Influence of anchorage systems on externally-bonded CFRP sheets used for flexural strengthening

B Al-Atta1,2*, R Kalfat1, R Al-Mahaidi1, A Al-Mosawe1
1 Swinburne University of Technology, Melbourne Australia
2 University of Baghdad, Baghdad, Iraq
*Corresponding Author

Abstract. Strengthening with carbon fiber-reinforced polymers (CFRP) has become one of the most significant methods of enhancing the flexural strength of reinforced concrete members. Extensive research has shown that externally-bonded CFRP sheets tend to debond from the soffit of the concrete members at much lower strains, compared with CFRP rupture strain. Different types of anchorage system have been developed to prevent or delay the debonding type failure, which leads to a higher utilisation of the CFRP sheets before failure occurs. This paper summarises some of the most efficient types of anchorage systems that have shown significant enhancement in terms of increasing the flexural bending capacity and the ductility of CFRP strengthened members. The study also presents a newly-developed type of anchor, known as a patch anchor, which has shown great effectiveness when used for shear applications. The influence of patch anchor on flexurally-strengthened slabs is investigated, where this anchorage type is trialed, and its effectiveness is discussed.

1. Introduction
Several new strengthening technologies have been introduced through recent decades. Carbon fiber-reinforced (CFRP) composites have become one of the most important materials that can be used for such purposes. Their light weight and ease of installation, corrosion resistance and strength-to-weight ratio have made CFRP more popular than other types of strengthening. However, a significant shortcoming of strengthening with FRP composites is the premature debonding-type failure, which occurs between the CFRP plate and the soffit of the concrete. This type of failure takes place at strain levels that are well below the strain capacity of the FRP sheets. The common types of FRP debonding failure is commonly observed by wide number of studies to date e.g. (1-3). Therefore, design guidelines including ACI 440.2R-08 (4) and AS 5100.8:2017 (5) limit FRP utilisation by applying reduction factors to ensure that the debonding type failure is prevented. These restrictions reduce the efficiency of FRP strengthening as the majority of the FRP strain capacity has not been utilised when debonded. Therefore, improving the bond properties between the concrete soffit and the FRP sheet is an important area of research that address the issue of debonding. This paper reviews different systems of anchorages that can be used to suppress debonding. Then, the study presents a new type of anchorage system for FRP sheets used for strengthening reinforced concrete (RC) slabs.

2. Literature Review

2.1. U-wrap anchors
The terms U-wraps, U-jacketing and U-strap are used interchangeably in the literature. Externally bonded U-wraps is one of the attractive anchorage systems due to its ease of application and corrosion resistance. This type of anchor involves applying U-shaped FRP sheet to the ends of FRP sheets used for retrofitting RC beams to prevent end debonding and cover separation failure (6). A U-wrap anchor can also be applied along the length of the FRP sheet to prevent other types of debonding, including IC debonding. This type of anchor can be made using same type of FRP sheet that is initially used for retrofitting the beam.
A study was undertaken to mitigate the concrete cover separation-type failure (7). Two types of U-wraps were tested i.e. vertical U-wrap and inclined U-wrap anchor. For vertical U-wraps anchors to suppress cover separation, a minimum width of 120 mm must be used, in order to shift the mode of failure to IC debonding instead of cover separation. Otherwise, the cover separation mode of failure would be shifted from the end of the plate to the inner side of the U-wrap. For inclined U-wrap anchors, a minimum width of 90 mm was sufficient to shift the mode of failure to IC debonding. The improvement resulted from using U-wrap anchors can be attributed to two causes i.e. reduction of the interfacial normal stresses in the region between the concrete soffit and the FRP plate, and suppression of the spreading of the horizontal cracks at the level of tensile steel reinforcement.

Another study has investigated the impact of using inclined U-wrap anchors on suppressing IC debonding (3). This involved testing eight beams, where a number of variables were studied including the width, the height and the inclination of the U-wrap. Results show that using these types of anchors can result in shifting the mode of failure from IC debonding to concrete crushing or FRP ruptures. The results of this study also showed that the larger the width of the U-wrap, the larger the increase in the load capacity. On the other hand, using a vertical U-wrap anchor to delay IC debonding type failure was inefficient. Research showed that using vertical U-wrap anchors yielded a load increase of 11 % only compared with unanchored specimens (2).

2.2. FRP Anchors

Loose fibers are bundled, or fiber sheets are rolled, to produce an FRP anchor which is also known as a spike anchor. It is one of various types of anchorage system that may be used to anchor FRP-strengthened RC slabs and beams. FRP anchors can be divided into two types i.e. single fan anchor and bow tie anchor (Figure 1). They consist of two components, the dowel and the fan. The dowel is inserted into a pre-drilled hole in the concrete which should have been previously filled with epoxy. The fan is splayed and epoxied on top of the FRP sheets, in order to distribute the concentrated local stresses.

![Figure 1. FRP Anchors a) single fan anchor, b) bow tie anchor (1)](image)

The effect of using FRP anchors on flexural behaviour of FRP strengthened RC slabs has been investigated (1, 8). The experimental program involved testing eight slabs under four points of bending. Two control specimens were used as a reference, these being an unstrengthened RC slab and a strengthened but unanchored RC slab. The other six slabs were strengthened and anchored with FRP anchors, each slab having a different layout of anchors. Results of this program show that FRP anchors are capable of increasing both the load capacity and the deformability of FRP-strengthened RC slabs. FRP anchors positioned along the shear span showed significant enhancement compared with FRP anchors distributed along the constant moment region. It was also observed that using closely-spaced...
anchors had reduced the rate of debonding spread, accompanied by a higher deformability of the slab’s behaviour. Using widely-spaced anchors gave a better ductility but with no load capacity enhancement. The optimum distribution of anchors is by applying anchors with higher fiber content near the pure bending area and lower FRP content but closely spaced along the end of the FRP sheet (1). Optimum distribution of FRP anchors resulted in 79% FRP utilisation before debonding compared with 45% utilisation in the case of a strengthened but anchored specimen. Another study was undertaken to increase the utilisation of FRP strengthened RC members (9). Results have shown a load increase of 270% was reached with only 175% increase in FRP material. It was also observed that small anchors and reduced spacings were able to fully develop the FRP strength, while larger spacings resulted in partial debonding.

2.3. Patch Anchors

An alternative method of anchoring RC beams strengthened with FRP materials is by using patch anchors. There are different types of patch anchors including uni-directional, bi-directional and quad-directional patches, all made from FRP materials. A study has investigated two different types of anchorage systems by laying uni-directional fabric perpendicular and parallel to the laminate i.e. anchor (Type 2) and anchor (Type 3), respectively (10). Both types of anchorage systems were tested on a joint scale and results were extrapolated into RC beams with FRP ligatures subjected to shear force. Figure 2 illustrates.

![Figure 2. Patch anchors: a) type 2, b) type 3 (10)](image)

Results showed that anchoring CFRP laminates using unidirectional CFRP patches, fibers perpendicular to laminate, increases the load capacity by 39-43% and the laminate strain before failure by 19-28% compared with unanchored joints. On the other hand, using patch anchors with fibers facing parallel to the laminate showed a better performance, as the load and ductility were increased by 46-57% and 18-37% respectively.

Another type of patch anchor is the bi-directional path anchor (11). The configuration of bi-directional patches allows their application around joints and in areas between the outer web and the bottom deck of a box girder section.

Three different joint configurations were tested i.e. anchor types 4, 5 and 6. All of the joints were strengthened with one layer of FRP laminate. Anchor type 4 consisted of one layer of bi-directional patch anchor while anchor type 5 included two patches, sandwiching the laminate between them. Anchor type 6 consisted of two unidirectional patches sandwiching the laminate between them in addition to another layer of bi-directional patches that was applied on top of the unidirectional patches. Results showed that bi-directional patch anchors were highly effective in increasing the load capacity
of the anchored joints compared with the unanchored specimens. Anchor types 4, 5 and 6 achieved load enhancement of 128 %, 100% and 195% respectively. This study was followed by another investigation to determine the size effect of patch anchors (12). It was concluded that a patch length of 300 mm is recommended to avoid slippage failure at lower loads.

3. Experimental program

3.1. Specimen design and FRP application
An experimental program was developed in a way analogous to previous studies (1) on FRP anchors for comparative purposes. The specimens were three slabs, 2700 mm long x 400 mm wide x 150 mm deep. Each slab was longitudinally reinforced with 2 xM10 mm diameter bars and 14 transverse tie bars of the same diameter. The first slab, PC1, was a control specimen made of reinforced concrete, RC, with no FRP strengthening. The second slab, PC2, was an RC slab strengthened in flexure using two layers of FRP unidirectional fabric sheets totalling 100 mm in width, 0.454 mm in thickness (0.227 mm per layer) and 2200 mm in length. The third specimen, PC3, was an RC slab strengthened using the same configuration as PC2 and anchored with four quad-directional patch anchors. Each patch anchor had a dimension of 400 mm wide x 300 mm long. Patch anchors were placed in potential debonding zones i.e. two patches at the ends of the FRP sheets and two patches below the point loads in the middle regions.

Before applying the FRP sheets to the slabs, each slab’s soffit was roughened using sandblasting to enhance the bonding properties. The soffit was later cleaned of any debris. After cutting the FRP sheet and the patches to the required positions, they were impregnated using a saturant-type epoxy. In the case of specimen PC3, a layer of patch anchors was first applied, followed by two layers of unidirectional FRP sheet. Next, a second layer of patches was saturated and applied on top of the FRP sheets to sandwich them. Specimens were the left in room temperature for curing.

3.2. Test set-up
A steel test frame was designed with special supports in order to perform the four-point bending test upside down as shown in Figure 3. This was to ensure that the tension side of the slab was facing upward, so that digital correlation photogrammetry (DIC) could be used to measure the strain along the length of the FRP sheet. A 500 kN actuator was welded to a spreader beam that distributed the load to two-point loads, spaced 800 mm apart. Strain gauges were mounted on the tension side of the slab to measure the strain along the FRP sheets. Laser extensometers were used to measure the maximum mid-span deflection of the slab specimens.
3.3. Material properties
After the slabs were tested, three cores were taken from each slab to test the compressive strength of the concrete. Slabs PC1, PC2 and PC3 were found to have a compressive strength of 70 MPa. The steel reinforcement bars had a tensile strength of 500 MPa and an elastic modulus of 200000 MPa.

The unidirectional FRP sheets had a tensile strength and an elastic modulus of 4900 MPa and 230 GPa respectively, while the quad-directional patches had a tensile strength of 4510 MPa and a modulus of elasticity of 230 MPa. The tensile strength of the saturant epoxy was also tested and found to be 29.5 MPa.

3.4. Results and discussion
The RC concrete slab PC1 experienced a ductile behaviour and failed at a maximum load of 28 kN. The slab continued to deflect beyond a displacement of 33 mm, but the test was stopped as the aim of the research was to measure the efficiency of patch anchors. The second slab, PC2, exhibited IC debonding mode failure (Figure 5). The FRP sheets debonded at a load of 62 kN and a deflection of 40 mm.

The anchored specimen, PC3, showed better behaviour in terms of both ductility and load capacity. The quad-directional patches improved the performance of the strengthened slabs and delayed the IC debonding failure. The slab failed by shear in concrete at a load of 78 kN and a deflection of 58 mm (Figure 4). All patches did not experience any type of debonding (Figure 6). However, the FRP sheets in regions between the patches showed partial debonding. Slab PC3 having failed by shear in the concrete, this indicates that the maximum efficiency of the patches was not tested. If the concrete shear failure had been prevented, the maximum load might have increased before slab’s failure. Results have also shown that FRP strengthening and anchoring had impacted the cracking load of the slabs. The cracking load had increased from 5.2 kN in PC1 to 17.4 kN in PC2 and PC3. The following figures and table summarize the results of this series of experiments.
Figure 4. Load–deflection curve

Figure 5. IC debonding (PC2)

Figure 6. Concrete shear failure (PC3)

| Slab | Peak Load (kN) | Cracking Load (kN) | Peak Strain (με) |
|------|----------------|--------------------|------------------|

Table 1. Summary of Results
### 4. Conclusion

This paper has reviewed the most efficient types of anchorage system that are used to anchor FRP strengthened RC members subjected to flexural actions. The paper has also presented the efficiency of quad-directional patch anchors, which can be used in anchoring FRP strengthened RC members subjected to flexural actions. Quad-directional patch anchors increased the load capacity and the maximum FRP strain by 25% and 17% respectively, compared with strengthened unanchored specimen (PC2). Using quad-directional patch anchors has also shifted the mode of failure from IC debonding in unanchored specimen PC2 to concrete shear failure in PC3. If the concrete shear failure had been prevented, the level of load increase and FRP utilisation would have been further increased.

### 5. Acknowledgment

The joint scholarship support given to the first author by Iraqi Ministry of Higher Education and Scientific Research and Swinburne University of Technology is gratefully acknowledged. The authors wish to thank the staff of the Smart Structures Laboratory of Swinburne University of Technology for the technical support provided during the experimental preparations.

### 6. References

1. Smith ST, Hu S, Kim SJ, Seracino R. FRP-strengthened RC slabs anchored with FRP anchors. Engineering Structures. 2011;33(4):1075-87.
2. Fu B, Chen GM, Teng JG. Mitigation of intermediate crack debonding in FRP-plated RC beams using FRP U-jackets. Composite Structures. 2017;176:883-97.
3. Fu B, Tang XT, Li LJ, Liu F, Lin G. Inclined FRP U-jackets for enhancing structural performance of FRP-plated RC beams suffering from IC debonding. Composite Structures. 2018;200:36-46.
4. ACI 440.2R. (2017). Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, American Concrete Institute, Farmington Hills, Michigan.
5. AS 5100.8 (2017). "Bridge Design Part 8: Rehabilitation and Strengthening of existing bridges" Standards Australia, ISBN: 9781760357214
6. Hasnat A, Islam MM, Amin AFMS. Enhancing the Debonding Strain Limit for CFRP-Strengthened RC Beams Using U-Clamps: Identification of Design Parameters. Journal of Composites for Construction. 2016;20(1):04015039.
7. Fu B, Teng JG, Chen JF, Chen GM, Guo YC. Concrete Cover Separation in FRP-Plated RC Beams: Mitigation Using FRP U-Jackets. Journal of Composites for Construction. 2017:04016077.
8. Kim SJ, Smith S. Behaviour of Handmade FRP Anchors under Tensile Load in Uncracked Concrete. Adv Struct Eng. 2009;12(6):845-65.
9. Orton S, Jirsa J, Bayrak O. Design Considerations of Carbon Fiber Anchors. J Compos Constr. 2008;12(6):608-16.
10. Al-Mahaidi R, Kalfat R. Investigation into CFRP plate end anchorage utilising uni-directional fabric wrap. Composite Structures. 2011;93(2):821-30.
11. Al-Mahaidi R, Kalfat R. Investigation into CFRP laminate anchorage systems utilising bi-directional fabric wrap. Composite Structures. 2011;93(4):1265-74.
12. Kalfat R, Al-Mahaidi R. Experimental investigation into the size effect of bidirectional fiber patch anchors in strengthening of concrete structures. Composite Structures. 2014;112:134-45.