NONLINEAR FE ANALYSIS OF RC BUILDING FLOOR DIAPHRAGMS WITH OPENINGS SUBJECTED TO IN-PLANE AND OUT-OF-PLANE LOADS

R. Khajehdehi\textsuperscript{1} and N. Panahshahi\textsuperscript{2}

ABSTRACT

To determine the inelastic seismic response of reinforced concrete (RC) buildings typically tri-linear in-plane load-deformation idealization is used for macro-modeling of the behavior of RC floor diaphragms to account for cracking and yielding prior to the failure. In 1980’s solid (without openings) beam supported RC two-way slab panels were experimental studied under in-plane monotonic and cyclic loads, with and without service gravity loads at Lehigh University to determine their in-plane load-deformation and hysteretic characteristics. Subsequently, these results were implemented in IDARC2, a nonlinear damage analysis computational tool developed for analyzing RC buildings with flexible floor diaphragms, and the idealized floor slab behavior were verified using two shake-table one-story scale RC buildings at SUNY/Buffalo. Due to lack of experimental data, in the present study a micro-model finite element approach is used to investigate the inelastic behavior of RC floor diaphragms with openings. A general purpose FE software is initially used to validate a nonlinear 3D model of the Lehigh University tested panels using eight node concrete brick elements combined with the embedded steel elements. Subsequently, a sensitivity study is conducted where the effects of opening size (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 deformation characteristic of the floor panels are investigated. The result indicates that the drop in ultimate in-plane load capacity of the floor diaphragm due to 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-deformation curve moves up from 30\% to about 50\% of the ultimate load capacity for slab with larger size openings.

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To determine the inelastic seismic response of reinforced concrete (RC) buildings typically tri-linear in-plane load-deformation idealization is used for macro-modeling of behavior of RC floor diaphragms to account for cracking and yielding prior to the failure. In 1980’s solid (without openings) beam supported RC two-way slab panels were experimental studied under in-plane monotonic and cyclic loads, with and without service gravity loads at Lehigh University to determine their in-plane load-deformation and hysteretic characteristics. Subsequently, these results were implemented in IDARC2, a nonlinear damage analysis computational tool developed for analyzing RC buildings with flexible floor diaphragms, and the idealized floor slab behavior were verified using two shake-table one-story scale RC buildings at SUNY/Buffalo. Due to lack of experimental data, in the present study a micro-model finite element approach is used to investigate the inelastic behavior of RC floor diaphragms with openings. A general purpose FE software is initially used to validate a nonlinear 3D FE model of the Lehigh University tested panels using eight node concrete brick elements combined with the embedded steel elements. Subsequently, a sensitivity study is conducted where the effects of opening size (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 deformation characteristic of the floor panels are investigated. The result indicates that the drop in ultimate in-plane load capacity of the floor diaphragm due to 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 variation from the initial linear portion of the in-plane load-deformation curve moves up from 30% to about 50% of the ultimate load capacity for slab with larger size openings.

Introduction

Floor diaphragm in-plane flexibility in concrete buildings was ignored for simplicity by structural engineers in practical design until ASCE7 Building Standard [1] acknowledged that this assumption can result in considerable errors when predicting the seismic response of RC buildings with diaphragm plan aspect ratio greater than 3:1. Such provisions are supported by a comprehensive experimental and analytical research conducted at University at Buffalo (SUNY) and Lehigh University in 1980’s for solid (i.e., without openings) beam supported reinforced concrete slab panels where their in-plane load deformation and hysteretic characteristics were experimentally evaluated using inelastic cyclic testing of slab panel subassemblies, with and without full-service (out-of-plane) loads [2] [3]. Subsequently, the results were implemented in

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the 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 the failure) and the three-parameter hysteretic model (to account for stiffness degradation, strength deterioration, and bond-slip pinching) for the slab elements [4]. In this macro-model approach, the RC building is idealized as a series of plane frames (consisting of inelastic beam, column, shear-wall elements) linked together by inelastic slab elements and transverse beams. Distributed flexibility was used to account for the effect of the spread plasticity at the member ends of all the inelastic elements. Furthermore, IDARC2 predictions of the inelastic performance of concrete floor diaphragms were verified by two shake-table tests of one-story concrete buildings [5][6].

Due to lack of experimental data on inelastic in-plane behavior of RC floor diaphragms with openings, a micro-model finite element approach is used. The effects of opening size and out-of-plane loading on the in-plane load deformation characteristic of the floor panels are investigated.

**Three Dimensional Finite Elements Modeling of RC Floor Diaphragms**

Three dimensional inelastic FE models of the prototype floor diaphragms of the end panels of the shown scale RC beam-supported floor slab subassemblies (Fig. 1) tested at Lehigh University are constructed utilizing ANSYS Solid 65 (an eight node concrete brick element) and REIN 264 (an axial element suitable for discrete modeling of the embedded reinforcing bars) using 72 volumes in order to properly placing the embedded top and bottom reinforcing steel in floor slabs and supporting beams, as shown in Fig. 2. The test specimen, which consists of three square panels supported on two shear-walls and four columns, were designed to represent a scale model of a portion of floor system in a medium-to high-rise building [3].

![Figure 1. Plan, elevation and dimensions of scaled test specimen (shown in mm) [3].](image)
Based on convergence study conducted, the prototype floor slab was meshed in 152 mm x 152 mm (plan dimensions) and in four layers through the thickness of the slab, and the stem of the supporting beams was divided into three layers. To properly model the boundary conditions of the slab panels, the slab and beam nodes attached to the wall were restrained against translation in all directions to model clamped fixed condition of the test specimen walls, and a single node at the center of bottom surface of the supporting columns was restrained only in vertical direction to model a sliding support used at the base of supporting pedestals.

Twenty-eight day compressive strength of concrete used in the end panel floor slabs, beams, and walls was 27.7 MPa, and in supporting columns was 34.5 MPa. ANSYS default nonlinear concrete material model (William and Warnke) is used [7]. Special care is taken to account for tension softening at the smeared cracks. Bi-linear steel stress-strain idealization with yield strength of 368 MPa and modulus of elasticity of 191 GPa is used for the steel reinforcing bars. Similitudes relationships are used to translate the specimen dimensions, reinforcing steel cross sectional area, concrete and steel materials properties, applied loads and floor slab deformations between the scaled test model and the prototype FE model.

**Correlation of FE and Test Results for Solid Slab Panels Subjected to Full Service Load**

Before performing the in-plane strength test in the laboratory, Panel 1 was subjected to full service gravity load as specified in the design of the prototype two-way slab (self-weight plus 3.83 kPa superimposed live load) by hanging weights from inserted hocks place uniformly at 540 mm spacing underneath the slab panel. The vertical displacements at the key locations of the floor panel were measured (0.847 mm as the average mid-span deflection of the edge beams perpendicular to the wall and 1.30 mm at mid-point of the slab panel) 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. Vertical maximum deflections of the beams and the slab panel determined from the FE analysis after adjusting the results by the scale factor are 1.30 mm and 0.706 mm, respectively. Also, the smeared crack pattern observed in the concrete elements compared well with the test results (Fig. 3).
Correlation of FE and Test Results for Solid Slab Panels Subjected to In-plane Load

In the experimental study, in-plane loads were applied monotonically along the edge beam parallel to the wall with presence of full service gravity load in Panel 1 (BV1MN) and in absence of gravity load in Panel 2 (BH2MN). Following the same loading sequence as in the experiment, the in-plane load-deformation curve obtained from the FE analysis compares favorably with the experimental results with regard to its shape and its prediction of the ultimate load capacity of the slab panel as shown in Figs. 4.

![Figure 3](image1.png)

Figure 3. Slab cracking under service gravity load: ANSYS (left) and experiment (right).

![Figure 4](image2.png)

Figure 4. In-plane load-deformation curve for slab panel with out-of-plane loading.
Similar comparison is made in Fig. 5 between the experiment and FE results for slab Panel 2 when no out-of-plane load is present when the in-plane loading is applied. Although the ultimate load capacity of the slab panel is predicted by the FE analysis reasonably well (117 kN), however, the ANSYS model could not reproduce the jagged shape of the load-deformation curve (caused by the breaking of few reinforcing steel bars [3]) resulting in negative slope of the load-deformation plot.

Figure 5. In-pane load-deformation curve for slab panel without out-of-plane loading.

It is also observed that the initial slope of the load deformation curves for both BH2MN and BV1MN tests are considerably smaller than that of the FE analysis. This has been explained in the experimental research due to the panels’ possible additional damage prior to the strength test [3]. Also, for the test BH2MN, the initial slope of the load-deformation curve as computed using the virtual work method (which also accounts for shear deformation) compares well with the value obtained from the FE analysis [8].

It is also noted that in the BV1MN test the stiffness decreased gradually and smoothly until the ultimate capacity was reached (unlike BH2MN). The reason is that the service gravity loads already started the development of some of the cracks at the plastic hinge region (the region between the end wall where the top slab and beam rebars were cut off) before the application of in-plane loads. In other words, existing cracks due to gravity loads made the transfer of the loads from cracked concrete to rebars more gradual when in-plane loads are 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.
FE Analysis of Slab Panels with Openings

Parametric Study and Design Code Requirements

Now that the constructed FE model is validated using the test results of solid slab diaphragm panels, the next step is to use it to investigate the effect of openings with different sizes in two-way RC slab panels subjected to in-plane and out-of-plane loads. The previous prototype slab model is used to incorporate the openings. Three different openings sizes in terms of their sizes with respect to the middle panel area considered: 6.25%, 14%, and 25%. These ratios are calculated by ignoring the overhanging parts of slab panel. The openings were placed within the middle strip region of the slab panel. The ACI Building Code (Sec. 13.4.1) permits openings of any size in slabs if the required serviceability and strength conditions shown by acceptable analysis methods are met [9]. Thus, as a routine design procedure, the missing rebars at bottom of slab at the opening location are added to the boundary of the openings to maintain full out-of-plane bending capacity of the slab panel.

Behavior of Slabs with Openings Subjected to Only to In-plane Loads

Under in-plane loading condition the slab model with 25% opening size demonstrated a different behavior compared to the solid slab. The first cracking occurred at about 12 kN at the top left and bottom right corners of the opening. However, these cracks did not create a major loss of stiffness in the slab (Fig. 6). As these cracks started to expand diagonally, second set of cracks appeared at about 31.2 kN at slab-wall junction, which resulted in the first major loss in stiffness in this model (Fig. 6).

![Figure 6. Load-deformation curve for slab with 25% opening (in-plane loading only).](image_url)

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 the rebars located at the opening corners. This means that the contribution of the cracks at the slab-wall junction were more on the in-plane stiffness loss of the slab panel than the cracks at opening corners. Fig. 7 illustrates the cracking pattern and stresses at steel rebars at first major stiffness loss.
At the load value of 51.6 kN the scenario was reversed, where the stresses in the rebars at the corners of the opening were larger than the rebars at slab-wall junction. In fact the corner rebars reached the yield stress first, which marked the second major loss of stiffness in Fig. 6. The stresses of the rebars at opening corners were approximately 1.4 times the stresses at the slab-wall junction. Finally at the load value of 81 kN the slab with 25% opening experienced failure by crushing of the concrete elements where an ultimate in-plane displacement of 20.7 mm was obtained, as shown in Fig. 6. Comparing these results with the ones obtained from solid slab analysis (Fig. 5), indicates that the changed the failure mechanism of the slab results in yielding of the steel rebars around the corners causing a major stiffness degradation of the slab and more even distribution of steel yielding in the slab panel.

Table 1 provides the summary of the results comparison of the slabs with and without openings subjected to in-plane loads. In the slab with 14% opening, the opening seemed to still be affecting the flexural behavior of the slab especially towards the failure. At the load value of 28.8 kN (30% of ultimate load), first concrete cracks started to appear at opposite corners of the opening, however this did not create a significant loss of stiffness in the slab. At the load value of 48 kN the cracks at opening corners were accompanied by a set of cracks at slab-wall region to mark the first major loss of stiffness. At the load value of 76.2 kN rebars at the opening corners exceeded the yield strength, approaching a similar behavior as in the slab with 25% where the rebars at opening corners reached the yielding stress first. The overall behavior of the slab with 6.25% is similar to the solid slab behavior for in-plane load but with slightly larger lateral deflection due to the reduced in-plane stiffness of the location of the opening. The small opening size also did not affect the failure mechanism. The shape of the load-deformation curves were similar and no major loss of stiffness was observed until the complete failure. Failure occurred shortly after rebar yielding at the plastic hinge area near the wall (same behavior was observed in solid slab).
Table 1. Results for slab with openings subject to in-plane loading.

<table>
<thead>
<tr>
<th>Opening Size</th>
<th>Load Capacity (kN)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>81</td>
<td>20.7</td>
</tr>
<tr>
<td>14%</td>
<td>93</td>
<td>11.3</td>
</tr>
<tr>
<td>6.25%</td>
<td>102</td>
<td>9.48</td>
</tr>
<tr>
<td>0% (solid slab)</td>
<td>117</td>
<td>8.04</td>
</tr>
</tbody>
</table>

Behavior of Slabs with Openings Subjected to In-plane and Out-plane Loads

In FE analysis of the slab with 25% opening subjected to both out-of-plane and in-plane loads the in-plane load carrying capacity slightly decreased (about 4%) due to presence of out-of-plane loads. The overall behavior of the slab was very similar to the model with in-plane loads only as shown in Fig. 8.

![Load-displacement curve comparison for slab with 25% opening](image)

**Figure 8.** Load-displacement curve comparison for slab with 25% opening

The FE analysis for the slab with 14% opening is compared with the result of in-plane loads only, it was seen that the load capacity decreased from 93 kN to 86 kN (10% drop) and the displacement increased from 11.3 mm to 13.72 mm. First significant change in the stiffness occurred at the load value of 26 kN (30% of load capacity) where the stress of the concrete elements exceeded the modulus of rupture. At the load value of 60 kN the rebars at opposite sides of the opening and near slab-wall junction started to yield simultaneously. This caused a relatively significant loss of stiffness in the slab. At the ultimate load value of 86 kN the rebars at plastic hinge locations yielded significantly resulting in-plane failure of the slab panel. In slab with 6.25 % opening the behavior was almost identical to the solid slab. The small opening size did not change the failure mechanism of the slab compared to solid slab. Table 2 provides the
summary of the FE analysis results comparison of the slabs with and without openings subjected to both gravity service and in-plane loads.

Table 2. Results for slab with openings subject to in-plane and out-of-plane loads

<table>
<thead>
<tr>
<th>Opening Size</th>
<th>Load Capacity (kN)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>78</td>
<td>23.9</td>
</tr>
<tr>
<td>14%</td>
<td>86</td>
<td>13.7</td>
</tr>
<tr>
<td>6.25%</td>
<td>92</td>
<td>10.21</td>
</tr>
<tr>
<td>0% (solid slab)</td>
<td>102</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Although this pattern indicates that the slab panel with openings behaves in a more ductile manner as the opening size increases (compared to the solid slab), however, since the in-plane strength in the slabs with 25% openings dropped considerably (by 24%), it was decided to strengthen this slab by adding two diagonal rebars (with a total cross-section area of 723 mm$^2$) at corners of the openings as recommended by Enochsson [10] in order to meet the Section 13.4.1 requirements of the ACI Building Code [9]. The non-linear ANSYS analysis results of the strengthened slab panel are given in Fig. 9, where its load-deformation curve is compared with the one obtained from analysis of the solid slab (without opening) and un-strengthened slab panel with openings. As it can be observed the adding the diagonal rebars at opening corners helped to recover the in-plane load capacity of 103 kN, meeting the ACI strength requirements in Section 13.4.1 successfully. In summary, it is concluded that adding diagonal reinforcement to the slab corners not only improves the out-of-plane load carrying capacity of the slabs (as recommended by Enochsson [10], but also it is effective in strengthening the in-plane load capacity.

![Figure 9. Load-deformation curve for the strengthened slab with 25% opening](image)
Conclusions

After the validation study of a 3D nonlinear finite element model is conducted by comparing the in-plane load deformation of RC solid floor diaphragms with the experimental results for slab subassemblies subjected to in-plane and/or out-of-plane loads, the FE model is used to study the effect of out of plane loads on the load-deformation characteristic of floor panels with various opening sizes (6.25%, 14%, and 25%). It is concluded that the larger the opening size, the less significant the effect of out-of-plane loading on the in-plane capacity of the diaphragms; and the smaller the opening size, the less change is observed behavior of the slab (in comparison with the solid slab). It is also observed that initial point of deviation from the elastic part of the load-deformation curve in 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. Also the failure mechanism of the slabs with openings is significantly different from the solid slabs. Finally, the positive contribution of inclined rebars placed at opening corners in strengthening the in-plane capacity of the slab panels with opening is effectively demonstrated by the use of the FE model.

Acknowledgments

The authors would like to thank Dr. Brad Cross and Dr. Jianwei Huang for their assistance.

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