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Effect of openings on in-plane structural behavior of reinforced concrete floor slabs

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ABSTRACT

To determine the inelastic seismic response of reinforced concrete (RC) buildings, typically a tri-linear in-plane load-displacement idealization is used for modeling the behavior of RC floor diaphragms, to account for cracking and yielding prior to failure. In the 1980s, solid (without openings) beam-supported RC two-way slab panels were experimentally studied at Lehigh University under in-plane monotonic and cyclic loads, with and without service gravity loads, to determine their in-plane load-displacement and hysteretic characteristics. Subsequently, these results could be implemented in nonlinear damage analysis computational tools developed for analyzing RC buildings with flexible floor diaphragms, ignoring the effect of openings. Due to the lack of experimental data, in the present study a finite element (FE) approach is used to investigate the inelastic behavior of RC floor diaphragms with openings. A general purpose FE software was initially used to create a nonlinear 3D model of the solid panels tested at Lehigh University, and the obtained results from the actual experiment were used to verify the validity of the FE model. This model uses eight-node concrete brick elements (SOLID65) combined with embedded steel reinforcement elements (REIN264). After the accuracy of the solid (with no opening) FE model was verified, openings were placed in the model, and then a sensitivity study has been conducted where the effects of varying opening sizes (0, 6.25%, 14%, and 25% of the floor panel area) and out-of-plane loading (zero and full service load) on the in-plane load-displacement characteristics of the floor panels are investigated. Results indicate that the drop in ultimate in-plane load capacity of the floor diaphragm due to the presence of out-of-plane service loading becomes less significant as the opening size increases (4% for 25% opening vs. 15% for the solid slab). Also, the first significant variation from the initial linear portion of the in-plane load-displacement curve moves up from 30% to about 50% of the ultimate load capacity for the slab with the larger size opening. The failure mechanisms changed due to the presence of the openings, where yielding of the bars around the opening corners appeared to significantly affect the behavior of the slabs. The positive contribution of inclined reinforcing bars, placed at opening corners, in strengthening the in-plane capacity of the slab panels with opening, is effectively demonstrated by use of the FE model.

1. Introduction

Floor diaphragm in-plane flexibility in concrete buildings was ignored for simplicity by structural engineers in practical design until the ASCE7 Building Standard [1] acknowledged that this assumption can result in considerable errors when predicting the seismic response of RC buildings with diaphragms having plan aspect ratios greater than 3:1. This is also corroborated by previous research conducted in this topic, concluding that using a rigid assumption for this type of RC building floor diaphragms may give non-conservative results [18,20,25].

A comprehensive experimental and analytical research study was conducted at the University of Buffalo (SUNY) and Lehigh University in the 1980s on solid (i.e., without openings) beam-supported RC slab panels. In the mentioned studies [5,6], the in-plane load-displacement and hysteretic characteristics of the solid slabs were experimentally evaluated using inelastic cyclic and monotonic testing of the slab panel subassemblies, with and without full-service (out-of-plane) loads. Subsequently, results were implemented in development of a computational tool (IDARC2) for inelastic dynamic analysis of RC buildings by using a tri-linear idealized moment-curvature assumption (to account for in-plane cracking and yielding prior to failure) [7]. However, these studies did not consider the effect of openings.

Furthermore, the presence of openings in floor diaphragms for architectural features, staircases, and elevator shafts is sometimes

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inevitable [23]. These openings will result in diaphragm stiffness reduction and can decrease the load carrying capacity of the member [2,3]. These types of diaphragms are usually designed ignoring opening effects. Therefore, their true response may be different than what is assumed. In other words, the presence of openings makes the behavior of floor diaphragms significantly more complicated and unpredictable [4].

A number of researchers have evaluated the structural behavior of RC slabs with openings in them. However, slabs were only subjected to out-of-plane gravity loads, and the effect of in-plane loads was not considered [8–10,22]. Radik et al. [24], Choi [3], and Florut et al. [4] investigated the effectiveness of different strengthening methods on improving load carrying capacity of slabs with and without openings using GFRP, FRC, and FRP, while slabs were only subjected to out-of-plane loads and again the effect of in-plane loads was not considered. Zhang et al. [29] conducted a numerical study on the effect of openings on floor slabs and concluded that presence of openings play an important role in determining the in-plane behavior of the slabs.

Al Harash et al. [25] investigated the effect of diaphragm openings and flexibility (versus rigid assumption) on seismic response of five 3-story RC buildings with end shear walls having plan aspect ratios of 4:1 using a damage computational tool (IDARC 2). Results indicated that inelastic in-plane floor deformations caused by presence of openings led to erroneous and non-conservative results when compared to the cases where rigid floor assumption with no openings were analyzed. Another important conclusion was that the effect of openings was significant, irrespective of the location that openings were placed. It is noteworthy that solid slab properties were used in the program to simulate inelastic in-plane behavior of diaphragms with openings. However, results of the present study suggest that solid slab in-plane load-displacement characteristics (first concrete cracking, yielding of bars, and ultimate failure) are significantly different than those of slabs with openings.

Due to the lack of experimental data on inelastic in-plane behavior of RC floor diaphragms with openings and limited research conducted on this topic (as evidenced from literature review conducted by the authors), an FE approach was used in the present study to investigate the effect of openings on in-plane behavior of RC slabs. First, a nonlinear 3D FE model was created to replicate the solid panels (without opening) tested at Lehigh University. After the accuracy of the FE model was verified by comparing results (load-displacement behavior, measured vertical and horizontal displacements, and cracking patterns) with ones obtained from the actual laboratory experiments conducted on solid panels at Lehigh University, openings were placed in the FE model. Analysis was performed on the FE models and inelastic behavior of the slabs with openings when subjected to in-plane and out-of-plane loads was investigated. Authors believe that most of the research conducted on RC slabs with openings are focusing on repairing or strengthening existing structures rather than trying to understand the mechanisms in which RC slabs are being affected when openings exist. Especially, the behavior of slabs with openings under in-plane loading conditions has not been investigated at all.

2. Three dimensional FE modeling of RC floor diaphragms

3D FE models of prototype floor diaphragms of left end panel of the shown scaled RC beam-supported floor slab subassemblies (panel #1 in Fig. 1) tested at Lehigh University were constructed. The test specimen, which consisted of three square panels supported by two shear-walls and four columns, was designed to represent a scaled model of a portion of the floor system in a medium- to high-rise building with an intermediate scaling factor of 4.5 [6].

76 volumes had to be created to model the test specimen. ANSYS SOLID65 (an eight-node concrete brick element capable of cracking and crushing) and REIN 264 (an axial element suitable for discrete modeling of the embedded reinforcing bars) were used in order to properly place the embedded top and bottom reinforcing steel in the floor slabs and supporting beams, as shown in Fig. 2. Based on the convergence study conducted on the FE model, a prototype floor slab was meshed in 152 mm × 152 mm size elements in four layers through the thickness of slab. Stem of the supporting beams was divided into three layers (Fig. 2). Fourteen

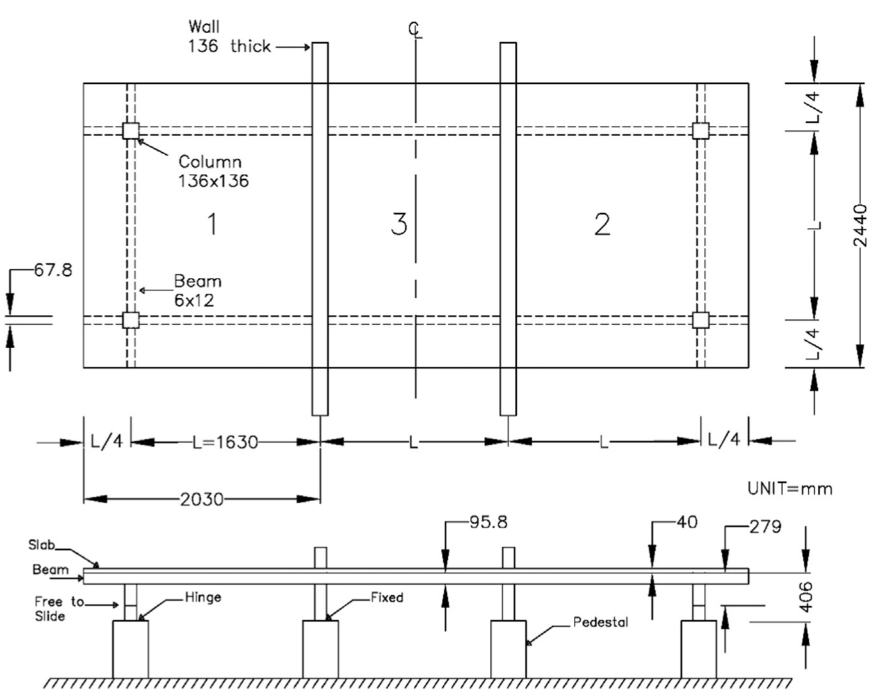

Fig. 1. Plan, elevation, and dimensions of the scaled test specimen (shown in mm) [6].

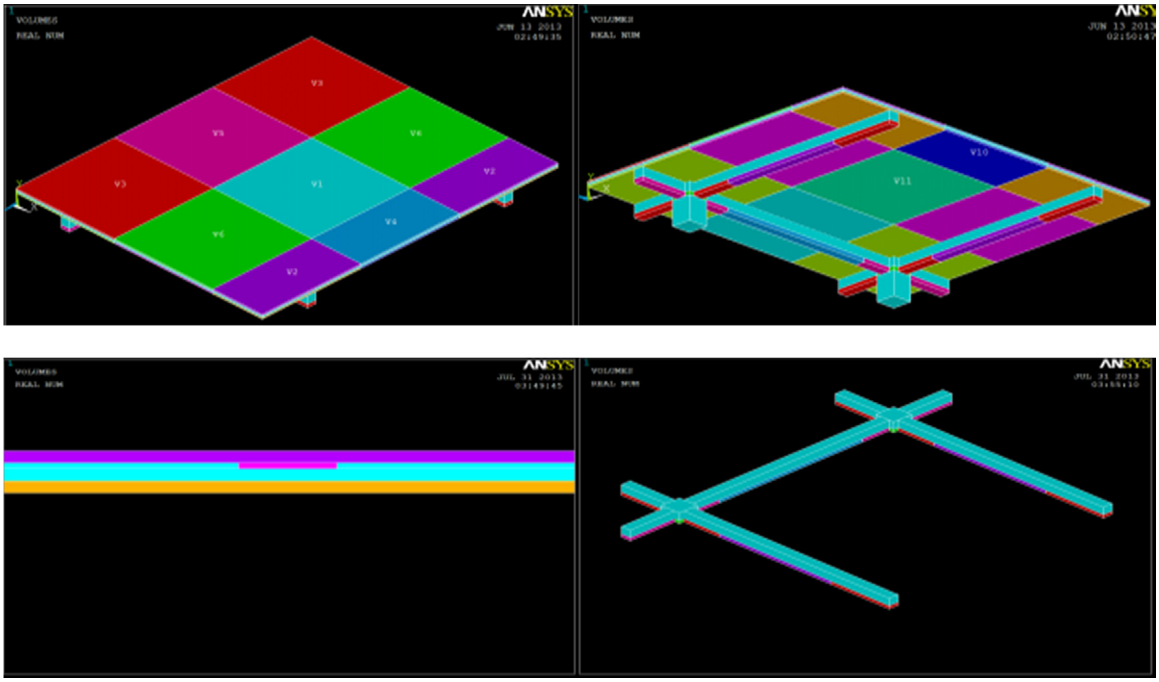

Fig. 2. Top slab (top left), bottom slab (top right), four layers through thickness of the slab (bottom left), three layers through stem of the beams (bottom right).

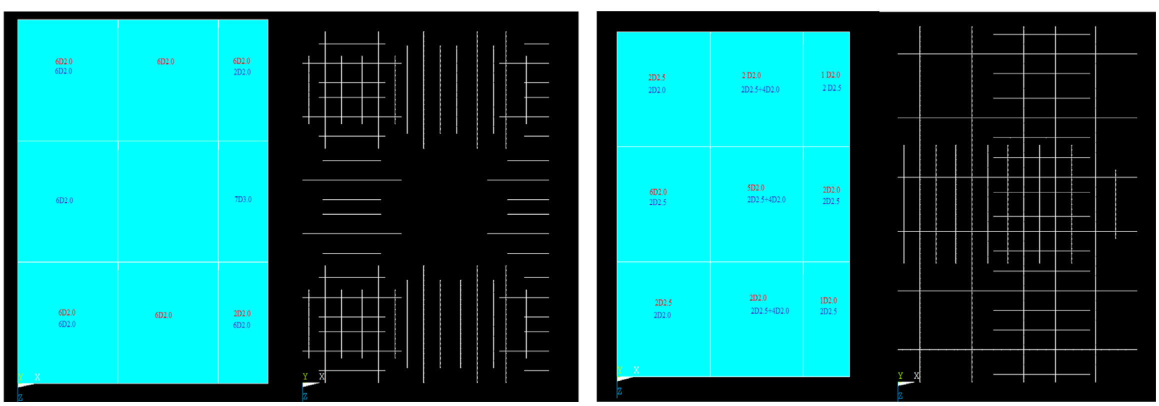

Fig. 3. The reinforcing bar arrangement; top slab (left), bottom slab (right).

sections had to be defined for REINF264 in two directions in the slab and beams due to the existence of three types of reinforcing bars (D.2.0, D2.5 and D3.0). There were fourteen required sections because in some locations two different reinforcements (with different cross sectional areas) had to be defined for both directions, which required defining four different rebar sections (Fig. 3). SOLID65 was assigned by selecting the appropriate volumes to construct concrete elements. Coordinates and orientation of the reinforcing bar element needed to be defined in the base element (SOLID65) along X, Y, Z or a specific angle. After which, the cross sectional area of the reinforcement (REINF264) was assigned. In this discrete rebar modeling method, a full bond is assumed between steel and concrete. Fig. 3 shows the rebar arrangement at the top and bottom of the slab (blue text represents number of bars parallel to the X direction [wall] and red color represents the perpendicular). The same procedure was followed to place 2D2.0 at top and 3D2.0 at bottom of the supporting beams running under the slab. Special care was taken to make sure the location and properties of reinforcing bars exactly matched ones used in the actual test specimen, as can be seen in a comparison made between the actual test and FE model rebar arrangements for top and bottom of the slab in Fig. 4.

To properly simulate boundary conditions of the actual experiment, slab and beam nodes in the FE model were restrained against translation in all directions to simulate the clamped fixed condition of the actual experiment. A single node at center of the bottom surface of supporting columns in the FE model was restrained only in vertical direction to simulate a sliding support (roller) used at the base of supporting pedestals in the actual experiment (Fig. 5).

Benefiting from numerical modeling method that does not pose any of the problems associated with an actual test (cost of materials, measurements, and work force), it was decided to use the real dimensions of the prototype for FE modeling in ANSYS. This also made the modeling process easier in general, since it required the definition of less sectional properties. The models used for FE analysis had real dimensions (not scaled) for convenience of specifying prototype member sectional properties including reinforcing steel details in ANSYS. Because of this, in order to have a correct comparison between the actual experiment and the FE models, results obtained from FE analysis had to be scaled down to match the ones from actual experiment. Similitude relationships were used to carefully convert specimen dimensions, reinforcing steel cross sectional areas, concrete and steel material

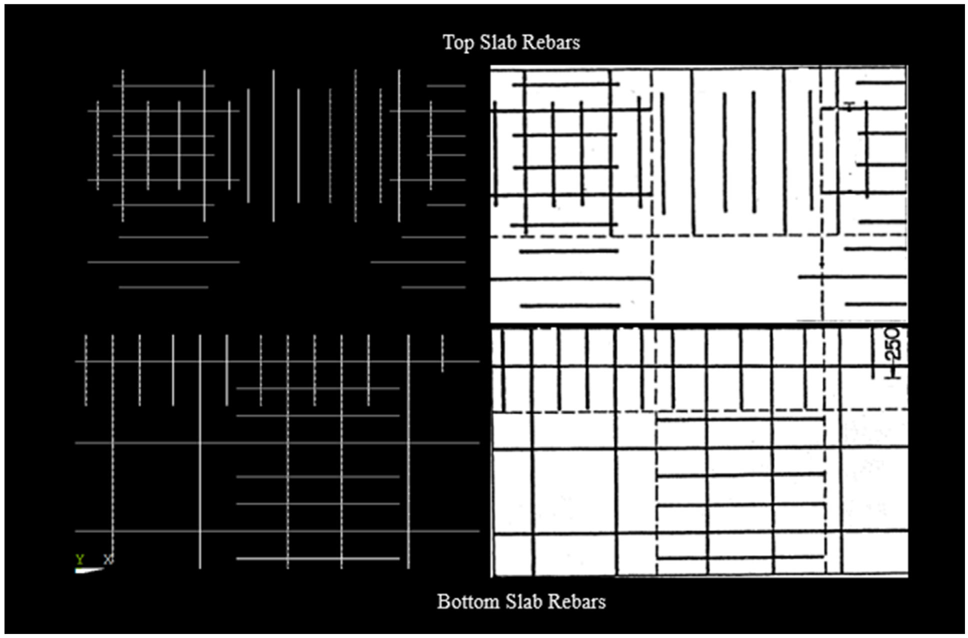

Fig. 4. The reinforcing bar arrangement comparison between the FE model (left) and the actual test specimen (right).

properties, and the applied loads from the actual experiment to the FE model. Similitude relationships were also utilized to relate the floor slab deformations, strain, and stress in steel and concrete between the actual test and the FE model for comparison purposes. Table 1 lists conversion factors used to properly construct the model and compare results between the FE model and actual experiment. (S=Scaled Factor of 4.5).

As described in the actual experiment's report [6], the sum of 80 psf live load, and dead load (the weight of actual RC slab panel) were used in the FE model to represent the full service load condition used in the actual experiment. Vertical live load was distributed uniformly along all the nodes located at top of the FE model. Dead load was included by defining the mass density of the concrete and steel materials in ANSYS material property module. Monotonic horizontal loads were scaled up by multiplying them by $S^2=4.5^2$ and they were applied along the beam parallel to shear wall in the FE model (Fig. 6). However, horizontal loads were applied in very small increments since the FE model experienced a high degree of non-linearity under that loading condition.

Table 1
The scaling relationships used to build the prototype FE model from the scaled experimental model (S=scaling factor of 4.5).

Parameter	Conversion factor to convert from scaled to prototype
Length	S
Area	S^2
Force	S^2
Stress	1

Twenty-eight-day compressive strength of concrete used in the end panel floor slabs, beams, and walls was 27.7 MPa. This value was 34.5 MPa in supporting columns. In the FE model, ANSYS

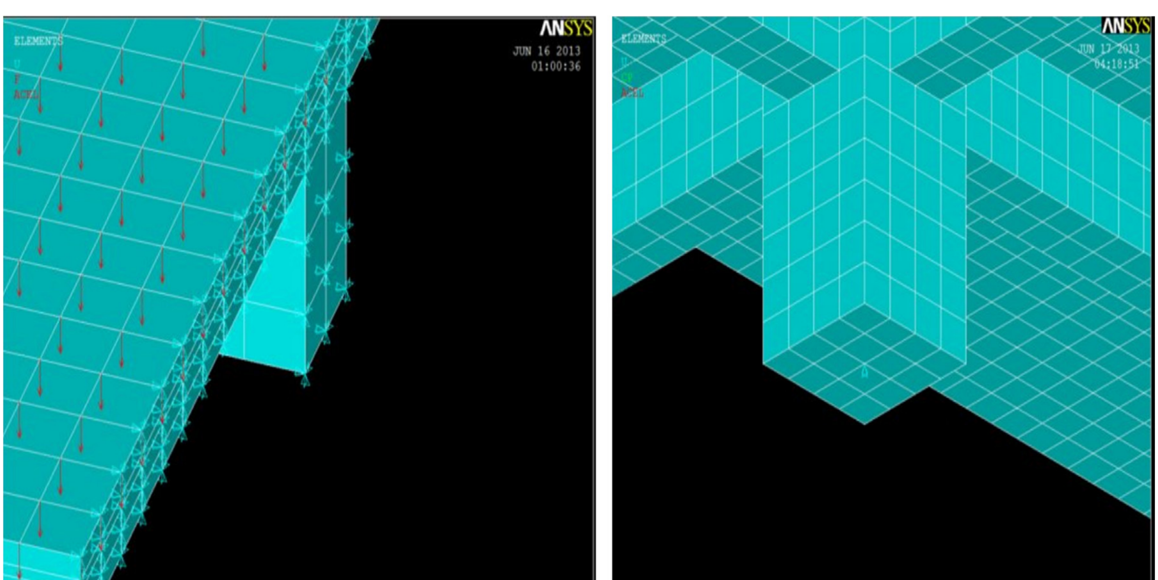

Fig. 5. Boundary conditions used in the FE model; restrained in all directions to simulate the wall connection (left), only restrained vertically to simulate the rollers used at bottom of the columns (right).

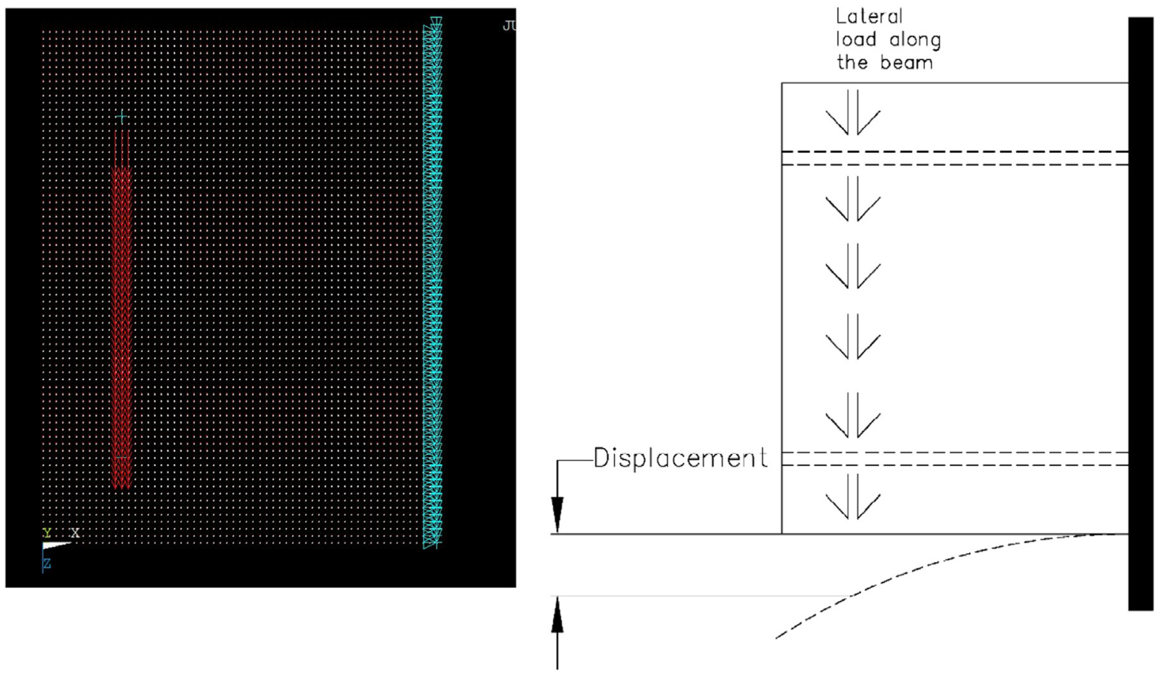

Fig. 6. Application of horizontal load; FE model (left), actual experiment (right).

default nonlinear concrete material model (Willam & Warnke [27]) was used. This model required nine input values listed below:

1. Shear transfer coefficients for an open crack;
2. Shear transfer coefficients for a closed crack;
3. Uniaxial tensile cracking stress;
4. Uniaxial crushing stress (positive);
5. Biaxial crushing stress (positive);
6. Ambient hydrostatic stress state for use with constants 7 and 8;
7. Biaxial crushing stress (positive) under the ambient hydrostatic stress state
   (Constant 6);
8. Uniaxial crushing stress (positive) under the ambient hydrostatic stress state
   (Constant 6);
9. Stiffness multiplier for cracked tensile condition.

Shear transfer coefficients are ranged from 0.0 to 1.0 with 0.0 being a smooth crack, which cannot transfer any shear force, and 1.0 being a type of crack behavior that can transfer the entire shear without any loss in a cracked section. Numbers of studies have been conducted to determine the accurate shear transfer coefficients for FE analysis of RC structures. Studies by Bangash [12], Hemmaty [13], Huyse et al. [14] and the parametric study conducted by Kachlakev et al. [15] have led to the conclusion that an open shear coefficient value chosen less than 0.2 does not lead to a converged solution. Therefore, a value of 0.4 has been suggested leading to successful results. For closed cracks, the value was chosen to be 0.8 according to studies by Kachlakev et al. [15], and Stehle et al. [16]. However, a parametric study was conducted by the authors on a cantilever RC beam FE model to confirm the accuracy of the values recommended, where results (stress at steel and concrete, and maximum deflection of the beam) of the nonlinear FE model were compared to those obtained using the hand calculation methods when the beam was subjected to a load that cracked the concrete [17].

Uniaxial tensile stress and uniaxial crushing stress (constants 3&4) were directly taken from the actual experimental results obtained from concrete cylinders [6]. With defining these two values, ANSYS automatically calculates constants 6, 7, and 8. Constant 9 defines the tension softening behavior of concrete after the stress in concrete exceeds the modulus of rupture (uniaxial tensile stress). When a crack occurs in concrete, setting the “key option (7)” in ANSYS settings to a value of 1 automatically reduces the stress by a value defined by constant 9 to point $T_c f_t$ (Fig. 7), and then gradually slopes down the value to zero. A default value of 0.6 is used in ANSYS for T_c (i.e., Constant 9 = 0.6), which is based on Willam & Warnke [27] concrete material model. A bi-linear steel stress-strain idealization, with a yield strength value of 368 MPa and a modulus of elasticity of 191 GPa, is used for steel reinforcing bars.

The type of analysis chosen for this FE model was static analysis incorporating material non-linearity. Non-linear material properties were defined for both steel and concrete as mentioned above. In this type of analysis, total applied load is divided into smaller load increments (load steps). At the end of each load increment the stiffness matrix–if changed due to material non-linearity–is recalculated before moving up to the next load increment. Newton-Raphson equilibrium iterations method is used in ANSYS to adjust the changes in stiffness in each load increment to account

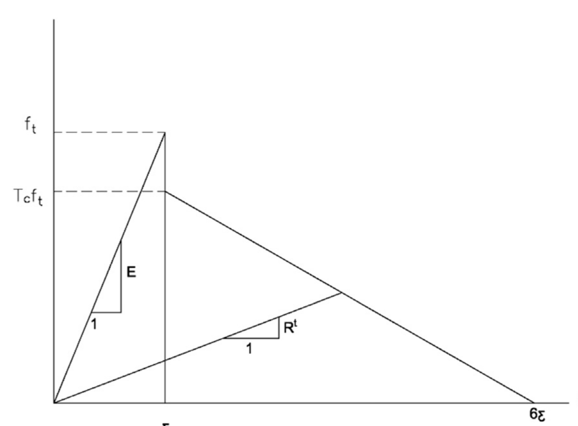

Fig. 7. Tension softening model for concrete used in ANSYS based on Willam et al.'s material model for concrete [27].

for nonlinearity [11]. This method checks for convergence within a tolerance limit defined in the program. Force and displacement convergence criteria were used in this study, however, ANSYS default tolerance limits did not yield to a converged solution because of highly non-linear behavior of the model. Therefore, the values were increased by a factor of 5 (chosen values were 0.5% for the force and 5% for the displacement tolerance limits). The effectiveness of using the greater tolerance values in order to minimize the convergence problems associated with SOLID65 element are confirmed in the study done by Wolanski [26].

2.1. Correlation of FE analysis and test results for solid slab panels subjected to full service gravity load (out-of-plane loads)

In the actual experiment, before performing the in-plane strength test, Panel 1 was subjected to full service gravity load as specified in design of the prototype two-way slab (self-weight plus 3.83 kPa superimposed live load) [6]. Loads were applied by hanging weights from inserted hooks placed uniformly at 540 mm spacing underneath the slab panel. Vertical displacements at key locations of the floor panel were measured (1.30 mm at mid-point of the slab panel and 0.847 mm as the average mid-span deflection of the edge beams perpendicular to the wall), while two parallel cracks were observed on top of the slab at the edge of the wall and at the edge of beam parallel to the wall (Fig. 8). Vertical maximum deflections of two beams and slab panel determined from the FE model analysis, after adjusting them by the scale factor, were 1.30 mm at the midpoint of the slab panel (marked as “Slab” in Fig. 8) and 0.706 mm as the average mid-span deflection of the edge beams perpendicular to the wall (marked as “1 & 2” in Fig. 8), indicating a close agreement with results obtained from the actual experiment. Also, as shown in Fig. 8, the crack pattern seen in concrete elements in the FE model compared well with the crack pattern that was observed in the actual experiment.

2.2. Correlation of FE analysis and test results for solid slab panels subjected to monotonic in-plane and out-of-plane Loads

In the actual experiment, in-plane loads were applied monotonically along the edge beam parallel to the wall, with presence of full service gravity load in Panel 1; this test was called BV1MN. Following the same loading sequence used in the actual experiment, the load-displacement curve obtained from the FE model analysis compares favorably with the actual experiment's results, with regard to its shape and its prediction of the ultimate load capacity as shown in Fig. 9. In the actual experiments' report, it was also noted that in BV1MN test, stiffness decreased gradually and smoothly until the ultimate load capacity was reached. This behavior was attributed to the development of cracks along the wall-slab region due to the effect of out-of-plane loads [6]. These cracks were also observed in the FE model after service gravity load was applied (Fig. 8). In other words, existing cracks made the transfer of loads from cracked concrete to reinforcing bars more gradual when in-plane loads were applied. However, the same phenomena (presence of cracks due to gravity loads) caused a 15% drop in in-plane load carrying capacity of the floor slab system in both the FE model and the actual experiment.

Based on observations made from the actual experiment, the cracking pattern was significantly different at the top and bottom of the slab. Most of the cracks at the top surface were confined near the slab-wall interface while many of the cracks at the bottom extended radially from the center of the slab [6]. This pattern was replicated accurately in the FE model analysis as shown in Fig. 10 where the cracking pattern of the top and bottom of the FE model are shown.

The initial slope of the load-displacement curve for BV1MN test set up obtained in the actual experiment was considerably smaller than that of the ANSYS FE model analysis. This discrepancy (the higher stiffness in the FE model) was also noticed in the original work conducted at Lehigh by Nakashima et al. [18] when they tried to compare their experimental load-displacement curve with the calculated one obtained using a 2D FE analysis. This difference in stiffness has been explained in their published paper as a result of the panel's possible additional damage prior to the strength test, the paper elaborates this more by saying: “*Shrinkage cracks were observed in specimen before the testing and they were believed to have contributed to the lower stiffness. Also, the remainder of the discrepancy can be attributed to minute cracks caused by accidental forces which might have been applied during the transportation of the specimens. In addition, the material properties used in the analysis, based upon the concrete cylinder tests, may not have represented the material properties in the specimens.*” [18]. To verify that this difference in stiffness was due to the damages to specimen prior to testing (and not due to having an inaccurate FE model) as stated by Nakashima et al. [18], authors decided to calculate the initial stiffness using the virtual work method and compare it with the value obtained from the FE model analysis [17]. By assuming the slab as a deep beam and accounting for all the reinforcements, the equivalent moment of inertia of the section was calculated. Then, the initial slope of load-displacement curve was computed using virtual work method where a small in-plane load within linear-elastic region was applied (this method also accounts for shear deformation). On the other hand, the same load value that was used in virtual work method also was utilized

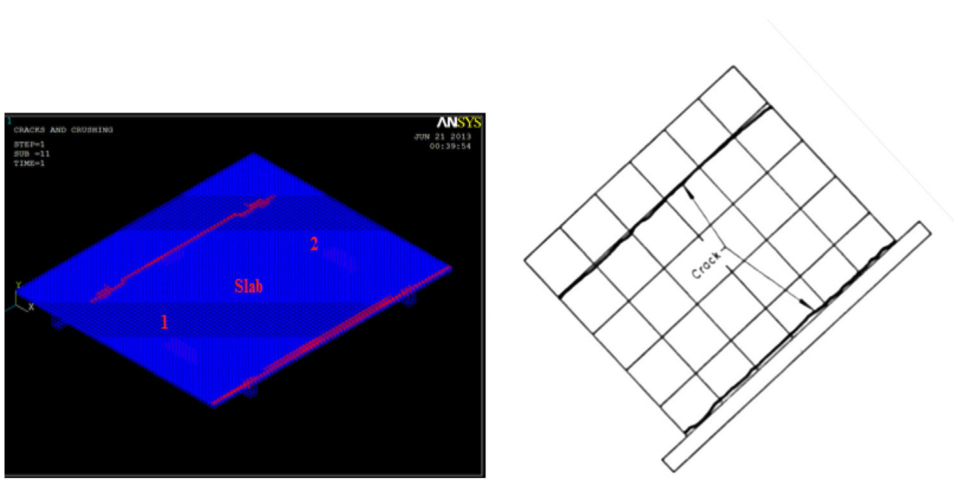

Fig. 8. The gravity load test cracking pattern; ANSYS (left), the actual experiment (right).

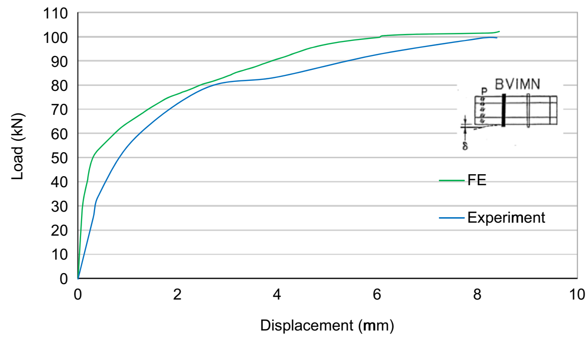

Fig. 9. In-plane load-displacement curves for the slab panel subjected to in-plane and out-of-plane loading.

in the FE model analysis and the corresponding stiffness was obtained from FE analysis. The stiffness obtained from virtual work method (hand calculation), compared well with the value obtained from FE analysis (virtual work stiffness/FE stiffness = 0.97) [17]. This may explain that the existing discrepancy between stiffness obtained from the FE analysis compared to that of obtained from the actual experiment can be due to the fact that the actual specimen had some cracks before it was tested.

3. FE analysis of slab panels with openings

3.1. Parametric study and design code requirements

Now that the constructed FE model was validated using the actual test results of solid slab panels, the next step was to use it to investigate effect of openings with different sizes in two-way FE RC slab panel models subjected to in-plane and out-of-plane loads. Three different opening sizes with respect to size of the middle panel area were considered: 6.25%, 14%, and 25% (Fig. 11). These ratios were calculated by ignoring overhanging parts of slab panel. The openings were placed within the intersection of two middle strip regions of slab panels. Sec. 13.4.1 of ACI Building Code permits the opening of any size in a slab if it is located at the intersection of two middle strips and if the required serviceability and strength conditions shown by acceptable analysis methods are met. However, it has size limitations for opening cuts at the intersection of two column strips (up to one-quarter of the span) and it does not allow openings in the intersection of a column strip and a middle strip [19]. As an ACI code requirement and a common design practice [9,21], the missing reinforcing bars at bottom of slab due to the presence of openings were added to the boundary of openings to maintain full out-of-plane bending capacity of the slab panel in this study.

3.2. Behavior of slabs with openings subjected to monotonic in-plane loads only

Under the in-plane loading condition, the FE model with 25% opening size demonstrated a different behavior compared to the solid slab. First cracking occurred at about 12 kN at the top left and bottom right corners of opening. However, these cracks did not create a major loss of stiffness in the slab (Fig. 12). As these cracks started to expand diagonally, a second set of cracks appeared at about 31.2 kN around the slab-wall junction region, which resulted in the first major loss in stiffness in this model (Fig. 13).

At this stage maximum steel stress of 250 MPa (68% of the yield strength) occurred at the slab-wall junction, which was almost 1.6 times the stress value in reinforcing bars located at opening corners. This means that the contribution of cracks at the slab-wall junction area were more on in-plane stiffness loss of the FE slab panel than cracks formed at the opening corners. Fig. 13 illustrates the cracking pattern and stresses at reinforcing bars at first major stiffness loss.

At the load value of 51.6kN the scenario was reversed, where stresses in reinforcing bars at corners of the opening were larger than stresses at reinforcing bars at the slab-wall junction area. In fact, corner reinforcing bars reached the yield stress first, which caused the second major loss of stiffness as shown in Fig. 12. Stress values of reinforcing bars at opening corners were approximately 1.4 times the stresses at slab-wall junction. Finally, at the load value of 81kN the FE slab model with 25% opening experienced failure by crushing of concrete elements where an ultimate in-plane displacement of 20.7 mm was obtained, as shown in Fig. 12. A comparison of these results with ones obtained from FE solid slab model analysis (Fig. 9), indicates that the changed failure mechanism of the FE slab model with 25% opening resulted in yielding of steel reinforcing bars around the corners, a major stiffness degradation of the slab, and a more uniform distribution of steel yielding in the slab panel.

In the FE slab model with 14% opening, it appeared that the opening still was affecting flexural behavior of the slab especially towards failure. At the load value of 28.8 kN (30% of ultimate load), the first concrete cracks started to appear at the corners of the opening, however, this did not create a significant loss of stiffness in the slab. At the load value of 48 kN cracks at the opening corners were accompanied by a set of cracks at the slab-wall region

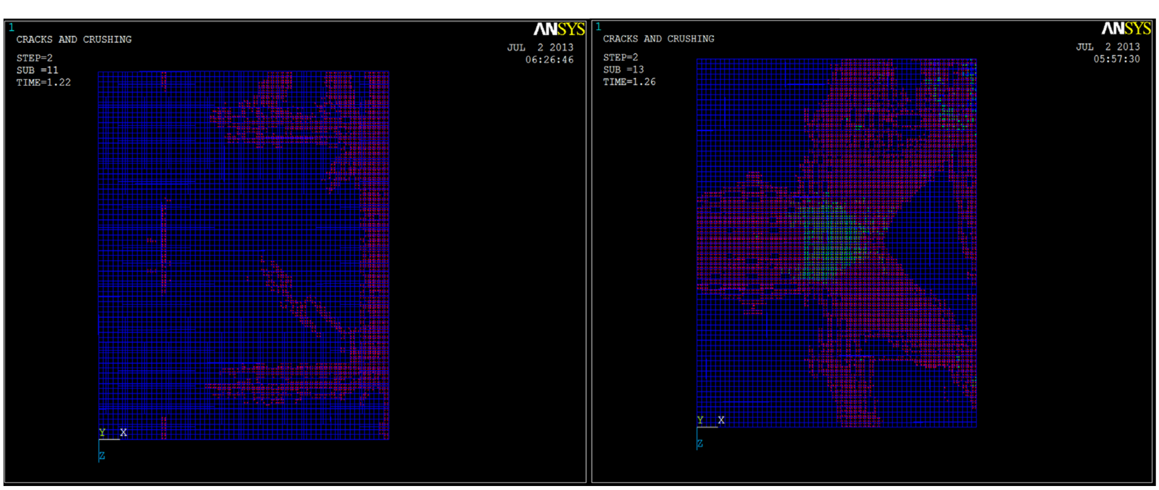

Fig. 10. The cracking pattern in BV1MN FE model; top slab (left), bottom slab (right).

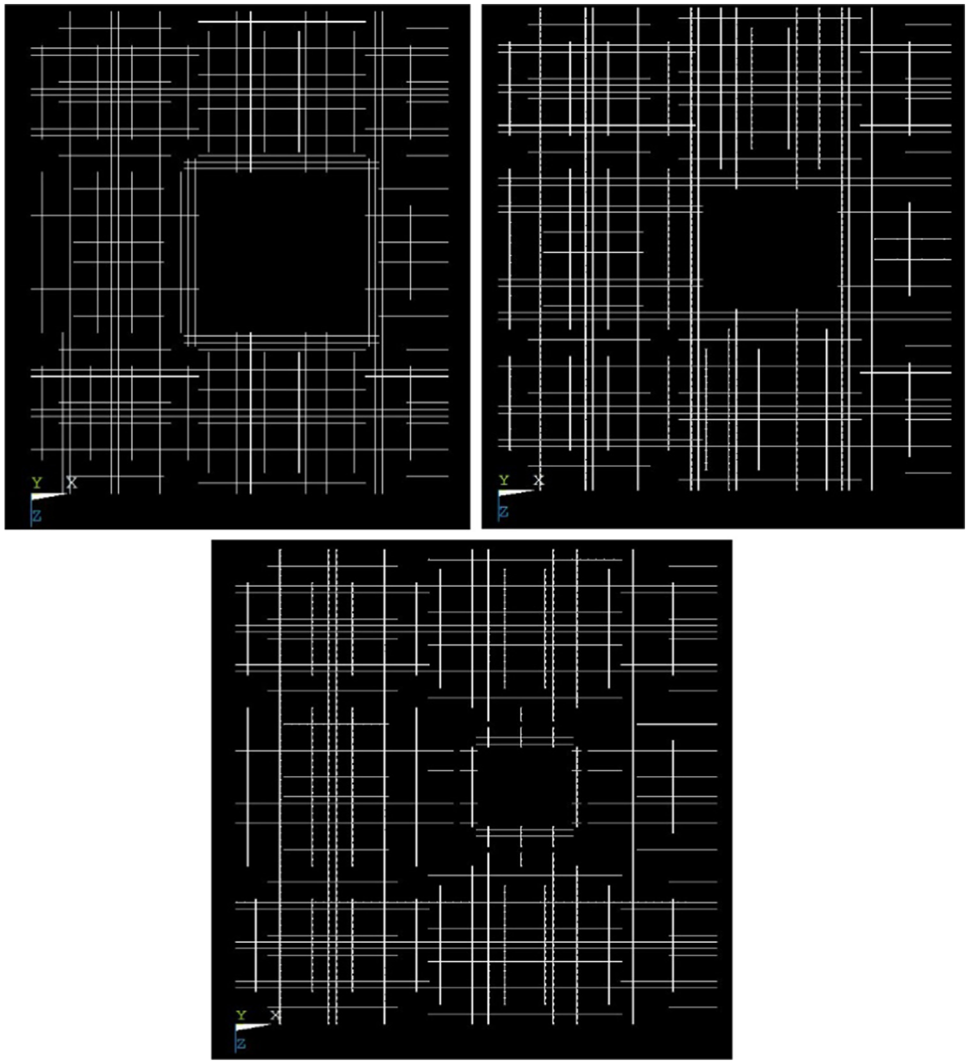

Fig. 11. FE models with openings; 25% (top left), 14% (top right), 6.25% (bottom).

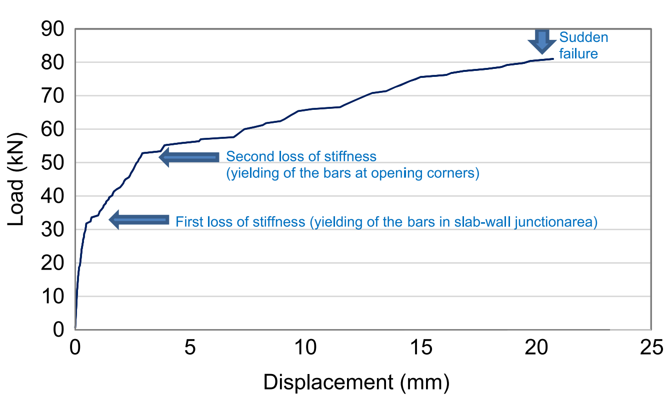

Fig. 12. Load-displacement curve for the FE slab with 25% opening subjected to in-plane loading only.

(top right) to cause the first major loss of stiffness. At the load value of 76.2 kN reinforcing bars at opening corners exceeded the yield strength. In-plane behavior of the FE slab model with 14% opening was similar to that of the FE slab model with 25% where, in both cases, bars at opening corners reached the yielding stress first. The overall in-plane behavior of the FE slab model with 6.25% was similar to that of the FE solid slab model, but with a slightly larger lateral deflection due to a reduced in-plane stiffness at the location of opening. A small opening size of 6.25% also did not affect the failure mechanism where the shape of load-displacement curve was similar to that of the FE solid slab model and no major loss of stiffness was observed. Table 2 provides a summary of the results of the FE slab analysis with and without openings subjected to in-plane loads.

3.3. *Behavior of slabs with openings subjected to in-plane and out-of-plane loads*

In the FE analysis of slab model with 25% opening subjected to both out-of-plane and in-plane loads, the in-plane load carrying capacity slightly decreased (about 4%), this decrease can be attributed to presence of out-of-plane loads. The overall behavior was very similar to that of the FE model subjected to in-plane loads as shown in Fig. 14. Suggesting that presence of out-of-plane loads had a minimal effect on in-plane behavior of the FE slab model with a larger opening size of 25%. When result of the FE analysis for slab with 14% opening subjected to in-plane and out-of-plane loads was compared to that of the slab with 14% opening subjected to in-plane loads only, it was seen that the in-plane load capacity decreased from 93 kN to 86 kN (10% drop) and lateral displacement increased from 11.3 mm to 13.72 mm. The first significant change in stiffness occurred at the load value of 26 kN (30% of load capacity) where the stress of concrete elements

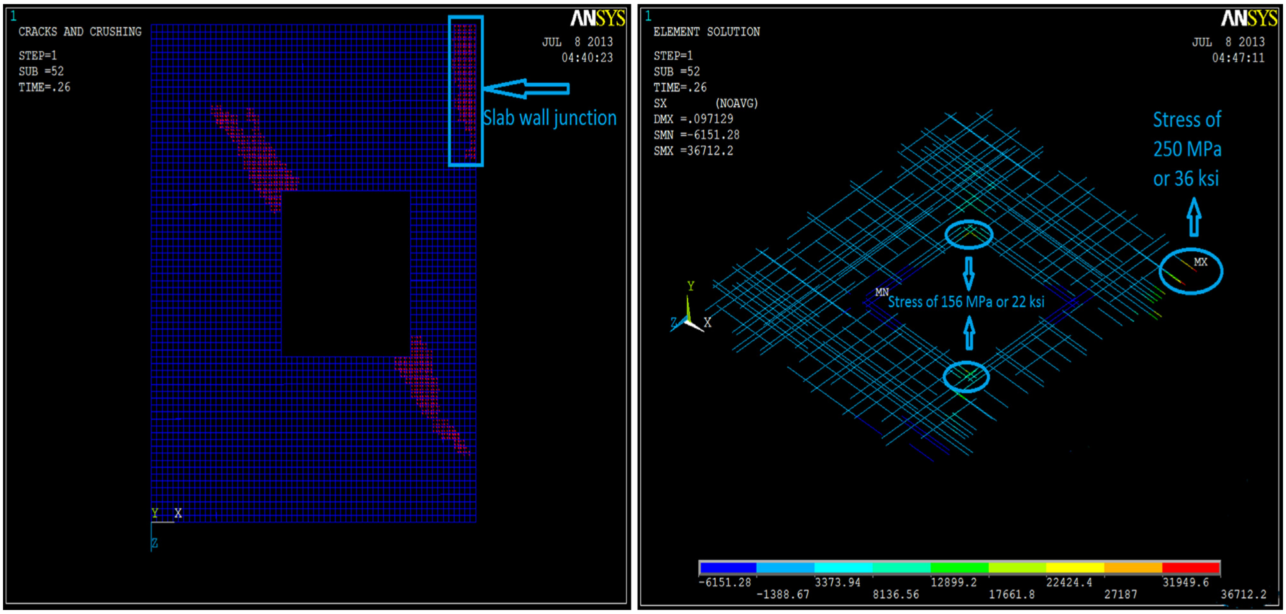

Fig. 13. The cracking pattern in concrete (left), and stresses in steel bars at the first major stiffness loss (right).

Table 2
Results for the FE slabs with openings subjected to in-plane loading.

Models with in-plane loads only		
Opening size	Load capacity (kN)	Displacement (mm)
25%	81	20.7
14%	93	11.3
6.25%	102	9.48
0% (solid slab)	117	8.04

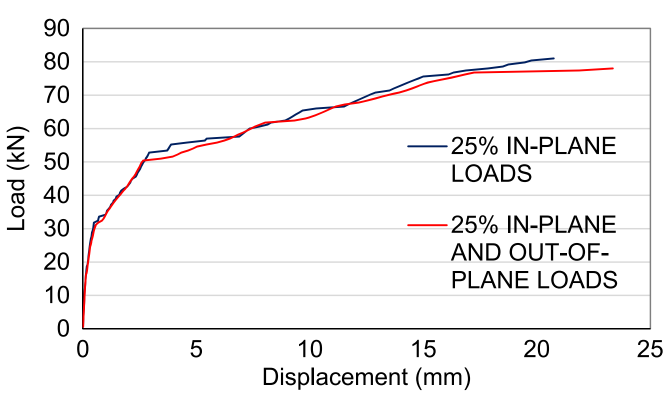

Fig. 14. Load-displacement curve comparison for the FE slab with 25% opening.

Table 3
Results for the FE slabs with openings subjected to in-plane and out-of-plane loads.

Models with in-plane and out-of-plane loads		
Opening Size	Load Capacity (kN)	Displacement (mm)
25%	78	23.9
14%	86	13.7
6.25%	92	10.21
0% (solid slab)	102	8.8

exceeded the modulus of rupture. At the load value of 60 kN bars at the corners of opening and near the slab-wall junction area started to yield simultaneously. This caused a relatively significant loss of stiffness in the FE slab model. At the ultimate load value of 86 kN bars at plastic hinge locations yielded resulting in in-plane failure of the FE slab model. In the FE slab model with 6.25% opening the behavior was almost identical to that of the solid slab. The small opening size slightly changed failure mechanism of the FE slab compared to that of the FE solid slab (Fig. 18). Table 3 provides a summary of the FE analysis results comparison of the slabs with and without openings subjected to both out-of-plane and in-plane loads.

Results suggest that the presence of out-of-plane loads in the FE slab models with openings decreased the in-plane load capacity and increased the maximum in-plane deflection. The same trend was observed in solid slab where the application of out-of-plane load decreased the in-plane load capacity and increased deflection. However, in presence of out-of-plane loads, the in-plane load capacity reduction was less pronounced for slabs having larger openings since they had less gravity load and gravity load appeared to be causing capacity reduction by creating two lines of cracks along the wall and the beam parallel to wall as shown in Fig. 8.

Also, results in Table 3 suggest that the FE slab models with openings behave in a more ductile manner as the opening size increases (compared to the FE solid model). However, in-plane load capacity in the FE slab model with 25% openings dropped considerably (by 24%). Therefore, it was decided to strengthen this slab by adding two diagonal bars (with a total cross-section area of 723 mm^2) at the corners of openings (Fig. 15) as recommended by Enochsson et al. [9] in order to meet Section 13.4.1 requirements of ACI Building Code [19]. The non-linear load-displacement behavior of strengthened FE slab panel with 25% opening is shown in Fig. 16, where its load-displacement curve is compared to ones obtained from an FE solid slab model and an un-strengthened FE slab model with 25% opening. As it can be observed, the addition of diagonal reinforcing bars at the opening corners helped to recover the in-plane load capacity to 103 kN, meeting ACI strength requirements in Section 13.4.1. This indicated that adding diagonal reinforcement to the opening corners not only improved out-of-plane load carrying capacity of slabs (as shown by Enochsson et al. [9]), but it was also effective in recovering the significant in-plane load carrying capacity drop that was caused by presence of 25% opening.

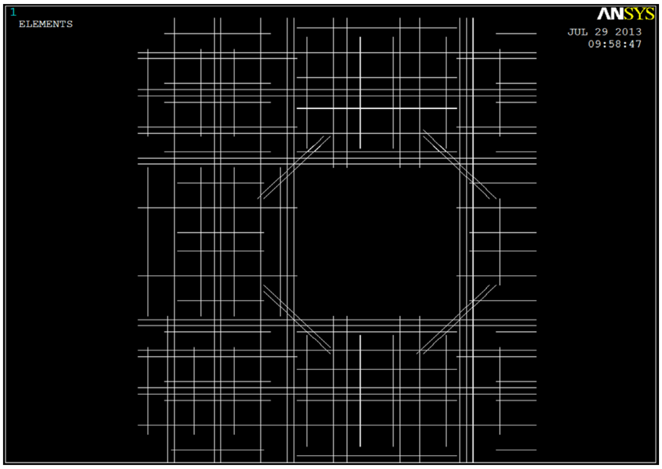

Fig. 15. Strengthening the FE slab model with 25% opening by adding diagonal bars at opening corners.

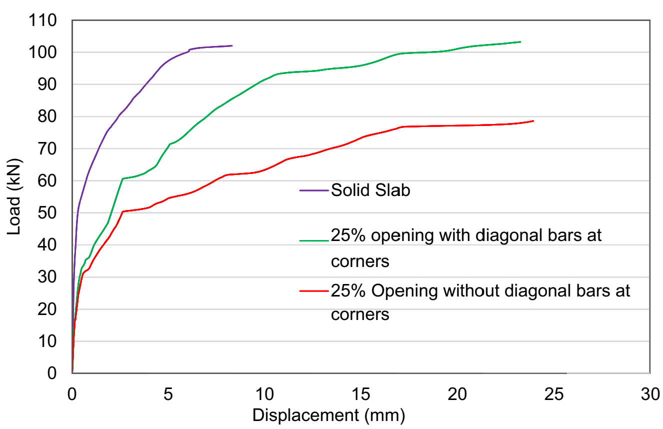

Fig. 16. Load-displacement curves for the FE solid slab, the FE slab with 25% opening and diagonal bars at opening corners, and the FE slab with 25% opening without diagonal bars.

3.4. Effect of openings on in-plane behavior of slabs

Openings clearly affected the failure mechanism of the FE slab models by causing the formation of plastic hinges around the opening corners, while the failure of the solid panels–as concluded by the experimental study performed at Lehigh University [6] and the 3D FE analysis conducted in this study–was due to the formation of the plastic hinges in region of maximum in-plane moment (shown in the left picture in Fig. 17). This change in behavior, mainly caused by formation of the additional plastic hinges around the opening corners, altered the shape of the load-displacement curve (i.e. moment-curvature curve) when compared to that of the solid slab. Compared to the solid slab behavior, presence of the openings seemed to have resulted in a disproportional deviation of the three important points of the load-displacement curve (concrete cracking, yielding of reinforcing bars, and ultimate failure) that can be used to construct the idealized trilinear moment curvature curve for analysis of buildings that have floors with openings in them. Fig. 18 compares the load-displacement behavior between the FE solid slab and the FE slabs with openings when subjected to full service (out-of-plane) and in-plane loads. In comparison with the FE solid slab, it can be seen that presence of a large opening size of 25% has affected the in-plane behavior of the FE slab in a highly disproportional manner. Also it can be seen that, even the presence of smaller opening sizes (6.25% and 14%) have affected the in-plane behavior of the slabs. Therefore, it can be concluded that, when the global structural in-plane behavior of buildings with floor diaphragms having openings is to be predicted, ignoring the effect of openings may give erroneous results.

The effect of openings (especially opening corners) on behavior of RC slabs also must be considered when trying to retrofit slabs with openings since results of this study clearly indicated that yielding of bars, and cracking of concrete around opening corners are highly influential in changing the in-plane behavior of slabs. This is very important since, as evidenced by the literature review conducted in present study on design and retrofitting/strengthening of RC slabs having openings, emphasis is mainly put on applying different types of strengthening methods uniformly around the boundary of openings ignoring the corners. Authors believe that this is because of the effect of openings on behavior of RC slabs, especially when subjected to in-plane loads is not understood/studied enough.

4. Conclusions

In short-to-high-rise RC buildings having a floor aspect ratio greater than 3:1, yielding and even collapse of floor diaphragms have been experienced in past earthquakes [28]. However, due to the lack of knowledge in understanding the true in-plane behavior of slabs with openings, currently floors are designed neglecting the effect that openings might have on in-plane characteristics of the floors. A 3D nonlinear FE model was used to validate the experimental results for slab subassemblies (with no opening) subjected to in-plane and out-of-plane loads. Then the FE model was used to study the effect of openings and out-of-plane loads on load-displacement characteristic of floor panels with various opening sizes (6.25%, 14%, and 25%). Results implicated that presence of openings clearly changed the in-plane behavior of RC slabs compared to those of slabs without openings and that this oversimplification in design and analysis of slabs by ignoring the opening effects might lead to erroneous results.

It is also concluded that the larger the opening size, the less significant the effect of out-of-plane loading on in-plane capacity reduction of the slabs; and the smaller the opening size, the less change is observed in in-plane behavior of the slabs (in comparison with the solid slab). The initial point of deviation from elastic part of load-displacement curve of the FE slabs with openings is somewhat at a higher level (M_{cr}/M_{ult} of 49%∼52% compared with M_{cr}/M_{ult}∼ 30% obtained in the solid slabs). The failure mechanism of FE slabs with openings is significantly different from FE solid slabs since the yielding of bars at opening corners appeared to significantly affect the slab behavior. This is very important since, as evidenced by the literature review conducted in the present study on design and retrofit/strengthening of RC slabs with openings, the emphasis is mainly put on applying different strengthening methods uniformly around the boundary of openings rather than strengthening the corners. Authors believe that this is because the effect of openings on behavior of RC slabs, especially when subjected to in-plane loads, is not understood/studied enough. The positive contribution of inclined reinforcing bars placed at opening corners in strengthening the in-plane load carrying capacity of slab panels with opening is effectively demonstrated by use of the FE model.

Finally, this study only considered three openings sizes, which were located at the center of the slab panel. The effect of larger opening sizes that are located in other areas of the slab (based architectural needs) must be also considered in future research. Also, other RC slab types (i.e. flat slabs) might behave differently in presence of openings and this must be also considered in future studies related to this topic.

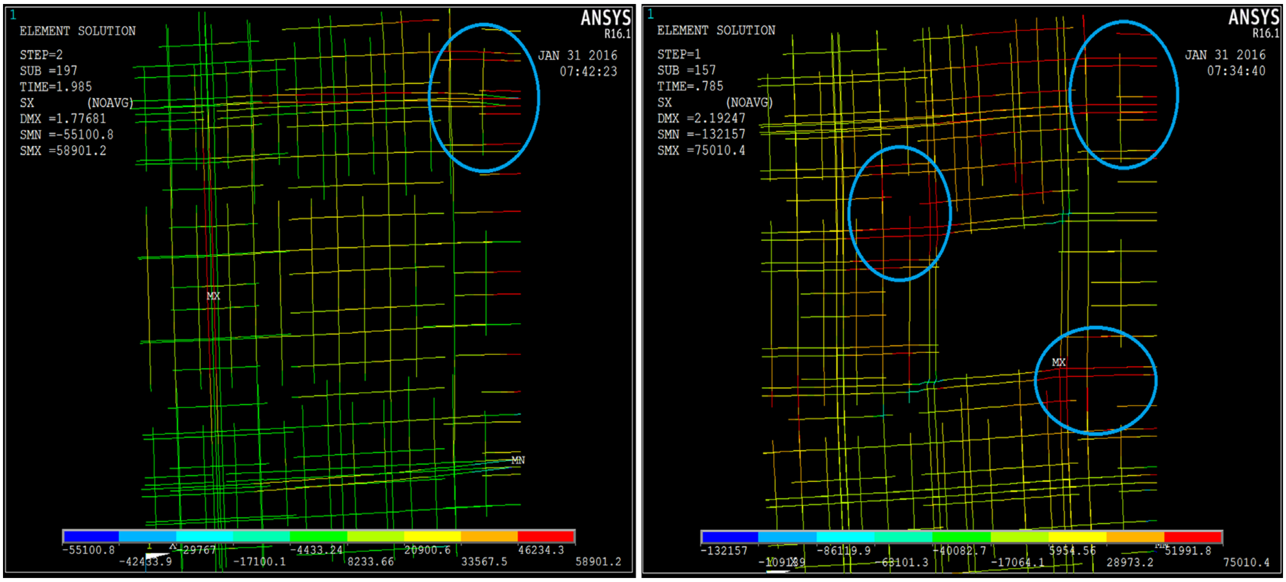

Fig. 17. Formation of plastic hinges before failure, indicated by blue circles at location of the maximum in-plane moment/moments; solid FE slab (left), FE slab with opening (right).

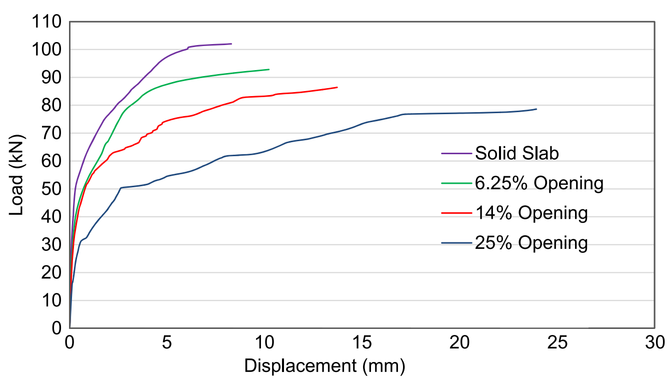

Fig. 18. Load-displacement curves for the FE solid slab and the FE slabs having different opening sizes.

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