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INFLUENCE OF MASONRY INFILLS WALLS ON THE SEISMIC BEHAVIOUR OF MULTI-STOREY WAFFLE SLABS RC BUILDINGS

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SUMMARY

In this work, we analyze the influence of masonry infill walls on the seismic performance of waffle slabs reinforced concrete (RC) framed structures. We analyze buildings of three, five and eight storeys, which are representative for a big number of housings in Barcelona, Spain. Capacity spectra have been obtained by performing pushover analyses and we have used a simplified procedure to obtain fragility curves, which define the probability of exceeding a damage state. As usually, five damage states are considered: none, slight, moderate, extensive and complete. From the assumption that fragility curves follow a lognormal cumulative function, they will be defined in terms of a mean spectral displacement $\overline{S_d}$ and its variability β. Our results clearly indicate that masonry infill walls may increase the capacity of this type of buildings and, therefore, they must be included in the analysis. A deterministic hazard scenario has been considered in order to evaluate the seismic behavior of the buildings. This scenario represents the biggest historical earthquake in Barcelona, and is defined by its elastic response spectrum. A spectral displacement of two cm is then used to analyze and discuss the expected damage probability distribution. The moderate and severe damage states show significant occurrence probabilities for a relatively small earthquake, showing the high vulnerability of this building typology. However, the influence of infill brick walls, which in certain areas are not considered in the seismic structural design, has proved to be important. Under the simplified assumptions here adopted, infill brick walls, if well designed and built, can considerably improve the seismic performace of this building typology. The main results of this work are being used to assess the seismic vulnerability of the RC buildings of Barcelona and to obtain seismic risk scenarios for the city.

Keywords: Capacity-Demand. Fragility curves. RC buildings. Masonry infill walls. Seismic risk.

INTRODUCTION

Vulnerability studies are very important to evaluate the seismic risk and its application is particularly interesting in urban areas located in low to moderate seismic hazard regions where the increase of the

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population and the absence of adequate seismic resistant prescriptions for buildings increment the seismic risk. Very often, in these areas, a large number of existing reinforced concrete (RC) frame structures have been designed mainly for gravity loads, or their lateral resistance has been determined without adequate seismic resistant considerations or according to old seismic codes, in which ductile detailing are not explicitly required. It is very likely that these buildings, when subjected to a maximum credible seismic event, suffer more damage than reasonable. Many of the actual housings in Barcelona, Spain, are multi-storey waffle slabs reinforced concrete buildings. In fact, this typology is the second most representative in the city and the number of this kind of buildings is increasing because, at present, this is the most extended construction way. This work is a contribution to the analysis of the seismic behaviour of these buildings and it faces the seismic risk analysis in an urban area situated in a low seismic hazard region. In addition to the analysis of the seismic performance of this type of buildings, we will analyze the influence of masonry infill walls. Six models have been analysed: high-rise (8-storeys), mid-rise (5-storeys) and low-rise (3-storeys). We will consider the cases with and without masonry infill.

The buildings, with and without masonry infill walls, are analysed by performing non-linear structural analyses. RUAUMOKO-2D program (Carr [1]) is used to obtain the capacity curves and the corresponding capacity spectra. A simplified method is then applied to get fragility curves, which define the probability to be reached or exceeded each damage state, and which, in this case, are given as a function of the spectral displacement S_d. It is assumed that these fragility curves follow a lognormal cumulative probability distribution and, therefore, they are defined by only two parameters: the mean value $\overline{S_d}$ and the standard deviation β. A deterministic hazard scenario, representing the maximum historical earthquake for Barcelona, is given in terms of the elastic 5% damped response spectrum allowing to compute the corresponding demand spectrum. This spectrum, in turn, takes into account the effects of energy dissipation by the inelastic behaviour and by the degradation of the building, when subjected to strong earthquakes. The intersection of both spectra (capacity and demand) is the well known *Performance Point*, which defines the maximum spectral displacement *Sd* and acceleration *Sa* representative for the response of the structure when it suffers the seismic action. A two cm S_d will be used to analyse the probabilities of occurrence for each damage state.

The results of this work are being used to draw seismic risk scenarios for Barcelona, and clearly indicate that it is convenient and significant to consider the masonry infill walls in the RC buildings analysis.

STRUCTURAL DESCRIPTION

Our structural models are based on a real RC eight-storey building, for which detailed structural plans were available. The five and three-storey buildings were modelled by using reasonable assumptions on their geometry and materials, starting from the data of the eight storey building. These three models are intended to be representative for three building classes in the city, low-rise, mid-rise and high-rise. Low-rise class contains one, two and three-storey buildings and mid-rise class, includes four, five and six-storey buildings. Very high buildings are not included in this study and they should be considered as special buildings.

The high-rise building model has a rectangular plan with 25.65×21.90 m and is 24 m high. In order to model the building as a frame, we assumed equivalent beams whose effective width between columns was assessed by using the SAP2000 non-linear program [2]. The floor slab is 0.28 m thick, the ribs width is 0.10 m, the abacus is 2.4×2.4 m. The dimensions of other structural elements such as columns and beams may vary in height. Columns dimensions may vary between 0.30×0.35m and 0.50×0.35m, and beam dimensions vary between 0.80×0.28 m and 1.30×0.28 m. Finally the assumed mechanical properties for the main materials involved in the construction are: concrete compression strength f_{ck}=20N/mm^2; steel yield stress f_y =510N/mm^2; elastic modulus E_C=30000 N/mm^2; shear modulus G=12500 N/mm^2. Reasonable values where assumed for the dimensions and material properties of the mid-rise and low-rise buildings.

SEISMIC EVALUATION

Several programs have been used to perform the non-linear dynamic analysis of the buildings. A complete evaluation of the stiffness, strength and ductility of the structure was performed by using RUAUMOKO-2D (Carr [1]) and BCSEC (Bairán [3]). STAC [4] program is a powerful tool oriented to stochastic analysis and allows generating numerical samples of parameters whose probability density function is known. It is intended to perform the analysis here presented in a probabilistic way, taking into account the uncertainties in the main parameters involved in the materials and models. The use of RUAUMOKO-2D program requires modelling the structure by means of plane frames, connected each other (see Figure 1) and the effect of the rigid diaphragm was introduced by constraining the nodes of the same storey.

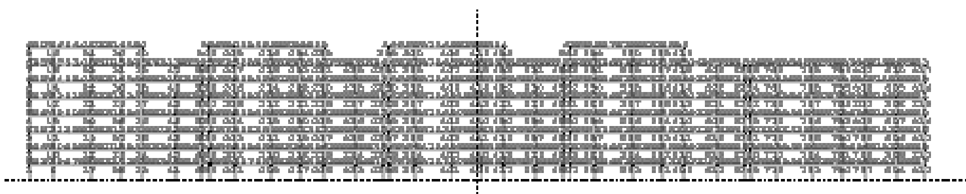

Figure 1: Frames for the analysis in RUAUMOKO-2D computer program.

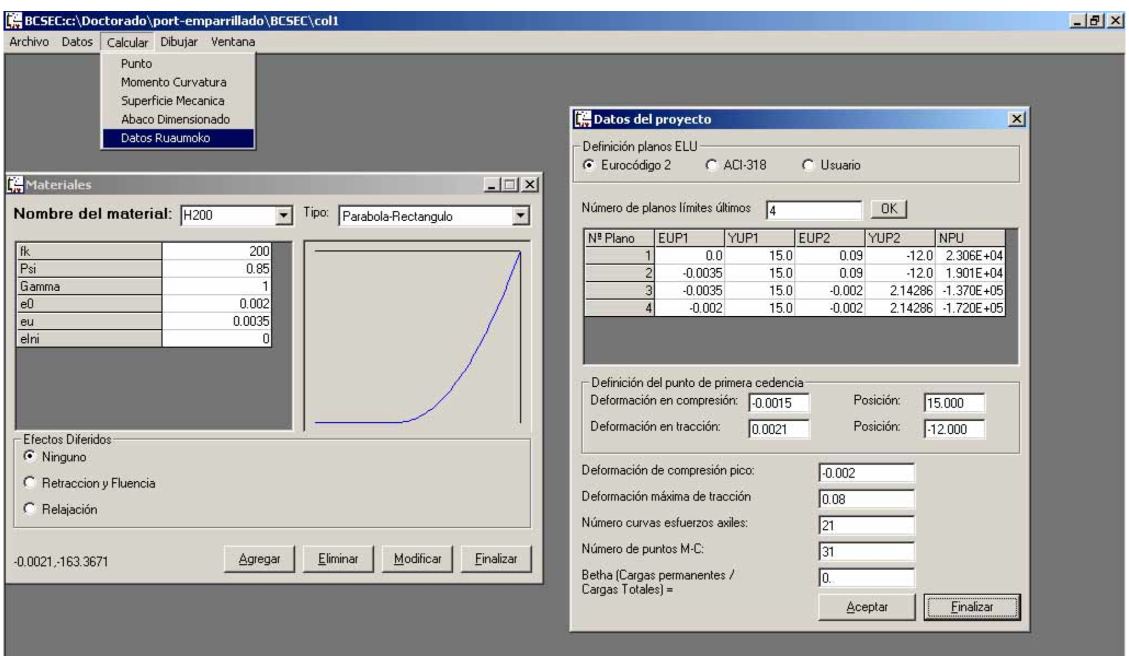

Figure 2: Materials definition and project date, BCSEC computer program.

BCSEC computer program allows obtaining the non-linear mechanical characteristics of cross thesections. In this program, the different materials composing the section and the corresponding stress-strain curves are defined. In this case, parabolic-rectangular and linear-rectangular curves have been assigned to the concrete and steel, respectively. The BCSEC program has been also used to calculate, in direct way, the moment-curvature curves in the points required by RUAUMOKO computer program (see Figure 2) (Moreno [5]).

The variability of the main parameters characterizing the materials of the RC buildings has been analysed. The probability density functions for the mechanical characteristics of the materials, together with their parameters are given in Table 1 (see also Yepez [6]). We can see in Table 1 the probabilistic or random variables, the assumed probability distribution, the mean value and the corresponding covariance. These stochastic variables will be used, in the next step of the work here presented, to perform the analysis by using a stochastic approach. STAC program will help us to perform numerical Monte Carlo simulations.

Table 1: Random variables

Variables	**Distributio n**	**Mean**	**COV**
$f_c^{'}$	Normal	20 N/mm^2	0.15
E_c	Normal	3.e4 N/mm^2	0.15
f_y	Lognormal	510 N/mm^2	0.11
Es_{max}	Normal	2.1e5 N/mm^2	0.09
f_y *reinforcemen t*	Lognormal	510 N/mm^2	0.11

RUAUMOKO-2D program incorporates a simplified model for considering masonry infill walls in RC frames (Crisafulli [7]). A truss model represents each masonry panel. This model considers the interaction between the panel and the frame, representing the most common failure made in the masonry panels: the shear failure. Five struts members represent each panel. Two parallel struts in each diagonal direction (Figure 3a) represent the rotational effects on the joints of the compression forces carried out across the diagonal of the panel.

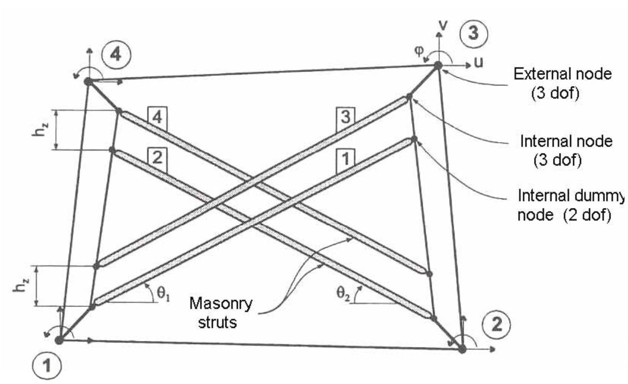

Figure 3a: Truss mechanism.

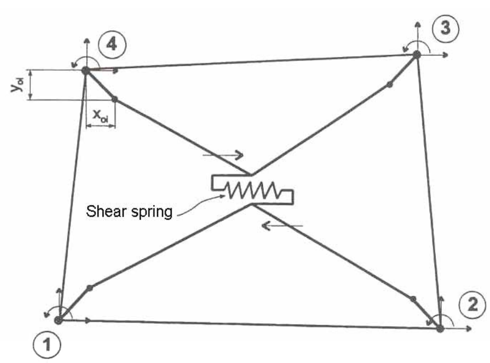

Figure 3b: Shear behaviour.

One strut more acts across two opposite diagonal corners and transmits the shear from the top to the bottom of the panel. It also could be subjected to compression and may connect different top and bottom corners depending on the panel deformation (Figure 3b).

To define the behaviour of the struts, representing the masonry panels, some mechanical and geometrical parameters are required. The main parameter is the compressive strength, $f'_{m\theta}$, which controls the strength of the strut, which in our case is $f'_{m\theta}$=0.80N/mm^2. The tensile strength, f'_t, represents the strength of the masonry, and can be assumed null in the case of lack of more detailed information. The elastic modulus, E_{mo}, which represents the initial slope of the strain-stress curve and it is assumed that $E_{mo} \geq f'_{m\theta} / \varepsilon'_m$, where ε'_m, is the strain at maximum stress (ε'_m=-0.003, Crisafulli [7]). The area of the strut is defined in such a way to fit the frame and the thickness of the panel is 9 cm. Figure 4 shows how the masonry infill walls are arranged into our high-rise building model. In this figure, mainly in the first floor, but also in many others, we can see how the struts are in non-linear compression and some plastic hinges appear in beams and columns (red dots or segments).

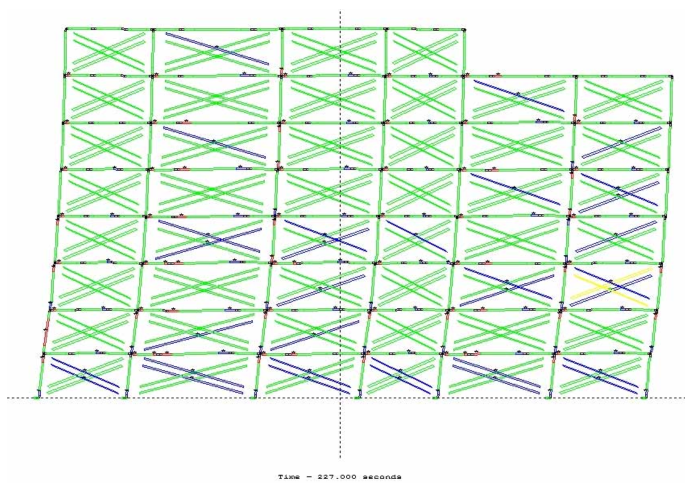

Figure 4: Typical frame with masonry infill walls.

STRUCTURAL CAPACITY AND SEISMIC DEMAND

The structural capacity is calculated by means of a non-linear static analysis with the RUAUMOKO program. We apply to the structure a monotonically increasing load until the ultimate load is reached. The loading pattern chosen in this work corresponds to the seismic equivalent static loading provided by the Spanish seismic code (NCSE-94 [8]). Thus, a pushover curve that relates the base shear V to the roof displacement Δ_{roof} is obtained. Figure 5 shows the capacity curves for the three building classes in the case that no masonry infill walls are considered. The pushover curves are then converted to capacity spectra. The well-known Acceleration-Displacement Response Spectrum (ADRS) format is adopted using the following equations:

$$S_a = \frac{V/W}{\alpha_1} \tag{1}$$

$$S_d = \frac{\Delta_{roof}}{PF_1 * \Phi_{1,roof}} \tag{2}$$

where S_a and S_d are spectral acceleration and displacement respectively, W is a modal weight, $\Phi_{1,\ roof}$ is the amplitude of mode 1 at roof level and α_1 and PF_1 are respectively the modal mass coefficient and the modal participation factor for the first natural mode.

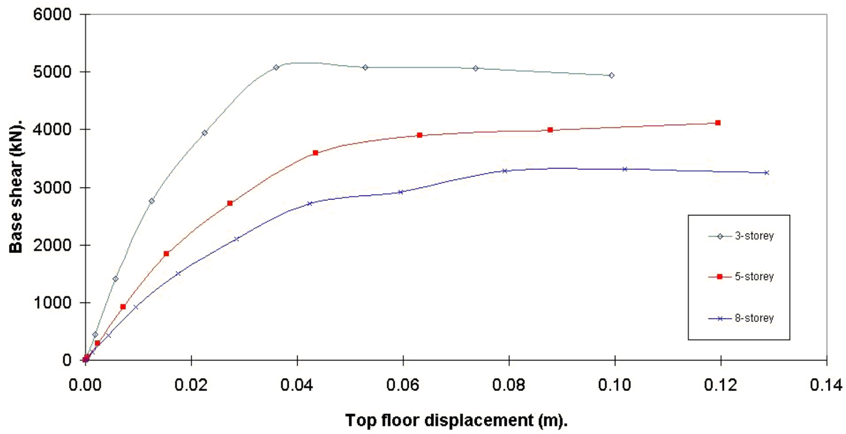

Figure 5: Capacity Curves, waffle slabs RC buildings with masonry infill walls.

Figure 6 shows the bilinear simplified representation of the capacity spectra for the five-storey building. Both cases, with and without masonry infill walls are shown. We can see that the masonry infill walls improve the building capacity. Only two points define the bilinear representation of the capacity spectrum: the yield capacity (*Dy, Ay*) and the ultimate capacity (*Du, Au*). These capacity spectra are used to determine the spectral displacements corresponding to damage states thresholds. Five damage states are considered: no damage, slight, moderate, extensive and complete. The corresponding threshold for each damage state has been defined by using the guidelines provided by Lagomarsino [9].

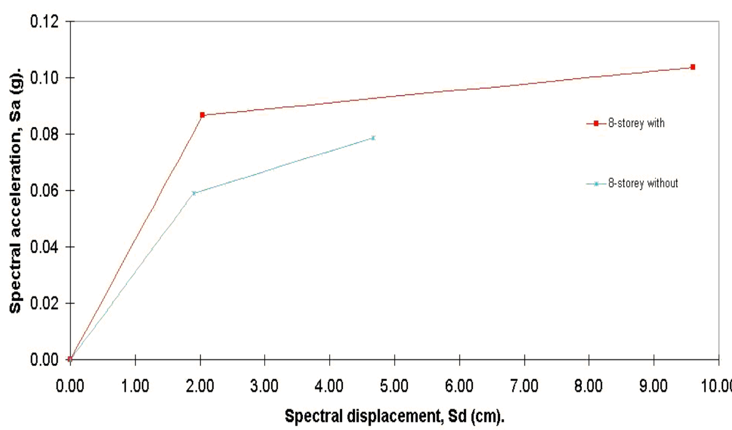

Figure 6: Bilinear capacity spectra, 8 storeys structure with and without masonry infill walls.

The case of the maximum historical earthquake occurred in Barcelona (deterministic case), has been used to perform damage and risk analysis. The Cartographic Institute of Catalonia (ICC) provided the corresponding 5% damped elastic response spectra. The demand spectra were obtained by means of the Capacity Spectrum Method (see ATC-40 [10]). Figure 7 shows the capacity and demand spectra corresponding to the three building classes when no masonry infill walls are considered. Figure 8 is an example on how the damage state thresholds are determined. In both figures, bilinear capacity spectra and inelastic demand spectra are represented. Figure 8 corresponds to the high-rise building class with masonry infill walls. Again, we can observe how the infill walls increase the capacity of the eight-storey building.

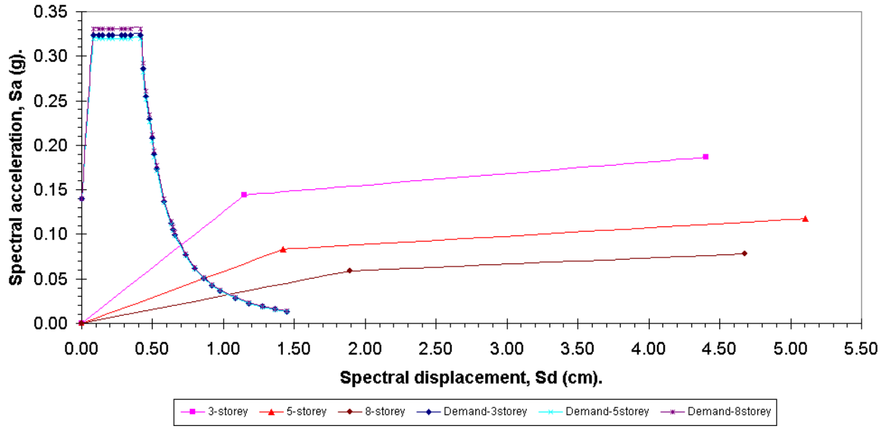

Figure 7: inelastic demand and bilinear capacity and spectra. (High, mid and low-rise buildings without masonry infill walls)

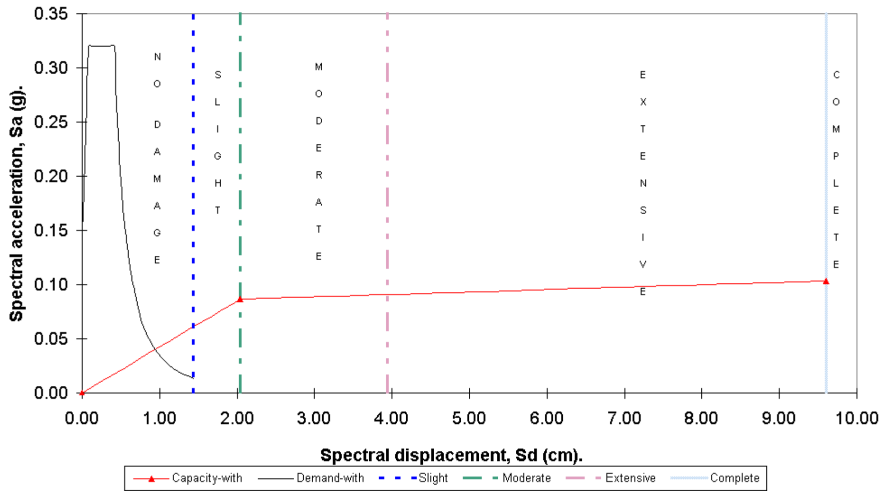

Figure 8: Threshold damage states. (8-storey building with infill masonry walls).

FRAGILITY CURVES

For each damage state, slight, moderate, extensive and complete, fragility curves represent the probability that the damage state be reached or exceeded as a function of the spectral displacement (S_d). These curves can be defined by the mean value of the spectral displacement $\overline{Sd}_{DS}$, corresponding to the threshold damage state *DS*, and its variability β, because it is assumed that a fragility curve follows the lognormal function given by:

$$P[DS/Sd] = \Phi\left[\frac{1}{\beta_{DS}} \cdot \ln\left(\frac{Sd}{\overline{Sd_{DS}}}\right)\right] \quad (3)$$

where Φ is the standard cumulative normal distribution function. The procedure to determine the variability associated with the damage state, β_{DS}, is estimated from the assumption that given a seismic scenario, the damage distribution for a building class, follows a binomial probability distribution.

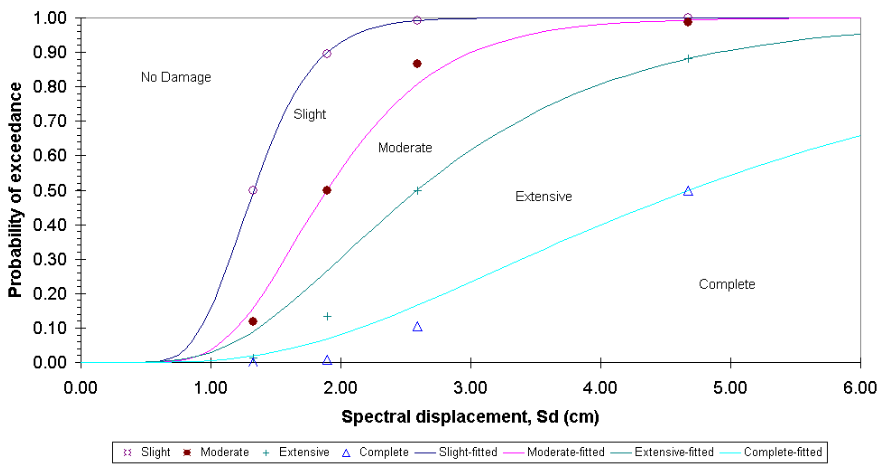

Figure 9: Fragility curves for 8-storey building without masonry infill walls.

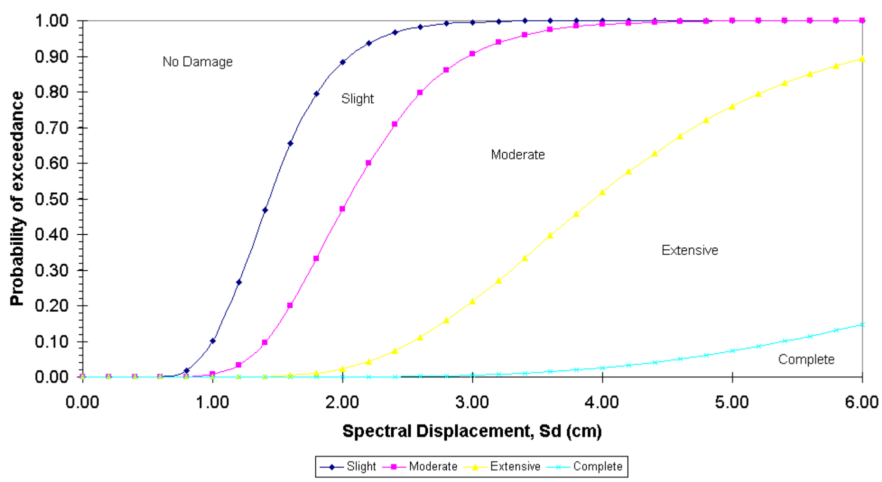

Figure 10: Fragility curves for 8-storey building with infill.

Therefore, we assign a 50% probability to the damage state for which the $\overline{Sd_{DS}}$ threshold is known (see Figure 8) and we determine the probabilities for the other damage states by fitting the corresponding binomial probability distribution. Then the standard deviation for each fragility curve is determined by means of a constrained least-squares procedure. Finally, due to the fact that five damage states are considered, four fragility curves are needed to completely define the probabilities for each damage state. Figure 9 shows the fragility curves obtained for the eight-story building without masonry infill walls. The individual damage state probabilities, used to fit the fragility curves by equation (3) in order to estimate the parameter β, are also plotted. Figure 10 shows the fragility curves for the same building when the masonry infill walls are included. We can see how the fragility of this building typology decreases. For example in the case of a spectral displacement of about 6 cm, the collapse probability is less than 15% for buildings with masonry infill walls, but for the same spectral displacement, the collapse probability is more than 60% for buildings without masonry infill walls.

In order to underline the influence of the masonry infill walls particular damage probability matrices has been obtained for the case of S_d=2 cm. Table 2 and Figure 11 present the obtained results.

Table 2: Damage Probability Matrices for the eight-storey building

Damage States	Without Infill	With Infill
No damage	7.0%	12.0%
Slight	37.0%	40.0%
Moderate	26.0%	46.0%
Extensive	22.0%	2.0%
Complete	8.0%	0.0%

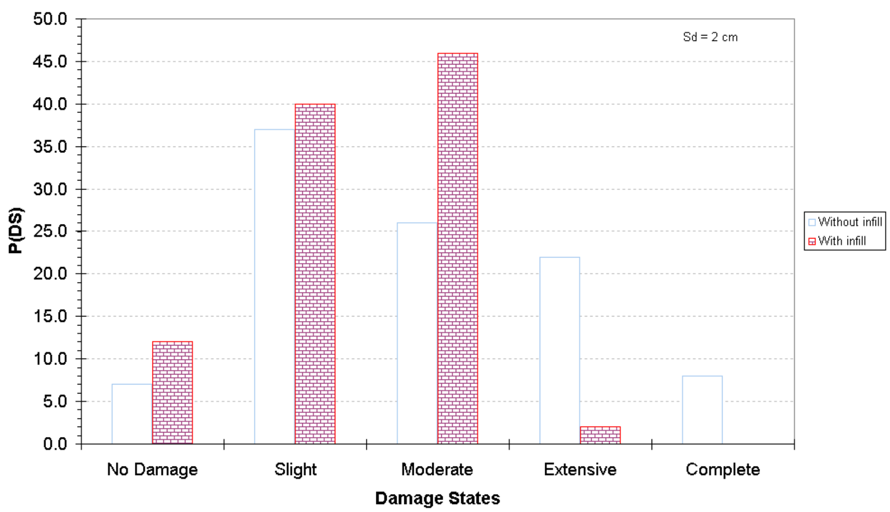

Figure 11: Damage states of the 8 storey building without and with infill.

Figures 9 and 10 clearly indicate that masonry infill walls increase the seismic strength of the RC waffle slabs buildings. Table 2 and Figure 11 show details of this improvement. Although no damage and slight damage states show similar probabilities, significant differences arise in the fragility curves corresponding to moderate, extensive and complete damage states. Complete collapses disappear when infill masonry walls are considered and extensive damage state probability is about 22% in the case of bare buildings and about only 2% for buildings with walls. Most of the reduced damage in the two extreme damage states concentrates into the moderate state, indicating the possible sense of the variation in the seismic behavior of such a building.

DISCUSSION AND CONCLUSIONS

This work is a preliminary approach to the influence of the masonry infill walls on waffle slabs reinforced concrete buildings, typical of Barcelona, Spain, a city located in a region of low to moderate seismic hazard. The procedures for obtaining, capacity and demand spectra and fragility curves, as well as probability damage matrices, have been pointed out. Certain simplifying assumptions have been made and, probably, the model used for the masonry panels may be not the most adequate for the characteristics of the masonry used in Barcelona. Our feeling is that the masonry model we have used may be more adequate to characterize masonry panels and infill walls of buildings in areas with higher seismic hazard, which include seismic resistant design. Therefore the obtained results may be biased. Any way, our results clearly indicate the importance of considering such masonry walls in the dynamic analyses and in the seismic risk evaluation. They clearly modify the seismic behavior and, under the assumptions here adopted, they improve the seismic strength of the structures. Anyhow more work is needed to refine the models and to improve the results.

The analysis of a 2 cm spectral displacement case indicates that the expected damage for the severe and complete damage states, moves to the moderate damage when infill walls are considered. None and Slight damage states show similar probabilities. This fact may indicate that, if properly designed and constructed, infill walls may prevent extreme damage states and, in this way, they may prevent pre-collapse and collapse of the buildings, which are responsible for most of injured people and deaths.

The methods and analyses here described are being used to draw seismic risk scenarios for Barcelona. Fragility curves are developed for the main building typologies and damage probability matrices are obtained for selected earthquake scenarios. A wide database about most of the housings of Barcelona is being used to plot seismic risk scenarios by mapping the expected damage for selected seismic events. Damage and risk scenarios are obtained by using ArcInfo software and Geographical Information System tools. It is intended that this work be useful to local authorities for earthquake prevention and seismic emergency management.

ACKNOWLEDGMENTS

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