Effect of Partition Weight on the Seismic Performance of Reinforced Concrete Frame Buildings

Orlando Arroyo 1, Jose Colombo 2

1 Universidad de La Sabana, Campus Universitario Puente del Común, Km 7 Autopista Norte Bogotá – Chía, Colombia
2 Universidad Diego Portales, Av. Ejército 441, Santiago, Chile

orlando.arroyo@unisabana.edu.co

Abstract. Reinforced concrete frame (RCF) buildings are widely used around the world and they are present in most urban areas. This situation has occurred because they are cost-efficient, have good seismic performance and because the materials and technologies required for their construction are available in many countries. One of the decisions during the design stage of new buildings based on this structural system is selecting the type of partitions. So far, in most developing countries the use of masonry brick walls to separate habitational spaces is still the predominant choice for most new projects. This situation stems from the fact that the selection of partition elements is often motivated by architectural, economic and cultural reasons, and because there is lack of information about the potential impact of the weight of partition elements on the seismic performance. This paper presents the evaluation of the effect of the partition weight on the seismic performance of RCF buildings. For this purpose, a six-story building was designed considering three different types of partitions: a) drywall, b) expanded-reinforced polystyrene and c) traditional clay partitions. Each building design was modelled in three-dimensions using fiber elements and subjected to nonlinear analyses. Based on these results, fragility curves were calculated for different seismic performance levels. The results of these evaluations show that seismic performance improves when lighter partitions are used, particularly in the nonlinear range. These buildings showed higher performance at the life-safety and collapse levels. All things considered, the results of this research show that the weight of partitions has a notable impact in seismic performance, and it suggests that it should be given careful consideration to its choice during the design phase of a project, and that cities planners should promote the use of lightweight partitions for new buildings.

1. Introduction

Reinforced concrete (RC) frames are widely used around the world. According to reports by the World Housing Encyclopedia, they represent 75% of the building stock in Turkey (WHE Report 64), 60% in Colombia (WHE Report 11) and 80% in Mexico (WHE Report 115), with similar participation in other emerging countries. This situation stems from the wide availability of the construction materials and technologies, and because of the good seismic performance demonstrated by RC frames during earthquake events.

The development of a construction project based on RC moment frames has several stages. One of them involves the selection of non-structural elements, such as ducting, pipework, cable trays,
suspended ceilings, cladding systems and non-load bearing partitions. Among non-structural elements, partitions are one of the categories with the largest amount of options in terms of materials. Presently, partitions are constructed using different types of materials, such as concrete bricks, clay bricks, gypsum boards, expanded polystyrene, glass, and several others which have different mechanical properties.

Accounting for this variety, seismic design codes such as the ASCE 7 [1] provide structural engineers with recommended load values for different types of partitions. They also required that they must be considered as a mass source for the seismic analysis, with no further consideration of their effects on the seismic performance. This topic motivated a significant amount of research in recent years, with lots of efforts invested in modeling and assessing the seismic behavior of RC frames constructed with infilled brick partitions [2]–[15]. Notwithstanding these advances, there is still need for more research about the effects of partitions on the seismic performance. In particular, the effects of the partition weight deserve investigation because it can be major source of the superimposed dead load and exert an influence on the P-Δ effects. This fact is of major importance in emerging countries, where the use of masonry brick walls –among the heaviest partitions– to separate habitational spaces is still the predominant choice for most new RC projects, mostly due to economic reasons.

This paper investigates the effect of the weight of partitions. Three types of partitions are considered, representing the case for light, medium and heavy partitions: gypsum (0.5 kN/m2), reinforced expanded polystyrene (1.1 kN/m2) and masonry brick partitions (1.8 kN/m2). After a short theoretical background, a six-story building is considered, which was designed per ASCE 7 [1] and ACI 318 [16] for the three types of partitions. The three designed buildings are modelled in three dimensions using fiber models in OpenSees, subjected to nonlinear static analyses, which are then used as input information for the SPO2FRAG to calculate fragility functions at the life safety and the collapse prevention limits.

2. Building description and designs
A six-story frame building shown in figure 1 is considered for this study. This building is meant for residential use and it is designed per the requirements of the ACI 318 and the ASCE 7 [1], considering three different partition types: a) clay masonry bricks, b) reinforced expanded polystyrene (REP) and c) gypsum board.

![Figure 1](image_url)
The building structural system is comprised of seismic frames located on its perimeter and interior gravity frames. The floor system consists of a one-way ribbed slab in the Y direction. Joists are 12 cm width by 40 cm height, with a 5 cm top slab. The building has a clear story height of 2.55 m, and its total height is 18 m. ETABS 2016 [17] is used to create a three-dimensional model of the building, where slabs are considered to create a rigid diaphragm. Column and beam sections are modeled using concrete with $f_c = 28$ MPa and reinforcing steel with $F_y = 420$ MPa. The program was configured to calculate the self-weight of the building and to perform a seismic analysis using the equivalent lateral force method for a base shear coefficient $C = 0.08$ ($R = 8$). Columns in the seismic system are pre-dimensioned to 60 cm x 60 cm and beams to 40 cm x 50 cm. For the gravity system, columns are 50 cm x 50 cm and beams 30 cm x 35 cm.

To account for the differences between the partitions weights, three different models are analyzed and designed with the superimposed uniform dead loads of table 1. These values are calculated based on typical contents of the buildings and considering partition weights of 1.8 kN/m$^2$, 1.1 kN/m$^2$ and 0.4 kN/m$^2$ masonry, REP and gypsum partitions, (based on values recommended per ). The last column of the table represents the axial loads acting on columns of the C axis, which are obtained from the 1.2D + 1.6L combination. As seen, there are differences in the superimposed design load in the first story, though not by the same percentage of the partition weight. The design for these columns indicates that a reinforcement ratio $\rho = 1.0\%$ is required in the three buildings, thus they are detailed with $14 \phi 16$.

The design of gravity beams results in a bottom and top reinforcement ratios of 1.3% and 0.9%, respectively.

### Table 1. Vertical loads for the six-story building

| Partition type                  | Superimposed dead load (kN/m$^2$) | Live load (kN/m$^2$) | Design load for 1$^{st}$ story gravity columns (kN) in C axis |
|--------------------------------|-----------------------------------|----------------------|-------------------------------------------------------------|
| Masonry bricks                 | 3.4                               | 1.8                  | 377.0                                                        |
| Reinforced expanded polystyrene| 2.6                               | 1.8                  | 352.8                                                        |
| Gypsum board                   | 2.0                               | 1.8                  | 334.7                                                        |

Because of the reduction of the partition weight, there are differences in the seismic forces of the buildings. As a result, the design for the first story columns varies for the three buildings. The three columns are 60 cm x 60 cm but they required $\rho = 1.7\%$, $\rho = 1.55\%$ and $\rho = 1.48\%$ for the masonry, polystyrene and gypsum partitions, respectively. The corresponding detailing of these columns is given by $16 \phi 22$, $16 \phi 22$ and $14 \phi 22$. The remaining columns and beams of the seismic system was identical for the three buildings.

### 3. Seismic performance evaluation

In order to investigate the differences in seismic performance, a three-dimensional model of each building is created in OpenSees [18], which includes the seismic and gravity members. Beam and columns are modeled using force-based elements with fibers of rebar, confined and unconfined concrete. The model uses five integration points and to avoid localization issues, the Constant Fracture Energy Criterion [19] is used with $G_y = 180$ N/mm. The modified Kent-Scott-Park model is used to model concrete, with properties $f_c = 28$ MPa, $f_{cc} = 33.6$ MPa, $\epsilon_c = 0.0019$. Steel reinforcement is modeled using a bilinear relation, with $E_s = 210$ GPa, $F_y = 420$ MPa, $F_u = 630$ MPa and an ultimate strain $\epsilon_u = 0.14$. The foundation is modeled as rigid, and the gravity loads for the model are calculated based on the expected loads and using the combination 1.05 D + 0.25 L. P-Delta effects are included. The seismic performance is evaluated using pushover analysis, with a load pattern proportional to the
first mode of vibration of the building. Displacement control is used in 1 mm increments with a target roof drift of 8%. Since the building is almost square, only the X direction is considered.

The pushover results for the three buildings are shown in figure 2. Since the seismic design forces are not the same as a consequence of having partitions with different weights, the Y axis shows the base shear (V) normalized by the design base shear of the buildings (V_{design}).

Several observations can be drawn from this figure. The elastic behavior is similar for the three buildings, with the building with masonry bricks showing slight differences from a 0.5% roof drift. This is expected because prior to these deformation levels, the P-Delta effects are not large enough to cause a significant deterioration of the buildings. The maximum base shear withstood by the three buildings occurred at approximately 1.6%, with V/V_{design} relationships of 3.08, 3.21 and 3.27 for the masonry, REP and gypsum configurations, showing that the partitions weight exerts a tangible influence for roof drifts between 0.5% and 1.6%, especially for when the building with masonry partitions is compared to its REP and gypsum counterparts. After this point, notable differences are observed for the three buildings, with the building with masonry partitions having the highest deterioration rate, followed by the buildings with REP and gypsum partitions. These results show that the partition weight exerts an importance influence on P-Delta effects in the post-peak range of buildings.

To further understand the effects of partitions weight on these building, the shear response of column C3 was recorded during the pushover (figure 3). As shown, the additional vertical load imposed by the weight of heavier partitions accelerates the loss of shear carrying capacity of the column. This behaviour was observed for all columns in the gravity system, most of which experience their first substantial decrease at 3.2% roof drift for the building with masonry partitions, and at 3.8% and 4.3% for the buildings with REP and gypsum partitions. These losses of capacity occurred around the analysis step where the models experience major convergence issues and the analyses could not continue.

The results of the pushovers served as input information for the SPO2FRAG [20] software, which was developed based on nonlinear dynamic analysis and converts pushover results to fragility functions. Two limit states are considered in this study: life safety and collapse prevention. A quadrilinear idealization was used for the corresponding pushovers are used to. These first level was set at 1.8% of the roof drift ratio, which corresponds to approximately the point of the maximum capacity of in the Pushover curve. The collapse prevention was set at 3% of the roof drift, which is a
smaller value the point where gravity columns suffer substantial damage for the building with masonry partitions.

Figure 3. Shear response of column C3

The fragility results for both limit states (Figure 4) corroborates the observations of the pushover analysis. In both cases, having a smaller partition weight translates into reductions of the fragility, as evidenced by the fragility building with gypsum partition being located at the rightmost of the plots, followed by the fragility of buildings with REP and masonry partitions.

Figure 4. Life safety and collapse fragility for the six story buildings

At the collapse prevention level, the building with masonry partition requires an acceleration $S_a = 0.94g$ for a 10% of probability of exceedance at the fundamental period $T_1$ of the building. In contrast, the accelerations required by the buildings with REP and gypsum partitions are $S_a = 1.1g$ ($T = T_1$) and $S_a = 1.24g$ ($T = T_1$), which represent an increase of 17% and 32%. These percentages should be taken as conservative values, as the collapse prevention limit for the buildings with REP and gypsum partitions may be higher than the 3% limit, which was adopted based on the gravity columns behavior during pushover for building with masonry partitions. For instance, applying the same criteria to the gypsum partition results in a 4% limit for its collapse prevention, requiring an acceleration $S_a = 1.44g$ for a 10% of probability of exceedance, a 53% increase respect to the building with masonry partitions. The performance at the life safety level shows a similar trend to the one at the collapse level. The required accelerations for a 10% probability of exceedance are $S_a = 0.69g$, $S_a = 0.88g$ and
Sa = 0.91g for the masonry, REP and gypsum partitions. Compared to the masonry partitions, the acceleration for REP and gypsum are 18% and 32% higher.

4. Conclusions

This paper investigated the effects of the partitions weight on the seismic performance of reinforced concrete buildings. A six-story building was designed using three different types of partitions: gypsum, reinforced expanded polystyrene (REP) and masonry bricks. The pushover results and the seismic fragility functions obtained for these buildings, support several conclusions:

- The performance at the collapse prevention level of the building improves with the use of lighter partitions. This was evidenced in that the acceleration needed for a 10% of collapse probability is 17% higher in the building which uses REP, compared to that of building with masonry brick partitions. The use of gypsum demonstrated better seismic performance, with a 32% acceleration compared to masonry, showing that reducing the weight of partitions correlates with improved seismic performance.
- This behavior is consistent with the lower ductility and the higher deterioration rate observed in the pushover of buildings with larger partition weight, which are more affected by the P-Delta effects.
- Reducing the partition weight brings similar improvements at the life safety performance level.
- The partition weight has a minimal effect on the seismic performance in the elastic range, as shown by the buildings having similar elastic stiffness, with the corresponding negligible differences in the pushover results for roof drifts lower than 0.5%.
- The influence of partition weight on the system overstrength of the buildings is small, with a 6.1% difference between the building with gypsum and masonry partitions. No difference was observed in the roof drift ratio at which the maximum base shear was reached.

All things considered, the partition weight exerts an influence on the seismic performance of RC frames that must be considered within the design/planning phase of these buildings. This influence varies from less than 5% in the elastic range to values greater than 30% at the collapse prevention level.

Future work in this area can be pursued in various directions. A first one involves considering the effects of different building configurations, such as the height and the span length, both of which can increase the P-Delta effects. A second worthy topic is investigating whether the additional ductility that stems from lighter partitions can be incorporated in the seismic design by allowing a higher seismic reduction factor (R). Finally, similar studies to this one can be conducted for buildings constructed using other structural systems, such as steel frames and RC walls.

References

[1] A. S. of C. Engineers, Minimum Design Loads and Associated Criteria for Buildings and Other Structures. 2017.
[2] K. Morfidis and K. Kostinakis, “The role of masonry infills on the damage response of R/C buildings subjected to seismic sequences,” Eng. Struct., 2017.
[3] M. Teguh, “Experimental Evaluation of Masonry Infill Walls of RC Frame Buildings Subjected to Cyclic Loads,” Procedia Eng., 2017.
[4] S. Hak, P. Morandi, and G. Magenes, “Prediction of inter-storey drifts for regular RC structures with masonry infills based on bare frame modelling,” Bull. Earthq. Eng., vol. 16, no. 1, pp. 397–425, Jan. 2018.
[5] R. R. Milanesi, P. Morandi, and G. Magenes, “Local effects on RC frames induced by AAC
masonry infills through FEM simulation of in-plane tests,” Bull. Earthq. Eng., vol. 16, no. 9, 2018.

[6] G. Blasi, F. De Luca, and M. A. Aiello, “Brittle failure in RC masonry infilled frames: The role of infill overstrength,” Eng. Struct., vol. 177, 2018.

[7] P. G. Asteris, L. Cavaleri, F. Di Trapani, and A. K. Tsaris, “Numerical modelling of out-of-plane response of infilled frames: State of the art and future challenges for the equivalent strut macromodels,” Engineering Structures, vol. 132. 2017.

[8] M. Kumar, D. C. Rai, and S. K. Jain, “Ductility reduction factors for masonry-Infilled reinforced concrete frames,” Earthq. Spectra, vol. 31, no. 1, pp. 339–365, Aug. 2015.

[9] A. Furtado, H. Rodrigues, A. Arêde, and H. Varum, “Simplified macro-model for infill masonry walls considering the out-of-plane behaviour,” Earthq. Eng. Struct. Dyn., 2016.

[10] D. Perrone, M. Leone, and M. A. Aiello, “Non-linear behaviour of masonry infilled RC frames: Influence of masonry mechanical properties,” Eng. Struct., 2017.

[11] P. B. K. Mbewe and G. P. A. G. van Zijl, “A simplified non-linear structural analysis of reinforced concrete frames with masonry infill subjected to seismic loading,” Eng. Struct., vol. 177, 2018.

[12] A. R. Barbosa et al., “Performance of Medium-to-High Rise Reinforced Concrete Frame Buildings with Masonry Infill in the 2015 Gorkha, Nepal, Earthquake,” Earthquake Spectra, vol. 33, no. Special issue 1. pp. S197–S218, Dec-2017.

[13] H. Burton and G. Deierlein, “Simulation of Seismic Collapse in Nonductile Reinforced Concrete Frame Buildings with Masonry Infills,” J. Struct. Eng., 2014.

[14] S. Tesfamariam, K. Goda, and G. Mondal, “Seismic vulnerability of reinforced concrete frame with unreinforced masonry infill due to main shock-aftershock earthquake sequences,” Earthq. Spectra, vol. 31, no. 3, pp. 1427–1449, Jan. 2015.

[15] K. Qian and B. Li, “Effects of Masonry Infill Wall on the Performance of RC Frames to Resist Progressive Collapse,” J. Struct. Eng., vol. 143, no. 9, p. 04017118, Sep. 2017.

[16] ACI, “Building Code Requirements for Structural Concrete and Commentary,” American Concrete Institute Farmington Hills, MI, 2011.

[17] A. Habibullah, “ETABS-Three Dimensional Analysis of Building Systems, Users Manual,” Comput. Struct. Inc., Berkeley, Calif., 1997.

[18] S. Mazzoni, F. McKenna, M. H. Scott, and G. L. Fenves, “OpenSees command language manual,” Pacific Earthq. Eng. Res. Cent., p. 451, 2006.

[19] J. Coleman and E. Spacone, “Localization Issues in Force-Based Frame Elements,” J. Struct. Eng., vol. 127, no. 11, pp. 1257–1265, 2001.

[20] G. Baltzopoulos, R. Baraschino, I. Iervolino, and D. Vamvatsikos, “SPO2FRAG: software for seismic fragility assessment based on static pushover,” Bull. Earthq. Eng., vol. 15, no. 10, pp. 4399–4425, Oct. 2017.