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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

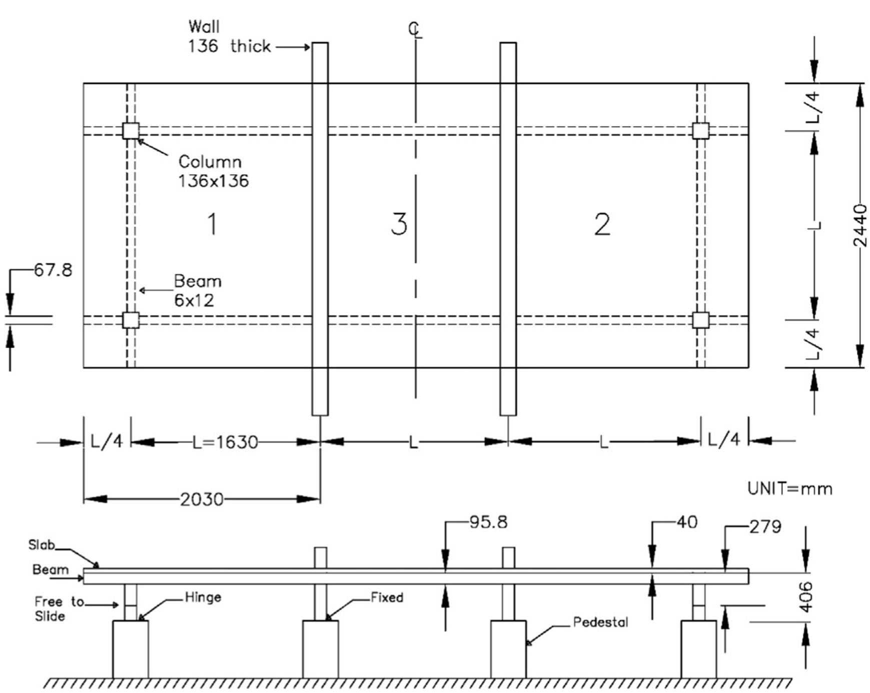

Fig. 1. Plan, elevation, and dimensions of the scaled test specimen (shown in mm) [6].