Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 3439-3449

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

INFLUENCE OF RIGID FLOOR ASSUMPTION IN SEISMIC ANALYSIS OF RC EXISTING BUILDINGS

Francesco Porco[1], **Sergio Ruggieri**[2], **and Domenico Raffaele**[3]

[1] Dep. Dicatech, Politecnico di Bari, Via Orabona, 4 – 70126, Italy
f.porco@poliba.it

[2] Dep. Dicatech, Politecnico di Bari, Via Orabona, 4 – 70126, Italy
sergio.ruggieri@poliba.it

[3] Dep. Dicatech, Politecnico di Bari, Via Orabona, 4 – 70126, Italy
d.raffaele@poliba.it

Keywords: RC existing building, seismic assessment, FEM, structural irregularity

Abstract. *The study concerns with the seismic analysis of reinforced concrete (RC) building, with particular attention to the role played by floor system. The rigid-floor assumption is often used for RC existing buildings' vulnerability assessment, in order to simplify the study of their structural behavior. Seismic codes (EC8, NZS4203, FEMA-273) provide a set of quantitative criteria related to deformation of diaphragm and average drift of the associated storey and qualitative criteria related to the shape of diaphragm. Despite in many cases this hypothesis can be considered sufficiently accurate, it is not always valid because it is related to several features of structure as floor geometry and materials, relative stiffness between floor system and vertical structural elements, shape of building, etc. In fact, unlike new structures, the main problem of RC existing buildings is not having geometrical and mechanical regular features (for example, in a ribbed slab, the irregular depth of the top concrete slab) as well as to present irregular dynamic parameters.*

When the floor system cannot be considered rigid, it may be studied as flexible slab with the increment of uncertainty related to stress states of structural elements.

In order to understand how the floor system influences the structural behavior, it has been investigated the seismic performance of several applications, extrapolated from real RC existing buildings, through numerical methods, with and without the rigid-floor assumption.

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5656.17499

1 INTRODUCTION

Existing RC buildings are mostly characterized by an unsatisfactory level of the technical design (mainly because the reference building codes are very obsolete), and the development of vulnerability studies is one of the main research focus that the scientific community has explored in the last years at different scales of analyses [1, 2, 3, 4]. These studies, together with the observation of post-seismic damage after recent earthquakes, have clearly shown that the seismic risk of existing RC buildings is very high, confirming the need of systematically assessing their safety level and to develop to this aim not only proper techniques for the modeling and analysis but also for the monitoring and control, especially in the case of strategic structures [5, 6]. In fact, on the one hand, existing buildings were designed by engineers through old codes, which do not take in exam the seismic actions, on the other hand existing buildings are often characterized by meaningful historical and artistic value.

Modern seismic codes, as Eurocode 8 [7] and consequently Italian NTC [8], suggest a performance based approach and guidelines that engineers can use in order to analyze the real behavior of existing structure and to choose the most suitable retrofit solutions. One of most important steps of the abovementioned performance approach is the nonlinear analysis of the structural model, static or dynamic, in order to define the structural capacity and compare it to seismic demand.

In this phase, a correct estimate of capacity is only possible through a correct finite element method (FEM) model, even if simplified, which takes into account a series of hypothesis on materials, geometry, loads, etc…

The FEM model, even on geometric regular existing building, must consider a presence of irregularity factors, which can change results of analysis. With this regard, a particular attention in analysis results has to be taken when the influence of in situ materials strength is included in FEM model, as shown in Uva et al., 2014 [9] and Porco et al., 2014 [10]; or when the influence of secondary structural elements as infill panels is considered, as shown in Porco et al., 2013 [11] and 2015 [12]; Fiore et al., 2014 [13] and 2015 [14]; Casolo et al., 2013 [15].

Clearly, these influence factors cause strong behavior difference on buildings analyzed, regarding to elements stiffness, masses and modal parameters.

In this paper, the attention is focused on one of these irregularity factors: a floor in-plane deformability. The influence of this factor, in the evaluation of seismic behavior of RC existing building, has been evaluated.

2 STATE OF THE ART

In RC buildings, floor system is a bi-dimensional structure loaded orthogonally to its plane by gravity loads and it distributes seismic actions among structural vertical elements. Generally, buildings are designed using the assumption of rigid floor, which is justified when floor is stiffer than vertical elements. To design new RC buildings, modern codes as Eurocode (consequently in Italian code) provides technological rules for several typologies of rigid floor. For example, to obtain an in-plane rigid behavior, a floor system must have a thickness of top concrete slab larger than 4 cm, as show in Figure 1 where a ribbed slab is represented:

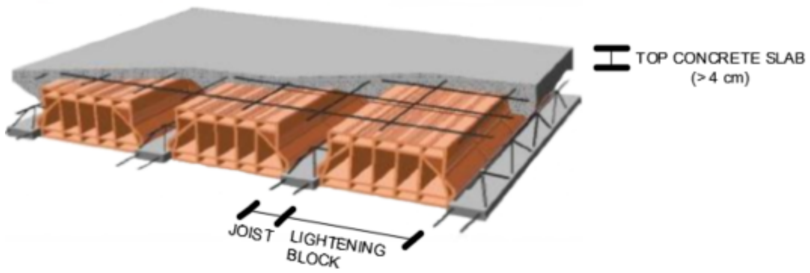

Figure 1 – example of rigid floor, according to Italian NTC

Some cases of South Italian existing RC buildings have no top concrete slabs (SAP slab), as shown in figure 2. In other cases, top concrete slab has a low thickness because of the presence of hydraulic or electrical systems or because of human mistakes.

Figure 2 – SAP slab (without top concrete slab)

The rule of top concrete slab thickness cannot be enough to define a rigid floor: its stiffness must be compared to the stiffness of structural vertical elements. With this regard, FEMA (1997) [16] provides a quantitative criterion which defines floor as either flexible, stiff or rigid. In particular way, it defines a factor λ as ratio between the maximum to minimum lateral in-plane deflection of floor, caused by horizontal actions. The ratio is shown in Eq.1, where X and Y are depicted in figure 3:

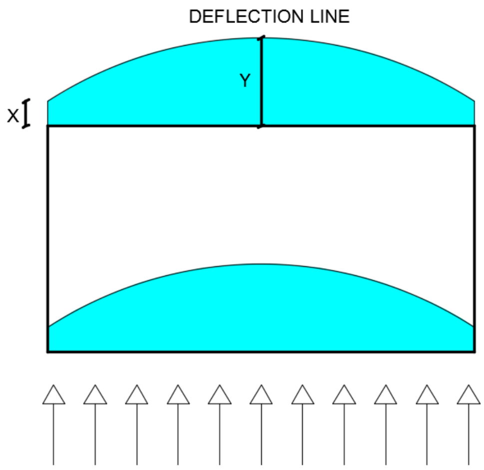

Figure 3 – In-plane displacement of slab, without the rigid floor assumption

$$\lambda = Y/X \tag{1}$$

If λ is larger than 2, the floor is deformable while if λ is lower than 0.5, the floor is rigid. If λ is included between 0.5 and 2, the floor is "stiff" (neither flexible nor rigid).

Eurocode 8 provides a qualitative criterion to define the rigid floor: the floor system is taken as being rigid if, when it is modeled with its actual in-plane flexibility, its horizontal displacements nowhere exceed those resulting from the rigid floor assumption by more than 10% of the corresponding absolute horizontal displacements in the seismic design situation.

As well as Eurocode 8, even NZS 4203 [17] provides a qualitative criterion, such as indications of rigid floor assumption invalidity, for instance abrupt discontinuities, major variations in in-plane stiffness or major re-entrant corners in diaphragms.

Moeni e Rafezy, 2011 [18], analyzed the rigid floor assumption on buildings with irregular shape in-plan, evaluating results in terms of Deflect/Drift ratio through qualitative and quantitative criteria provided by several international codes, such as those aforementioned. Authors tested the efficiency and accuracy of all indications available in the matter of floor deformability.

Previously, several studies have been carried out in order to study the deformability of floor and its effect on the structural behavior.

Saffarini and Qudaimat, 1992 [19], analyzed several RC buildings to compare the difference between rigid floor and flexible-floor analyses. They found that the rigid-floor assumption is accurate for buildings without shear walls, but it can cause errors for building systems with shear walls. The study made up of a numerical model where some parameters were varied, such as number of stories, story height, slab type, building-plan aspect ratio, regularity of building plan, openings in the slab, the sizes and spacing of columns and shear walls.

Kunnath et al., 1991 [20], studied the effect of deformable floor system on irregular buildings, using a simplified macro modeling scheme which included an inelastic behavior. Results of research showed that, the base shear is larger when the floor is flexible, rather than when it is rigid and elastic. However, incrementing the number of ways and floors, interior frames have a higher base shear with a larger strength and ductility demand.

Dolce et al., 1994 [21], studied the inelastic dynamic response of a large number of floor systems simple models. On their cases studied, they analyzed the variability of the ratio k_{floor}/k_{vert}, using a spring model and varying elements stiffness. They obtained that, when the stiffness distribution of structural vertical elements is uniform, the flexibility of floor system is negligible, while when the structures have important re-entrances, the deformability effect is relevant.

Other authors studied this problem (Ju and Lin, 1999 [22]; Fleishman and Farrow, 2001 [23], Lee at al., 2002 [24]; Fouad at al., 2012 [25]; Bakar et al. [26], 2014; Tena-Colunga et al., 2015 [27]), observing the differences of results of modal parameters and stresses, obtained by different modeling methods and using the hypothesis of rigid floor or not.

Relying on results obtained by the abovementioned authors and using indications provided by international seismic codes, the aim of this paper is to show the differences of simple numerical applications' structural behavior, on the basis of a variation of the FEM model, which take or not into account the rigid floor assumption.

3 STRUCTURAL FEM MODELS

In order to study the influence of the floor deformability, two FEM models are carried out using FEM software SAP2000 [28].

The reference case is a single storey RC frame building, which has one bay in both direction, dimension in plan of 3 x 6 m and height of 3 m. Beams and columns have dimension of 30 x 30 cm and floor is constituted by a ribbed slab with joists of ordinary dimension (10 x 20 cm). Top concrete slab has a thickness of 4 cm, minimum value which Italian code considers to assume the hypothesis of rigid floor. Strength class of concrete is 25/30, according to [4]. In the reference case, it is considered only dead load, neglecting non-structural and accidental loads.

The first model is a “frame model” which considers a rigid floor hypothesis by applying a constrain “diaph” at every nodes of plane. Dead loads are inserted on a shell “none” which is linked to every nodes of plane.

The second model is a “solid model” which does not consider a rigid floor hypothesis. In this case, columns are modeled as frames while beams and slab are modeled using solid elements, meshed each centimeter, in order to modify both thickness of edge beams and thickness of concrete slab.

The two above mentioned models are shown in Figure 4.

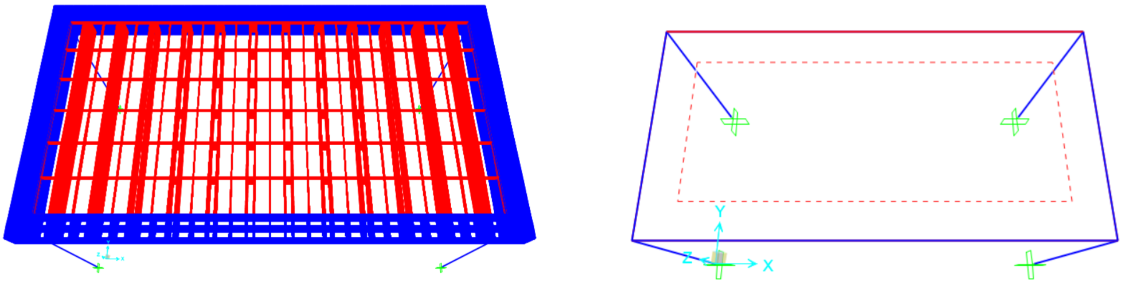

Figure 4 – Reference models

In both models, one dimension of vertical elements is varied, from a ratio between section sides of 1:1 to 1:4, in order to vary the ratio between floor stiffness and structural vertical element stiffness. In addition, columns have been replaced by shear walls (modeled through shell elements), with thickness which varying from 20 cm to 40 cm. For each models, it is evaluated the difference of period and participating mass, through a modal analysis, which compare the two FEM model typology.

Moreover, same comparison is carried out for same models with 3 and 5 storeys. In Figures 5-6-7 histograms of the differences aforementioned are shown. Periods and participating mass of the solid models are indicated in green while same parameters of the diaph models in grey.

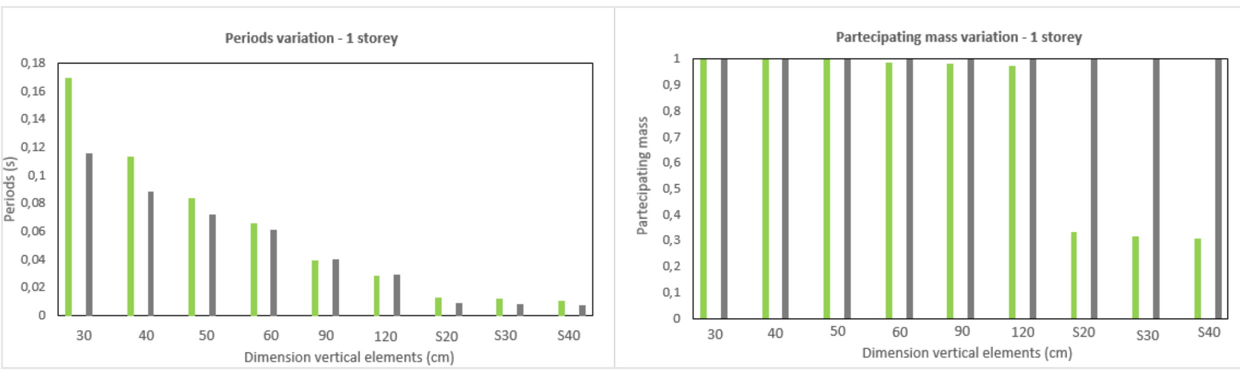

Figure 5 – 1 storey models variations

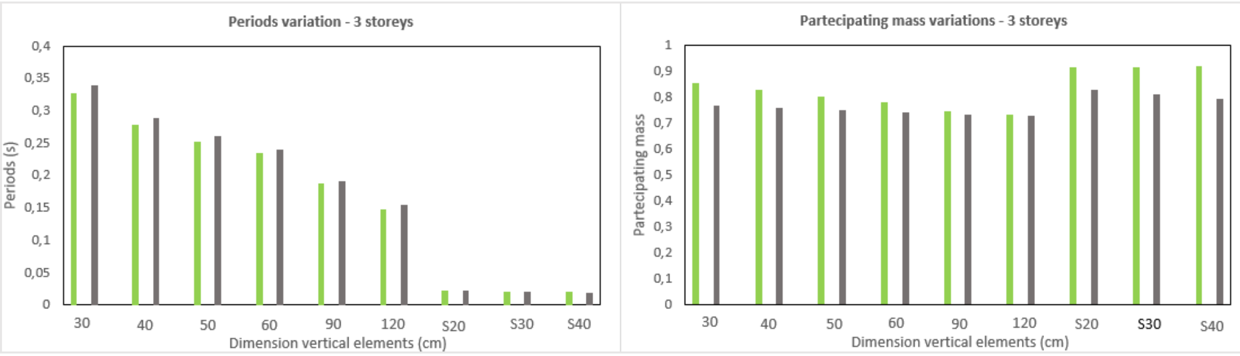

Figure 6 – 3 storeys models variations

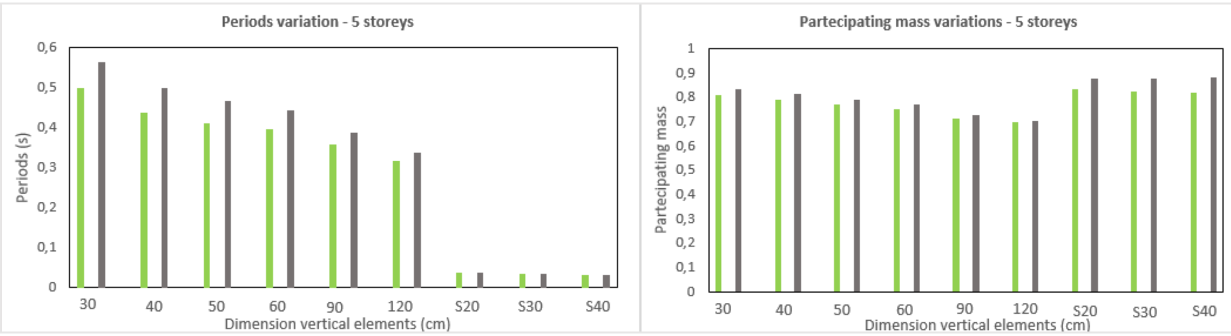

Figure 7 – 5 storeys models variations

Subsequently, modal analyses are carried out on a single storey RC frame building, which has one bay and doubling dimension in plan (3 x 12 m) and height of 3 m. Histograms of the differences of periods and participating mass are shown in figure 8, using same colors for model typology.

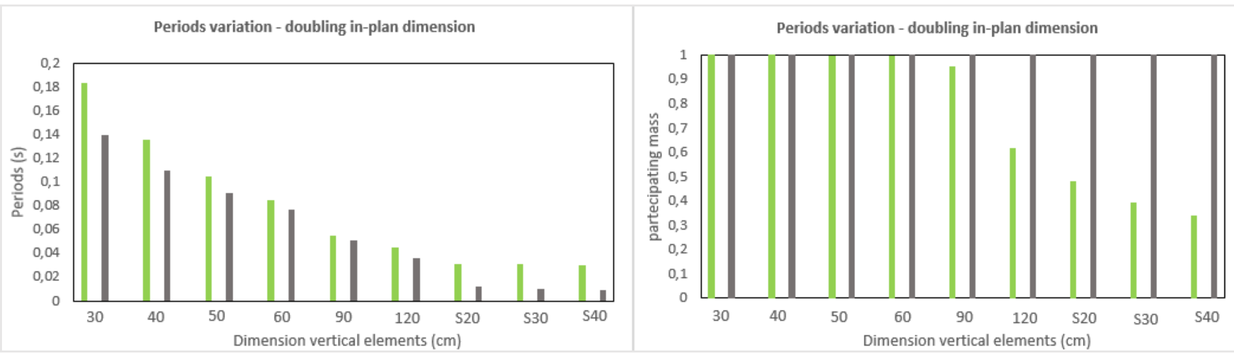

Figure 8 – 1 storey models variations – doubling in-plan dimensions

Using solid models, it is possible to study if the floor is rigid or deformable. Particularly, relying on the quantitative criteria provided by [5], maximum deflection and interstorey drift for reference model has been monitored and the ratio between them has been calculated (ratio Deflect/Drift). In the same way, this ratio has been calculated, increasing the number of storeys and the ratio of dimension in plan. In figure 9 histograms show these ratios, even considering the variation of structural vertical elements dimension. In blue are represented the cases with columns for structural vertical element while in red are represented the cases with shear wall. When the values exceed 2, the floor is deformable. When the number of storeys increases, the ratio is always calculated on the first floor, because in that plane is detected the maximum ratio Deflect/Drift.

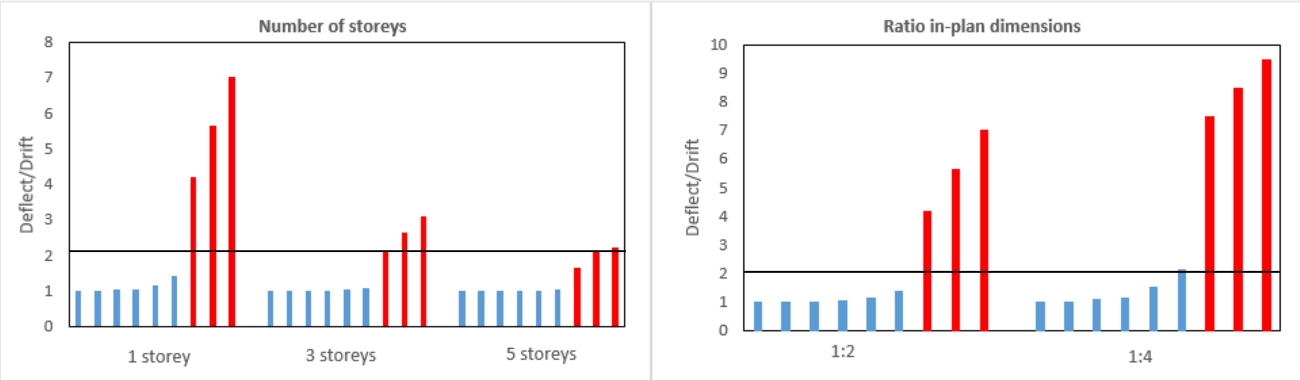

Figure 9 – Deflection/Drift ratio variations, increasing number of storeys and in-plan dimensions

4 NUMERICAL APPLICATIONS

In order to understand when the floor can be deformable in RC existing building, two numerical applications, extrapolate from two real case study, have been analyzed using solid models. For this purpose, a single storey RC frame building is assumed as new reference model. It has dimension in plan of 6 x 12 m. and height of 3 m. Beams and columns have dimension of 30 x 30 cm. It has one bay in long direction and two bays in short direction, in order to simulate the resistant frames in one way, as in RC existing building designed without using of seismic codes. The new reference model is shown in Figure 10a.

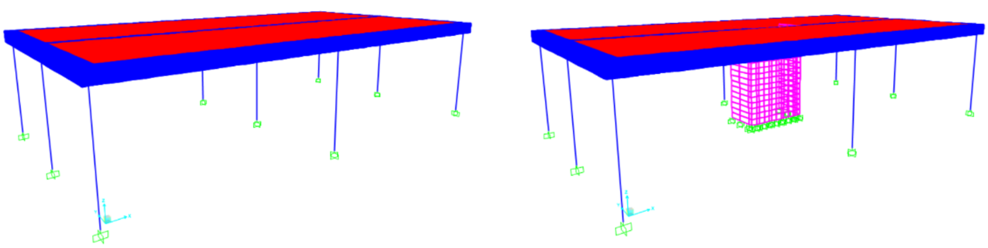

Figure 10a – 10b – 1st application

In first application, the new reference model is compared with a same model, which has a C-shape shear walls instead of the central column, in which there is an elevator, as shown in Figure 10b. Clearly, in a floor there is an opening. The ratio Deflect/Drift is evaluated increasing the thickness of walls from 20 cm to 40 cm, keeping constant the opening dimension. The histogram of figure 11b shows the results: the comparisons among each model and new reference model. In Figure 11a is displayed a typical deformed shape of this application, where Deflection is the maximum displacement in-plane and Drift is the minimum displacement in-plane.

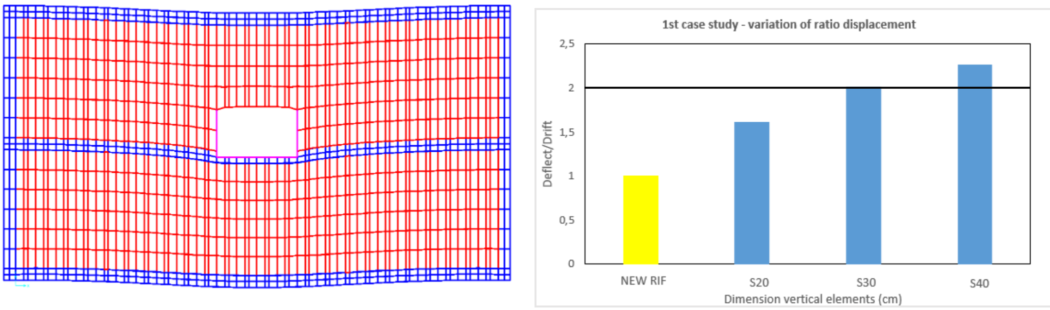

Figure 11a – 11b – Deflect/Drift ratio results of 1st case study

In second application, the new reference model is compared with the same model, where are varied the dimensions of external columns under central beam and the dimensions of other structural elements is not varied. Specifically, one dimension of columns taken in exam, is increased up to obtain a ratio between them section sides of 1:4. This application is representative of the typical case in which a possible way to retrofit a RC existing building is taken into account, regularizing its dynamic behavior. Figure 12, in terms of ratio Deflect/Drift, exhibits the results.

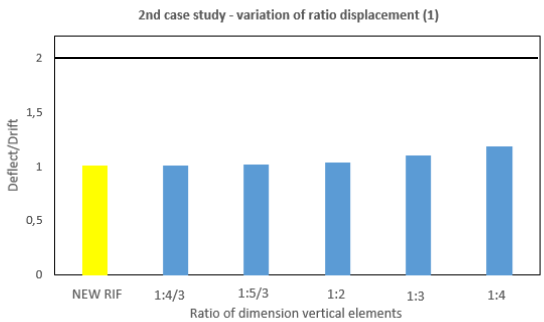

Figure 12 - Deflect/Drift ratio results of 2nd application – increment of ratio dimensions columns

Subsequently, the external columns under central beam have been substituted with shear walls of 30 cm and the variation of ratio Deflect/Drift is evaluated, increasing the length of walls from 1.30 m to 4.30 m. A comparison between new reference model and modified model is illustrated in Figure 13.

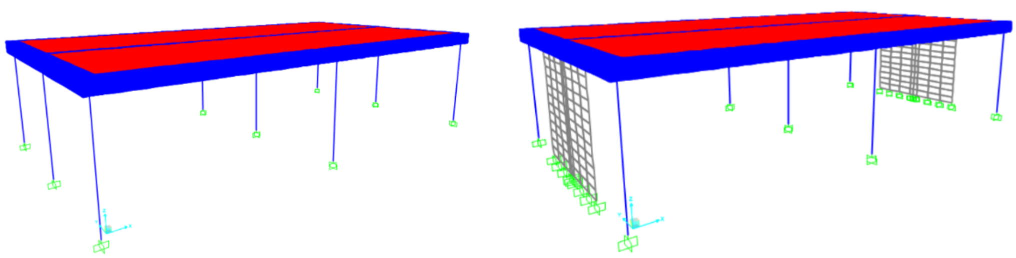

Figure 13 - 2nd case study – shear walls length increment

The results, in terms of ratio Deflect/Drift, and the deformed shape in-plane are explained in figure 14.

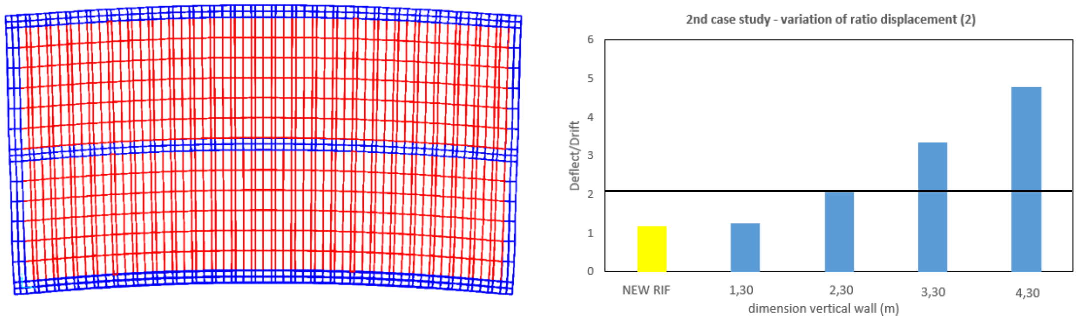

Figure 14 - Deflect/Drift ratio results of 2nd application - increment of shear walls length

5 CONCLUSIONS

In this paper, simple models of RC existing building are analyzed in order to evaluate structural behavior, using or not the rigid floor assumption. These analyses have been achieved varying the ratio between floor stiffness and structural vertical element stiffness. For considering the rigid floor hypothesis, "frame models" are carried out using a constraint on each point of plane. These models have been compared to analogues "solid models" and modal parameters differences have been evaluated. Furthermore, for each models, ratio Deflect/Drift has been evaluated, varying on the reference model, the number of storeys and the dimension in plan.

Same analyses have been accomplished on the two numerical application. The first case study compares a new reference model with same model having a C-shape shear wall, the second one compares the new reference model with same model, having some columns whose dimensions in thickness and length was varied.

Results are summarized as follow:

- The two different types of modeling have shown that on the same model, when the structural vertical elements are columns, variations of modal parameters (periods and participating mass) are negligible, rather when the model has shear walls, same parameters have high variations;
- Increasing reference model's storeys number, the results, in terms of Deflect/Drift ratio, show that the rigid floor assumption is more and more appropriate;
- Increasing in-plan dimension of the reference model, the results, in terms of Deflect/Drift ratio, shown that the rigid floor assumption is less and less appropriate;
- The two numerical applications analyzed shown that rigid floor assumption cannot be always considered correct. In the first case, the presence of C-shape shear wall, at constant opening in the floor, as soon as the thickness increases, the floor becomes more deformable. In the same way, in the second case, the addition of shear walls on the structure perimeter, as soon as their length increases, the plane becomes more deformable.

Future aims of the research are study the floor behavior, under seismic actions, when the thickness of top concrete slab is smallest of 4 cm and when changing the edge beam dimensions.

ACKNOWLEDGEMENTS

The research presented in this article was partially funded by the Italian Department of Civil Protection in the framework of the national project DPC-ReLUIS 2014-2018.

6 REFERENCES

[1] D. Perrone, M. A. Aiello, M. Pecce, F. Rossi., Rapid visual screening for seismic evaluation of RC hospital buildings. *Structures,* **3**, 57-70, 2015. doi:10.1016/j.istruc.2015.03.002.

[2] I. Iervolino, G. Manfredi, M. Polese, G. M. Verderame, G. Fabbrocino, Seismic risk of R.C. building classes. *Engineering Structures*, **29**(5), 813-820, 2007. doi:10.1016/j.engstruct.2006.06.019.

[3] G. M. Verderame, M. Polese, E. Cosenza, Vulnerability of existing R.C. buildings under gravity loads: A simplified approach for non sway structures. *Engineering Structures*, **31**(9), 2141-2151, 2009. doi:10.1016/j.engstruct.2009.03.014.

[4] G. Uva, C. A. Sanjust, S. Casolo, M. Mezzina, ANTAEUS project for the regional vulnerability assessment of the current building stock in historical centers. International *Journal of Architectural Heritage*, **10**(1), 20-43, 2016. doi:10.1080/15583058.2014.935983.

[5] S. Hans, C. Boutin, E. Ibrahim, P. Roussillon, In situ experiments and seismic analysis of existing buildings. part I: Experimental investigations. *Earthquake Engineering and Structural Dynamics*, **34**(12), 1513-1529, 2005. doi:10.1002/eqe.502.

[6] G. Uva, G. Porco, F. Porco, A. Fiore, Monitoring and safety for prestressed bridge girders by SOFO sensors. *Journal of Civil Structural Health Monitoring*, **3**, 3-18, 2013. doi: 10.1007/s13349-012-0029-9.

[7] CEN. Eurocode 8: Design of structures for earthquake resistance. Part 3: Assessment and retrofitting of buildings. Brussels, 2005.

[8] DM 14/01/2008, Norme Tecniche per le Costruzioni. Gazzetta Ufficiale n. 29. Rome 2008.

[9] G. Uva, F. Porco, A. Fiore, M. Mezzina, The assessment of structural concretes during construction phases. *Structural Survey*, **32**(3), 189-208, 2014. doi:10.1108/SS-06-2013-0023.

[10] F. Porco, G. Uva, A. Fiore, M. Mezzina, Assessment of concrete degradation in existing structures: a practical procedure. *Structural Engineering and Mechanics*, **52**(4), 701-721, 2014. doi:10.12989/sem.2014.52.4.701.

[11] F. Porco, A. Fiore, G. Uva, D. Raffaele. The influence of infilled panels in retrofitting interventions of existing reinforced concrete buildings: a case study. *Structure and Infrastructure Engineering*, **11**(2), 162-175, 2015. doi:10.1080/15732479.2013.862726.

[12] F. Porco, G. Porco, G. Uva, M. Sangirardi, Experimental characterization of "non-engineered" masonry systems in a highly seismic prone area. *Construction and Building Materials*, **48**, 406-416, 2013. doi:10.1016/j.conbuildmat.2013.07.028.

[13] A. Fiore, F. Porco, G. Uva., Effects of the yield and ultimate strengths of the equivalent strut models on the response of existing buildings with infill panels. *International Jour-*

nal of Structural Engineering, **6**(2), 140-157, 2015. doi:10.1504/IJSTRUCTE.2015.069690.

[14] A. Fiore, F. Porco, G. Uva, M. Sangirardi, The influence of uncertainties of infill panels relative to the seismic response of RC existing buildings, *WIT Transactions on the Built Environment*, **141**, 479–490, 2014. doi:10.2495/SUSI140411.

[15] F. Porco, A. Fiore, S. Casolo. Comparison between seismic retrofitting solutions for existing reinforced concrete buildings: a case study. *International Journal of Structural Engineering*, **5**(3), 242-261, 2014. doi:10.1504/IJSTRUCTE.2014.063035.

[16] Federal Emergency Management Agency (1998), National Earthquake Hazard Reduction Program Guidelines for Seismic Rehabilitation of Buildings, FEMA-273, Washington, D.C..

[17] Standards Association of New Zealand [1992] Code of practice for general design and design loading for buildings: NZS 4203, Wellington, New Zealand.

[18] M. Moeni, B. Rafezy., Investigation into the Floor Diaphragms Flexibility in Reinforced Concrete Structures and Code Provision. *Global Journal of Researches in Engineering*, **11**(1), 25-35, 2011. ISSN: 0975-5861.

[19] H. Saffarini, M. Qudaimat, In-plan e floor deformations in RC structures. *Journal of Structural Engineering*, **118**(11), 3089- 3102, 1992. ISSN 0733-9445.

[20] S. K. Kunnath, N. Panahshahi, A. M. Reinhorn, Seismic response of RC buildings with inelastic floor diaphragms. *Journal of Structural Engineering ASCE*, 117(4), 1218-1237, 1991. ISSN 0733-9445.

[21] M. Dolce, V.D. Lorusso, A. Masi, Seismic response of building structures with flexible inelastic diaphragm. *The structural design of tall buildings*, **3**, 87- 106, 1994.

[22] S. H. Ju, M. C. Lin, Comparison of building analyses assuming rigid or flexible floor. *Journal of Structural Engineering ASCE*, **125**, 25-39, 1999. http://dx.doi.org/10.1061.

[23] R. B. Fleischman, K. T. Farrow, Dynamic behaviour of perimeter lateral-system structures with flexible diaphragms. *Earthquake engineering and structural dynamics*, **30,** 745–763, 2001. doi: 10.1002/eqe.36.

[24] D. Lee, H.Kim, Efficient seismic analysis of high-rise building structures with the effects of floor slabs. E*ngineering Structures,* **24**(5), 613-623, 2002. http://dx.doi.org/10.1016/S0141-0296(01)00126-2

[25] K.Fouad, Z. Ali, R. Mustapha, Structural Analyses with Flexibility Effect of the Floor Slabs. 15 World Conference on Earthquake Engineering, Lisbon, 2012.

[26] M. Ahmadi, S. A. Bakar, H. S. Abbas, Investigation into diaphragm flexibility using shear wall. *Journal of the Croatian Association of Civil Engineers - Građevinar*, **66**(9), 831-836, 2014. doi: 10.14256/JCE.1049.2014

[27] A. Tena-Colunga, K.L. Chinchilla-Portillo, G. Juarez-Luna, Assessment of the diaphragm condition for floor systems used in urban buildings. *Engineering Structures*, **93**, 70–84, 2015. http://dx.doi.org/10.1016/j.engstruct.2015.03.025

[28] Computer and Structures I. SAP2000, Advanced 18. Structural Analysis Program– Manual – Computer and Structures, Inc, Berkeley, California, USA, 2015.