

# STRENGTH VERSUS DRIFT LIMITATION EFFECTS ON CODE-COMPLIANT SEISMIC-RESISTANT FLAT SLAB BUILDINGS

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## ABSTRACT:

This paper quantifies the relative contribution of minimum stiffness (i.e., code drift limit) versus minimum strength requirements to an economic and reliable design of low- to mid-rise flat slab buildings located in moderate seismic zones (0.25g) and dimensioned as per the emerging version of the seismic design code in Egypt. Two building schemes are considered: “columns-only” and “columns-shear walls” reinforced concrete flat slab buildings. Three versions of each type, namely 4-, 8- and 12-story are investigated with a *theme* layout representative of typical office building construction. The procedure starts by designing the flat slab buildings for “gravity only” loadings. Then, each building is checked for compliance to code seismic design requirements for strength (“No-collapse Limitation”) and stiffness (“Damage Limitation”) through bi-directional multi-mode response spectrum analysis performed on three dimensional computer models of the structure. Re-dimensioning of lateral resisting structural members is applied in order to achieve code-compliant structures under the code estimated seismic demand. In a final step, the design of all studied buildings is revisited and lateral load carrying elements are once more re-dimensioned to satisfy strength requirements only, thus completely ignoring code drift limitation. Buildings are then compared in terms of relative quantities of construction materials to estimate (1) the benefit of adding shear walls to the somehow inherently flexible flat slab buildings; and (2) the penalty which stringent design code analysis constraints may impose on the design economy of such building systems.

**KEYWORDS:** Flat slab, strength, stiffness, drift limit, no-collapse limitation

## 1. INTRODUCTION

One of the most common floor systems for the construction practice in many earthquake vulnerable parts of the world is the reinforced concrete flat slab. Flat slab construction possesses major and various advantages over conventional slab-beam-column construction and is therefore in wide spread use in most Middle East and Mediterranean countries. The flat slab system’s structural efficiency, however, is often hindered by occasionally poor performance under earthquake loading due to inherent insufficient lateral resistance. This undesirable behavior is mainly due to the absence of deep beams and/or shear walls in the flat slab system which generally gives rise to excessive lateral deformations. Hence, it becomes more important to give further attention to the study of this structurally appealing system, yet controversial in terms of its seismic efficiency, reliability and vulnerability.

Flat slab systems in current construction practice are commonly used for relatively light residential loads and for spans from 4.5m to 6m. For heavy industrial or office building loads and/or for larger spans, flat slabs are used with drop panels or column capitals. The flat slab type of construction provides architectural flexibility, more clear space, less building height, easier formwork, and consequently, shorter construction time. However, flat slabs are susceptible to significant reductions in stiffness as a consequence of slab cracking that can arise from construction loads, service gravity loads, temperature and shrinkage effects, and lateral loads [1]. Hence in regions of high seismic risk, flat slab construction should only be used as the vertical load carrying system in structures braced by frames or shear walls, which are responsible for the lateral capacity of the structure [2, 3]. More specifically, Megally and Ghali [4] suggested that the primary lateral load resisting structural elements, such as shear walls, should be combined with flat slabs in seismic zones to keep the lateral drift ratio lower than 1.5%. In spite of the above recommendations, flat slab systems are often adopted as the primary lateral load

resisting system and their use proves popular in seismically active regions. In these cases, the design of flat slab buildings is typically carried out in a similar manner to ordinary frames. Where this practice is followed, Chow and Selna [5] reported that the response under moderate earthquakes indicates extensive damage to non-structural elements even when code provisions for drift limitations are satisfied. Prevention of such damage is important, as it accounts for the greatest portion of total repair costs [6]. It is therefore misleading to employ the performance levels defined for regular concrete frames in the case of flat slab buildings without due regard to the inherent flexibility of these structures.

Rigorous definitions are thus required for the design limit states of flat slab buildings. These design limit states play a significant role in the preparation of an efficient, reliable and yet economic code-compliant seismic-resistant flat slab buildings. To satisfy code drift (i.e., stiffness) limits or in code's wording "damage limitation requirement", and to qualify for minimum strength (i.e., capacity or "no-collapse") requirements are the two primary controls on the seismic design of a structure. The goal of the novel work presented in this paper is to quantify the relative contribution of these two counteracting design requirements (minimum stiffness versus minimum strength) to an economic design of low- to mid-rise (up to 12-story) flat slab buildings located in moderate seismic zones (0.25g) and dimensioned as per the emerging version of the seismic design code in Egypt [7]. These new seismic provisions are in line with current European norms for seismic design of buildings [8]. Buildings are thus compared in terms of relative quantities of construction materials to estimate (1) the benefit, or sometimes the un-necessity, of adding shear walls to the originally somehow inherently flexible flat slab buildings; and (2) the penalty which a stringent design code drift limit or code analysis procedures/constraints may impose on the design economy of such building systems. The paper additionally presents a proposed modification to code analysis procedure to relax some of the noted restrictions in order to achieve a more economic, but still safe and reliable, design of flat slab buildings for moderate seismic zones.

It is nonetheless important to note that the authors are not promoting the use of conventional (not braced by frames or shear walls) flat slab systems as the main lateral load resisting system for the case of mid-rise buildings (above 8-story high) in zones of moderate and high seismicity. The present study is rather a comparative and informative investigation of various seismic-resistant flat slab buildings counterbalancing safety, reliability and economy aspects.

## 2. CASE STUDY BUILDINGS AND CODE SEISMIC DESIGN CRITERIA

The case study buildings are 4-, 8- and 12-story reinforced concrete flat slab buildings with a typical floor height of 3m. Building's layout is essentially bi-symmetric in plan, rectangular in shape and representative of benchmark typical office buildings in current practice (refer to Figure 1). The preliminary thickness of the slab is 23cm with a 30cm-thick drop panels at columns. All columns have a square cross-section with dimensions as shown in Table 2.1 where buildings are designed for gravity loads only and designated from now on as Gravity Buildings (GB). Shear walls are 25cm thick and are located – once introduced – as shown in Figure 1. Proposed shear walls provide nearly equal contribution to the lateral stiffness in both directions of the building. Henceforth, NF4W and NF4 refer to 4-story buildings with and without shear walls, respectively.

Table 2.1 Columns dimensions for different GB models with and without shear walls

Building Type		NF4 & NF4W	NF8 & NF8W	NF12 & NF12W
Columns dimensions (Floors / size,mm)	Corner Column C1	1-4 / 300x300	1-8 / 350x350	1-3 / 400x400 4-12 / 350x350
	Edge Column C2 & C3	1-4 / 400x400	1-2 / 500x500 3-4 / 450x450 5-8 / 400x400	1-3 / 600x600 4-6 / 500x500 7-12 / 400x400
	Interior Column C4	1-2 / 500x500 3-4 / 400x400	1-2 / 750x750 3-4 / 650x650 5-6 / 500x500 7-8 / 400x400	1-3 / 950x950 4-6 / 800x800 7-9 / 650x650 10-12 / 500x500

Case study buildings are designed according to the load requirements in the emerging new Egyptian provisions for loads on structures [7]. For gravity load design, dead loads include the self weight of the structure, a typical floor cover of  $150\text{kg/m}^2$  and partition (wall) loads of  $200\text{kg/m}^2$ . A live load of  $500\text{kg/m}^2$  is also considered. On the other hand, for seismic design purposes, a total seismic mass including self weight and floor covering plus 50% of live load is considered. The seismic design has been carried out assuming a soil type B, an importance factor of 1.0 and a seismic zone 5 (as per Egyptian zoning system) with a design ground acceleration,  $a_g$ , of  $0.25g$  associated with the code reference probability of exceedance of 10% in 50 years. Code Elastic Response Spectrum (ERS) type 1 is adopted [7] – known as type 2 in [8] – and is shown in Figure 2 for the case study buildings describing the seismic hazard based on the site conditions considered in this research. For comparison purposes, also shown in Figure 2 is the code Design Response Spectrum (DRS) for elastic analysis of the buildings after introducing a lateral force reduction factor  $R$  (equivalent to  $q$  factor in the EC8) of 5. Note that in order to avoid excessively low design acceleration values (and hence un-conservative designs) at medium to long periods that may arise from inaccurate modeling of structures the code is imposing a constant minimum design acceleration of  $0.2a_g$ . Such enforced lower bound sometimes introduces too much conservatism into the design.

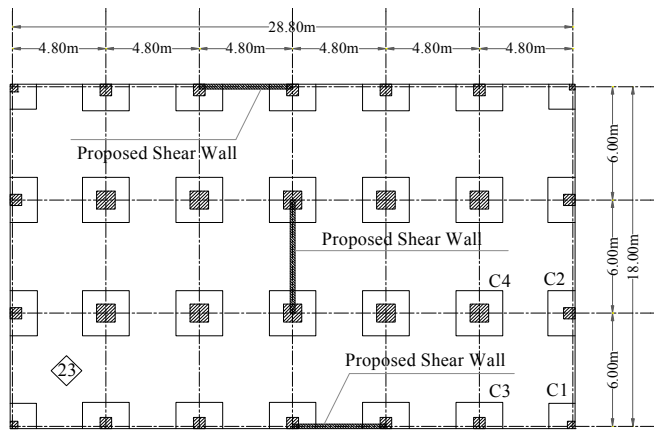


Fig. 1. Typical plan of case study flat slab buildings.

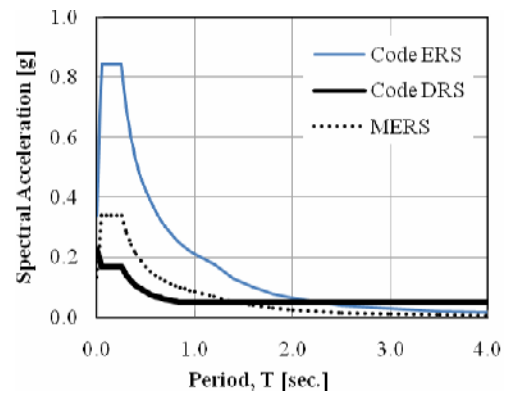


Fig. 2. Code elastic and design acceleration response spectra for case study buildings

The main design requirements specified by code are the “no-collapse” and the “damage limitation” requirements. Satisfying the “no-collapse” requirement depends mainly on the strength of the designed elements to resist all expected stress resultants that occur as a result of the seismic actions. Design seismic actions correspond to the reference seismic hazard associated with a reference probability of exceedance of 10% in 50 years (or a reference return period of 475 years). In a complementary step, the structure shall be also checked to withstand a seismic action having a larger probability of occurrence (minor earthquake) than the design seismic action associated with the “no-collapse” requirement, without occurrence of damage to structural and non-structural elements. Such seismic action is used to verify the “damage limitation” requirement. It has a probability of exceedance of 10% in 10 years (or a return period of 95 years) and is almost equal to half of the design seismic action for the “no-collapse” limit state taking into account the importance factor of the building. As per code, the “damage limitation” requirement is satisfied if the interstory drifts are limited to a given fraction of the story height depending on the type and fixation form of the non-structural elements. The interstory drift associated with the design seismic action for the “no-collapse” limit state has thus to be first reduced to take into account the lower return period of the seismic action associated with the “damage limitation” requirement. Implicit in the use of this reduction is the assumption that the response spectrum of the seismic action for the “no-collapse” requirement has the same shape as the spectrum of the seismic action for “damage limitation” requirement (i.e., the latter is a scaled down replica of the former). For buildings investigated herein, this reduction factor is taken equal to 2.0 and the interstory drift limit is set to 0.005 of the story height associated with non-structural elements of brittle materials that are attached to the structure.

Although the “damage limitation” requirement is verified under a seismic force less than what is used for verifying the “no-collapse” requirement, the former may still have the controlling effect on the design of inherently flexible systems such as the flat slab buildings studied in this research. Absence of beams between

columns in flat slab construction significantly reduces the lateral stiffness of the buildings, hence increases the value of the building's period and thus contributes to the amplification of the interstory drift. The increase in the building's period should have attracted less seismic forces for such inherently flexible systems. However, unfortunately, this never happens due to the imposed constant minimum design acceleration in the code design response spectrum which often aggravates the situation (i.e., further increases the drift demands).

### 3. ANALYSIS AND DESIGN APPROACH

A three dimensional computer model is built for each building. Shell elements are used to model the slab and walls while frame elements are used to represent columns [9]. Columns are assumed fixed to the foundations thus ignoring effects of foundations flexibility on the overall response of the building. Seismic analysis also considers the effect of accidental eccentricity as per code requirements. Furthermore, second order (P-Δ) effects and limitations are checked and considered through the following code condition computed at each story:

$$\theta = P_{\text{tot}} \cdot d_r / (V_{\text{tot}} \cdot h) \leq 0.1 \quad (3.1)$$

where  $\theta$  is the interstory drift sensitivity coefficient;  $P_{\text{tot}}$  is the total gravity load at and above the story considered;  $d_r$  is the design interstory drift induced by the design seismic action (i.e., determined by a linear elastic analysis based on the code DRS, i.e., reduced by R, then magnified back by a displacement behavior factor approximately assumed equal to R);  $V_{\text{tot}}$  is the total seismic story shear; and  $h$  is the story height. If this condition is satisfied, second order effects need not be taken into account. Otherwise, P-Δ effects are approximately considered by multiplying the relevant seismic action effects (i.e., internal forces) by a factor equal to  $1/(1-\theta)$ . The value of the coefficient  $\theta$  shall never exceed 0.3; otherwise, column sizes shall be increased to avoid instability problems. The total seismic design effects are computed by combining 100% of the seismic demand in one direction and 30% of the seismic demand in the orthogonal direction. Different code design requirements (be it strength, drift, or "loosely" a  $\theta$  value not exceeding 0.3) are then considered to be verified for a given building once the corresponding Capacity/Demand (C/D) ratio is greater than or equal 1.0.

Various seismic design scenarios are performed in this paper on the six case study buildings, all starting from the GB version. They result in the following versions of seismic-resistant flat slab buildings depicted below:

- *CB version*: refers to code-compliant flat slab building where (1) "no-collapse" – in terms of satisfying strength of different structural elements considering second order effects – and (2) "damage limitation" – in terms of satisfying code interstory drift limits under reduced hazard – requirements are jointly satisfied. Code DRS shown in Figure 2 featuring the constant acceleration lower bound of  $0.2 a_g$  is adopted.
- *MCB version*: is a modified version of the CB building by ignoring the code pre-specified constant acceleration lower bound when both checking drift and estimating  $\theta$  values for approximately quantifying second order (P- Δ) effects. In other words, checking drift and  $\theta$  is carried out for a scaled down version of the code ERS shown in Figure 2 by directly dividing its ordinates by the R factor, as well as by a reduction factor of 2.0 accounting for the lower return period of the seismic action associated with the code "damage limitation" requirement, then magnified back by a displacement behavior factor approximately assumed by the code equal to R in line with the commonly recognized "equal displacement rule". This proposed step entirely discards any limitation on seismic design demands arising from the lower bound on the design acceleration specified by code and reflected into the code DRS. The Modified Elastic Response Spectrum (MERS) used for checking drift in the context of this step is also shown in Figure 2 for comparison purposes. However, "no-collapse" requirement is still verified for the code DRS with the lower bound on the design acceleration.
- *SB-D version*: also known as "strength-only" compliant building, refers to another modified version of the CB building by ignoring "damage limitation" requirements, i.e., ignoring any limitation on the interstory drift value. Strength checks considering second order effects, along with applicable code limits on  $\theta$ , are though considered based on straining actions retrieved from modal analysis using code DRS with pre-specified lower bound on design acceleration. This is an illustrative and informative version attempting –

when compared with the CB version – to quantify the relative contribution of the “damage limitation” versus the “no-collapse” requirements to the final design of the inherently flexible flat slab systems.

- *MSB-D version*: refers to a primitive hypothetical version of the SB-D building by further ignoring the second order effects, and hence code bounds on  $\theta$ , and only designing for strength under code DRS, i.e., considering lower bound on  $a_g$  for conservatism.

Note that SB-D and MSB-D versions are code non-compliant buildings where the code “damage limitation” requirement has been liberally ignored for educational and comparison purposes. On the other hand, MCB version, despite being as well a code non-compliant building, is promoted herein since it provides a potential economic version of the inherently flexible flat slab building yet without risking safety. In other words, code pre-specified constant acceleration lower bound of  $0.2a_g$  is ignored while quantifying drift and second order effects. This step is promoted in order not to penalize flat slab buildings through assigning unrealistically large seismic forces – that will actually never happen due to inherent system flexibility – resulting in unjustifiably overestimated drift values. Strength is still verified for the code DRS with lower bound on  $a_g$  for conservatism.

It should be recognized that throughout the various seismic design scenarios accomplished in this study the reinforcement ratio in columns was kept constant in the order of 1 to 1.3%. In case there is a need to increase the strength of columns or lateral stiffness of the building, cross section dimensions of the columns are increased. However, for buildings with shear walls, the design strategy is different; shear wall cross section is kept constant while its reinforcement ratio is allowed to increase to acquire additional strength, if needed, and columns cross sections are allowed to increase to gain extra lateral stiffness, if needed. It should be made clear that the design strategy for columns and shear walls is therefore not an optimized one. For example, the optimized design strategy for buildings that include shear walls would have been to increase number of shear walls in case there is a need to enhance the lateral stiffness or strength to satisfy seismic code requirements. While for buildings with columns only as lateral resisting elements, in case of unpractical columns dimensions required to satisfy seismic code requirements, the optimized approach would have been to engage shear walls into the lateral resisting system. However, the present non-optimized design approach is instead followed to keep the initial layout of lateral stiffness distribution within the building unaltered (i.e., to preserve initial stiffness scheme lumped at columns) and hence, to maintain a constant reference for the spatial distribution of lateral stiffness for comparison purposes. Consequently, the resulting columns dimensions, and accordingly concrete quantities, may be looked at in a hypothetically illustrative way rather than literally.

#### 4. COMPARATIVE RESULTS AND DISCUSSIONS

Seismic design scenarios introduced herein when applied to the six various studied GB buildings result in four different seismic-resistant building versions, namely: CB, MCB, SB-D and MSB-D for each case. Figure 3 gives ratios between concrete quantities for vertical lateral load-resisting elements (i.e., columns, and shear walls if any) of all permutations of seismic designed buildings and the corresponding code-compliant GB building. Figure 4 gives similar information but for the relative total concrete quantities for each designed building, i.e., including all structural elements (columns, shear walls, slabs and drop panels). From both figures, one could conclude that GB buildings, designed solely for gravity, are automatically verified for all code seismic design requirements (thus resulting in CB buildings) for the case of NF4, NF4W and NF8W buildings. In other words, concrete dimensions and reinforcement of all structural elements in the GB building remain unaltered and the CB building is a replica of the GB building. However, this is not the case for other studied buildings. For instance, for NF8, total concrete quantities of structural elements for the CB version are 1.5 times quantities for the corresponding GB version. This ratio even scores a value of 4.5 when calculated for vertical lateral load-resisting elements (i.e., columns only). Analogous results are observed for NF12 and NF12W but with larger concrete quantity ratios – either total quantities or quantities of vertical structural elements only – especially for the case of NF12 which is inherently more flexible due to the absence of shear walls.

It is very interesting to note that such relative concrete quantities are somehow reduced for the proposed seismic design scenario resulting in the MCB version which is literally not a seismic code-compliant building. All MCB flat slab buildings with shear walls designed herein have same concrete quantities of the corresponding GB buildings. Similar conclusion is also reached for NF4 (*low-rise* buildings without shear walls). However, for

inherently flexible mid-rise flat slab buildings without shear walls, MCB version features concrete quantities for columns that are 2.4 and 3.7 times quantities of the corresponding GB building for the cases of NF8 and NF12, respectively. In a supplementary effort, seismic-resistant design has been performed for strength only requirements, yet considering second order effects on calculated seismic demands (including bounds on  $\theta$  based on code DRS) but ignoring any limit on drift. Resulting concrete quantities of vertical lateral load-resisting elements for these SB-D building versions, as expected by intuition, are larger than those for the corresponding GB buildings for NF8, NF12 and NF12W featuring inherent flexibility in their system. They are also larger than quantities of the corresponding MCB buildings but to a lesser extent. It is also worth noting that all studied flat slab buildings when designed for gravity only are directly able to withstand the expected code seismic design demands associated with the “no-collapse” requirement with no additional measures (MSB-D versions); however, second order effects on seismic demands and the “damage limitation” requirement specified by code have been completely ignored. These MSB-D versions are presented herein just for illustrative purposes.

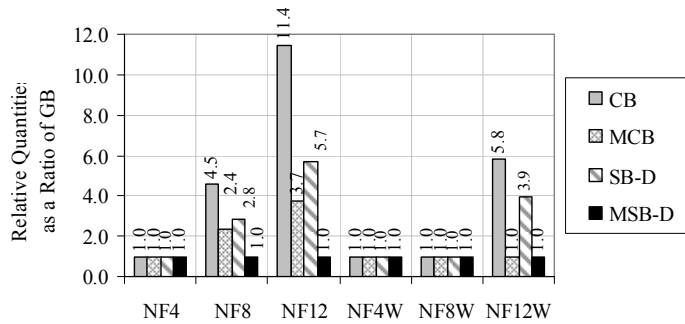


Fig. 3. Relative concrete quantities for vertical lateral load-resisting elements.

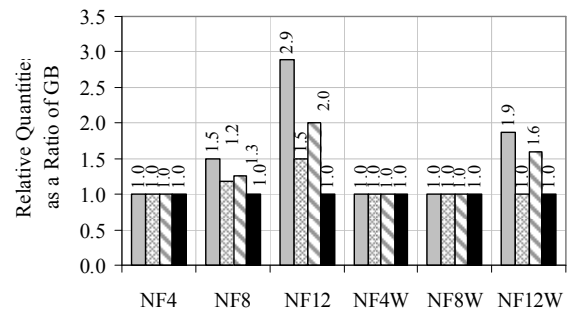


Fig. 4. Relative total concrete quantities.

The authors are here nonetheless stressing on the fact that concrete quantities estimated and presented in Figures 3 and 4 shall be regarded as hypothetical or illustrative since they are not following an optimized design decision as explained above. This design was though devised in order to maintain the same reference initial spatial distribution of lateral stiffness lumped at the columns locations for comparison purposes. Therefore, in a complementary step that may realistically be of more significance, ratios of required stiffness of corresponding columns sections rather than ratios of concrete quantities are then calculated for different seismic-resistant building versions and summarized in Table 4.1. To clarify, values in Table 4.1 refer to *overall* stiffness multipliers that are to be applied to all columns per each floor of GB buildings in order to satisfy each of the different seismic design scenarios introduced in this paper. One can still draw from these stiffness multipliers given in Table 4.1 comparable conclusions to those previously derived in form of relative concrete quantities.

For completeness, a sample Figure 5 shows distribution of C/D ratios for columns biaxial load effects (strength), drift, and interstory drift sensitivity coefficient  $\theta$ , up the height of NF8 building for the seismic-resistant code-compliant CB version as well as for the proposed MCB version. Data in this figure and similar data for other buildings are further summarized in Figs. 6 and 7 for CB and MCB versions, respectively, reporting minimum C/D ratio observed up the height of each building for each of the three major design requirements. Note that a value of C/D of 1.0 in these figures reveals a building optimally dimensioned to resist this seismic design requirement (be it strength, drift or  $\theta$ ). Furthermore, the lowest C/D ratio among the three design requirements indicates which one among them has controlled the final seismic design of a given building. For example, for code-compliant CB building, one could state that strength requirement is the controlling seismic design factor for stiff flat slab building versions NF4W and NF8W (with shear walls), while code drift limit requirement is the controlling design factor for rather flexible buildings (either columns-only mid-rise buildings such as NF8 and NF12, or columns-shear walls upper mid-rise buildings such as NF12W). Conversely, both stiffness and strength requirements equally control the design of low-rise columns-only flat slab building NF4. On the other hand, as noted from Figure 7, drift is never the controlling seismic design factor for promoted MCB version of flat slab buildings irrespective of the number of stories and of the presence or absence of shear walls. It may be further noted from the results presented that strength is the controlling design factor for inherently somehow stiff (or less flexible) systems such as NF4, NF4W and NF8W, while the code design limit imposed on interstory drift sensitivity coefficient  $\theta$  is the controlling factor for relatively flexible systems such as NF8,

NF12 and NF12W. It is worth stating though that the bound enforced on  $\theta$  is a sort of partial and implicit fulfillment of some drift limit although such limit is not explicitly stated in terms of a clear interstory drift value.

Table 4.1 Stiffness multipliers for various seismic-resistant building versions.

Floor	CB	MCB	SB-D	MSB-D	CB	MCB	SB-D	MSB-D
	NF4				NF4W			
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	NF8				NF8W			
1	9.9	4.0	4.0	1.0	1.0	1.0	1.0	1.0
2	9.9	4.0	4.0	1.0	1.0	1.0	1.0	1.0
3	16.7	6.8	6.8	1.0	1.0	1.0	1.0	1.0
4	16.7	6.8	6.8	1.0	1.0	1.0	1.0	1.0
5	38.8	7.6	15.8	1.0	1.0	1.0	1.0	1.0
6	38.8	7.6	15.8	1.0	1.0	1.0	1.0	1.0
7	33.6	3.6	11.8	1.0	1.0	1.0	1.0	1.0
8	33.6	3.6	11.8	1.0	1.0	1.0	1.0	1.0
	NF12				NF12W			
1	42.7	7.1	10.6	1.0	11.8	1.0	5.9	1.0
2	42.7	7.1	10.6	1.0	11.8	1.0	5.9	1.0
3	42.7	7.1	10.6	1.0	11.8	1.0	5.9	1.0
4	85.4	14.2	21.1	1.0	23.7	1.0	11.9	1.0
5	85.4	14.2	21.1	1.0	23.7	1.0	11.9	1.0
6	85.4	14.2	21.1	1.0	23.7	1.0	11.9	1.0
7	194.9	16.5	48.2	1.0	53.7	1.0	26.9	1.0
8	194.9	16.5	48.2	1.0	53.7	1.0	26.9	1.0
9	194.9	16.5	48.2	1.0	53.7	1.0	26.9	1.0
10	411.7	15.6	101.9	1.0	114.8	1.0	57.6	1.0
11	335.2	15.6	75.8	1.0	86.9	1.0	41.8	1.0
12	335.2	15.6	75.8	1.0	86.9	1.0	41.8	1.0

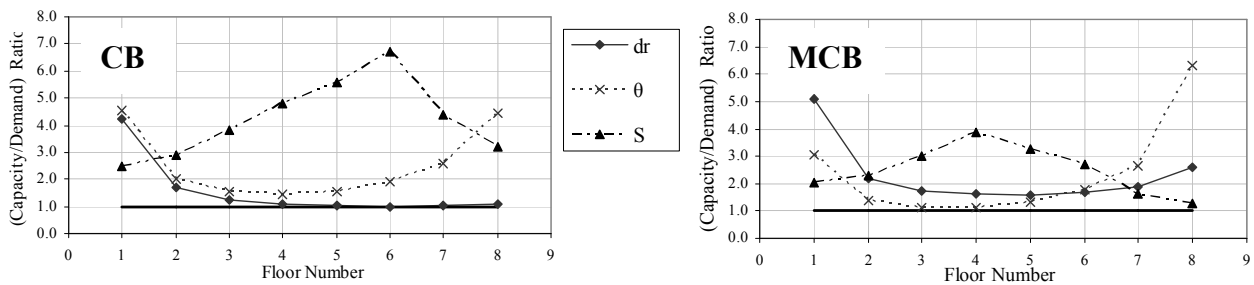


Fig. 5. Distribution of C/D ratios for strength, drift and  $\theta$  up the height of NF8 building.

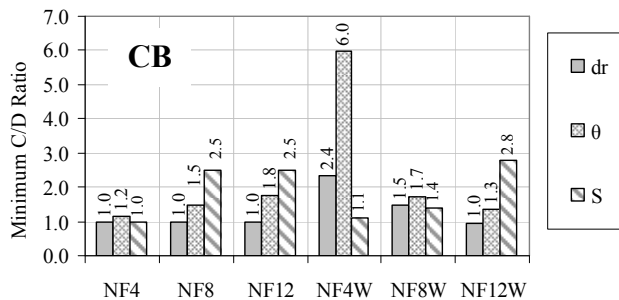


Fig. 6. Reported minimum C/D ratio for each of the three major code design requirements up the height of studied buildings. (CB versions)

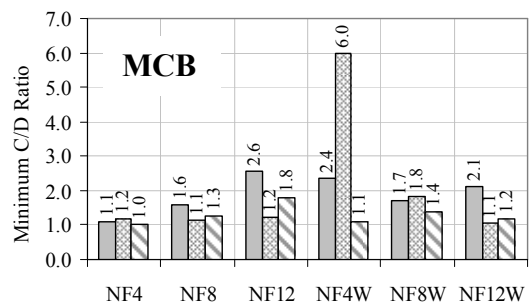


Fig. 7. Reported minimum C/D ratio for each of the three major code design requirements up the height of studied buildings. (MCB versions)

## 5. CONCLUSIONS

The present study demonstrates that shear walls engagement in inherently flexible flat slab systems is essential for mid-rise buildings (8-story high and up) in order to achieve an economic, efficient, and reliable seismic-resistant code-compliant structures. Moreover, as a general conclusion, the present work also shows that designing flat slab systems only for gravity loads is not sufficient for a given building to qualify for design code's seismic demands except for low-rise buildings and/or in the presence of shear walls but still not for high-rise buildings. For example, specific results indicate that shear walls in flat slab buildings, up to 8-story high, designed solely for gravity loads as per code's requirements render these buildings conforming to seismic code demands under code's design earthquake without additional concrete quantities. On the other hand, introducing shear walls in higher rise (12-story) flat slab buildings that were dimensioned exclusively for gravity loads reduce additional concrete quantities of vertical lateral load-resisting elements that are still required to render these buildings seismic-resistant code-compliant buildings. Furthermore, a slightly modified code's seismic design scenario promoted in this paper, which provides the so-called MCB flat slab building version, renders all "columns-shear walls" buildings solely designed for gravity automatically qualified for code seismic demands. This design scenario entirely ignores pre-specified code's lower bound on design acceleration when estimating second order effects and drift demands (i.e., "damage limitation" requirement), while it still enforces such limit for strength design checks (i.e., "no-collapse" requirement). This customized seismic design scenario further enhances the design economy for columns-only mid-rise flat slab buildings by reducing additional concrete quantities for columns required beyond cross sections dimensions necessary for "safe-for-gravity" buildings.

It is nonetheless important to realize that conclusions drawn in this paper are only valid for moderate seismic zones (0.25g) and for flat slab buildings up to 12-story high. Extrapolation of the results presented herein to other seismic hazards and/or to higher buildings shall be the subject of a similar extensive effort before being either applied or denied.

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