CFRP-STRENGTHENING OF PRECAST CONCRETE SLABS FOR OPENINGS

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ABSTRACT

In some cases openings are necessary after the slab construction to accommodate structural modifications for ducts, pipes, utilities, and elevators. The present study involves the development of three-dimensional complex nonlinear finite element analysis (FEA) models of precast slabs with and without openings. One solid precast slab and five slabs with various opening shapes but equal areas were considered. The openings in the slabs were retrofitted with carbon fiber-reinforced polymer (CFRP) sheets around their perimeters to restore the original flexural strength and stiffness of the floors. Rectangular, square, diamond, circular, elliptical shape openings were investigated for the control and the corresponding CFRP-strengthened slab models. An experimental study on a reinforced concrete (RC) solid slab, and as-built and CFRP-strengthened slabs with rectangular opening reported in the literature was used to validate the accuracy of the proposed FEA models. The finite element analysis results revealed that the slabs with rectangular and elliptical openings outperformed the slabs with other opening shapes in terms of the stiffness and the ultimate flexural strength capacity. The CFRP-strengthening enhanced the performance of all the slabs with various openings as compared to their corresponding control models. Through CFRP reinforcement the losses in the stiffness and the flexural strength caused by the cutouts were restored. In the case of the slab with rectangular shape openings, similar level of flexural strength and increased stiffness values were attained as compared to the slab without opening.

Keywords: ANSYS, CFRP, Concrete, Finite element analysis, Openings, Slab

INTRODUCTION

Due to structural and/or functional requirement changes, it is often necessary to introduce sectional openings in the existing slabs of buildings and industrial facilities. This can be due to the need for the installation of elevators, escalators, staircases, or even utility ducts for heating and air conditioning, resulting in the creation of a cutout and removing of associated concrete and reinforcing steel bars[1]. In this case, the structure would require additional reinforcement for strengthening to restore its ability to resist the imposed loads.

FRP composites are extensively used as an innovative way of strengthening precast concrete structural members partly due to the ease of installation, lightweight, immunity against corrosion, high tensile strength, and availability in convenient forms. Few researchers studied structural response of slabs with openings. Vasques and Karbhari[1] investigated the effectiveness of externally bonded FRP composite strips for strengthening of slabs with one type of opening shapes only. They concluded that externally bonded FRP strips can be used to restore the original load carrying capacity of slabs weakened by cutouts. Enochsson et al[2] studied the slabs with cutout and the amount of CFRP reinforcement ratio to restore their load carrying capacity equivalent to the corresponding slabs without openings. Tan and Zhao[3] investigated the strengthening of openings in one-way slabs using CFRP composites. They considered one type of opening shape with various dimensions located at the center of the slabs with the exception of one near the edges. They concluded that the CFRP systems can effectively enhance the load carrying capacity and the stiffness of slabs with opening if the premature failure due to the FRP debonding is prevented. To the best of authors' knowledge, there are no studies on slabs with various opening shapes in the literature. In particular, investigations on finite element analysis which takes into account material and geometrical nonlinearities of CFRP-strengthened precast concrete slabs with openings are extremely limited.

The present research contributes in filling this perceived void in literature by proposing the development of reliable and highly complex nonlinear finite element analysis models of as-built and CFRP-strengthened precast concrete slabs with various opening shapes. Equal areas of circular, diamond, elliptical, rectangular, square shape openings were considered to explore the effect of opening geometry on the slab performance. The openings in the slabs were retrofitted with carbon fiber-reinforced polymer (CFRP) sheets around their perimeters to restore the original flexural strength and stiffness of the floors. The nonlinear finite element program ANSYS[4] was used to model the slabs. A successful outcome for the proposed study would significantly reduce the dependency on costly and time consuming large-scale experimentation while maintaining a high degree of predictive capacity in capturing realistic characteristics of concrete slabs. The accuracy of proposed finite element models was validated through experimental results reported in the literature by Tan and Zhao[3]. In the following sections the finite element analysis modeling development, simulation results, and conclusions are discussed.

FINITE ELEMENT ANALYSIS MODELING OF SLABS

To develop the finite element analysis slab models, element types, material models, geometry and mesh size, and boundary conditions were selected in ANSYS software program. The details are presented next.

ELEMENT TYPES

A three-dimensional reinforced concrete element, "Solid65", was used to model the concrete. Solid65 element is capable of cracking in tension and crushing in compression with options for large plastic deformation, nonlinear material property, and element death and birth attributes. It is defined by eight nodes and has three translational degrees of freedom at each node. In this study, Solid65 element without reinforcing bars and with all mentioned attributes was used.

A three-dimensional spar element, "Link8", was employed to model all reinforcement bars. Link8 element is a two-node uniaxial tension-compression element with three degrees of freedom at each node. Plasticity, creep, swelling, element death and birth, stress stiffening, and large deflection capabilities are the features for this element. In the present study, the plasticity and element death and birth options were exercised.

To model carbon fiber reinforced polymer (CFRP) sheets, finite strain shell element, "Shell181", was employed. "Shell181" is suitable for modeling thin to moderately thick shell structures with a membrane option. Again, plasticity, stress stiffening, large deflection, birth and death, and nonlinear stabilization are the features of this element. Shell181 element is a four-node element with six degrees of freedom at each node and it only has translational degrees of freedom with the membrane option. The birth and death, and nonlinear stabilization options of this element were implemented in development of FEA models.

MATERIAL MODELS

Concrete is a quasi-brittle material and has different behavior in compression and tension. A William-Warke[5] material model with five input parameters was used as a failure criterion for the concrete. The uniaxial stress-strain curve for the concrete was defined according to Desayi and Krishnan[6] and Gere and Timoshenko[7] equations. The compressive and tensile strengths of the concrete, and the shear transfer coefficients (β_t), representing the conditions of the crack face, were required as the input data for the ANSYS software program. The extreme β_t limits of 0 and 1 represent the absolute loss of shear transfer (smooth crack) and no loss of shear transfer (rough crack), respectively. Lower values of shear transfer coefficient induce convergence problems due to the sliding (shear) across the crack face and therefore, smaller load increment should be employed during the crack formation [ANSYS[12]]. The value of shear transfer coefficients reported in the literature varied between 0.05 and 0.25 Bangash[8] and Hemmaty[9]. In the current study a preliminary analysis was carried out to calibrate the shear transfer coefficient values in order to avoid the convergence problem during the nonlinear analysis and to achieve the utmost smooth shear transfer across the crack face. Shear transfer coefficient values of 0.02 for the open crack and 0.2 for the closed crack found to be suitable for the present numerical analysis.

The constitutive material properties of reinforcement bars were represented as an elastic-perfectly plastic material model and were assumed identical in tension and compression. Perfect bond assumption between the steel bars and concrete was enforced by connecting Link8 steel bar element nodes with adjacent Solid65 concrete nodes so that the two materials share the same nodes.

The CFRP composite was characterized as an orthotropic material model with options for fiber orientation layer. Perfect bond assumption between the CFRP sheets and concrete was implemented by connecting adjacent nodes of Shell181 and Solid65 element to share the same nodes.

MESH GENERATION AND BOUNDARY CONDITIONS

A preliminary analysis was conducted on the control slab model by varying the size of the mesh from coarse to fine, and by comparing the deflections and compressive stresses responses to identify a workable mesh density that would provide accurate results. Due to the symmetry and to minimize the computation time, only a quarter of the slab was modeled. The displacement in the direction perpendicular to the plane of symmetry was set to zero. To achieve even stress distributions and to avoid stress concentration, 30 mm thick by 100 mm wide, and 30 mm thick by 200 mm wide steel plates were added at the locations of the applied loads and supports, respectively (see Fig. 1 for more details). Three-dimensional Solid45 elements were used to model the steel plates. The slabs were simply-supported.

NONLINEAR SOLUTIONS AND FAILURE CRITERION

Death and birth options of each element were employed to capture the post peak behavior. The total load was applied in series of load steps. An ANSYS Parametric Design Language (APDL) macro code was used between load steps to identify the yielding of reinforcement elements and to deactivate (kill) adjacent concrete and FRP elements to simulate the crushing of the concrete cover.

Newton Raphson method option in ANSYS was employed to satisfy the convergence at the end of each load increment within the tolerance convergence norms. The minimum and maximum load increments were controlled and predicted by ANSYS automatic load stepping based on the response of the structure for the previous load increment. In concrete cracking, reinforcement bar yielding, and post peak phases, a gradual small load increment was applied to capture the stiffness loss due to the crack propagation. As previously defined under Material Models section, the William-Warke[5] failure criterion was employed for the concrete material and the failure of FE slab model was recognized when the analysis stopped to converge for 0.001 kN load increment using APDL loading code.

FINITE ELEMENT ANALYSIS RESULTS OF VALIDATED MODELS

Tan and Zhao[3] conducted an experimental study on CFRP strengthened one-way reinforced concrete slabs with openings. Using ANSYS program software, three of their test specimens labeled as RA1, RA2, and AS5 were selected to validate the proposed finite element models of the present study. Specimens RA1, and RA2 were control RC slabs without and with openings, respectively. Specimen RA2 opening was 1100 mm long by 1000 mm wide located at the center of the slab. AS5 was the same as RA2, but it was strengthened by the CFRP strips along the perimeter of the opening.

The concrete compressive strength of specimens RA1, RA2 and AS5 were 41.2 MPa, 48.0 MPa, and 45.9 MPa respectively. The poison's ratio of the concrete was assumed as 0.2. The tensile strength and elastic modulus of concrete was calculated according to ACI 318-05[10]. Areas of longitudinal and transverse bars were 78.5 mm^2 and 50.3 mm^2, respectively. Longitudinal reinforcement bars had a yield strength value of 600 MPa and elastic modulus of 165 GPa. Transverse reinforcement bars' yield strength and elastic modulus were 640, and 175 GPa, respectively. The poison's ratio of reinforcement bars was assumed as 0.3. Geometry, reinforcement details, loadings position and the CFRP layout are presented in Fig. 1. The CFRP strips were 200 mm wide by 1.2 mm thick with an elastic modulus of 165 GPa, and ultimate tensile strain of 1.7% along the unidirectional fibers.

The state of stiffness and flexural strength can be described by the load versus deflection curves. Fig. 2 shows comparison of experimental and numerical results of RA1 (solid slab) and RA2 (slab with opening) and AS5 (CFRP-strengthened slab with opening) specimens.

An immediate transfer of stresses from the concrete to the reinforcement bars was observed in the finite element analysis results with the first crack occurrence, once the tensile strength of concrete was reached. This phenomenon was witnessed in the load deflection plots with a small horizontal plateau at the early loading stage. Relatively, a large deflection was observed for a small load increment due to the first crack formation accompanied by the stiffness loss as compared to the previous load step (see Fig. 2).

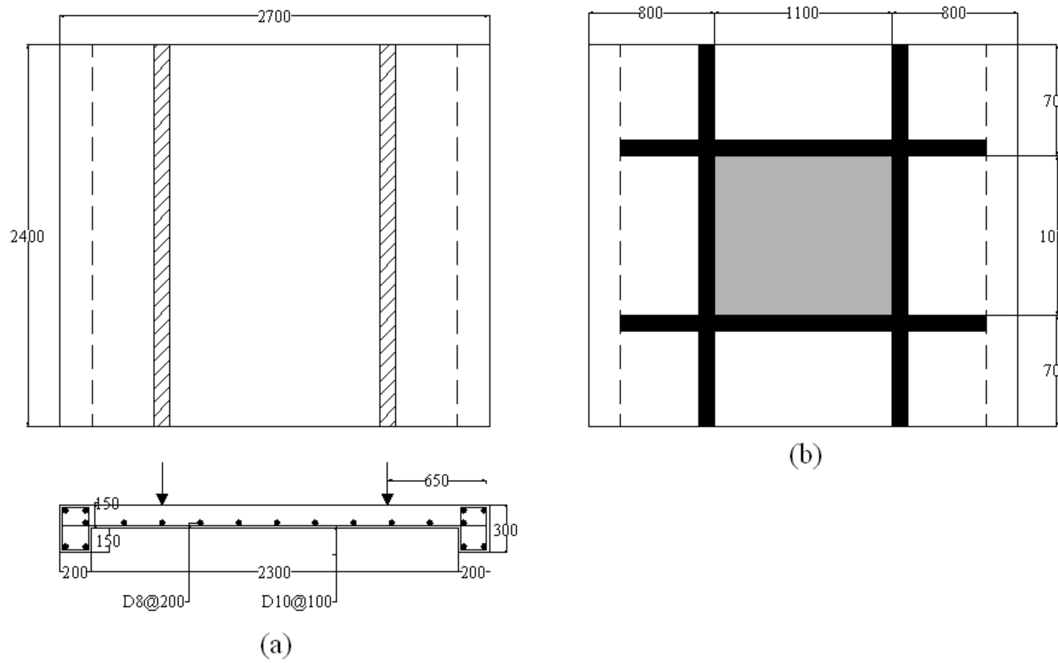
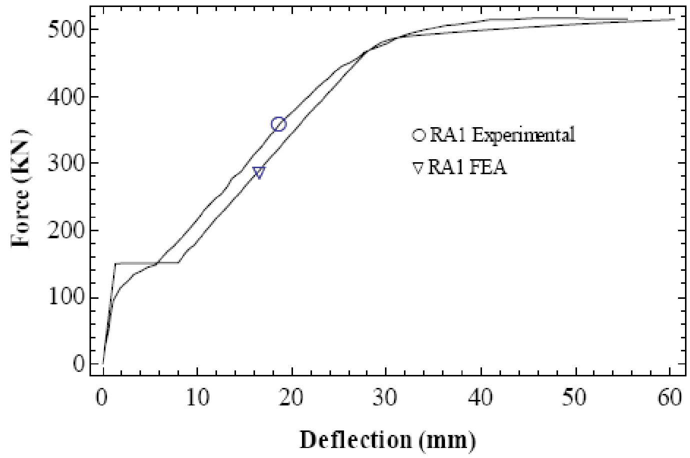


Fig. 1 Slab details of FE validated model (a) geometry, reinforcement details, and loadings position; (b) CFRP reinforcement layout (mm)

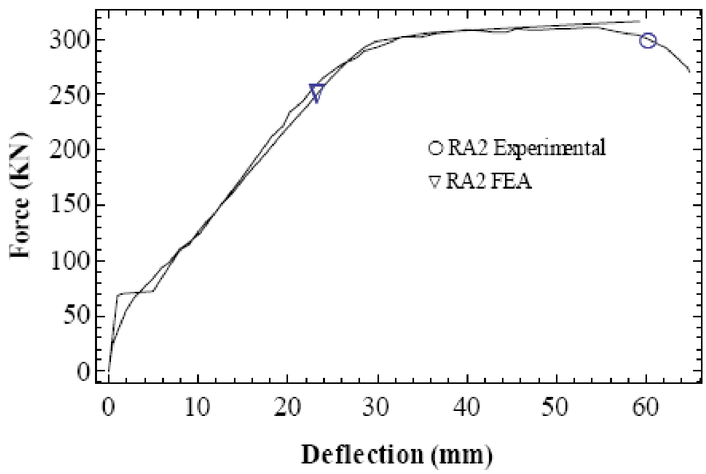
The developed finite element models were able to capture the rapid change in the slope in the nonlinear portion of the load versus deflection curves beyond the first cracking stage which was in agreement with the experimental results. Furthermore, the yielding of steel reinforcement bars was demonstrated with the formation of plateau in the FEA load deflection plots for specimens RA1 and RA2 as also reported in experimental results.

For AS5 specimen, the internal reinforcement bars did not yield in the experiment or in the finite element slab model. This specimen failed by the CFRP debonding in the experiment as well as FE analysis as identified by zigzag portion in the load versus deflection plots. The ultimate stage yielding plateau behavior was closely captured with death and birth option of Solid65, Link8 and Shell181 elements used in the FE analysis.

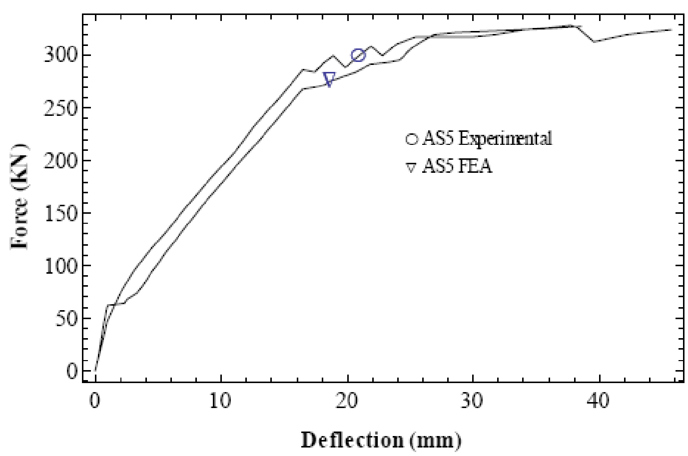
Finite element analysis and experimental results were in good agreement in all pre-cracked, cracked, and ultimate stages for RA1, RA2, and AS5 specimens. This validates the accuracy of the proposed finite element models for further parametric study.



(a) Slab RA1



(b) Slab RA2



(c) Slab AS5

Fig. 2 Experimental and FEA load versus deflection curves

CASE STUDIES OF AS-BUILT AND STRENGTHENED PRECAST CONCRTE SLABS WITH VARIOUS OPENING SHAPES

Various case studies of as-built and CFRP-strengthened precast concrete slabs were investigated using the validated finite element models and techniques to optimize the opening shapes for the minimum amount of losses in the stiffness and the flexural strength caused by the cutout in the slabs. The slab opening shapes considered were circular, diamond, elliptical, rectangular, and square with equal areas. Dimensions, location, and geometry of the openings are shown in Fig. 3. Slab dimensions, steel reinforcement details and properties, and boundary conditions were identical to the validated models for all case studies. The concrete compressive strength was assumed as 40.0 MPa. Table 1 shows the material properties of the selected CFRP sheets, which were Tyfo® SCH-41 Composite type manufactured by Fyfe Company LLC[11]. The CFRP sheets consisted of one layer unidirectional fiber and had a 200 mm width in all strengthened case studies. The main focus of the present study was on the various shapes of the opening for the slab while keeping the effect of other variables constant. For this reason the total area of openings, the amount of the CFRP reinforcements and the layouts were similar for all case studies and additional diagonal CFRP reinforcements were not provided for shapes with sharp edges. The CFRP-reinforcement layouts are shown in Fig. 4.

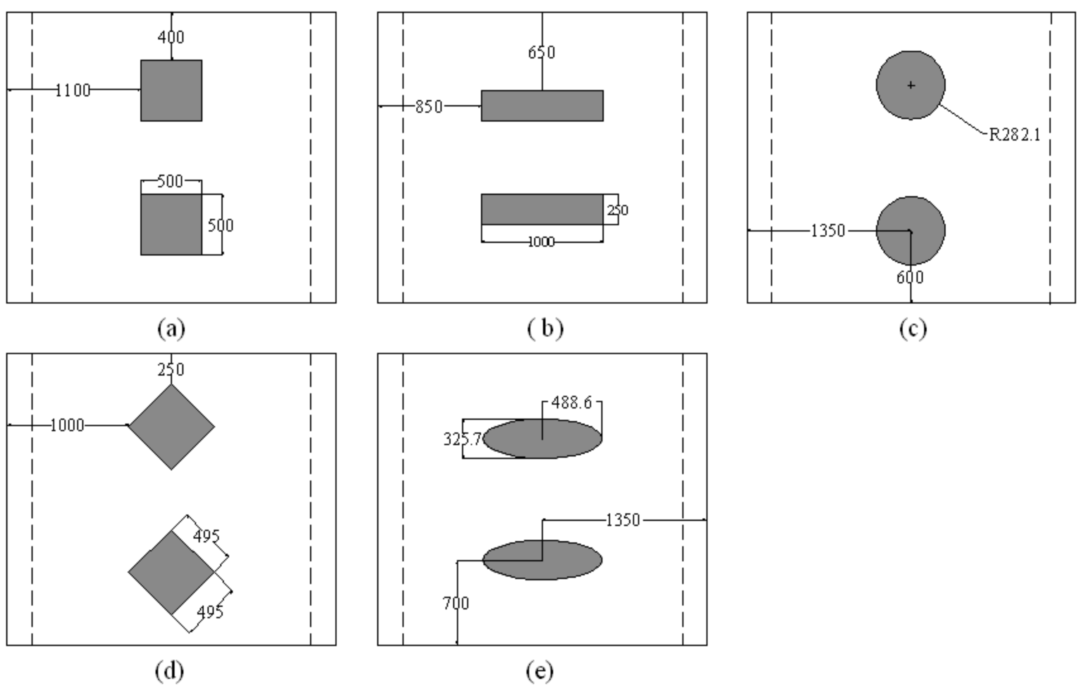


Fig. 3 Location, geometry and dimensions of openings for: (a) square; (b) rectangular; (c) circular; (d) diamond; and (e) elliptical openings (mm)

Table 1 Properties of the CFRP sheets

Properties	ASTM Method	Test Value	Design Value
Ultimate tensile strength	D-3039	986 MPa	834 MPa
Ultimate elongation	D-3039	1%	1%
Tensile modulus	D-3039	95.8 GPa	82 GPa
Laminate thickness per ply	---	1.0 mm	1.0 mm

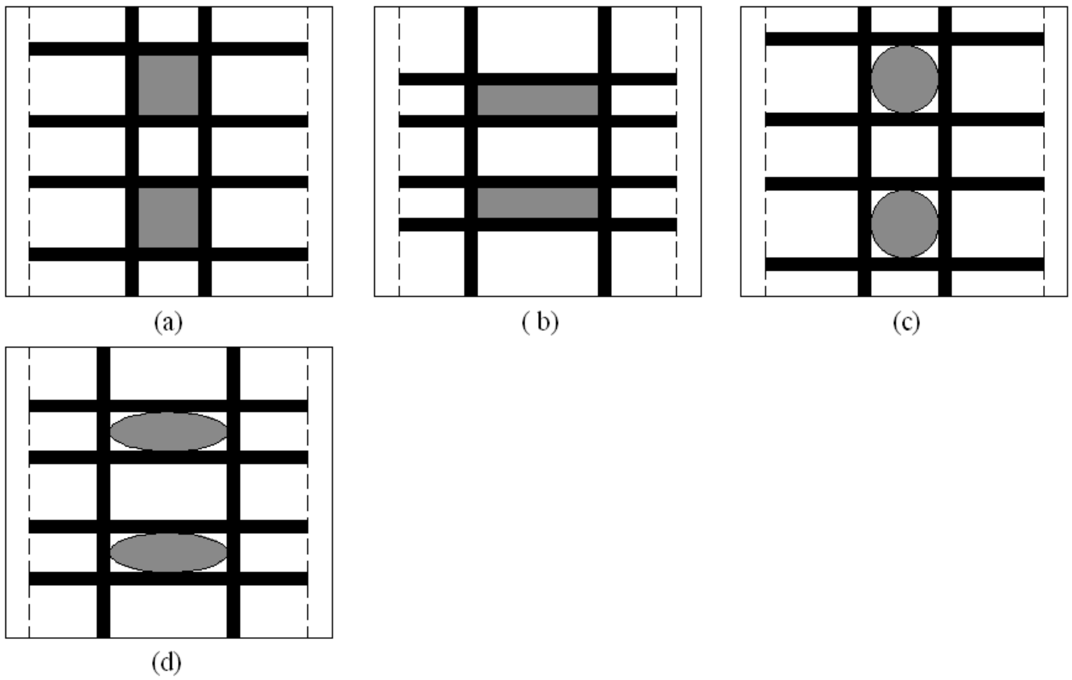


Fig. 4 CFRP reinforcement layout for: (a) square openings; (b) rectangular openings; (c) circular openings; and (d) elliptical openings

As-Built Precast Concrete Slabs with Various Opening Shapes FEA Results

Load versus deflection curves in Fig. 5 demonstrate the characteristics of as-built precast concrete slabs without and with various opening shapes. The as-built precast concrete slab with rectangular shape openings exhibited the least amount of stiffness and flexural strength losses. The as-built precast concrete slabs with rectangular, elliptical, square, circular and diamond shape openings lost 15.7, 38.7, 41.6, 48 and 51.6% of ultimate load carrying capacity when compared to the solid precast slab.

The slope of the load versus deflection curve represents the stiffness of the precast concrete slab at certain loading level. In this study the mean stiffness values were reported after the first crack formation stage as each slab exhibited identical linear behavior up to the cracking load. As-built precast concrete slabs with square and elliptical shape openings had comparable loss of stiffness. Among all, the slabs with diamond and circular shape openings exhibited the highest stiffness loss (34.4%) as compared to the solid precast concrete slab. This loss in the stiffness became more apparent as the loading continued beyond the first crack formation. The case study of the slab with diamond shape openings was dropped in the subsequent investigation on the CFRP-strengthened slabs. This was due to the poor structural performance out of all considered opening shapes and numerical instability in the finite element analysis of strengthened precast concrete slab with diamond shape openings.

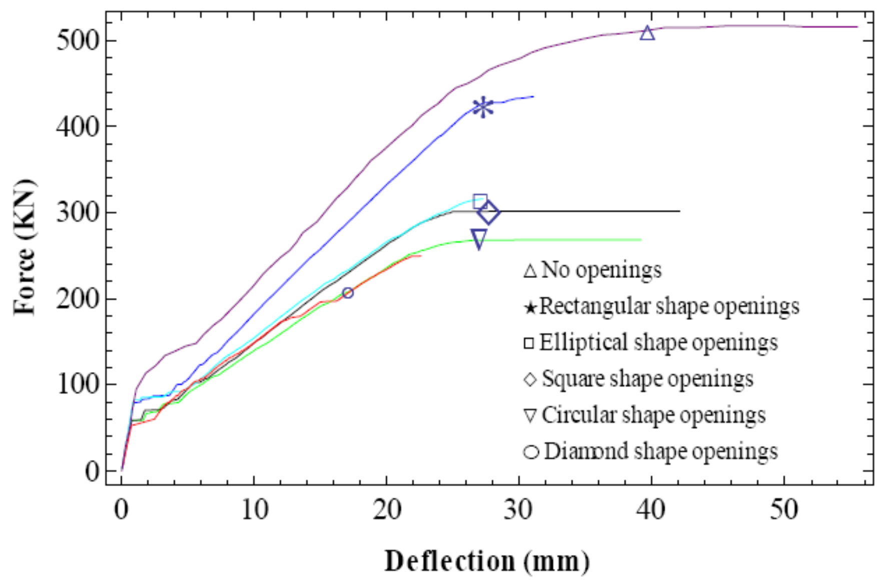


Fig. 5 Load-deflection plots of as-built slabs with various opening shapes

FEA Results of CFRP-Strengthened Precast Concrete Slabs with Various Opening Shapes

The CFRP-strengthened precast concrete slabs with various opening shapes were investigated to study the restored amounts in the stiffness and flexural strength, and the extent of CFRP-strengthening effectiveness.

The load versus deflection curves of retrofitted slabs are shown in Fig. 6. Similar to as-built case studies, the strengthened precast concrete slab with rectangular shape openings outperformed other opening shapes in terms of the gains in stiffness and flexural strength. These gains became more apparent as the loading continued beyond the first crack. Moreover, the CFRP-strengthened precast concrete slab with rectangular shape openings sustained a similar level of maximum ultimate load and a 26% increase in the maximum stiffness as compared to the solid precast concrete slab.

The CFRP-strengthened precast concrete slabs with square and circular shape openings attained lower ultimate loads as compared to the solid slab. The one with elliptical shape openings restored its original stiffness, but lost 11% of the original ultimate load carrying capacity. In terms of deflection, the solid slab followed by the the slab with circular shape openings had the largest values. In contrast to the ductile failure type observed in the solid precast slab, all CFRP-strengthened precast concrete slabs with openings had brittle type of failure with the exception of the circular shape openings. Similar behaviors were witnessed in the experimental study of the CFRP-strengthened slab with rectangular opening (AS5) which was used to validate the accuracy of the proposed FEA models

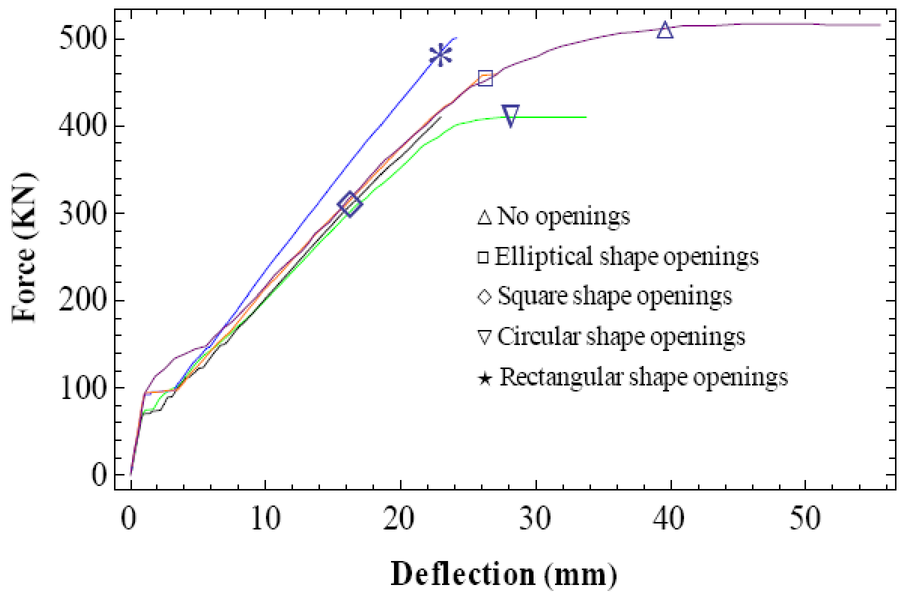


Fig. 6 Load-deflection plots of strengthened slabs with various opening shapes

Stress Contours

A cutout in the slab causes disturbance in the transfer of stresses. An increase in the stress level was observed at the opening edges and at the corners if the opening size was large. Stress contours were plotted to examine the stress gradients near and around the openings. Fig. 7 shows top concrete surface stress distributions of the CFRP-strengthened precast concrete slabs with various opening shapes. The light colors represent lower stress values such as negative compressive stress values. The dark colors represent higher stress values such as positive tensile stress values.

Irregular gradient stress distributions were observed in strengthened precast concrete slabs adjacent to square, circular and elliptical shape openings. Relatively uniform gradient stress distributions were observed nearby rectangular shape openings. This phenomenon was attributed to higher aspect ratio of rectangular opening dimensions as compared to other slab opening types. The uniform gradient stress distributions prolonged the formation of stress concentrations around the opening edges and enhanced the structural performance of strengthened precast concrete slab with rectangular shape openings. In all the plots, uneven stress gradients were observed at the applied load locations.

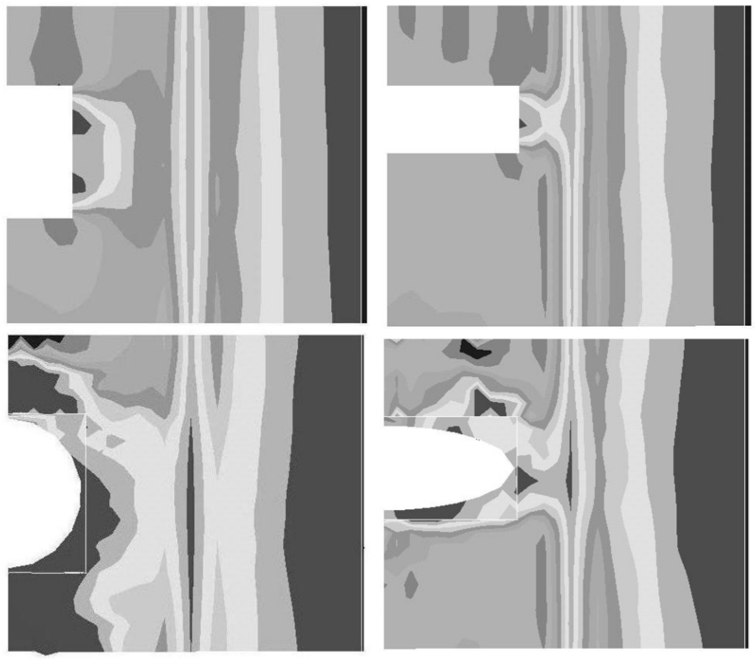


Fig. 7 Stress contours of a quarter of slab models with various opening shapes

CONCLUSIONS

The finite element analysis has shown that CFRP-strengthening is effective in restoring and even increasing the structural performance of precast concrete slabs with openings. The finite element results demonstrated that rectangular shape openings outperformed other opening shapes with minimum amount of losses in the stiffness, flexural strength, and ultimate load carrying capacity. All CFRP-strengthened precast concrete slabs with openings had brittle type of failure with the exception of the slab with circular shape openings

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