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Punching shear strengthening of reinforced concrete slab-column connections using externally bonded CFRP

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ABSTRACT: Punching shear is one cause of the flat slab-column connection failure. The brittle shear failure happens without warning. Along with the safety concerns, the lack of sufficient strength in the connection could lead to severe damage to the structure and the need for costly reconstruction. This paper presents the results of developed finite element models of reinforced concrete (RC) slab-column connections using ANSYS© computer software program at the Ohio Super Computer. In order to increase the punching shear capacity, carbon fiber reinforced polymer (CFRP) sheets were applied at the bottom of the slab around the perimeter of the column. The developed nonlinear finite element analysis model could accurately simulate the response of RC slab-column connection. The finite element analysis results of slab-column connection strengthened with the CFRP sheets showed an increase in the punching shear capacity and overall ductility as compared to as-built model.

1 INTRODUCTION

One cause of the flat slab-column connection failure is from punching shear. The brittle shear failure happens without warning. Along with the safety concerns, the lack of sufficient strength in the connection could cause a failure that would be devastating to the structure's integrity and in turn result in costly reconstruction.

Older slab-columns were designed deficiently and therefore are subject to potential punching shear failure. For example the earthquake loads were not originally considered in the design of the slab-column connection. Some other issues that have been previously over-looked are short rebar development lengths, thick columns with thin slabs, thin columns with thick slabs, or even lack of required reinforcing for strength.

Many of these failures can be avoided or delayed with the proper application of additional reinforcing materials such as fiber reinforced polymers (FRP). External FRP retrofit application is one method to provide additional strength and ductility to RC slabs. The practice of using the FRP for structural purposes was first implemented in the 1980's and is still under investigation due to the lack of design codes and scattered data. In the past, steel plates have either been mechanically fastened, or applied with resin, to a concrete surface to resist the tensile forces in the concrete. Due to steel's corrosive nature, constructability issues, and in tight spaces using steel plates for strengthening may not be practical. On the other hand, the FRP sheets can be used to retrofit the RC members through surface application with little effort while providing a similar structural improvement as the steel.

The FRP materials are non-corrosive, lightweight, and easy to apply. These materials, including carbon, aramid and glass have been used for strengthening of existing floor systems, bridge components, and masonry wall structures among others. For example, in the slab or beam, a brittle shear failure might be the governing mode of failure. By proper FRP application, this mode of failure can either be changed to flexural failure, which is not as sudden, or it can be avoided completely if the capacity and flexibility of the member is increased.

Studies performed on external FRP retrofitting of RC slab-column connections for punching shear have shown increase in strength and displacement capacity [Chen et al (2008), Harajli et al (2006), Sharaf et al (2006), Chen and Li (2005), Ebead and Marzouk (2004), El-Salakawy et al (2004), Harajli and Soudki (2003)]. Few of these studies employed the finite element analysis in modeling RC flat slabs [Chen et al (2008), Phuvoravan and Sotelino (2005), Xiao and O'Flaherty (2000), Polak (1998)]. The present study employed nonlinear finite element analysis software program, ANSYS©, to investigate the punching shear of as-built and carbon fiber reinforced polymer CFRP-retrofitted RC slab-column connections.

2 FINITE ELEMENT ANALYSIS MODELING OF SLAB-COLUMNS

For validation purpose, the FEA model of as-built slab-column was developed using an existing experimental study in the literature (Sharaf et al, 2006). After the FEA model was validated against the experimental results, the CFRP-retrofitted slab-column connection model was developed for comparison with as-built model.

2.1 Geometry

Since the sole purpose of the validation model is to attain the same results as the as-built specimen described as in the experimental study reported by Sharaf et al, 2006, the geometry used in the FEA modeling must also match the geometry of each experiment as close as possible. When setting up the geometry of the slab, variables such as the slab depth, width and height, reinforcement bars location, and boundary conditions, were considered in developing the model and generating the mesh associated with each element type. Figure 1 shows the dimensions of a quarter of the slab-column connection model using two axes of symmetry that were gathered from the information provided in the aforementioned existing test specimen.

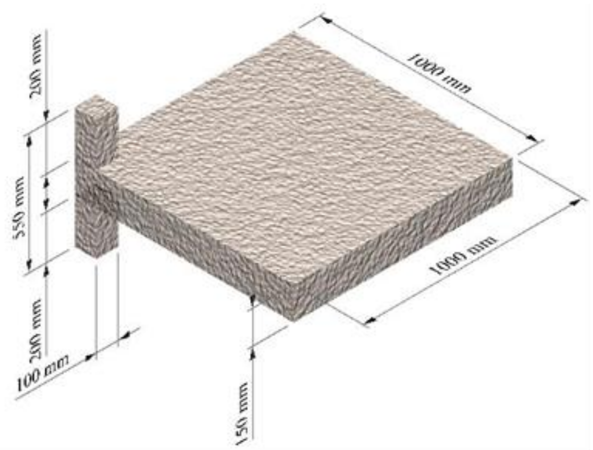

Figure 1. Isometric view of ¼ of slab dimensions.

2.2 Elements and material properties

In order to model the concrete, steel supports, internal reinforcing steel and CFRP sheets, Solid65, Solid45, Link8, and Shell 181 elements were used, respectively. The following describes the assumptions taken when using each element, as well as the material properties and failure criteria associated with each material.

2.3 Concrete modeling

Solid65 which is an 8-node brick element was used for the concrete. Each node on the element has three translational degrees of freedom and transfers displacements and forces. The element has the unique ability to model the crushing, cracking and creep associated with concrete material properties. This ability of the Solid65 element allows the crack and crushing patterns to be displayed visually. The crack patterns are traits that can be very helpful in identifying the areas where CFRP strengthening is needed.

When generating the mesh for the Solid65 elements, it was extremely important to keep in mind the location of the internal reinforcing, support and load locations as well as the aggregate size. The meshing in the present study took all of these characteristics into account by using a mesh size of 25 mm. This size seemed reasonable since it was not smaller than the largest aggregate size, and allowed a fairly accurate placement of internal reinforcing among other things.

The compressive concrete strength, f'_c, was equal to 28 MPa as reported in the control specimen by Sharaf et al, 2006. The ultimate strain, ε_{cu}, was assumed to be equal to 0.0038.

2.4 Steel reinforcement modeling

The modeling of reinforcing bars was done using Link8 element in ANSYS©. Link8 is a 2-node line element with three translational degrees of freedom per node and does not account for the moment transfer.

When meshing Link8 element, the same size elements that were previously defined in the concrete mesh generation were used. This would allow node to node connections for the concrete reinforcing steel bars in the development of the FE model. Figures 2-4, show the top, bottom and side view of reinforcing steel layout, respectively, that were used in the validation models as well as CFRP-retrofitted slab. The tensile strength of steel reinforcement was 410 MPa.

2.5 Carbon fiber reinforced polymer (FRP) sheet modeling

The modeling of CFRP sheets is done by using the Shell 181 element. Shell 181 is a 4-node plate element that is useful in modeling thin, stacked layers of material; such as CFRP strips and sheets. The Shell 181 element allows for multiple layers to be accounted for as well as the ability to specify the thickness, orientation and various strengths in different directions for each layer. There are other shell element options in ANSYS© capable of producing accurate results. However, this element was selected since the number of nodes in the element matched the number of nodes on the surface of the concrete, and, the element is equally capable of producing accurate results. The Shell 181 elements were used in the CFRP-strengthened model. Figure 5 illustrates the CFRP sheet configuration at the bottom of the concrete slab.

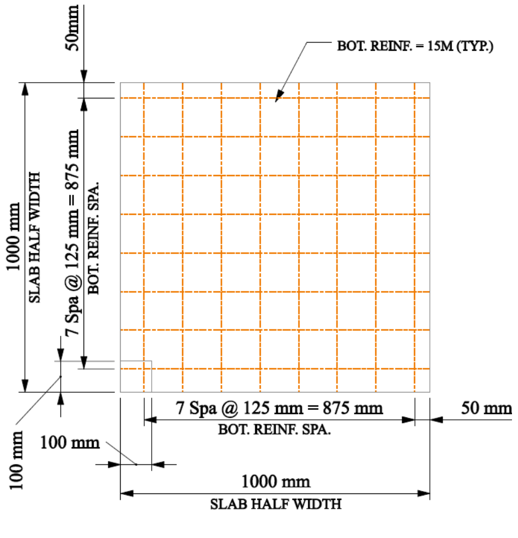

Figure 2. Bottom reinforcement layout.

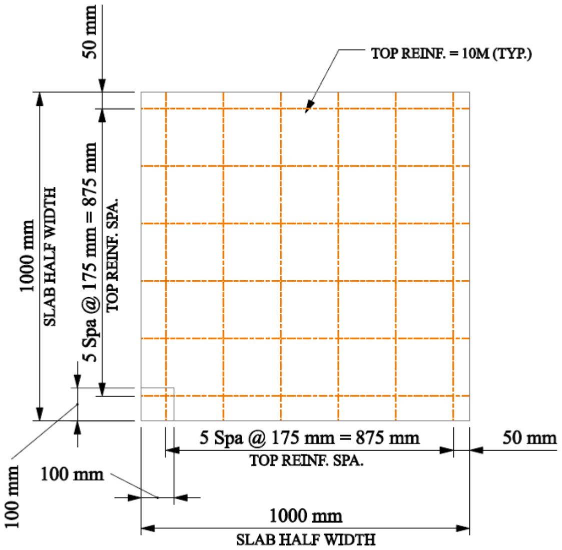

Figure 3. Top Reinforcement layout.

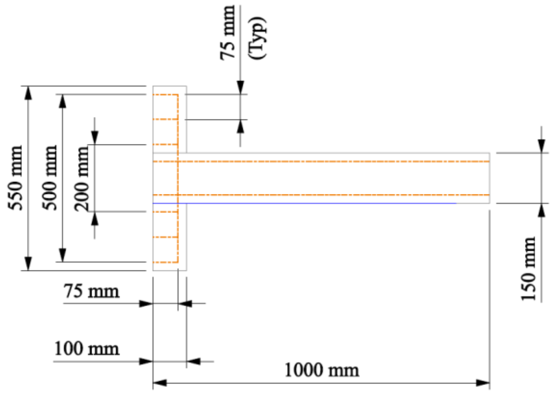

Figure 4. Side view reinforcement layout.

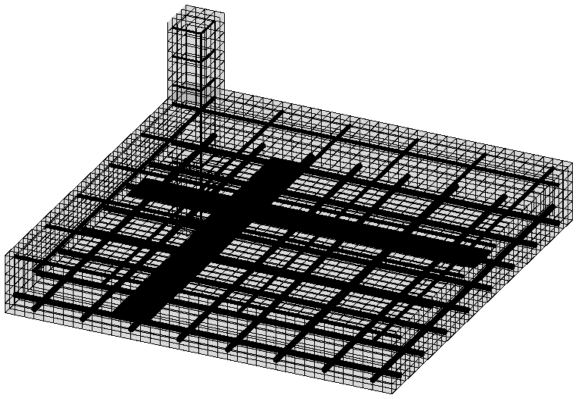

Figure 5. Addition of CFRP sheet (Shell181).

2.6 Load and support steel plates modeling

To model the load plate and support steel plates, for all the models, Solid45 elements were used. The Solid45 element is an 8-node brick element that is appropriate for modeling isotropic materials such as steel. The presence of steel plates would result in even distribution of loads on all the concrete element nodes. This cannot be achieved by simply applying the load directly to the Solid65 element. Figure 6 illustrates the location of the support plate and the load plate used in development of the FE models.

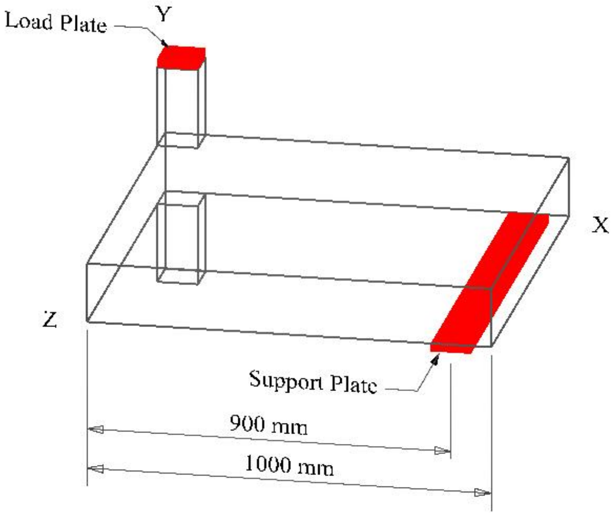

Figure 6. Support and load plate location.

2.7 Boundary conditions

Symmetrical boundary conditions were applied at the lines of symmetry in all FE models to allow modeling a quarter of the slab-column connections. The slab was simply-supported, the only boundary conditions at the support location needed was to restrict the displacement in the vertical direction (y-axis). To account for the symmetrical boundary conditions, all nodes along the lines of symmetry were restrained from motion perpendicular to that line of symmetry.

2.8 Validated FE results of as-built slab-column connection

Comparative analysis of experimental results of the “control” specimen reported by Sharaf et al, 2006 and the FE model are shown in Figure 7. In general, the results were in good agreement. The differences in both curves can be attributed to various assumed material properties necessary in the FE models that were not reported in the experimental study. The mesh size and load steps could also affect the FE results.

The advantage of a finite element analysis, as compared to experimental study, is that the data for any given node can be obtained. Figure 8 shows the stress contours in the concrete of the slab-column control validation model.

Another advantage of finite element analysis is the ability to use the failure criteria defined for the concrete to show the locations of cracking and crushing that occur in the model. Figure 9 illustrates these crack patterns as they would have developed in the specimen under perfect loading conditions. The circles represent cracking that had occurred in the element, the hexagon represents crushing in the element. Red circles represent first crack, green illustrates the strain vectors for the control model. These strain vectors aid in showing the direction and magnitude of the strain in the concrete which aide in showing the direction of the cracking. By knowing the magnitude and direction of the strain the CFRP can be laid out to resist those strains and allow the member to gain strength and flexibility under the given loading condition.

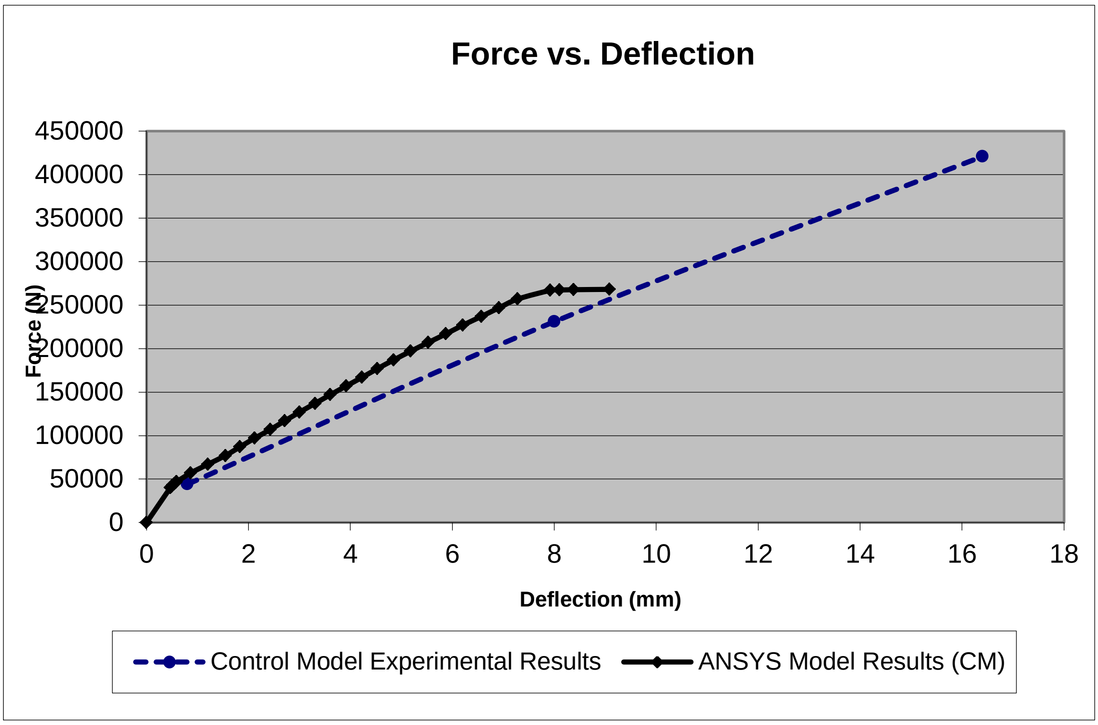

Figure 7. Force versus deflection curves of control test specimen and validated FE model.

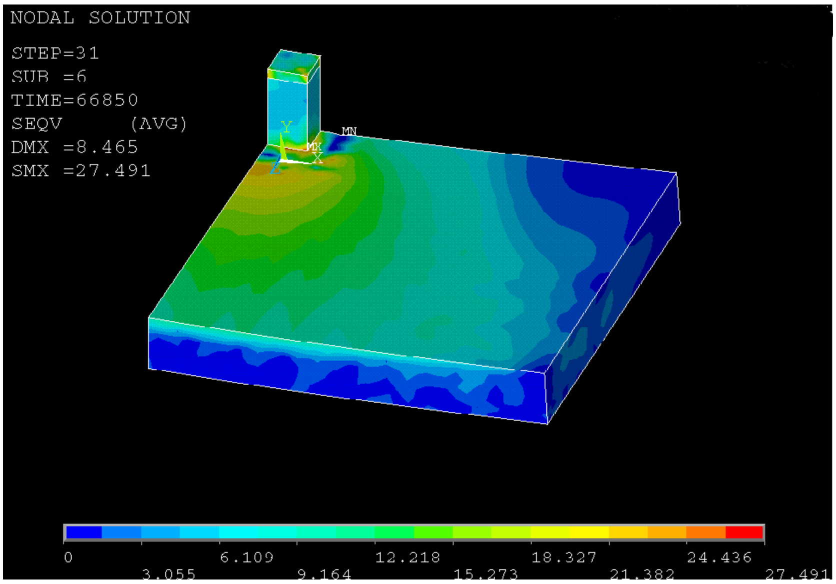

Figure 8. Stress contours in control model near failure time.

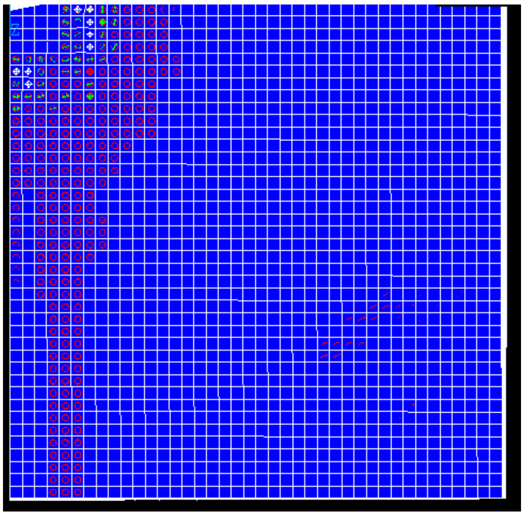

Figure 9. Crack patterns in as-built model at failure

2.9 FE results of CFRP-retrofitted slab-column connection

Once the FE results for the as-built RC slab were verified, and they were in good agreement with the experimental results of the study by Sharaf et al, 2006, the FEA model of CFRP-strengthened slab-column was developed using the geometry, material properties and loadings of the validated control model. Table 1 shows the material properties of the CFRP, from the manufacturer's data sheets. Two layers of CFRP were used around the perimeter of the column. The CFRP sheets were 225 mm wide.

Table 2 shows comparison of FEA maximum load and deflection values of the as-built and CFRP-strengthened slab-columns. Compared to as-built model, the CFRP-strengthened slab-column, the load and displacement capacities have increased. Figure 10 shows the crack patterns at failure in the concrete of the CFRP retrofitted slab. The cracks had reduced as compared to as-built slab-column.

Table 1. (SikaWrap® Hex 230C) Material properties for CFRP-strengthened model

Property	Symbol	SI Units	
Tensile Strength	f_{tx}	894	MPa
Tensile Modulus	E_x	65402	MPa
Tensile elongation, %	ε_x	1.33	%
Ply Thickness	T	0.381	mm

Table 2. Maximum force and deflection

FE Model	Max Load (kN)	Change %	Max Deflection (mm)	Change %
As-Built	233.0	0	6.48	0
CFRP-Strengthened	277.8	19.23	7.33	13.12

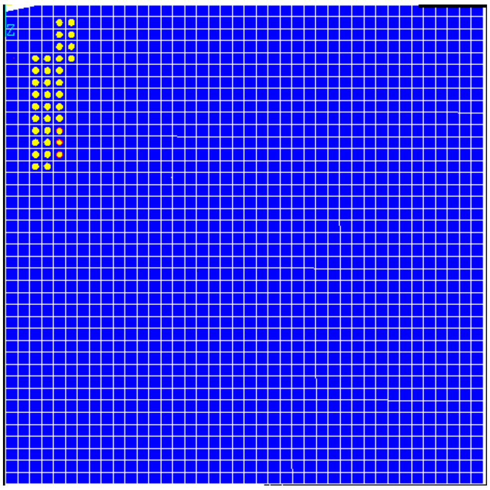

Figure 10. Crack patterns in CFRP-strengthened model at failure

2.10 Conclusions

An effective method of retrofit technique was employed to upgrade the punching shear of existing RC slab-columns by CFRP application. Nonlinear finite element analysis models were developed for as-built and CFRP-strengthened slabs and the results of as-built model was validated against an experimental study reported in the literature. The following conclusions are drawn from the present investigation. The FE validated control slab-column model and corresponding test specimen results were in good agreement. The slab-column strengthened with CFRP showed a greater punching shear capacity over the as-built model.

2.11 References

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