and wrapped specimens; and (b) axial load vs. strain of compressive and tensile CFRP strips for bonded and wrapped specimens.

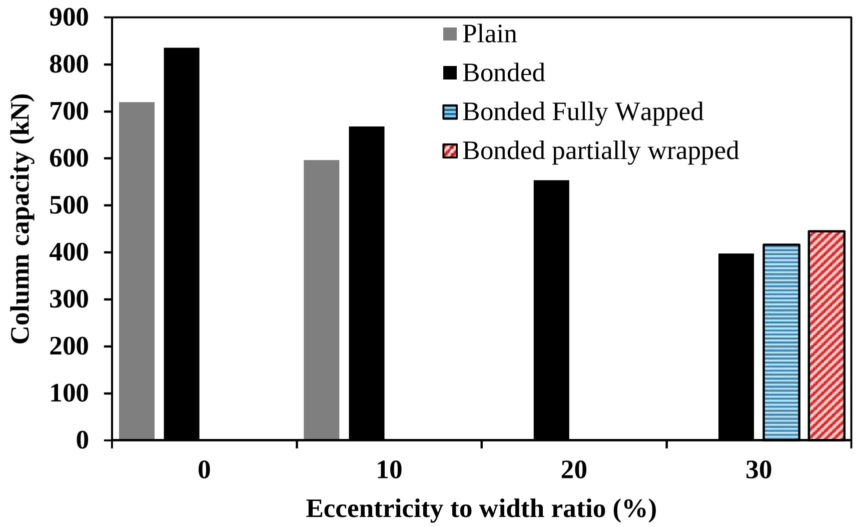



**Fig. 9—** Summary of test results.