The effect on the interfacial strength of the length/width ratio of FRP sheet bonded to concrete

W. Al-Juboori¹, and L. Weekes²

¹ Dep. Of Civil Engineering, Faculty of Engineering, University of Kufa
Email: Wisams.aljuburi@uokufa.edu.iq
² Address: School of Computing, Science and Engineering, University of Salford, Salford M5 4WT, Email: L.Weekes@salford.ac.uk

Abstract. Fibre reinforced polymer laminates are commonly used for the retrofit of ailing reinforced concrete structures for both shear and flexure. Recent studies have been undertaken regarding bond behaviour, but these have not advanced significantly to apply in a general manner to FRP sheets. This paper presents the effect of the length/width ratio on the bond stress and strength between FRP laminates and concrete. The experimental and the theoretical study give the same effect of the length/width ratio. Experimental bond models were tested of 7 specimens with 3 bonding techniques and compared with predictions from finite element models. Mesh sensitivity studies were carried out for the FE modelling, and compatible crack patterns were observed between FE models and the experimental samples. The FE shows clearly the distribution of principal stress in the concrete and explains the failures observed in the experimental tests. This study shows that the width of CFRP sheet has more influence than the length. Also it can be concluded that increasing the CFRP sheet width leads to a propensity for concrete de-bonding. This also illustrates how existing expressions for bond strength match with the observed results. In general the results show that an increase in width provides more load capacity than a relative increase in length even some design methods do not interest to the effective of width/length sheet ratio.

Keywords: Shear test; Concrete; FRP; Strengthening; Bond strength; Bond stress; Theoretical derivation.

1. Introduction
External bonding of fibre reinforced polymer (FRP) plates or sheets have emerged as a popular method for the retrofit strengthening of reinforced concrete (RC) structures [1-2]. This technology offers unique advantages with respect to the traditional strengthening techniques, including good immunity to corrosion, low weight and excellent mechanical properties. Furthermore, the hand lay-up allows this reinforcement to be adapted to the shape of any structural element [3-5]. The performance of the FRP-to-concrete interface in providing an effective stress transfer is of crucial importance [6-8]. Indeed, a number of failure modes in FRP-strengthened RC members are directly caused by de-bonding the FRP from the concrete. Therefore, for the safe and economic design of externally bonded FRP systems, a sound understanding of the behaviour of FRP-to-concrete interfaces needs to be developed and a reliable bond-slip model established.

The anchorage between concrete and FRP sheets plays an important role in reinforcing design. As a brittle material, FRP shows a lack of ductility, and the failure mode occurs suddenly without preceding
yielding. Recently, many studies have been undertaken to understand the bond behaviour between concrete and FRP sheets, but current understanding is not sufficiently advanced for FRP sheets to be applied in general, on actual structures. For these reasons, in terms of adhesion, it is necessary to confirm the safety of FRP sheets, or to seek a bond length and width considered to provide an adequately safe bond stress, so as to prevent the appearance and progress of bond rupture. In cases where the bond rupture or anchorage rupture is unavoidable, it is necessary to obtain the rupture strength experimentally, based on reliable data that adequately consider safety factors. This paper presents a new expression for the prediction of the bond stress and strength of FRP sheets with concrete that compares favourably with experimental results.

1.1 Research significance and objective
The broad objective of this paper is to understand the influence of the length and the width of the FRP on the ultimate stress/strain at de-bonding. The specific objectives of this paper are:
- To study the influence of the length and width of FRP sheet on the interfacial shear stress distribution in the FRP during de-bonding;
- To propose interfacial shear stress and bond strength models that can provide effective bond length and effective bond width for externally bonded FRP sheet; and
- To increase the database on bond behaviour between FRP sheet and concrete.

2. Experimental Programme
2.1 Test set-up
FRP–concrete bonding has been investigated by testing a number of specimens with CFRP reinforcement bonded to concrete prisms. The nominal dimensions of the prismatic concrete blocks are as follows: length (L = 280 mm), width (b = 200 mm) and height (h = 90 mm). The CFRP sheet was bonded in the centre on both sides of the concrete block. The concrete blocks had been sawn into two separate parts as shown in Figure 1, and then re-jointed by two threaded rods.

![Figure 1: Process of preparing two concrete blocks for bond testing.](image)

In a typical test, the tensile load is applied to the ends of a steel bar, which has been cast inside the concrete block. Figure 2 shows the steel bars inside the timber moulds, which have also been cut into two parts with concrete block. In addition, there are two longitudinal holes provided to facilitate clamping of the sample ‘halves’ prior to testing whilst loading into the tensile test machine. These were released before testing, as shown in Figure 3(c). Also a plastic membrane was placed between the two parts of concrete block to prevent any additional bond from the adhesive.

The samples were to be tested in a 50kN tensile test machine. To negate the effects of any eccentricity causing moment on the sample during testing, a ‘ball and socket’ connection was employed, as shown in Figure 3(b). Global slip was measured using two LVDTs that were set up on both sides of concrete
block close to the edge of the boundary surface of two concrete parts as shown in Figure 3(a). The surfaces of the concrete blocks, where the CFRP sheet would be glued, were ground to a fine finish with a stone wheel to remove the top layer of mortar, just until the aggregate was visible (approximately 2-3 mm); due to the very small dimension of the marble powder glued to the wheel, the concrete surface was very smooth (see Figure 2).

![Figure 2. Casting processes of specimens.](image)

![Figure 3. Detail of bond-slip test.](image)
2.2 Material properties

- **Concrete:** The average compressive strength \( f'_c = 51 \, MPa \) at 28 days and at the date of specimen testing was evaluated from uniaxial compression tests.

- **CFRP system:** Material properties for the unidirectional CFRP sheets were based upon information supplied by [Weber]. The nominal thickness, \( t_f \), of the carbon fibres contained in the FRP sheet was equal to 0.1178 mm. The tensile strength and the Young’s modulus of the composite sheet based on the sheet thickness were equal to 3900 MPa and 240 GPa, respectively.

2.3 Test programme

The experimental programme comprised of 7 specimens with 3 bonding techniques as shown in Figure 4. Each specimen was made up of two separate concrete sections without any bond between them other than the CFRP sheets. All these specimens had the same bond area. The purpose of this test was to understand the effects of changing the dimensions of the CFRP sheet (length and width) and the difference in strength contribution of CFRP for sheets and strips. To examine the consistency in results, three specimens were provided for arrangement B1-1, while two arrangements were provided for B2-3 and B2-4.

![Figure 4. Detail and techniques of specimens tested.](image)

3. Test results and discussion

All the figures in this section show the tensile load at the bar ends versus the average reading of the two gauges which were mounted on both sides of concrete block. To understand the shear stress at the FRP-to-concrete interface, the bond area is constant in almost all specimens. Therefore all results are compared with B1-1, which has CFRP sheet on both sides (100 mm x 100 mm). Figure 5 illustrates the experimental bond-slip results of the specimens.

First of all, as some of these graphs show, there is a difference in behaviour of specimens which have the same strengthening technique. Some of the reasons for this may be as follows:

- The eccentricity between the top and bottom grips
- Differences in thickness of adhesive
- Difference in concrete strength which affects the bond-slip for the CFRP-concrete interface
- On occasions, adhesive can enter between the contacting surfaces of the concrete blocks. This may lead to changes in bond-slip behaviour.
Figure 5. Load vs. total slip experimental bond-slip results of specimens.

Figure 6. Typical failures of specimens

Figure 6 shows selected photos after failure of the specimens. All of the samples failed by de-bonding (there were no failures by rupture). Some of these photos show that there is laminar failure (a type of de-bonding) happening in the concrete. The concrete used for the samples was normal concrete but its strength was high (51MPa) if it is compared with most commonly used concrete strengths. It can be seen that there are two types of de-bonding failure in the specimens of this study (adhesive de-bonding and concrete de-bonding). Table 1 illustrates that an increase in CFRP sheet width leads to a propensity for concrete de-bonding rather than adhesive de-bonding. Almost all of the specimens which failed with
concrete de-bonding gave high load capacity. Because there is more than one specimen for each case, all the curves present the average behaviour of each case (the details are shown in Figure 5).

Table 1. Specimen data.

| Specimen | Maximum load | Failure mode     |
|----------|--------------|------------------|
| B1-1a    | 20.3         | adhesive de-bonding |
| B1-1b    | 22.4         | adhesive de-bonding |
| B1-1c    | 27.5         | concrete de-bonding |
| B2-3a    | 15.6         | adhesive de-bonding |
| B2-3b    | 16.9         | adhesive de-bonding |
| B2-4a    | 24.93        | concrete de-bonding |
| B2-4b    | 27.5         | concrete de-bonding |

Figure 7 focuses on the effect of the total length to width ratio of CFRP sheet. The three cases (B1-1, B2-3, and B2-4) in this figure have the same area (10000 mm²) and the same thickness (t=0.1178 mm). This appears to indicate that the width of CFRP sheet has more influence than the length. Also it can be concluded that increasing the CFRP sheet width leads to a propensity for concrete de-bonding as shown in Figure 6. The theoretical implications of this are explored in the following section.

4. Numerical analysis

The Finite Element method is a numerical method which can approximate and solve complex structural problems to within acceptable boundaries. Finite element analysis was first developed by the aircraft industry to predict the behaviour of metals forming for wings. The ANSYS finite element program has been comprehensively developed to the extent that it has applications across the whole engineering spectrum [14]. In particular, civil engineers are frequently interested in modelling materials such as steel and concrete, the latter requiring complex methodology in its representation. As concrete is an orthotropic material that exhibits nonlinear behaviour during loading, this behavior is numerically implemented in ANSYS [15]. A number of previous researchers have used the finite element method to provide insight into the behaviour of the FRP-concrete bonded joints, and CFRP-strengthened RC beams. Hemmaty et al. [16] considered a nonlinear adherence-shear law based on the experimental studies between concrete and reinforcement in the modelling of reinforced concrete elements. While modelling the adherence-shear relationship, they used a nonlinear spring/damper element COMBIN39 (element in ANSYS) for their main modelling. Also, X.Z. Lu et al. in 2009 [17] used COMBIN39 to model the interface between the FRP elements and the supports. The study of X.Z. Lu et al. [17]
presented a numerical study of the FRP stress distribution at de-bonding failure in U-jacketed or side-bonded beams using a rigorous FRP-to-concrete bond–slip model and assuming several different crack width distributions. This element type COMBIN39 was used in the present study. Huyse et. al [18] presented a paper concerning analysis of reinforced concrete structures using the ANSYS nonlinear concrete model. This paper considers the practical application of nonlinear models in the analysis of reinforced concrete structures. The results of some analyses performed using the reinforced concrete model of ANSYS are presented and discussed. The differences observed in the response of the same reinforced concrete beam, caused by variations in a material model that is always basically the same, are emphasized. The consequences of small changes in modelling are discussed and it is shown that satisfactory results may be obtained from relatively simple and limited models. Santhakumar et. al. in 2004 [19] presented a numerical study to simulate the behaviour of retrofitted reinforced concrete beams strengthened with CFRP laminates using ANSYS. The effect of retrofitting on un-cracked and pre-cracked reinforced concrete beams was studied, and the behaviour of beams obtained from the numerical study showed good agreement with the experimental data. There was no significant difference in behaviour between the un-cracked and pre-cracked retrofitted beams. Al-Mahaidi et al. [20] studied the behaviour of three shear deficient T-beams strengthened using web-bonded CFRP plate. The experimental results have shown that repairing the beams with CFRP strips enhances their shear capacity. The increase in strength ranged between 68% and 87%. Nonlinear finite element modelling and analysis with DIANA was used to investigate the behaviour of these beams assuming plane stress conditions and perfect bond between the concrete surface and the web bonded CFRP strips. Finite element analysis was shown to be capable of predicting the ultimate strength, stiffness of the beams and strain levels in CFRP plates with reasonable accuracy. The cracking patterns and crack inclinations produced by the finite element model were also comparable to the patterns observed from testing. Fanning [21] presented nonlinear models for reinforced and post-tensioned concrete beams. The finite element software used (ANSYS) included dedicated numerical models for the nonlinear response of concrete under loading. These models usually included a smeared crack analogy to account for the relatively poor tensile strength of concrete, a plasticity algorithm to facilitate concrete crushing in compression regions, and a method of specifying the amount, the distribution and the orientation of any internal reinforcement. The numerical model adopted by ANSYS is discussed in this paper. Appropriate numerical modelling strategies are recommended and comparisons with experimental load-deflection responses are discussed for ordinary reinforced concrete beams and for post-tensioned concrete T-beams. The finite element modelling of experimental specimens using ANSYS Ver.12 is presented here. The ultimate purpose of a finite element analysis is to recreate mathematically the behaviour of an actual engineering system. Three and two dimensional nonlinear finite element analysis is used here to simulate the performance of the experimental model and thereby to employ these methods for further investigation. Initially, the FEA requires meshing of the structure, and, after loading, stresses and strains are calculated at integration points within these elements. An important step in the FE modelling is the selection of an appropriate mesh density. A convergence of results is obtained when an adequate number of elements are used in a structure (i.e. a mesh sensitivity study). This is practically achieved when an increase in the mesh density has a negligible effect on the results. Therefore, in this FE modelling, a convergence study was carried out initially to determine an appropriate mesh density. At first ANSYS models for implicit analysis were created within the ANSYS pre-processor. They comprised SOLID65 elements to represent the concrete, and SOLID46 elements were used to simulate the CFRP sheets and adhesive layer, with LINK8 elements representing the steel bar. The properties of CFRP sheets and adhesive are illustrated in Table 2. For a convergence study, a quarter of the full specimen was used by taking advantage of symmetry of the specimen and loading, as shown in Figure 8.
Table 2. Summary of material properties of CFRP and adhesive.

| Material | Elastic modulus | Poisson’s ratio |
|----------|----------------|-----------------|
| CFRP     | $E_x=240$ GPa  | $\nu_{xy} = 0.22$ |
|          | $E_y=31$ GPa   | $\nu_{yx} = 0.22$ |
|          | $E_z=31$ GPa   | $\nu_{yz} = 0.3$  |
| adhesive | $E=10$ GPa     | $\nu = 0.3$     |

Figure 8. Use of a quarter model.

Figure 9 illustrates three different mesh densities for the same case. The difference was in the width of elements (6.25 mm, 12.5 mm, and 25.0 mm). The comparisons between the experimental results and the FEA results of the three different element widths (25 mm, 12.5 mm and 6.25 mm) are shown in figures 10 to 12 respectively. These figures represent total slip in the CFRP sheet and the total tensile load. It is clear that FE predictions are in close agreement with corresponding test results. It should be noted that the use of a 12.5 mm element width gives the best compatibility between experimental and FE results. Experimental behaviour was close to theoretical behaviour in the elastic case. In contrast, there was disparity with the inelastic case as shown in figures 9 to 11. This is because of the difficulties of the ANSYS program in representing the actual solution when the stiffness value is small or when it is zero. Also in this stage, many types of elements were used to simulate the CFRP sheet with adhesive. The use of layered element SOLID46 provides the best solution for the behaviour and de-bonding process of the CFRP sheet. This element provides full connection between the CFRP sheet and adhesive. This is compatible with the actual physical case. Also it provides a simple approach for simulating the CFRP sheet in single or double layers.
Figure 9. Mesh for half of model in ANSYS (for example: B1-1).
Figure 10. Total slip versus tensile load for pure tension samples (width elements = 25mm).

Figure 11. Total slip versus tensile load for pure tension samples (width elements = 12.5mm)
Figure 12. Total slip versus tensile load for pure tension samples (width elements = 6.25mm)

Symbols shown at the element centre are based on the status of all of the element’s integration points. If any integration point in the element has crushed, the crushed (octahedron) symbol is shown at the centre. If any integration point has cracked or cracked and then closed, the cracked symbol is shown at the element integration point or at the centre. If at least five integration points have cracked and then closed, the cracked and closed symbol is shown at the element centre. Finally, if more than one integration point has cracked, the circle outline at the element centre shows the average orientation of all cracked planes for that element. Figures 13 and 14 show the crack patterns of concrete sections. The similarity between the theoretical and experimental results provides additional evidence to show that the FE model of this study is an acceptable simulation for CFRP and for the bond relationship between CFRP and the concrete section.

Figure 13. The theoretical and experimental crack for B1-1.
In the experimental work of this study, three samples (B1-1, B2-3, and B2-4) have the same area (10000 mm²). However, they give broad range of load capacity because they have different width to length ratios of sheet, as illustrated in section 3. To understand this influence, we will concentrate on the contour stress and make comparisons between the existing design methods to understand how they address this effect. Slices of the half FE model are taken to show the contour stress distribution on the outer surface of the concrete section and at the same depth, as shown in Figure 15.

Figure 16 shows the contour stress of FE models (width of the elements = 12.5mm). There are many points that can be noted in this figure. The value of the stress ranged between (-4 MPa to 40 MPa). The maximum stress (at an applied load = 15 kN) in B2-3, B1-1, and B2-4 was 38.19 MPa, 11.37 MPa, and 9.45 MPa respectively. Even with all the specimens at the same applied load and having the same area of CFRP sheet, the distribution of stress and maximum stress are different. This provides an initial understanding for the effect of the ratio of the width/length of the sheet. In addition to this, the stress in the case of sample B1-1 was concentrated in small area and reached deeper into the model than for other cases. This led to failure of the B1-1 samples with a low load capacity. However, we can conclude that
the width of CFRP sheet has more influence than the length. Figure 17 compares the existing design methods of bond strength. The Sato and Lzumo studies do not account for the effect in width/length sheet ratio. Therefore their prediction for bond strength differed from experimental observations. When compared with other studies, it is the predictions of Iso which provide the closest agreement.

Figure 16. Contours of principal stress

Figure 17. Comparison between existing predictions.
6. Conclusion
A modified expression for the prediction of bond strength has been presented which demonstrates a high level of accuracy when compared with experimental tests, and it has been corroborated with finite element analysis. It is proposed that this model should form the basis of improved design rules for concrete members strengthened with FRP.

The work has also led to the following conclusions:

i. The width of CFRP sheet has more influence than the length.
ii. Increasing the CFRP sheet width leads to concrete de-bonding.

References
[1] Al-Rousan R., Issa M., Fatigue performance of reinforced concrete beams strengthened with CFRP sheets, Construction and Building Materials 25 (2011) 3520–3529.
[2] Lu XZ, Chen JF, Teng JG, Ye LP, Jiang JJ Rotter JM. RC beams shear-strengthened with FRP: Stress distributions in the FRP reinforcement. Construction and Building Materials 23 (2009) 1544–1554.
[3] Cottone A., Giambanco G., Minimum bond length and size effects in FRP-substrate bonded joints, Engineering Fracture Mechanics 76 (2009) 1957–1976.
[4] Yuan H, Teng JG, Seracino R, Wu ZS, Yao J. Full-range behaviour of FRP-to-concrete bonded joints. Engineering Structures 26 (2004) 553–64.
[5] Yao J., Teng J.G., Chen J.F., Experimental study on FRP-to-concrete bonded joints, Composites: Part B 36 (2005) 99–113
[6] Pellegrino C., Tinazzi D., and Modena C., Experimental Study on Bond Behavior between Concrete and FRP Reinforcement, Journal of Composites for Construction, 12 (2008).
[7] Bonacci J. F., and Maalej M., Externally Bond FRP for Service-Life Extension of R Infrastructure, Journal of Infrastructure Systems, Vol.6, No. 1, March 1, 2000.
[8] Lu XZ, Teng JG, Ye LP, Jiang JJ. Bond–slip models for FRP sheets/plates externally bonded to concrete. Eng Struct 27(2005) 938–950.
[9] Yang YX, Yue QR, Hu YC. Experimental study on bond performance between carbon fiber sheets and concrete. Journal of Building Structures 22 (2001) 36–42