Modeling of Punching Shear Strengthening of Reinforced Concrete Slabs with CFRP Sheets

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Abstract: This paper presents analytical investigations for evaluating the punching shear strengthening of RC slabs using Carbon Fiber Reinforcement Polymer (CFRP) sheets. In terms of load capacity and maximum displacement, Model code 2010 provided new equations to estimate the rotation of slabs. The equations are based on critical shear crack theory. In this study the results from FEM verified via experimental data were compared to the results from the equations. A total of four reinforced concrete slabs with and without CFRP laminates were modeled via finite elements (FE) method adopted by ANSYS 14. The results obtained from the FE analysis are compared with the experimental data and Model code Level II equations for slabs with different strengthening conditions. The comparisons are made for load-deflection curves at slab centre and punching shear strength. The results from finite element analysis were calculated at the same locations as the experimental investigation. The accuracy of the finite element models, assessed by comparison with the experimental results, appeared to be in good agreement. The developed methods are used for further interpolation of the data and more detailed investigation of the effects of different factors of influence.

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1. Introduction

Punching shear behaviour of a concrete slab is provided by four different elements. They include the contribution from un-cracked concrete above the neutral axis, aggregate interlock, dowel action and residual tensile stresses across the inclined cracks. The bottom steel reinforcement is one of the design parameters known to influence the punching shear capacity of concrete slabs (Ebead et al., 2002). Increasing the reinforcement ratio of steel results in cracks with lower widths and depths and slab becomes more ductile. Lower crack width increases the contribution of aggregate interlock as well as the contribution of residual tensile stresses to the punching capacity. On the other hand, shallow depth of the cracks increases the contribution of un-cracked concrete to punching capacity. Thus, increasing the bottom steel reinforcement ratio increases the overall punching capacity. It is expected that adding FRP reinforcement to the tension face of concrete slabs will increase the punching capacity as if increasing the bottom steel reinforcement ratio.

Some typical solutions to strengthen against punching shear are shown in Figure 1(a) through (e). They comprise enlargements of the support region by widening of the columns (refer to Figure 1(a) through (b)), strengthening of the flexural reinforcement by casting a concrete topping or gluing reinforcement (refer to Figures 1(c) and (d)), or installing shear reinforcement (refer to Figure 1(e)). Those possibilities can, however, be impractical in many situations, as they require access to the upper face of the slab (refer to Figure 1(c) and (d)), which is usually covered by soil or floor, or enlarging the support region (refer to Figure 1(a) and (b)), which is not always possible due to architectural and space requirements. The system (refer to Figure 1(f)) consists of a series of inclined shear reinforcing bars, bonded within an existing slab and installed by drilling holes only from the soffit of the slab. The performance of the system is confirmed by the results of an experimental test program, showing the significant increase both on the punching shear resistance (ensuring sufficient strength) and on the deformation capacity of the slabs, allowing redistribution of internal forces to avoid progressive collapse (Fernandez et al., 2010).

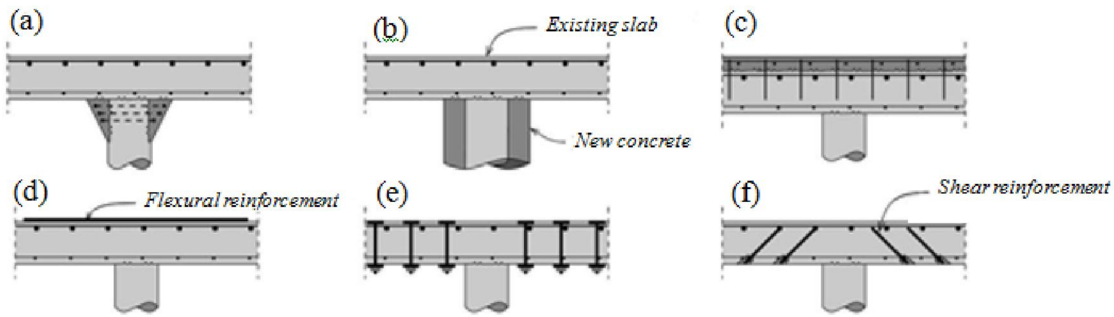


Figure 1: Strengthening of RC slabs against punching shear (Fernandez et al., 2010)

Several researchers have investigated different methods to strengthen interior slab-column connections against punching including use of steel plates and bolts (Marzouk and Jiang, 2007; Zhang, et al., 2001; Ebead and Marzouk, 2002), transverse prestressed reinforcement (Ghali et al., 1974) and more recently the use of fibre reinforced polymer (FRP) composites externally bonded to the slab tension face (Tan et al., 1996; Harajli and Soudki, 2003; Sharaf, et al., 2006). Despite of additional strength to the slab, these strengthening methods are elaborate, difficult to install, expensive and aesthetically not pleasing. Slab strengthening by FRPs is simple, does not change the slab appearance and does not require excessive labour. However, there is limited literature on the effectiveness of externally bonded FRP strips in increasing the two-way shear capacity of interior slab-column connections.

EXPERIMENTAL RESULTS USED FOR VERIFICATION

For verification of FE models the experimental punching shear tests of four reinforced concrete slabs by M.R Esfahani ,M.R. Kianoush, A.R Moradi (2009) is described. Two among the four slabs were control ones and the other two were strengthened with externally bonded CFRP sheets.

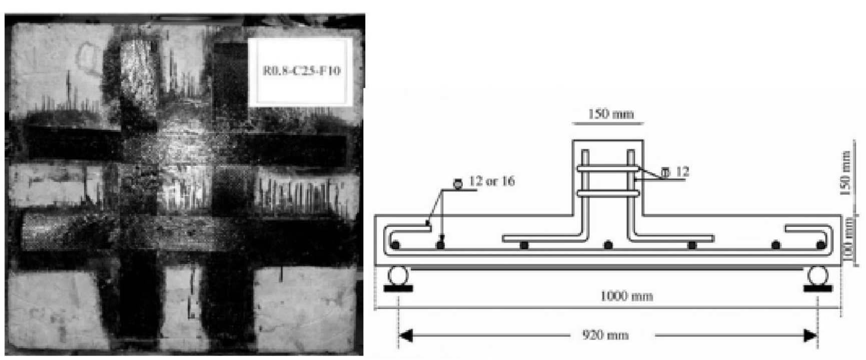


Figure 2: Details of the RC slab and CFRP sheet positioning on the bottom side of the slabs (M.R Esfahani, M.R. Kianoush, A.R Moradi (2009)

A total of four slab specimens with the dimensions of 1000×1000×100 mm were subject of interest in aspect of verification. Concrete mixture based on the design compressive strengths of 25 MPa was used for the slab specimens. Two different sizes of reinforcing bars were used in specimens. R08-C25-F0 and R1.6-C25-F0 are the control samples with internal steel reinforcement ratio of 0.8 % and 1.6% respectively. R0.8-C25-F15 and R16%-C25-F30 are the CFRP-strengthened samples with CFRP laminate's width of 150 mm and 300 mm respectively.

The clear concrete cover for reinforcing bars was 15 mm for all specimens. The CFRP sheets used for strengthening of slabs have the thickness of 1.2 mm, Modulus of Elasticity 237 GPa and the tensile strength of 3800 MPa.

The samples were supported on four simply supported edges, each of them free to lift in vertical direction. At the centre of each slab column stud with 150×150 mm area is manufactured, the details are given in figure 2.

Hydraulic jacks were used for providing the loading. The linear variable displacement transducers (LVDT) were used for measuring the deflection in the centres of slabs. During the stage at which the loads were being applied, electronic pressure transducer was employed to measure the magnitude of the loads.

The data from above mentioned experimental research has been used for verification and comparison with two different analytical approaches – Model Code 2010 numerical calculations and FEM using ANSYS software.

MODEL CODE 2010

Model Code 2010 provided new equations to estimate the rotation of slabs. These equations are based on critical shear crack theory (CSCT) initially developed by Muttoni (Muttoni, 1985). In the model code the following equation (level II equation) based on his research has been adopted:

(1)

$$\Psi = 1.5 * \frac{r_s}{d} * \left[\frac{f_y}{E_s}\right] * \left[\frac{V}{V_{flex}}\right]^{1.5}$$

Where r_s is radius of circular slab element, d is the distance from extreme compression fibre to the centre of the longitudinal tensile strength, f_y is yield strength of steel reinforcement, E_s is the modulus of elasticity of reinforcement, V is shear force and V_{flex} is shear force associated with flexural capacity of the slab.

The load-displacement curves obtained from both experimental investigation and finite element modelling can be transferred to punching shear strength- rotation curves by taking into account the following steps:

(2)

$$\Psi = \frac{\Delta}{[(L-L0)*0.5]}$$

Where Δ is the displacement at centre of slabs, L is full length of slab and L_0 is the column width. The rotation is multiplied by the factor d/ (d_{g0} + d_g) to eliminate the effects of slab thickness and size of aggregates. Where d_g is the maximum aggregate size and d_{g0} is the reference size equal to 16 mm.

FINITE ELEMENT MODELLING

The slab model was created in ANSYS 14. Material and section properties as detailed above were defined in the software. Simply support condition is assigned at four edges of slab and this assumption is to be maintained in all models. For the comparison purposes six samples are constructed for predicting the load-displacement relationship. Fig 3 illustrates the position of the column by red color as loaded area.

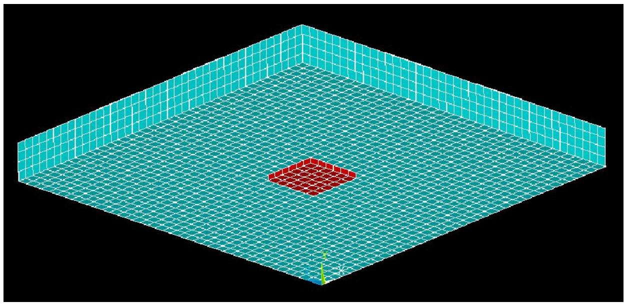


Figure 3: Bottom side of slab where the load is applied

1.1 *Concrete*

An eight-node solid element, Solid65, was used to model the concrete. The solid element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The following properties are entered in ANSYS for modelling of the concrete:

Elastic Modulus: 31 GPa

Ultimate uni-axial compressive strength: 25 MPa

Poisson ratio: 0.2

1.2 *Steel Reinforcement*

Internal steel reinforcement is smeared across the element and is not directly represented in the actual model. It was defined based on the stress-strain results of the uni-axial tensile tests given. The behavior was defined as a bilinear curve (linear elastic with strain hardening). The elastic part of the behavior was defined by the longitudinal elastic modulus and Poison's ratio of 0.3, while the plastic part was defined by true stress and true plastic strain, a linear descending branch was then specified when the strain exceeded the limiting strain of the ultimate tensile strength.

Elastic modulus: 210 GPa

Ultimate uni-axial compressive strength: 493 MPa

Poisson's ratio: 0.3

1.3 *FRP Sheets*

FRP composites are materials that consist of two constituents. The constituents are combined at a macroscopic level and are not soluble in each other. One constituent is the reinforcement fibre, which is embedded in the second constituent: a continuous polymer, called matrix. The FRP composites are anisotropic materials. Figure 4 shows a schematic representation of FRP composites.

A layered solid element, Solid185, was used to model the FRP composites. The element allows for up to 100 different material layers with different orientations and orthotropic material properties in each layer. The element has three degrees of freedom at each node and translations in the nodal x, y, and z directions. Nodes of the FRP layered solid elements were connected to those of adjacent concrete solid elements in order to satisfy the perfect bond assumption.

The local coordinate system for the FRP element was defined. In this system the x direction represents the fibre direction whilst the y and z directions are perpendicular to the x direction. In the model in this study the thickness, elastic modulus and tensile strength of the CFRP laminates were assumed to be 1.2 mm, 237 GPA and 3800 MPa respectively to correspond to the available experimental data.

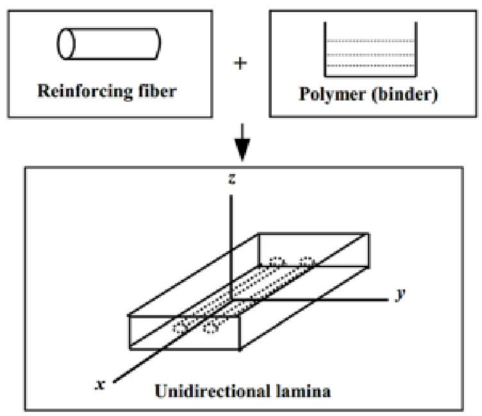
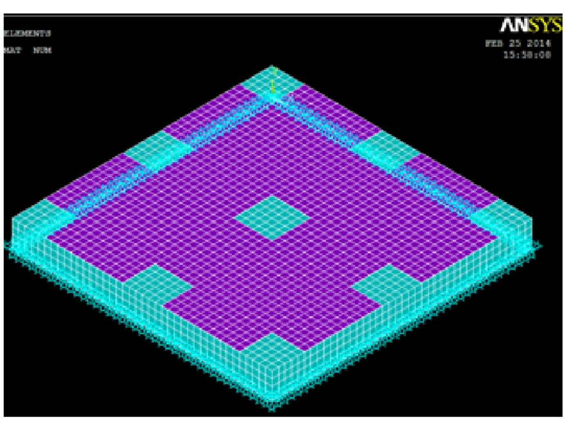


Figure 4: Schematic representation of FRP composites (Gibson 1994)



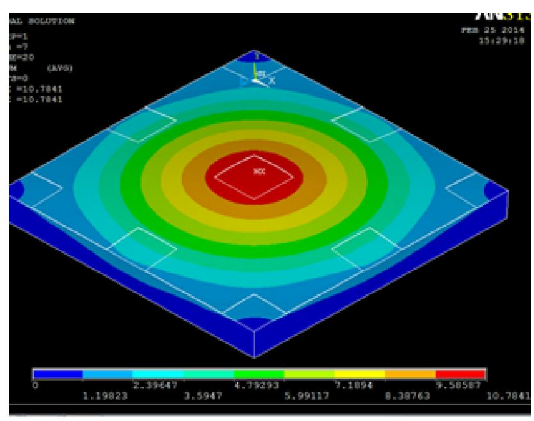


Figure 5: FE meshing for R1.6-C25-F30 sample Figure 6: Displacement counter plot for R1.6-C25-F30

The model for R1.6-C25-F30 sample is illustrated in figure 5 and 6 where the boundary conditions and corresponding contour plot for the displacement are also shown.

RESULTS AND DISCUSSION

Based on equations and using the load-displacement curves, the load- rotation curves were drawn for samples series R08 and R16 shown in figure 7 to 10.

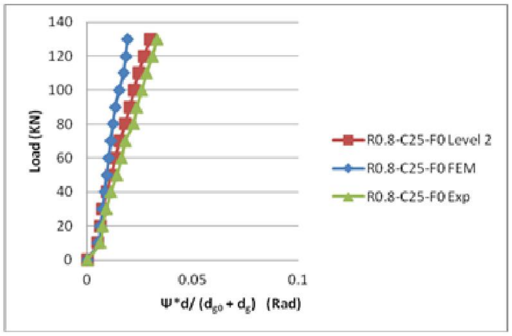


Figure 7: Load- Rotation curve for R0.8-C25-F0

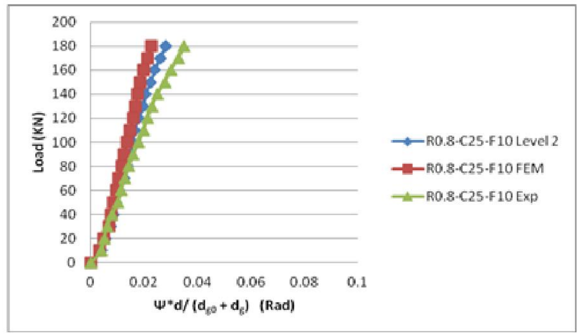


Figure 8: Load- Rotation curve for R0.8-C25-F10

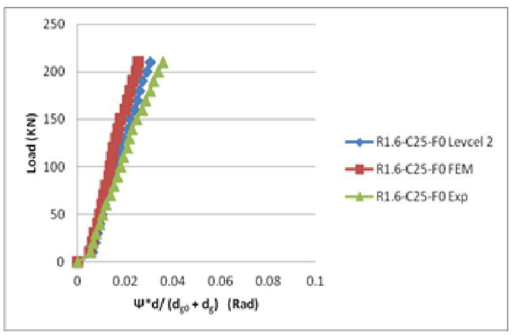


Figure 9: Load- Rotation curve for R1.6-C25-F0

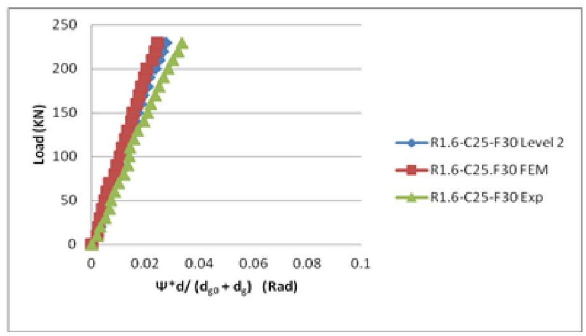


Figure 10: Load- Rotation curve for R1.6-C25-F30

Experimental results showed that the tested samples failed in punching shear apart from R0.8-C25-F0 which failed in flexural mode with wide flexural cracking after relatively large displacement. The low flexural reinforcement ratio in this case caused more flexible behaviour without sudden drop in load carrying capacity; however R0.8-C25-F10 failed in relatively brittle mode with a sudden drop in the load-displacement relationship. The change of the failure mode was due to the increase of flexural tensile capacity resulting from the CFRP sheets application.

The small differences between finite element results and experimental results might be due to microcarcks produced by shrinkage and present in the concrete, which reduce the stiffness of the actual RC slabs, while the FE models do not include micro cracks. Perfect bond between the concrete and CFRP plates is not completely corresponding to experimental data as well.

It can be concluded from figures 7 to 10 that level 2 equation has predicted the rotation of the slab specimens to an acceptable level of accuracy. It is clearly shown that the results from all methods are close to each other. The comparison between the finite element, experimental and equation results confirm the validity of the finite element modelling.

Accordingly the finite element models were further utilized for punching shear strengthening to simulate the effect of CFRP sheets with different widths in comparison with the experimental ones. They are indicated correspondingly as R0.8-C25-F15, R0.8-C25-F30, R1.6-C25-F10 and R1.6-C25-F15 samples. The results are given in figures 11 to 13.

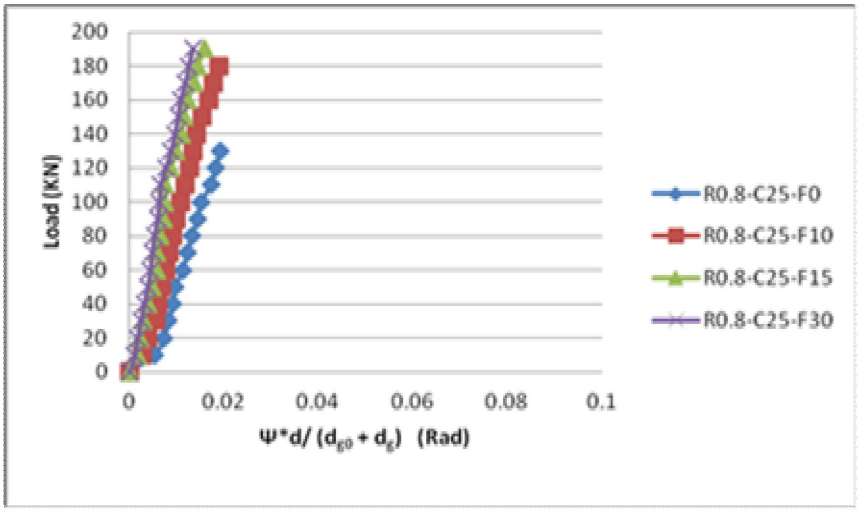


Figure 11: Load-rotation curves for R0.8 samples

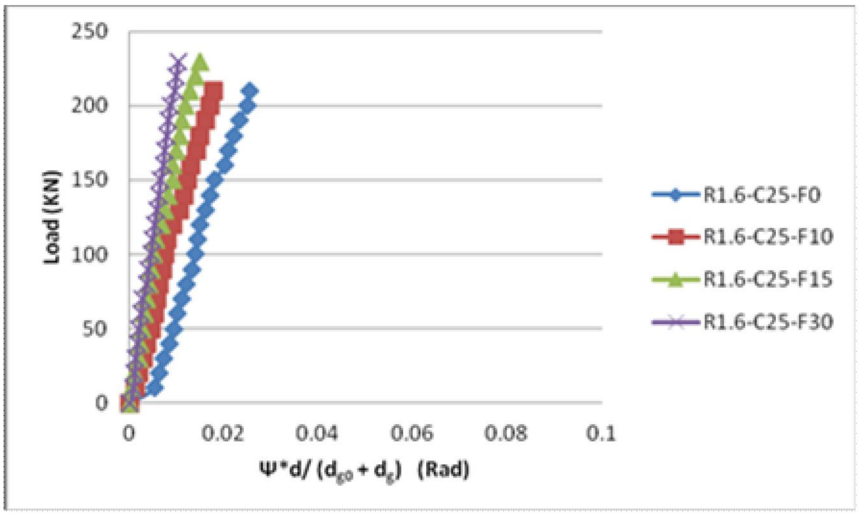


Figure 12: Load-rotation curves for R1.6 samples

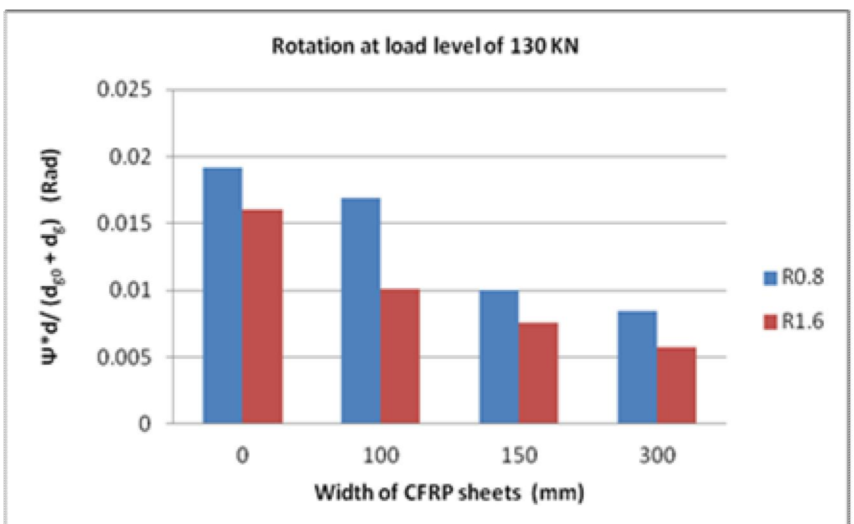


Figure 13: Rotations at level of 130 KN for R0.8 and R1.6 samples

CONCLUSIONS

The results indicate that the Level 2 model code and Finite Element modelling are both reliable for slabs with high and low reinforcement ratios strengthened by CFRP sheets. The main conclusions developed due to finite element modelling are:

- Increasing the width of the carbon sheets above 150 mm for the investigated type of samples is not producing significantly better results.
- Slabs with higher internal reinforcement ratio are having similar results for 100, 150 and 300 mm up to 130 KN of load and more significant difference above this level.
- Maximum increase of the stiffness of R0.8-C25 samples is approximately 100 % at 130 KN load and for R1.6-C25 samples is approximately 200% at 130 KN.
- At fixed level of loading of 130 KN the decrease of deformability for R1.6 is faster for lower width of CFRP sheets and slower for widths above 150 mm.

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