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MODELLING OF CFRP STRENGTHENED CONCRETE BEAM TO QUANTIFY THE EFFECTS OF BOND PARAMETERS IN FLEXURE

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Abstract: Application of Carbon Fiber Reinforced Polymer (CFRP) materials is an emerging technique for retrofitting concrete structures. Performance of composites mainly depends on the adhesive component which uses to create the bond between CFRP and concrete. A variety of commercial products of epoxies and CFRP materials are available in the market. Therefore a range of mechanical properties of such products is accessible. The bond performance may vary with the type of selected materials. Identification of flexural performance of CFRP strengthened concrete beams with variable material properties of CFRP and Epoxy is the main connotation. In general, application of CFRP materials to enhance flexural capacity extends throughout the span of the beam. Since CFRP materials are relatively expensive, it is important to quantify the performance difference with usage of material. A numerical model was developed to predict the performance of CFRP strengthened concrete beams and also to quantify the effects of different control parameters and mechanical properties on flexural performance of the composite. The model results are in good agreement with the experimental results. Parametric studies were also carried out to verify the performance with varying bond properties and mechanical properties of CFRP. The results indicate that the normal modulus of CFRP is appropriate for strengthening concrete elements. Increased flexural performance cannot be expected by increasing material usage. Use of number of layers doesn't provide an economical solution in strengthening of beams. The paper provides recommendations for strengthening concrete elements in economical way.

Keywords: CFRP/Concrete composites; Finite Element Modelling; Mechanical properties; Epoxy; Bond length

1. Introduction

Fiber Reinforced Polymer (FRP) materials were introduced to Civil engineering applications as an excellent solution in retrofitting the structures. During the last three decades, the life cycle of many degraded structures were significantly improved by these applications. FRP composites possess many advantages over various common building materials such as light weight, good corrosive resistance, high strength to weight ratio, easy installation, very low conductivity, flexibility in adapting to field conditions and resistance to chemical resistance [1]

FRP materials are classified into various types such as Carbon Fiber reinforced Polymer (CFRP), Aramid Fiber Reinforced Polymer (AFRP) and Glass Fiber Reinforced Polymer (GFRP) based on the constituent material types. Available in various forms such as sheets, laminates rods and strips. CFRP is the most commonly used FRP material because of low cost and high fatigue resistance. CFRP is light and more ductile than the glass laminates subsequently available. It is a thin material that can either be applied as an external bonded reinforcement or near surface mounted reinforcements. CFRP performs as a secondary reinforcement to the previously installed steel reinforcement in concrete and provides additional strength and ductility for strengthened beams [2].

CFRP is installed to concrete by binding them with a thermoset resin. The orthogonal material properties of CFRP and the slip properties of the resin could affect the overall performance of the composite [2-4]. Therefore, though the models are predicted to fail under classic failure modes such as rupture, shear or crushing due to compressive forces, it could rather prematurely fail due to interfacial debonding and the cover seperation [5-7]. These phenomenon are mainly depends on the surface properties of substrate, material properties of epoxy and concrete, and the bond length [8].

Varieties of commercial products of CFRP materials and epoxy adhesives are available in the market. Performance of retrofitted member may vary with the selected material type and their mechanical properties [9]. In this research, CFRP strengthened concrete beam was modelled using a commercially available finite element analysis software [10]. Experimental investigation conducted by Pham [11] at Monash University, Australia was used to validate the numerical model. Parametric study was also conducted considering a range of material properties of CFRP and epoxy. This paper presents the overview of test programme, development of numerical model, validation, parametric studies and results.

2. Finite Element Modelling

2.1 FE Mesh

The finite element method (FEM) is the leading discretization method in computational mechanics. The basic notion in the physical interpretation of the FEM is the subdivision of the mathematical model into disjoint (non-overlapping) components of simple geometry [10]. In the present study, the FE software used is ANSYS 15. Concrete sections were modelled using Solid65 element type [10]. Steel reinforcement is modelled with Link180 (line element) and CFRP/Epoxy interface is modelled with Shell181 [10]. Target and contact elements are developed for contact mechanisms. Concrete is meshed as hexahedral sweeping where certain incremental dimension spacing is maintained. Concrete has a solid mesh size of 50 mm x 50 mm x 50 mm. CFRP/Resin composite is meshed as 50 mm x 50 mm shell elements as shown in Figure 1. Since the composite is defined as shell elements, the aspect ratio is maintained as 1.

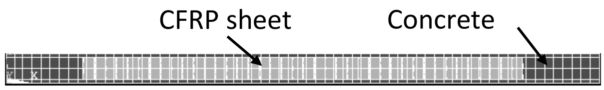

Figure 1: FE mesh – Plan view of CFRP strengthened concrete beam

2.2 Material Properties

Grade 50 concrete was used for modelling as used in the experiments. In order to precisely simulate the concrete behaviour, ANSYS requires an input of a number of parameters. The modulus of elasticity of concrete (EX) is calculated by the gradient of the stress-strain curve developed based on the design codes [12]. Poisson ratio (PRXY) is taken as 0.2. Uniaxial cracking stress and uniaxial crushing stress indicate the ultimate tensile strength and the ultimate compressive strength, respectively. Shear transfer coefficients represent the condition at the crack face while it is opened (loaded) and closed (reversed). Values range from 0 to 1 where 0 stands for a smooth crack, when shear transfer is completely lost, while 1.0 stands for a rough crack with no loss of shear transfer. The initial portion of stress strain curve is linear lasting up to about 30% – 40% of the ultimate load and then the curve becomes non-linear, with large increments of strains are recorded for small increments of stress. The summary of the values considered in the analysis is listed in Table 1.

Table 1: Properties of Concrete [10]

Elastic modulus	29000 MPa
Density	2500 kg/m^3
Poisson ratio	0.2
Open Shear Transfer Coefficient	0.4
Closed Shear Transfer Coefficient	0.6
Uniaxial Cracking Stress	2.5 N/mm^2
Uniaxial Crushing Stress	50 N/mm^2

The elastic modulus of steel reinforcement is 200,000 N/mm^2 and Poisson ratio is 0.3. Tensile strength of the main bars (12 mm diameter) is 650 N/mm^2. The stirrups (10 mm diameter) are designed to have a tensile strength of 480 N/mm^2. Strain hardening of the steel is not incorporated since it is not critical [13]. CFRP is an orthotropic material though its properties are predominant in the axial direction. Epoxy Resin is idealized as a homogeneous material. Table 2 and 3 show the properties of CFRP and epoxy used for the modelling, respectively. These values are extracted from the experimental study done by Pham [13].

Table 2: Properties of CFRP [13]

Layer Thickness	0.176 mm
Density	1700 kg/m³
Elastic Modulus (axial)	240000 MPa
Elastic Modulus (lateral)	3900 MPa
Tensile elongation	0.4%

Table 3: Properties of Epoxy Resin [13]

Thickness	1 mm
Elastic Modulus	3750 MPa
Yield Stress	49.1 MPa

2.3 Geometry and Boundary Conditions

The dimensions and the boundary definitions are in correspondence to the experimental study [13] that is used to validate the model. The total length of reinforced concrete beam is 2700 mm and the cross section (depth x width) was 260 mm x 140 mm. Reinforcements of 12 mm diameter steel bars were used as main top and bottom bars while 10 mm mild steel bars were used for shear links. Nominal cover of 40 mm was provided from both the top and bottom faces. However, only 20 mm cover was provided from the side faces. Shear links were spaced at 125 mm from both the longitudinal ends up to 1000 mm inwards (towards the mid span). Figure 2 shows the steel reinforcement arrangement in the model.

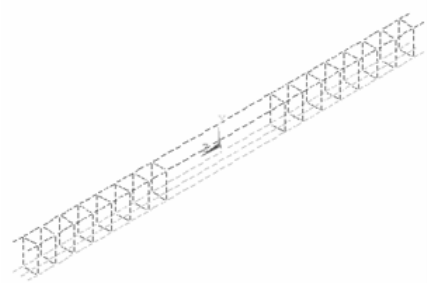

Figure 2: Steel reinforcement arrangement

Pin support conditions were provided at 200 mm from the both ends as shown in Figure 3. One support is fixed only in the vertical direction (roller) and the other support is fixed in the vertical and axial directions (pinned). CFRP and epoxy is created together as shell sections [8] Contact pair is created between epoxy adhesive and concrete surfaces. Penalty method is used for analysis. The behaviour of the contact surface is defined as bonded at initial contact.

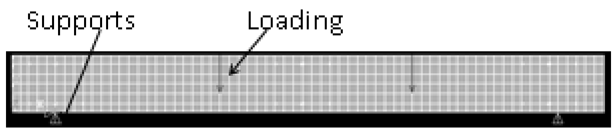

Figure 3: Support conditions, loading and mesh

CFRP sheets are installed at the tension face of the beam. The width of the sheet is 100 mm. It is attached to the mid span of the bottom surface (where tensile forces are usually developed) of the concrete beam with 2000 mm in length. The thickness of the CFRP sheet is 0.176 mm.

3. Test Programme

A set of long beams were tested at Monash University, Australia [13]. The beams were tested in four-point bending with a total span of 2300 mm. The shear span was chosen to be 700 mm leading to a shear span to depth ratio of approximately 3. The beams were loaded using the Instron universal testing machine with a 250 kN load capacity. The beam was placed on two steel support blocks, which seated on two low friction bearing strips to allow horizontal movements. Load cells of 100 kN capacity were placed underneath the bearing steel blocks to measure the reactions of the supports. The load from the actuator was transferred to the beam through an I-beam and two rollers. Figure 4 shows the typical longitudinal details and the load points of the experimental study.

CFRP sheets were bonded to the concrete beam using epoxy resin. The beams were loaded at a rate of 1 mm per minute for most of the time.

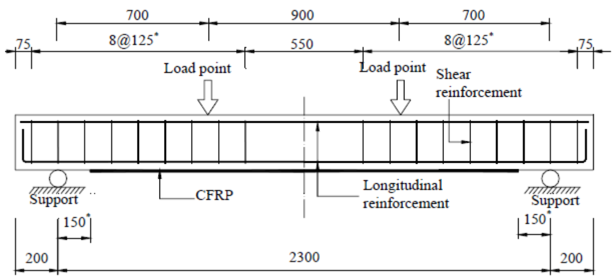

Figure 4: Typical beam details [13]

4. Model Results and Validation

Transient load was applied in 50 N load steps to the model. Newton-Raphson iterative process solver was used for analysis. Von –Misses stress-strain relationship was selected. CPU Processor with 2.2 GHz capacity was used for modelling. The model was run for approximately two hours. Analytical and experimental results were compared and the variation of deflection at mid span was observed and plotted in Figure 5. The model results were then plotted against the results of Pham [13]. It has been shown that both predicted (model) and test results have a similar load - deflection behaviour. The results interpret that the model predicted results differ less than 7% from the experimental results (Table 4, Figure 5). This indicates that the predicted results have a good agreement with the experimental results.

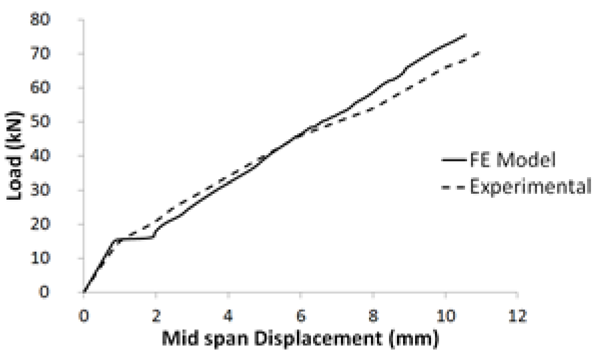

Figure 5: Load – Displacement curves

The flat part of the FE model curve shows the transition period from linear to non-linear analysis. Experimental curve shows a change in the gradient (Young's modulus reduction) at this location. This further validates the results. There are slight variations as the workmanship effects suffered by the field results and the on-site behaviour of the concrete are not considered under a framework of guidelines used for model definition and assumptions in modelling.

Table 4: Validation of the FE Model

Conditions	Model	Experiment	Difference
Failure Load	75.5 kN	70.7 kN	6.8%
Deflection	10.6 mm	11 mm	3.6 %

A few details from the validated model is extracted to observe the pattern of failure. The beam displacement due to the applied load and the Von Mises stresses developed in the CFRP sheet are shown in Figure 6(a) and 6(b) respectively.

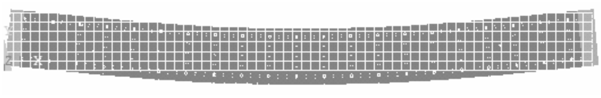

Figure 6(a): The magnified shape of beam displacement due to the applied loads

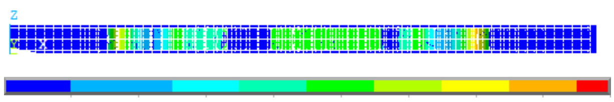

Figure 6(b): Von Mises Stresses developed in CFRP sheets

5. Parametric Study

Parametric studies were carried out to understand the effects of properties of CFRP and epoxy resin in performance of retrofitted concrete beams.

5.1 Optimizing the use of CFRP

The length of the CFRP sheets installed in the bottom surface is adjusted to different parameters to analyse the flexural resistance developed in the FE

beam models. Three samples were selected with varying CFRP bond lengths (b) of 2000 mm (validated model), 1800 mm 1500 mm and 1200 mm spanning symmetrically on both sides from the middle. The bond length (b) to span (s) ratios, were 0.87, 0.78, 0.65 and 0.52. The material properties of concrete, FRP and adhesive resin for the above FE models are provided in Table 1, Table 2 and Table 3 respectively. The results are shown in Figure 7 and Table 5.

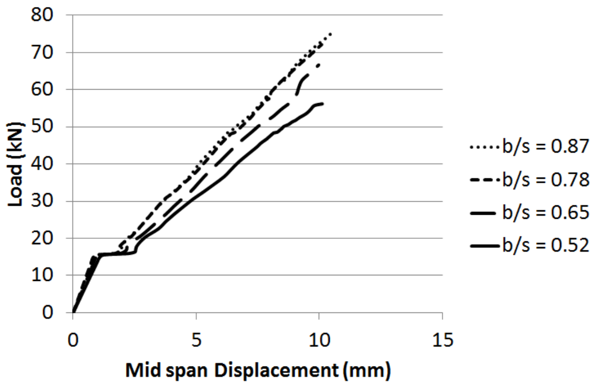

Figure 7: Load Displacement curves when CFRP is strengthened with different b/s ratios

Table 5: Predicted performance when CFRP is strengthened with different bond length to span ratios (b/s)

b/s	Failure Load (kN)		Mid span Displacement (mm)	
0.87	75.5	-	10.6	-
0.78	72.1	- 4.5 %	10.1	- 4.7 %
0.65	66.7	- 11.6 %	10	- 5.7 %
0.52	56.2	- 25.6 %	10.1	- 4.7 %

Due to 10%, 25% and 40% decrease in the CFRP sheet along its axial direction, the failure load is predicted to be reduced by 4.5%, 11.6% and 25.6% respectively. The rate of decrement is significantly higher when the CFRP applied bond length is reduced from 1500 mm to 1200 mm. The mid span displacement is approximately identical at the failure.

Another set up of parametric study discusses the number of strengthening layers of CFRP sheets installed in the concrete beam. In this study, CFRP layers of 1, 2 and 4 (each layer having a thickness of 0.176 mm) are analysed in addition to the validated model with 6 layers of CFRP sheets. The results are shown in Figure 8 and Table 6. The material properties used for modelling are listed in Tables 1, 2 and 3. The bond length of 2000 mm was considered for this analysis.

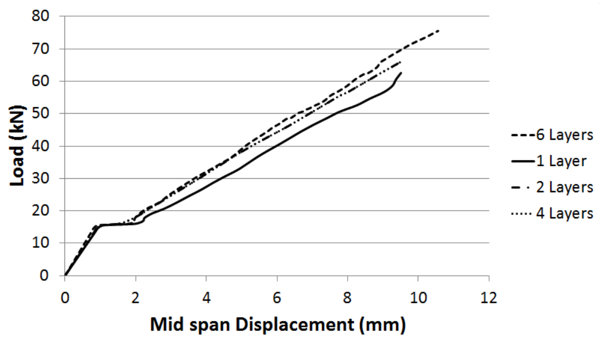

Figure 8: Load Displacement curves when CFRP is strengthened in various layers

Figure shows similar ductile nature slightly higher failure load with increased number of CFRP layers.

Table 6: Predicted performance when CFRP is strengthened in various layers

Layers	Failure Load (kN)		Mid span Displacement (mm)
6	75.5	-	10.6
1	62.6	- 17.1%	9.5
2	66.1	- 12.5 %	9.5
4	72.1	- 4.5 %	10.4

Strengthening capacity increases with the number of CFRP layers. Around 17% of the capacity loss is predicted when the number of layers in the present model is reduced from six to one. Concrete crushing and de-bonding are the main failure modes observed in the numerical analysis.

5.2 Effects of Epoxy Resin properties

The structural and binding properties of adhesive resin contribute to the overall capacity of the structure. Several epoxy resin brands are available in the market. In addition to the resin used to validate the model, another three different types of brands are tested in the present study. The validated model is maintained as the control model.

The material properties of concrete and FRP are provided in Table 1 and Table 2, respectively. The properties of the adhesive materials and the subsequent results at failure are provided in Table 7 and Table 8, respectively. The load – displacement curves from the FE models are plotted in Figure 9.

Table 7: Material properties of epoxy adhesive

Adhesive type	Young's Modulus (MPa)	Yield Stress (MPa)
1	3750	49.1
2	1515	17.2
3	2140	21.7
4	5240	50.3

All adhesive resin materials are considered to be spread to a thickness of 1 mm. In modelling, resin is considered as shell type element connected to FRP using node to node contact elements.

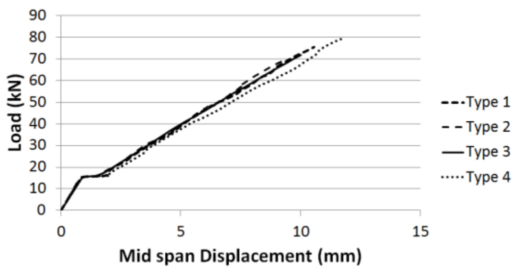

Figure 9: Load Displacement curves with various epoxy resin material types

All the selected adhesives indicate similar performance in load – displacement curves. However adhesive type 4 contains relatively high young Modulus and Yield stress when compare with other selected adhesive types. A slight increment in failure load only can be noted with this adhesive.

Table 8: Predicted performance with various epoxy resin material types

Adhesive	Failure Load (kN)		Mid span Displacement (mm)	
1	75.5	-	10.6	-
2	68.9	91.3%	11.8	111.3%
3	71.9	95.2%	11	103.8%
4	79.6	105.4%	9.2	86.8%

From the tested four types, the predicted results suggest that less than 15% (105.4 % - 91.3%) of the failure load is affected based on the use of epoxy resin. Higher modulus will increase the stiffness hence the mid span displacements vary by 24.5% (111.3% - 86.6%) between the adhesive resins tested. However, de-bonding can be delayed with use of relatively stiff resins.

5.3 Effects of properties of CFRP

Another set of analysis were conducted to identify the effects of CFRP properties on the flexural capacity of the composite. In practice, CFRP material of standard modulus, intermediate modulus, high modulus and ultra-high modulus types are available in the market. In this study, four different modulus of CFRP were selected as shown in Table 9.

Table 9: Material properties of CFRP

Modulus Type	Tensile Modulus (GPa)	Tensile Strength (GPa)
Normal	240	4.5
Intermediate	320	5
High	400	4.5
Ultra-high	640	4

The CFRP bond length is maintained as in the validated model (2000 mm spanning symmetrically from the mid span of the beam). The properties of concrete and adhesive are provided in Table 1 and Table 3, respectively. The results of the study are shown in Table 10 and Figure 10.

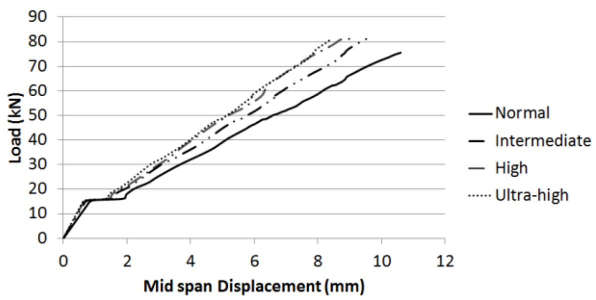

Figure 10: Load Displacement curves with various CFRP material types

The slopes of linear relationships indicate in Figure 10 shows a clear difference with varying modulus of CFRP. However, a slight reduction in failure load can be seen with decreased ductility of composite.

Table 10: Predicted performance with various CFRP modulus

Modulus Type	Failure Load (kN)		Mid span Displacement (mm)	
Normal	75.5	-	10.6	-
Intermediate	81.3	107.7%	9.7	9.5%
High	81.2	107.5%	9	84.9%
Ultra-high	81	107.2%	8.4	79.2%

The model results show that the use of higher modulus type CFRPs increase the total flexural capacity by less than 8%. However, the mid span displacement is significantly reduced by more than 20%. The tensile strength of the CFRP materials influences the load carrying capacity of the composites. Low deflections are encountered in higher modulus materials.

5.4 Effects of substrate properties

The final set of parametric studies was conducted to verify the influence of the substrate properties in the flexural performance of composite beam. Concrete grade is increased from Grade 20 to Grade 50 in ten steps. Non-linear performances of the concrete at different grades are developed based on the design codes [12]. The CFRP and adhesive properties are provided in Table 2 and Table 3, respectively. The bond length of CFRP is 2000 mm spanning symmetrically from the mid span of the beam (as in validated model). The results of this study are shown in Table 11 and Figure 11.

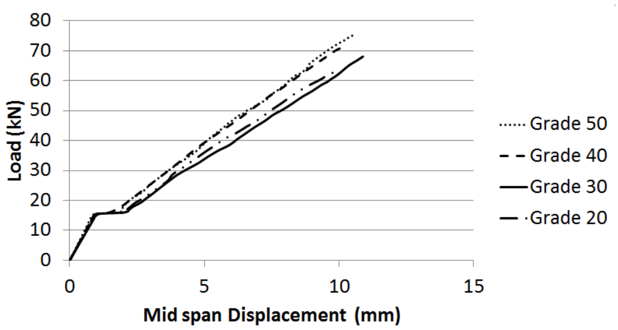

Figure 11: Load Displacement curves with various substrate properties

Table 11: Predicted performance with various Concrete Grades

Grade of Concrete	Failure Load (kN)		Mid span Displacement (mm)	
50	75.5	-	10.6	-
40	71.4	94.6%	10.2	96.2%
30	68.1	90.2%	10.9	102.8%
20	63.4	84%	10	94.3%

The failure load reduces by 16% when the substrate grade is reduced from Grade 50 to Grade 20. Due to the application of FRP, the poor mixes of concrete shall be remedied as the FRP materials withstand a significant portion of the failure load. Mid span displacements are approximately identical at the point of failure.

6. Conclusions

A numerical model was developed to quantify the effects of bond parameters on flexural performance of CFRP strengthened concrete beam. The model predicted results indicated a good agreement with experimental results. The following conclusions can be made from this study:

A range of percentage (52% - 87%) of strengthened spans was considered. It indicates at least 3/4 of clear span should be strengthened for better performance. It is no need to extend the CFRP sheet all over the span. The bonded span does not affect significantly on the ductility of composite beam in the considered range.

Number of layers was another important aspect investigated. Considerable strength increment cannot be noted with increased number of layers of CFRP. When the usage of CFRP increases in six times, the noted strength increment was 17.5% with respect to strengthening with a single layer. Therefore, use of number of layers is not an economical solution in a strengthening project because relative strength increment is low when comparing with increased material usage.

The properties of adhesive resin significantly influence on flexural performance of CFRP/concrete composites. It is important to select an adhesive with relatively good mechanical and thermal properties.

CFRP materials are available in the market with different properties; in the range from normal modulus to ultra-high modulus. The material cost is considerably high with increased quality in properties. All the available types used in this analysis indicated similar performance. In general, the weaker parts of concrete/CFRP composites are the substrate and adhesive resin. Therefore, normal modulus of CFRP can be recommended for strengthening any type of concrete elements.

The substrate properties significantly affect on strength performance of CFRP strengthened concrete beams.

Acknowledgement

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