Numerical Investigation of RC Beam Using Externally Bonded Fibre Reinforced Polymer Laminate Using Ansys Software

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Abstract: Due to its exceptional properties such as good tensile strength, serviceability, corrosion resistant, and light weight, externally bonded Fibre reinforced polymer (FRP) is increasingly being utilized to support reinforced concrete (RC) structures. De-lamination of FRP-plate with concrete cover owing the most prevalent type of failure is due to different stress concentration at the bonded plate's end (stresses at end). The behaviour of the FRP-concrete interface is an important component in preventing debonding failures in RC structures. As a result, for the safe and cost-effective design of externally bonded FRP systems, a deeper understanding of FRP behaviour for concrete interfaces is necessary. The primary goal of this research is to investigate the behaviour of the FRP-concrete interface. Finite element (FE) simulations utilising the ANSYS Finite Element software are used to investigate the interaction behaviour. For the parametric investigation, FE simulation models are built to investigate the impact of various variables on the binding behaviour of FRP and concrete surfaces by altering the width and thickness of the FRP laminate. Different thickness of FRP 2 mm, 4 mm, 6 mm and different widths 75 mm and 100 mm are taken. Based on the results the multi variable nonlinear regression and multi variable logarithmic Finite element (FE) simulations utilising the ANSYS Finite Element software are used to investigate the interaction behaviour. For the parametric investigation, FE simulation models are built to investigate the impact of various variables on the binding behaviour of FRP and concrete surfaces. Regression study is conducted out, and the best fit for the parameters under evaluation is found. The above analysis results are compared with the published work for validation.

Key words: FRP, ANSYS Software, nonlinear regression, logarithmic regression.

1. Introduction

Structural member deterioration is currently among the most serious issues in the building sector. Many factors contribute to the deterioration of RC structures, including reinforcement corrosion, ageing, and poor planning or implementation, exposure to hazardous conditions and as a result of various natural disasters Because a total reconstruction of the structures is not cost-effective, structural members can be strengthened by strengthening or retrofitting. [1-3]. In earlier, External reinforcement for reinforced concrete structures was provided by bonded steel plates. This method is used to improve the structural element’s strength. Even the technique of steel bonding is simple, economical and efficient; corrosion of steel involves in the degradation of interface at steel
and concrete. In terms of external bonding, strengthening concrete elements with FRP is a common technology nowadays [4-8]. In recent years, As an externally epoxy-bonded reinforcement for concrete, FRP plates have mostly replaced steel plates, due to (superior properties) like Toughness, high lifetime, corrosion/fire resilience, and lightweight are just a few of the benefits. FRP plate can enhance stiffness and load bearing capacity as reinforcing steel, but it also lowers ductility and creates fragility failure modes, which are undesirable in structural design. Delamination of the FRP-plate and the surrounding concrete cover as a result of pressures at the plate's end, according to previous studies, is the most prevalent failure. FRP composite materials are made up of high-strength continuous fibres inserted in a polymer matrix, such as glass, carbon, or steel wires [9-13].

1.1 Advantages Of FRP

- Increases flexural strength
- Increases shear strength
- Increases stiffness at working loads
- Reduces width of crack and enhance durability and corrosion resistance
- Economical compared to other conventional methods
- High tensile strength & long-term durability
- Repairs are fast with minimal disruption of service.

1.2 Debonding Failure Modes

In latest days, there has been a lot of study on the behavior and stability of these FRP-reinforced Structural members, the majority of which has been done in the last decade [14–20]. A number of failure modes have been found as a result of this study. Figure 1.1 represents the representation of 6 key failure modes which are (a) failure in bending due to rupture of FRP, (b) Crushing of compressive concrete causes flexural failure, (c) Shear failure (d) concrete cover separation (e) plate end interface debonding, and (f) intermediate fracture driven interfacial debonding are all examples of interfacial debonding. The first three failure modes depicted in Figure 1.1 are not completely different from ordinary RC beams; however there are several key changes [21-23].The 3 failures ways indicated on the right are specific to beams bonded with a soffit plate and are not seen in ordinary RC beams. Because they occur well before (a) or (b) section flexure failure or the (c) shear failure in mode, these techniques are typically referred to as pretreatment failure methods.

![Figure 1.1 (a) FRP Rupture](image-url)
Figure 1.1. (b) Crushing of Concrete at compression

Figure 1.1 (c) Shear failure

Figure 1.1. (d) Concrete Cover Separation

Figure 1.1. (e) Plate End Interfacial Debonding
1.3 Objectives

- The main purpose of this study is to create a model that can forecast the maximum transmitted load to the bond for a FRP laminate that is externally attached.
- Perform Finite Element Simulation by taking into account a variety of elements that influence the binding behavior of FRP and concrete, such as stiffness (laminate thickness times elastic modulus), material properties, and laminate thickness.

2. Numerical Investigation

2.1 Introduction

Finite element software ANSYS is used to do the numerical analysis. The prism is modeled considering the material properties of concrete and FRP for the analysis. The analytical study is conducted for the modeled element considering various parameters influencing the bond action through indirect method.

2.2 Finite Element Model Development

ANSYS 19.0 is used to describe a concrete prism with an associated GFRP laminate, as seen in the single shear test presented in this paper. The impacts of different GFRP laminate widths, such as 50 mm and 75 mm, and different thicknesses, such as 2 mm and 6 mm, are explored and compared. The dimensions of the concrete prism are 400 mm x 150 mm x 150 mm. The length of the FRP bond is 300 mm. As shown in Fig. 2.2, the effect of altering width and thickness of FRP laminate with different concrete grades M25, M30, and M35 is studied by modelling adhesive development lengths on the stress distribution. For the complete developed models, the free end of the FRP laminate (unattached) is 100 mm long.

2.2.1 Concrete

The concrete is assumed to be multi-linear isotropic stress-strain curve, in which a limiting compressive strain, \( \varepsilon_{cu} = 0.0035 \) is assumed. Once the compression strain limit is reached, the concrete is considered to be crushed and has possessed no strength. Concrete was modelled using eight node solid element (Soild185) incorporated with micro plane model which can translate in x, y, and z directions with three degrees of freedom at each node. Figure 2.1 represents the stress strain curve respectively.
2.2.2 GFRP Laminate

FRPs are considered linear elastic until tension. The bonded FRP composites are modelled using SOLID185 element. The properties considered for GFRP laminate are:
- Density = 2050 kg/m$^3$
- Young’s modulus in X = 20 GPa
- Young’s modulus in Y, Z = 7 GPa
- Poisson’s Ratio = 0.3
- Shear Modulus in X = 1.5 GPa
- Shear Modulus in X = 2.5 GPa

2.2.3 Contact

A CONTA174 & TARGE170 interface component is a 3D zero-layer component defined by an 8-node sequential interface element that replicates an interface between two surfaces, with the separation indicated by an increasing displacement between nodes within the interface element itself as part of the delamination process. Figure 2.2 represents FE Model.
2.3 Numerical Modelling

- Concrete is modeled using eight node solid element (SOLID185) incorporated with micro plane model and FRP as SOLID185. The interface between FRP and concrete is modeled as CONTA174 & TARGE170.
- The block movement is restrained in the lateral and transverse directions.
- Displacement controlled loading was applied at a un-bonded end of the FRP.
- The results of the developed FE model in terms of normal stress along the FRP plate are obtained.

3. Results and Discussions

3.1 Introduction

The numerical analysis is carried by considering various parameters such as thickness of FRP, width of FRP and grade of concrete. The results from the parametric study are discussed in this Chapter.

3.2 Numerical Results

A displacement of 25 mm is functional to the free end of FRP at 0 to 1 sec time interval. Figure 3.1 shows the various axial stress in X direction at 0.23 seconds, where stress is maximum. The stress gradually decreases to the other tip show the transfer of force by bond to the concrete. A smaller portion of FRP is fully stressed in transferring the bond stress and most of the portion the stress is very less.

![Figure 3.1 Stress at Time 0.23 Seconds](image)

Figure 3.2 shows the stress in FRP at the time 1 sec. Since the debonding occur under the load, no longer transfer from FRP to concrete. The stress throughout the concrete is zero.
From the debonding failure mode of FRP, the contact behaviour of FRP with concrete is studied. The debonding behaviour of FRP is explained in four stages. The four stages include Far Open, Near Contact, Sliding and Sticking. From the Figure 3.3, it is seen that the bonding between FRP and concrete is different at different stages. There are four stages of debonding failure modes are observed. At the front portion, there is no contact between FRP and concrete which is called as Far Open. The next stage is Near Contact where FRP is in contact with concrete. The third stage shows that the FRP is sliding with concrete. Final stage shows that the FRP is sticking at the tip of the concrete.
Figure 3.4 shows the variation of stress at different time from Time History analysis. The stress initially increases and maximum stress obtained at 0.23 seconds at the mid node of free end of FRP laminate. Then the stress decreases and becomes zero after debonding.

![Figure 3.4 Time history Plot](image)

### 4. Parametric Study

#### 4.1 Load Vs. Thickness plots for various concrete grades.

For concrete grades M25, M30, and M35, the load under varying thicknesses of FRP laminate is plotted using two different laminate widths of 75 mm and 100 mm. which is shown in Figure 4.1 (a), (b), and (c) respectively. Where $f_{ck}$ = characteristic compressive strength

![Load vs Thickness plots for M25 grade](image)

(a) Load vs Thickness plots for M25 grade

![Load vs Thickness plots for M30 grade](image)

(b) Load vs Thickness plots for M30 grade
From the Figure 4.1, it is evident that increase in concrete grade increases the load carrying capacity. But the variation is insignificant or less. As well as, increasing the thickness generally reduces the maximum load.

4.2 Load Vs. Thickness Plots for Various Widths

The load vs thickness plots for 75 mm width and 100 mm width are depicted in Figure 4.2 (a) and Figure 4.2 (b).
4.3 Load vs. $f_{ck}$ Plots for Various Thickness

The load carrying capacity improves as compressive strength increases. Also, when compared to other classes, the FRP thickness 2 mm with concrete grade M35 supports the largest load.

![Load vs $f_{ck}$ plots for various thicknesses](image)

Figure 4.3 Load vs $f_{ck}$ plots for various thicknesses

4.4 Statistical Analysis

The models are proposed based on the existing relationships in literature [4]. The multi variable nonlinear regression analysis and multi variable logarithmic regression analysis are carried out to find
the best fit of the proposed model. here Degrees of freedom (df) The number of independent variables in our regression model is denoted by regression df. The parametric research is carried out for various concrete grades M25, M30, and M35. In this example, multiple FRP thicknesses of 2 mm, 3 mm, 4 mm, 5 mm, and 6 mm are used, as well as varied widths of 75 mm and 100 mm; the regression df is 3. The total number of observations (rows) in the dataset divided by the number of variables being estimated yields the residual df. Three FRP laminates were chosen from a data set of 26. The first column of the table contains test results from a single lap pull out test setup in which FRP sheets with a width of 100mm were externally attached to a concrete block using a wet lay-up bonding technique, as performed by Ueda T, Dai JG 2004 [4]. To witness a complete peeling off process, a bond length of 330mm was used. Displacement control loading was used throughout testing. LVDT Transducers were used to measure slip between the concrete surface and the FRP sheet.

4.5 Multi Variable Nonlinear Regression

An examination of multi-variable nonlinear regression is done. A regression curve relating the maximum force was fitted into the data in this research. The following mathematical relationship between the above-mentioned quantities was discovered as a consequence of this study. \( P_{\text{max}} \) is the maximum withdrawal force for a given anchoring (bond) length, the greatest load bearing capability following bond breakdown (Slip). It changes according to the thickness, breadth, and slope of the concrete. Using the Ansys outcomes dataset, the mathematical expression was generated based on ANOVA multi variable nonlinear & logarithmic regression.

\[
P_{\text{max}} = 0.804 \cdot f_{\text{ck}}^{0.082} \cdot b_{f}^{1.045} \cdot t_{f}^{-0.137}
\]

Multi variable nonlinear Regression analysis results are illustrated in Table 1. The Residual squared is calculated using an ANOVA analysis, as illustrated in Table 2.

| Parameter | Estimate | Standard. Error | Confidence Interval (95%) |
|-----------|----------|----------------|--------------------------|
| A         | 0.804    | 0.267          | 0.255 - 1.353            |
| B         | 0.082    | 0.059          | -0.039 - 0.203           |
| C         | 1.045    | 0.059          | 0.925 - 1.166            |
| D         | -0.137   | 0.02           | -0.179 - 0.095           |

| Source         | Sum of Squares | df  | Mean Squares |
|----------------|----------------|-----|--------------|
| Regression     | 278504         | 4   | 69626.100    |
| Residual       | 471.871        | 26  | 18.149       |
| Uncorrected Total | 278976        | 30  |              |
| Corrected Total | 7346.63       | 29  |              |

The R\(^2\) value is 0.9363, which is the best fit for the proposed model.
4.6 Multi Variable Logarithmic Regression

An examination of multi-variable nonlinear regression is carried out. A regression curve relating the maximum force was fitted into the data in this research. The following mathematical relationship between the above-mentioned quantities was discovered as a consequence of this study.

\[ P_{\text{max}} = 29.335 \log(b_f) + 30.306 \log(t_f) - 30.645 \log(f_{ck}) \]

Regression analysis and ANOVA analysis results are listed in Table 3 and Table 4.

Table 3. Parameter Estimates - Multi Variable Logarithmic Regression.

| Parameter | Estimate | Standard. Error | 95% Confidence Lower Bound | Upper Bound |
|-----------|----------|-----------------|---------------------------|-------------|
| A         | 29.335   | 5.946           | 17.136                    | 41.535      |
| B         | 30.306   | 3.507           | 23.11                     | 37.502      |
| C         | -30.645  | 7.792           | -46.632                   | -14.659     |

Table 4. ANOVA - Multi Variable Logarithmic Regression.

| Source            | Sum of Squares | df | Mean Squares |
|-------------------|----------------|----|--------------|
| Regression        | 139114         | 3  | 46371.5      |
| Residual          | 1510.55        | 27 | 55.95        |
| Uncorrected Total | 140625         | 30 |              |
| Corrected Total   | 7408.93        | 29 |              |

The R\(^2\) value is 0.796, which is the best fit for the proposed model.

The above two models were compared with the experimental outcomes of Uda & Dai [4]. Table 5 shows the validation of results for the CFRP specimen. The nonlinear regression analysis showed variation of loads between 0.8 % to 1.98 % and logarithmic regression analysis showed variation of loads between 0.7 % to 1.5 %. From the above comparison, Power model have predicted the maximum load reasonably than the logarithmic model. Parametric results are shown in Table 6.

Table 5. Validation of Results.

| Specimen code | P\(_{\text{Ana}}\) (kN) | P\(_{\text{cal}}\) | P\(_{\text{Ana}}/P_{\text{cal}}\) | P\(_{\text{cal}}\) | P\(_{\text{Ana}}/P_{\text{cal}}\) |
|---------------|-------------------------|-----------------|-----------------------------|-----------------|-----------------------------|
| CR1L1         | 22.90                   | 28.31           | 0.80                        | 32.38           | 0.71                        |
| CR1L1         | 26.50                   | 29.79           | 0.89                        | 29.33           | 0.90                        |
| CR1L1         | 22.30                   | 28.18           | 0.80                        | 30.66           | 0.73                        |
| CONCRETE | WIDTH | THICK | Load (kN) |
|----------|-------|-------|-----------|
| M25      | 75    | 2     | 91.9848   |
| M25      | 75    | 3     | 80.58443  |
| M25      | 75    | 4     | 74.1015   |
| M25      | 75    | 5     | 80.83988  |
| M25      | 75    | 6     | 75.1536   |
| M25      | 100   | 2     | 118.7722  |
| M25      | 100   | 3     | 101.2215  |
| M25      | 100   | 4     | 111.8904  |
| M25      | 100   | 5     | 103.804   |
| M25      | 100   | 6     | 100.2888  |
| M30      | 75    | 2     | 91.13265  |
| M30      | 75    | 3     | 81.80033  |
| M30      | 75    | 4     | 74.6904   |
| M30      | 75    | 5     | 82.61888  |
| M30      | 75    | 6     | 75.64635  |
| M30      | 100   | 2     | 120.7818  |
| M30      | 100   | 3     | 112.308   |
| M30      | 100   | 4     | 103.3404  |
| M30      | 100   | 5     | 109.9625  |
| M30      | 100   | 6     | 100.7856  |
| M35      | 75    | 2     | 90.3333   |
| M35      | 75    | 3     | 78.83145  |
| M35      | 75    | 4     | 76.1781   |
| M35      | 75    | 5     | 83.0115   |
| M35      | 75    | 6     | 77.3856   |
| M35      | 100   | 2     | 122.29    |
| M35      | 100   | 3     | 108.6654  |
| M35      | 100   | 4     | 114.4976  |
| M35      | 100   | 5     | 110.6015  |
| M35      | 100   | 6     | 101.124   |

**Table 6.** Parametric Results.
5. CONCLUSIONS

5.1 Conclusions

- When the thickness of FRP varies, the maximum load carrying capacity decreases in all specimens until the thickness reaches 4 mm, at which point the load remains constant.
- The load carrying capability improves as the width increases. The load carrying capability of 100 mm width FRP is 39% higher than 75 mm width FRP for the same thickness of 4 mm.
- The grade of concrete has the least impact on increasing load carrying capacity of the three parameters. In general, the LCC is proportionate to the concrete grade, yielding the same outcome as before.
- From the nonlinear regression analysis, the Corrected sum of squares of the mathematical expression \( P_{\text{max}} = 0.804f_{\text{ck}}^{0.082}b^{1.045}t_{f}^{-0.137} \) is found to be 0.936, and hence it is the best fit for the considered parameters.
- The Rectified sum of squares of the mathematical equation is derived through logarithmic regression analysis is \( P_{\text{max}} = 29.335 \log(b)+ 30.306 \log(t_{f})+ -30.645 \log(f_{\text{ck}}) \) is found to be 0.796.
- The nonlinear regression analysis and logarithmic regression analysis are validated. The nonlinear analysis and logarithmic analysis showed variation of results between 0.8 % to 1.98 % and 0.7 % and 1.5 % respectively with that of the published work.
- From the above comparison, Power model have predicted the maximum load reasonably than the logarithmic model.

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