Extension of bridge cap beams with CFRP composites: experimental investigation

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Abstract. As rapid increase of traffic volume, bridge widening has been extensively conducted and studied. Compared to conventional method, such as constructing new bridge piers, extension of cap beam offers a more economical solution for limited amount of bridge widening. This paper presents and experimental investigation of extended pier cap beams reinforced with various Carbon fiber reinforced polymer (CFRP) systems. Four quarter-scaled hammer headed RC cap beams were cast and tested. Failure mode and load-displacement response were evaluated and reported. It was observed that the extended and CFRP reinforced beams exhibited good structural behavior in terms of ultimate strength, stiffness and ductility.

1. Introduction
The widening of bridges has become common, especially in recent decades. There are several factors that contribute to the demand for wider bridges such as increased traffic volumes, safety hazards of narrow bridges and provision for bike lanes or pedestrian ways. In order to prevent stresses caused by differential settlements, bridge widening usually involves addition of un-connected new substructure, along with un-connected new superstructure [1-2]. For limited widening of bridges, e.g. addition of one driving/emergency lane, extension of the pier cap beam offers an attractive economical solution. Depending on the strength of the existing substructures, strengthening of the column and foundation will probably be needed.

Many systems are applicable for bridge strengthening in general, and bridge widening in particular. These reinforcing systems include external post-tensioning steel [3-4], and ordinary reinforced concrete jacketing (cast-in-place or shotcrete). However, these reinforcing systems have disadvantages such as difficult in application and lack of durability. Carbon fiber reinforced polymer (CFRP) composites have been widely used for bridge strengthening, applications included flexural and shear strengthening of girders, axial strengthening of circular pier columns, and seismic strengthening of pier columns [5-12].

This paper presents an experimental investigation on application of CFRP composites on extended pier cap beams for bridge widening purpose. CFRP plate with/without anchorages and CFRP sheet reinforcing system were tested and test results are presented and evaluated.

2. Extension of bridge cap beams and CFRP reinforcing system
As an alternative of build new piles, a bridge could be widened by just extending the pier cap beams, as shown in Figure 1. In order to maintain the same centre line of the highway, the pier cap beam will be extended on both sides, rather than on one side. Unless the existing pier column and foundation have extra reserved strength, such increase in bridge width is associated with increase in the width of
the bridge pier, as well as strengthening of the bridge columns and foundation. If the existing pier column does not have extra reserved strength, or the overhanging portion of the pier cap beam needs to be limited, then the column should be strengthened/widened, as shown in Figure 2.

![Figure 1. Bridge widening with extended cap beam.](image)

**Figure 2. Bridge widening with extended cap beam and column strengthening**

Additional load resulted from the extensions produces larger bending moment. As a result, additional flexural reinforcement is required. Two types of CFRP flexural reinforcement (sheet/plate) are applied to the extended beam and tested. Figure 3a. shows the CFRP plate reinforcing system, along with CFRP sheet anchors at the end of the cantilever. Figure 3b. shows fully wrapped CFRP sheet flexural reinforcing system.

![Figure 3. CFRP reinforcing system (a) CFRP plate system with CFRP sheet anchor; (b)fully wrapped CFRP sheet system](image)

### 3. Experimental test

This experimental program aimed to investigate the effectiveness of CFRP plate/sheet reinforcing systems used on extended cap beams. A total of four non-prismatic hammer-headed pier cap beams were cast and tested. PB1 was a reference specimen, PB 2 and PB3 was reinforced in flexure using
400 mm² CFRP plates with/without anchor system (CFRP sheets). PB4 was reinforced with 400 mm² fully wrapped CFRP sheets.

3.1. Specimen description and test setup
Specimens were prepared as follows: (1) At the tip of the cantilever beam, a small portion of the concrete was chipped out to expose the main top steel bars, (2) Exposed main bars were then threaded to extension steel bars, (3) Concrete of the extension part was cast after roughening the interface. In real practice, dowel bars across the interface are recommended to ensure higher shear force transmission. (4) Specimens were externally reinforced with different CFRP systems. Manufacture procedure is shown in figure 4.

![Figure 4. Specimen manufacture](image)

The CFRP plate was a commercial unidirectional carbon fiber product having a tensile strength of 2400 MPa. The CFRP sheet used was a unidirectional carbon fiber sheet. The CFRP sheets had a tensile strength of 3400 MPa, and a nominal thickness of 0.167 mm. The beams were subjected to monotonic loading at the free end of the cantilevers using two vertical positioned 1000 kN MTS actuators. Loads were applied using displacement control of 3 mm per load stage, until failure.

4. Test results
Test results are summarized in Table 1. PB1 failed by crushing of concrete in the compression zone after the steel had yielded. PB2 failed by debonding of CFRP plate from the tip. PB3 failed by CFRP plate slipped its anchorage system, after concrete has crushed in compression zone at bottom, which was visible. PB4 failed by CFRP sheet rupture at corner of the specimen after concrete crushing.

| Reinforcing system description | Ultimate capacity (kN) | Failure Mode |
|-------------------------------|------------------------|--------------|
| PB1 Reference                 | 250                    | CC\(^a\)     |
| PB2 CFRP plate without anchor | 269                    | FD\(^b\)     |
| PB3 CFRP plate with anchor    | 376                    | AF\(^c\)     |
| PB4 CFRP sheet                | 391                    | FR\(^d\)     |

\(^a\) Concrete crushing. \(^b\) CFRP debonding. \(^c\) Anchor failure. \(^d\) CFRP sheet rupture.

PB1, the reference beam, failed in a ductile manner with tensile steel yielding at 8 mm displacement, which was confirmed by the strain gauges as well, and concrete crushing at a displacement of 42 mm, as shown in Figure 5. The beam was loaded to a displacement of 45 mm, it could be predicted that this beam could keep its load carrying capacity to larger displacements, if the test setup loading system could handle larger displacements. This is a desirable typical failure mode for an under-reinforced flexural member, which exhibited good ductility.
PB2 failed in a brittle manner at a load of 268.8 kN. The flexural CFRP plates debonded from concrete surface before tensile steel bars had yielded, as shown in Figure 6. PBL1S1A0 exhibited slightly higher capacity and higher stiffness in elastic range than the reference beam. This test was immediately stopped by equipment safety control system due to sudden drop in load. It is very likely this beam would perform as the reference beam if loading was continued.

PB3 failed by slipping of CFRP plate on one side of the beam from the CFRP sheet anchor, at a displacement of 41 mm, as shown in Figure 7. “Slipping” is defined as pullout slip of CFRP plates from the CFRP sheet anchor system. Tensile steel yielded at a load of 329.6 kN, and associated displacement of 13.2 mm. After the CFRP plates had slipped, the beam maintained a capacity of 280 kN, which is slightly higher than the capacity of Reference Beam PBREF, until reaching the maximum traveling range of the actuators.
PB4 exhibited the best ductility compared to other specimens. Steel yielded at a displacement of 13 mm and CFRP rupture occurred at a displacement of 64 mm. CFRP sheet rupture at corner is shown in figure 9.

It can be seen from Table 1. that CFRP plate without anchor system can slightly improve the ultimate strength of the extended cap beams since debonding of the CFRP plates dominated the failure. When an anchorage system was applied, the ultimate capacity was improved by 50%, however, anchor failure was still observed on this specimen. Load-displacement diagrams are shown in figure 9.

5. Conclusion
In this study, an experimental investigation on the performance of quarter-scaled reinforced concrete hammer headed non-prismatic pier cap beams, extended on verges and reinforced with different CFRP systems, was performed. Based on the test results, the following conclusions could be drawn:
1. For hammer head non-prismatic pier cap beams, extensions on verges and reinforcement with CFRP systems is an effective solution for widening of bridges. Although fine cracks may form at the interface between old and new concrete, it has negligible effect on structural behaviors. Dowel bar are recommended across the interface. Additional load due to widening entails flexural strengthening of the extended cap beams.

2. Flexural CFRP composites are effective in improving the ultimate flexural capacity of extended pier cap beams. Failure mode of extended pier beams reinforced with CFRP plate without anchor is premature debonding of CFRP plates. CFRP plates slipping is the common failure mode of CFRP plate reinforced beams with CFRP sheet anchors, this failure mode occurs if the forces on CFRP composites reach the bond strength of the anchor system.

3. Ductility of extended and CFRP plate reinforced pier beams depends on anchor strength. However, ductility of CFRP sheet reinforced beams depends on CFRP tensile strength and corner treatment. CFRP sheet system is recommended as it can make more use of tensile property of CFRP composites.

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