Numerical Analysis of RC Slab with opening strengthened with CFRP Laminates

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Abstract. Openings in reinforced concrete (RC) structural floor slabs are sometimes necessary created as a result of variations in architectural function or structural upgrades, amongst other reasons. Architecture reasons for making openings may include change-of-usage, or improvement of air circulation, and lighting. Openings in structural slabs may reduce their strength and stiffness or may transform the original failure mode of the slab to different failure patterns. In the past decades, externally bonded fiber reinforced polymer (FRP) sheets have become popular to strengthen or rehabilitate RC structures for traditional force actions such as flexural, shear, or torsion. Strengthening and rehabilitation of beams, floor slabs, and columns may be necessary for seismic or non-seismic applications. This paper reports the results of numerical study to evaluate the effectiveness of strengthening of two-way RC floor slabs with openings, using carbon FRP (CFRP) composite sheets. Ten numerical models were created, consisting of a reference model with the slab having opening but not strengthened, and nine models with an opening and CFRP laminates applied to the tension side of the slab. The strengthening laminates varied in thickness and width. The results indicate that CFRP laminates can significantly enhance both the flexural capacity and overall stiffness of the floor slab containing openings. Increasing the thickness of CFRP laminates decreases the deflection of midspan. Load-deflection curves were generated, and ultimate load, and ductility index were discussed.

1. Introduction
Structural openings in various sizes and shapes may need to be created in reinforced concrete (RC) slabs, which may reduce their ductility, stiffness, and load-carrying capacity, [1]. Experimental studies demonstrated the effectiveness of several concrete slab strengthening techniques and various layouts of carbon fiber reinforced polymer (CFRP) laminates. For example, increasing the number of CFRP layers increases the load-carrying capacity of reinforced concrete slabs [2]. Zhao & Tan [3] demonstrated that externally bonded CFRP laminates enhance the load-carrying capacity and stiffness of one-way RC slabs with openings, provided the laminates are anchored properly. Muhammed [4] tested eight self-consolidating concrete slabs with small and large openings and demonstrated that CFRP sheets increased the load-carrying capacity of the slab by 46.67 and 55.7% for small and large openings, respectively, and reduced structural cracks at the corners of openings. Khajehdehia and Panahshahib [5] evaluated the effect of openings on structural response of concrete slabs and noted that failure to account adequately for effects of openings can lead to erroneous results and possibly unsafe design. Siliem et al. [6] evaluated the effectiveness of different layouts of CFRP laminates used to strengthen slabs with openings located in the positive moment zone. The CFRP layouts examined by the authors included
externally bonded CFRP laminates, externally bonded CFRP laminates with CFRP anchors, and near surface mounted (NSM) CFRP strips. The authors observed that slab strengthening with NSM CFRP strips produced the highest load-carrying capacity compared to strengthening using externally bonded CFRP laminates. On the other hand, externally bonded CFRP laminates produced slightly higher flexural strength while significantly enhancing the stiffness, compared to the other two methods [6].

Anjaly and Preetha [7] studied the structural response of waffle slabs with and without openings and observed the impact of openings sizes and locations on load-carrying capacity. The authors concluded that limited additional design considerations are needed if the size of an opening located at the intersection of two column strips does not exceed 10% of the column strip width. However, if the opening is located at the intersection of a column strip and a middle strip, the opening size is limited to 20% of the column strip width. Abdullah [8] simulated response of two-way concrete slabs using 3D brick elements to represent concrete, truss elements to model reinforcing steel bars, and 2D shell elements to model the FRP strengthening laminates. Eskandarinadaf and Esfahani [9] conducted full-scale tests on six two-way RC slabs with opening near mid-pan, and one slab without openings tested as reference, by applying monotonic and cyclic loads until failure. The set of six slabs with openings consisted of five strengthened slabs and one un-strengthened (control) slab. This research aims to numerically investigate the viability of using CFRP to upgrade the flexural response of RC slabs with large opening at middle strip.

2. Debonding failure of FRP-strengthened RC structural members
Debonding failure occurs when the FRP laminate separates from the structural member due to reasons such as initiation or propagation of a major crack in the vicinity of the interface region. Debonding failure results in significant decrease in member capacity. Debonding may occur within a constituent element, or at the interfaces of the bonded materials, following the path with the least amount of energy.

Under flexural loading, failure of FRP strengthened structural elements can occur with full composite action between FRP laminate and the structural element, or after loss of full composite action [8]. When full composite action exists between FRP and structural element, failure may occur due to: 1) yielding of reinforcing steel followed by concrete crushing, 2) steel yielding followed by rupture of FRP laminate, 3) concrete crushing following steel yielding, or 4) shear failure [8].

3. Modelling slippage between CFRP and RC Slab
The bond stress-slip models suggested by Lu et al. [10] are recognized widely and are used in the finite element analysis implemented in this article. The response at the CFRP-RC slab interface is represented by a relationship between the local shear stress, τ, and relative displacement, s. The interfacial fracture energy per unit bond area is the area under the τ-s curve, which is the energy required for complete debonding of the laminate. The model developed by Lu et al. is shown in figure 1 and described by Equations (1) to (11). The bond stress, τ (MPa), at the CFRP-RC slab interface is given by Equation (1).

\[ \tau = \tau_{max} \frac{s}{s_0} \]  

(1)

Where \( \tau_{max} \) is the maximum bond stress and \( s_0 \) the corresponding bond slip, for the ascending part, i.e., \( S \leq S_0 \), as shown in figure 1.

The maximum bond stress, \( \tau_{max} \), is a function of concrete tensile strength, \( f_t \), and can be determined using Equation (2).

\[ \tau_{max} = 1.5 \beta_w f_t \]  

(2)
Figure 1. Bond-slip model for beams and two-way slabs strengthened with conventional technique [10].

The value of the bond slip, $S_0$ (mm), is a function of the concrete tensile strength, $f_t$, according to Equation (3).

$$S_0 = 0.0195 \beta_w f_t + S_e$$  \hspace{1cm} (3)

The value of $S_e$ is given Equation (4).

$$S_e = \tau_{max}/K_0$$  \hspace{1cm} (4)

The value of $K_0$ is given by Equation (5).

$$K_0 = K_aK_c/(K_a + K_c)$$  \hspace{1cm} (5)

Where $K_a$ is given by Equation (6).

$$K_a = G_a/t_a$$  \hspace{1cm} (6)

And $K_c$ is given by Equation (7)

$$K_c = G_c/t_c$$  \hspace{1cm} (7)

Where, $G_c$ is the shear modulus of concrete and the parameter $t_c$ is the thickness of a layer of concrete that would deform along the interfacial slip surface [10]. Precise evaluation and definition of the parameter $t_c$ needs further research. However, the effect of higher accuracy of the parameter $t_c$ on the bond–slip curve is generally too small in practical applications. In this context, the simplified model described by Equation (8) to (11) does not include the parameter $t_c$ but still leads to a bond–slip curve which is highly similar to results obtained from higher accuracy models developed at the meso-scale to account for $t_c$ being as small as 5 mm [10]. The FRP width factor, $\beta_w$, given by Equation (8) and depends on the width of the FRP laminate, $b_f$(mm), and the width of the concrete structural element, $b_c$(mm).

$$\beta_w = ((2.25 - b_f/b_c)/(1.25 + b_f/b_c))^{0.5}$$  \hspace{1cm} (8)

The bond stress, $\tau$ (MPa), for the descending part of the slip-bond stress model ($S > S_0$) is given by Equation (9).

$$\tau = \tau_{max}e^{[-\alpha(s/s_0-1)]}$$  \hspace{1cm} (9)

Where,

$$\alpha = \frac{1}{G_f} - \frac{2}{\tau_{max}S_0 - \frac{3}{S}}$$  \hspace{1cm} (10)
The interfacial fracture energy at the CFRP-concrete interface, \( G_f \) (N.mm/mm\(^2\)), is calculated according using Equation (11).

\[
G_f = 0.308\beta_w^2\sqrt{f_t}(K_a)
\]

The function \( f(K_a) \) is intended for future extension of the model to FRP-concrete interfaces where the adhesive layers are very soft. In most of the commonly used adhesive layers with \( K_a \geq 2.5 \text{ GPa/mm} \) and \( f(K_a)=1 \), studies have shown that the effect of the adhesive layer stiffness on \( G_f \) is very small [10]. Dai et al. [11] conducted analytical and experimental studies on concrete elements strengthened using FRP laminates with various thicknesses, FRP material types (carbon, aramid, and glass) and different adhesives (CN-100, SX-325, FR-E3P, FP-NS). The authors developed the analytical model described by Equation (12) and (13). The model depends for the most part on fracture energy, \( G_c \) and interfacial ductility index, \( B \). The investigators proposed Equation (12) to predict the maximum interfacial pull-out force, \( P_{max} \), which assumes zero end slip boundary condition [11].

\[
P_{max} = b_f\sqrt{2E_f t_f G_f}
\]

The bond slip at CFRP-concrete interface, \( s_{max} \) (mm), corresponding to the maximum bond strength \( \tau_{max} \) (MPa), can be determined from Equations (13) and (14) respectively.

\[
S_{max} = 0.693/B
\]

\[
\tau_{max} = 0.5BG_f
\]

Equation (15) is used to calculate the interfacial fracture energy, \( G_c \), which depends on the properties of concrete, adhesives, and the stiffness of FRP laminates.

\[
G_f = 0.446\left(\frac{G_a}{t_a}\right)^{-0.352}f_c^{0.236}(E_f t_f)^{0.023}
\]

Where, \( E_f \) (MPa), is the modulus of elasticity of CFRP strip and \( t_f \) (mm) is the thickness of CFRP strip. The values of another interfacial parameter \( B \) is given by Equation (16).

\[
B = 6.846(E_f t_f)^{0.108}\left(\frac{G_a}{t_a}\right)^{0.833}
\]

Where \( G_a \) (MPa) is shear modulus and \( t_a \) (mm) is the thickness of the adhesive layer.

Based on the models discussed in the previous paragraphs, this paper discusses strengthening of RC slabs using finite element models created using primarily two parameters: 1) the interfacial fracture energy \( G_f \) and, 2) the ductility index \( B \). The parameter \( G_f \) affects the ultimate load-carrying capacity at the interface of concrete and CFRP, whereas the parameter \( B \) influences the bond stress-slip relationship. The fracture energy at the concrete-CFRP interface depends on the mechanical properties of adhesives and concrete strength. However, when the adhesive shear stiffness is decreased, the maximum interfacial bond stress decreases, while the interfacial fracture energy and the interfacial ductility both improve. This in turns improves the interfacial load transfer capacity [11]. Mohamed and Khattab [12] discussed the process of estimating the bond length based on North American concrete design codes, therefore, the topic will not be discussed in this article.

4. Model description

In this study, a 3D finite model is developed to simulate the behaviour of RC slab with large opening and strengthened by CFRP surrounding the opening. Ten slabs were modelled including one with opening used as control slab, and nine slabs strengthened with various widths and thicknesses of CFRP surrounding the opening as summarized in Table 1. Control slab, S0, has been design according to ACI
318 [13], figure 2 (a) shows plan view and dimension of the control slab S0, and figure 2 (b) shows location and dimension of CFRP laminates. Control slab is 300 mm thick and supported by 600 x 600 mm concrete columns. Slab is reinforced with top and bottom mesh of 12 mm diameter bars spaced at 200 mm. Additional 16 mm top reinforcement bars are added over the columns at spacing of 200 mm. The details of reinforcing steel patterns of the control slab are shown in figure 3. Additional 16 mm diameter bottom reinforcement bars spaced at 200 mm are added in both span 1-2 A&B and 1-2 B&C. Properties of concrete and reinforcing steel are shown in Tables 2 and 3, respectively.

**Table 1. Designation and description of the specimens**

| Designation | CFRP Width (mm) | CFRP Thickness (mm) |
|-------------|-----------------|---------------------|
| Control (S0)| 300             | 1.0                 |
| S300-1      | 450             | 1.0                 |
| S300-2      | 450             | 2.0                 |
| S300-3      | 450             | 3.0                 |
| S450-1      | 600             | 1.0                 |
| S450-2      | 600             | 2.0                 |
| S450-3      | 600             | 3.0                 |
| S600-1      | 600             | 1.0                 |
| S600-2      | 600             | 2.0                 |
| S600-3      | 600             | 3.0                 |

**Table 2. Material properties of Concrete**

| Property                              | Value |
|---------------------------------------|-------|
| Modulus of elasticity, E (GPa)        | 33    |
| Poisson’s ratio                       | 0.15  |
| Characteristic compressive strength, f'c (MPa) | 33 |
| Characteristic tensile strength(f_t), MPa | 2.2 |

**Table 3. Properties of reinforcing steel bars**

| Property                        | Value |
|---------------------------------|-------|
| Nominal Diameter (mm)           | 12 & 16 |
| Elastic modulus E (GPa)         | 200   |
| Poisson’s ratio                 | 0.3   |
| Yield Stress (N/mm²)            | 450   |
| Tensile Strength (N/mm²)        | 610   |
| Ultimate Strain (%)             | 16    |

**Figure 2. (a) Plan and dimension of control slab S0; (b) location and dimension of CFRP**
Figure 3. Steel reinforcement of control slab S0

CFRP strips were glued to the tension face of the concrete slab surface around the opening. CFRP strip widths are 300, 450, and 600, and nominal thicknesses are 1, 2, and 3 mm. In each slab model with opening, the quantity of CFRP around the opening was calculated such that the capacity of section with and without the opening is the same. The mechanical properties of CFRP sheets are shown in Table 4.

Daud et al. [14] studied the post-fatigue interfacial bond stress-slip relationship and have shown that as the CFRP plate stiffness increases, both the ultimate bond strength, \( t_s \), and fracture energy, \( G_s \), decrease, for concrete compressive strength in the range of 22.6 MPa to 52.8 MPa. Typical properties of epoxy bonding agent (epoxy resin) are shown in Table 5 [14].

### Table 4. Material properties of CFRP

| Property                                         | Value   |
|-------------------------------------------------|---------|
| Tensile strength of fibers (MPa)                | 4300    |
| Elastic modulus of fibers (MPa)                 | 238,000 |
| Strain at break of fibers (%)                   | 1.8     |
| Major in-plane Passion's ratio, \( \nu_{12} \)  | 0.3     |
| Major in-plane Passion's ratio, \( \nu_{23} \)  | 0.25    |
| Major in-plane Passion's ratio, \( \nu_{13} \)  | 0.25    |
| Tensile strength (MPa)                          | 30      |
| Tensile elastic modulus in flexure (MPa)        | 3800    |

### Table 5. Material properties of epoxy resin layer [14]

| Property                                         | Value   |
|-------------------------------------------------|---------|
| Interfacial bond strength, \( t_s \) (MPa)       | 6.4-2.51 |
| Interfacial bond stiffness, \( K_s \) MPa/mm     | 300     |
| Interfacial fracture energy \( (G_s) \), MPa/mm  | 0.78-0.491 |

5. Finite element model
The general-purpose finite element software ABAQUS [15] was used to develop the simulation models of the strengthened and un-strengthened RC slabs. Concrete was modelled using a 3D eight-node linear brick element with reduced integration and hourglass control. The embedded reinforcing steel bars were modelled using linear two-node truss elements with three degrees of freedom at each node. The CFRP composite plate was modelled using linear 3D three-node triangular facet thin shell element. A dense mesh of this element type may be required in order to obtain accurate results during the analysis. STRI3 element offers much of the same capabilities of the conventional shell element S4R5, but STRI3 cannot be used with thick shell problems. ABAQUS cohesive surface was used to model the cohesive connection at the interface of the CFRP strips and concrete slab, the cohesive surface technique was used. Static pressure was applied to the top surface of the loading plate over a concrete contact surface.
that 20 mm wide. A full Newton nonlinear analysis technique was conducted for each of the models. Figure 4 shows the finite element mesh of the RC slabs strengthened with CFRP.

Figure 4. FE model of RC slabs strengthened with CFRP.

6. Discussion and Results

In this section, the results of the finite element are reported including load-deflection relations, load-strain relation, ultimate load, and ductility index.

6.1. Load-deflection relationships

The load-deflection response of the control slab and CFRP strengthen RC slabs are shown in figure 5. Control slab, S0, exhibited a linear deflection response until initiation of flexural cracks, indicated by the initiation of nonlinearity of the load-deflection curve. In the post-cracking stage, the deflection increased at a higher rate until yielding of tensile steel took place. Following yielding of steel, plastic deformation continued to increase until the specimen reached its peak load at an average deflection value of approximately 51.2 mm. Slab with opening strengthened using CFRP strips that are 600 mm wide and 3 mm thick (S600-3) showed the highest stiffness compared to all slabs including the control model. Model S300-1 in which slab opening was strengthening with smallest CFRP strip width (300 mm) and smallest strip thickness (1 mm) showed higher stiffness compared to control slab S0. It is worthy to note that the same stiffness was obtained for slabs S450-2 and S600-1.

6.2. Ultimate load carrying capacities

The ultimate load-carrying capacity of the slab represents the load at which the concrete is crushed in compression, or at which the FRP debonded or ruptured. Ultimate load-carrying capacity and percentage increase in ultimate load compared to control slab s0 are shown in Table 6 and figure 6, respectively. Strengthening slab opening with CFRP having a width of 600 mm and thickness 3mm (S600-3) produced the highest load-carrying capacity compared to all other strengthening strips as well as the control slab. Strengthening slab with CFRP strips having a thickness of 1 mm significantly improved the load-carrying capacity compared to the control slab. Similarly, strengthening slab opening with CFRP strips having a thickness of 3 mm improved the load capacity significantly compared to the control slab.

| Specimen  | Ultimate load capacity (kN) |
|-----------|-----------------------------|
| Control (S0) | 107.5          |
| S300-1     | 109.23         |
| S300-2     | 111.34         |
| S300-3     | 115.00         |
| S450-1     | 112.40         |
| S450-2     | 121.23         |
| S450-3     | 124.97         |
| S600-1     | 115.48         |
| S600-2     | 128.73         |
| S600-3     | 135.84         |

Table 6. Ultimate load capacity for CFRP strengthening RC slab.
Figure 5. Load - Deflection Curve for RC slabs strengthened with CFRP.

Figure 6. % increase in Ultimate Load capacity for RC slabs strengthened with CFRP.

6.3. Ductility index

Ductility is an important performance indicator of RC structures, in part as it offers an early indication of impending collapse. Moment redistribution in continuous RC structures is largely dependent on ductility of the structural element and system [16]. When RC structures are strengthened with FRP laminates, ductility could be compromised in exchange for improved load-carrying capacity. The ductility index, \( \mu \), given by Equation (17) is defined as the ratio of the mid-span deflection, \( \Delta_p \), at peak load to the mid-span deflection at first yielding, \( \Delta_{y1} \).

\[
\mu = \frac{\Delta_p}{\Delta_{y1}}
\] (17)
Table 7 gives the ductility indices for the control slab and for the strengthened slab systems examined in this study. The deflection values used to calculate the ductility index were taken from figure 5.

Table 7. Ductility indices for CFRP strengthening RC slab.

| Specimen      | $\Delta_y$ (mm) | $\Delta_p$ (mm) | $\mu$ |
|---------------|-----------------|-----------------|-------|
| Control (S0)  | 357.47          | 51.16           | 6.99  |
| S300-1        | 146.25          | 64.48           | 2.27  |
| S300-2        | 145.74          | 52.76           | 2.76  |
| S300-3        | 171.47          | 56.05           | 3.06  |
| S450-1        | 99.11           | 37.97           | 2.61  |
| S450-2        | 179.08          | 53.25           | 3.36  |
| S450-3        | 196.78          | 54.31           | 3.62  |
| S600-1        | 121.09          | 42.21           | 2.87  |
| S600-2        | 217.12          | 53.34           | 4.07  |
| S600-3        | 260.25          | 55.80           | 4.66  |

Figure 7, shows that maximum ductility reduction occurs when slab opening is strengthening with CFRP strips having a thickness of 1 mm, while the minimum ductility reduction occurs in slabs strengthened with CFRP having a thickness equal of 3 mm. The ductility index of Strengthened slab tended to decrease as the amount of CFRP is increased.

Figure 7. % Decrease in Ductility for RC slabs strengthened with CFRP.

7. Conclusions

Finite element analysis was conducted to examine the effectiveness of strengthening reinforced concrete slab that contain large opening. The models included one control slab with large opening and nine slabs with openings but strengthened with CFRP sheets around the opening. The thickness of CFRP sheets are 1, 2, and 3 mm. For each CFRP thickness, three models were created for three CFRP sheet widths of 300, 450, and 600. The following conclusions were noted from analysis results:
1. The use of CFRP laminates to strengthen reinforced concrete slab with large opening reduces deflections and increases load carrying capacity. The load-carrying capacity increases with increase in the amount of CFRP.
2. The ductility index of concrete slab strengthened with CFRP laminates decreases as the amount of CFRP increases. All the CFRP strengthened slabs exhibited brittle response.
3. Despite the brittle behavior of the strengthened RC slab with opening, CFRP strengthening has the ability to recover the strength and stiffness of the control reinforced concrete slab (without CFRP strengthening) especially in the elastic region.
4. Increasing the thickness or width of CFRP sheets increases the load-carrying capacity of the strengthened slab compared to the control slab.
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