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Assessment of the diaphragm condition for floor systems used in urban buildings

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ABSTRACT

A study devoted to define the diaphragm condition using linear-elastic analyses for structures with the most widely used floor systems in Mexico (two-way ribbed RC slabs, beam and block, steel decks and waffle RC flat slabs) is presented. The models were analyzed under lateral loading. Previously proposed force and displacement criteria were used to assess their behavior as diaphragm. Two variables that favor the potential flexibility of the diaphragm were assessed in the research: (a) the plan aspect ratio of buildings and (b) the stiffness of the floor system.

Different plan aspect ratios for the buildings were considered in the study. All models were analyzed under uniformly distributed lateral loading with Ansys finite element software using refined meshes. In order to assess the behavior of the different floor systems as a diaphragm, force and displacement criteria were used. The diaphragm condition was assessed using the following parameters: (a) profiles of lateral displacements (Δ) obtained in the top level of the studied floor systems normalized with respect to the lateral displacements at the same level for a rigid diaphragm model (Δ_{rigid}) and (b) the amplification factor for the base shear of central frames with respect to perimeter frames. Flexibility indexes already proposed in the literature were evaluated in the study. Based upon the results of the described parametric study, it can be concluded that a floor system designed according to building codes and the recommendations of manufacturers, plus the experience of prestigious practicing engineers, could lead to floor systems that behave reasonably as rigid diaphragms when the floor spans are not very large (6 m or less), commonly used in apartment buildings. However, this observation cannot be generalized, because other design practices may favor the presence of semi-rigid, semi-flexible or flexible diaphragms, particularly for floor spans of 10 m or more, frequently used in office buildings.

1. Introduction

There is a wide variety of structural options for floor systems used in buildings today as a direct consequence that construction technologies are developed to primarily satisfy the needs for a more economic, faster and more efficient building industry. Many of these structural solutions have been developed to satisfy first the primary function of a floor system, which is to resist and distribute efficiently the vertical loads within the structure. However, the adequacy of such floor systems to resist and distribute efficiently lateral loads (winds and/or earthquakes) should not be directly extrapolated without making a formal assessment. Assuming that floor systems behave as rigid and strong diaphragms under lateral loading without studies (analytical and/or experimental) can seriously compromise the integrity of buildings that use such systems. Unfortunately, some of these floor systems are being used in cities where the earthquake hazard is very important (for example, Mexico City) without conducting experimental and/or analytical studies that would provide further information on how competent they are under lateral loading.

There are available analytical and experimental research studies that evaluate the diaphragm condition under lateral loading for some floors systems. However, such studies do not cover all floor systems that are currently being used in large urban cities, particularly the relatively newer floor systems.

Most available studies were conducted for traditional floor systems. For example, there are experimental [1–4] and analytical [5–8] studies that have shown that for slab thicknesses (h) required to resist vertical loads, ribbed RC slabs, RC flat slabs and the traditional beam and block floor systems reasonably behave as rigid and strong diaphragms under lateral loading for plan aspect ratios up to two ($A/B \leqslant 2$). However, for plan aspect ratios

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larger than two ($A/B > 2$), these floor systems are not stiff enough and, therefore, their lateral flexibility should not be neglected [5,9–16].

On the other hand, the rigid diaphragm condition cannot be warrant for different plan aspect ratios and/or a reduced solid slab thickness (h) for other floor systems which has been used widely for decades, such as the RC waffle flat slabs [17–19], precast beam and block [20] or steel decks [21], particularly when the steel deck does not include a concrete topping [22–24]. Relatively ''new'' RC floor systems, such as posttensioned RC waffle flat slabs with large styrofoam blocks [1 m by 1 m (3.3 ft × 3.3 ft), even longer], where previous studies are not available (up to the authors' knowledge), might not behave as rigid diaphragms also.

Irregular plan configurations [11,12,16,25] and large floor openings [12,15,26] also favor the diaphragm flexibility.

It is well documented in the specialized literature that the seismic response of structures with flexible diaphragms substantially differs from the one of structures with rigid diaphragms [6,9–15,24,27–39].

Assuming having two identical structures, with the only difference that one has a rigid diaphragm and the other one has a flexible diaphragm, the following differences in their dynamic behavior might be observed under seismic loading:

(a) the periods of vibration for the structure with flexible diaphragms are larger than those for the structure with rigid diaphragms [10,13,22–24,29,30,36,40–42]. Therefore, depending on the underlying ground conditions (soil profile type), the structure with flexible diaphragms might be subjected to larger (ascending branch) or smaller (descending branch) spectral accelerations with respect to the structure with rigid diaphragms,
(b) translational mode shapes for the structure with flexible diaphragms are dominated by diaphragm deformations (also known as ''diaphragm action''), whereas for the structure with rigid diaphragms, translational modes are defined by the deformation of the vertical resisting elements (columns, walls, braces, etc.). As a consequence of this difference, an uneven distribution of peak accelerations and displacements are developed in the lateral-resisting elements of the structure with flexible diaphragms in a given story of interest [10,26–30,32,34,35,42]. As a matter of fact, for very flexible diaphragms, peak floor accelerations and displacements are considerably larger, particularly at the diaphragm center [26–30,34,43]. In addition, for very flexible diaphragms, the more flexible lateral-resisting vertical elements also develop larger peak accelerations and displacements than the stiffer lateral-resisting vertical elements [29,35,43]. The described behavior is very different from the one observed in a structure with rigid diaphragms, where peak accelerations and displacements are the same for all lateral-resisting vertical elements and, therefore, lateral forces are distributed in proportion to their lateral stiffness. Therefore, under a rigid diaphragm condition, the more rigid lateral-resisting vertical elements attract a higher proportion of the seismic forces,
(c) for the structure with flexible diaphragms, important out-of-plane deformations are imposed by the floor systems to the lateral-resisting elements perpendicular to the seismic loading, such as perimeter beams [44,45] or walls [29,30,35,43]. In many instances, such deformations are responsible for partial collapses of such elements (particularly unreinforced masonry walls) or severe cracking (for example, RC beams and walls), as it has been observed in past earthquakes, for example, Umbria-Mache [46], Loma Prieta [47] and Northridge Earthquakes [48]. In contrast, out-of-plane deformations usually are not as important in structures with rigid diaphragms,
(d) if there are important stiffness and mass asymmetries within a floor plan, the structure with rigid diaphragms would develop an important modal coupling and be subjected to an important torsional response. In contrast, torsional effects are considerably reduced in a structure with flexible diaphragms [6,26,30]. This is one of the beneficial aspects of the diaphragm flexibility: reduces the torsional coupling.

Then, it can be affirmed that the diaphragm flexibility significantly modifies the seismic response of structures. Therefore, it is not wise under any circumstances to assume that it is safe and conservative to perform an earthquake-resistant design of structures with flexible diaphragms using analytical tools and design procedures commonly used in structures with rigid diaphragms.

Therefore, an analytical study was conducted to assess, in the elastic range of response, the type of diaphragm condition (rigid, semi-rigid, semi-flexible or flexible) for the floor systems most widely used in Mexico in urban buildings: two-way ribbed RC slabs, precast RC beam and block, steel decks and RC waffle flat slabs with fiberglass or styrofoam blocks molds. The potential orthotropic behavior of precast RC beam and block and steel decks was evaluated. Detailed information for this study are reported elsewhere [49]. The most relevant aspects for the study are presented and discussed in following sections.

It is worth noting that diaphragm orthotropic behavior has been largely ignored in most previous studies, except for a few of them [8,29,30,38,39,43]. It was shown in a recent experimental study that the orthotropic behavior of traditional plywood diaphragm construction was significant, with up to 32% reduction in shear stiffness for diaphragms loaded perpendicular-to-joists [38,39].

2. Models under study

Models were developed to be representative of the most widely used structural system (RC moment-resisting frames) and floor systems for urban buildings in Mexico, Mexico City in particular. Building models were then divided in two groups: apartment buildings and office buildings, because office buildings are usually designed and constructed with considerably larger bay widths.

For apartment buildings, a bay width of 6 m (19.7 ft) was considered, which is typical for low income and medium income building developments (high-income building developments have larger bay widths, usually 10 m or 32.8 ft). The following floor systems were considered (Fig. 1):

(a) Ribbed RC slabs, designed according to the reinforced concrete guidelines of Mexico's Federal District Code (NTCC-04 [50]).
(b) Precast beam and block, designed according to the Manual of a Mexican manufacturer [51].
(c) RC waffle flat slabs with styrofoam blocks of 40 cm × 40 cm (15.75 in. × 15.75 in.), using the design procedure of a Mexican Structural Design Firm [52], which it is based in the direct design method of NTCC-04 (similar to the one defined in ACI 318 Code [53]).

For office buildings, bay widths of 10 m (32.8 ft) and 15 m (49.2 ft) were considered, a range that covers bay widths typically used in Mexico City today. The following floor systems were considered (Fig. 2):

(a) Ribbed RC slabs, designed according to NTCC-04 [50].