# THE INFLUENCE OF INFILL PANELS ON VULNERABILITY CURVES FOR RC BUILDINGS

**B. Borzi[1], H. Crowley[2] and R. Pinho[3]**

[1] *Associate Researcher, European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata 1, Pavia, Italy*
[2] *Researcher, European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata 1, Pavia, Italy*
[3] *Assistant Professor, Department of Structural Mechanics, University of Pavia, Via Ferrata 1, Pavia, Italy*
*Email: b.borzi@eucentre.it*

**ABSTRACT :**

A Simplified Pushover-Based Earthquake Loss Assessment method (SP-BELA) for the definition of vulnerability curves has recently been proposed. A prototype structure is introduced to describe the behaviour of a selected structural type. Conceptually, the method can be applied to any structural typology. When reinforced concrete buildings are taken into account, a simulated design procedure is adopted to define section dimensions and the reinforcement of the structural elements of a random building population. SP-BELA adopts a simplified method of analysis to define the pushover curve of each building of the population. Since SP-BELA is based on a mechanics-based interpretation of structural behaviour, through a pushover curve, it is straightforward to account for the influences of different structural layouts on the vulnerability. The research work described herein has been undertaken to highlight the influence of infill panels on the vulnerability curves. In this paper, vulnerability curves for both seismically designed and non-seismically designed reinforced concrete buildings are presented assuming the following conditions: bare frames, regularly distributed and irregularly distributed infill panels along the height of the building. A comprehensive validation exercise of the simplified methodology used to produce the pushover curves is also documented.

**KEYWORDS:** Reinforced concrete, vulnerability assessment, infill panels, simplified pushover

## 1. INTRODUCTION

In this paper a Simplified Pushover-Based Earthquake Loss Assessment method (SP-BELA) for the definition of vulnerability curves is presented. SP-BELA is an analytical method that defines pushover curves using a simplified mechanics-based procedure to define the base shear capacity of the building stock and a displacement-based framework, which is based on the rotation capacity of the structural elements at different limit state conditions and the displacement profile of the response mechanism. Conceptually, the method may be applied to any structural typology by simply changing the simplified methodology adopted to define the pushover curve. The influence of infill walls, either regularly or irregularly distributed, on the vulnerability curves for reinforced concrete (RC) buildings is studied herein. In order to define vulnerability curves, the ground motion intensity is modelled using a displacement response spectral shape which is anchored to a range of values of peak ground acceleration (PGA); for a given value of PGA, the displacement response at the effective period of vibration of the building is compared with the displacement capacity. The benefits of this type of intensity measure are the following: displacements are known to be well correlated with damage and the relationship between the frequency content of the ground motion and the period of vibration of different classes of RC buildings is taken into account.

## 2. SIMPLIFIED PUSHOVER-BASED ASSESSMENT METHOD

In this section the proposed vulnerability methodology, SP-BELA, is briefly described. More details on the derivation and implementation of the method are given in Borzi *et al*. (2008). The SP-BELA method combines the definition of a pushover curve using a simplified mechanics-based procedure in order to define the base shear capacity of the building stock, which together with the limit state displacements of the frame can be used to calculate the secant stiffnesses and subsequently the limit state periods of vibration. The displacement-based framework proposed by Calvi (1999) is than adopted to evaluate whether each building of the population survive or fail each limit state condition.

The pushover curve in SP-BELA is calculated for buildings with a layout in-plan as shown in Figure 1 (e.g. Masi, 2004; Cosenza *et al.*, 2005; Iervolino *et al.*, 2007). This prototype structure is for seismically designed frames, whilst the typology chosen for non-seismically designed buildings differs slightly as it has the frames oriented in one direction only, and in the orthogonal direction the frame effect is guaranteed by an effective width of the floor slab. For what concerns the infill panel distribution, two different typologies (regularly or irregularly infilled) have been considered herein, as shown in Figure 2.

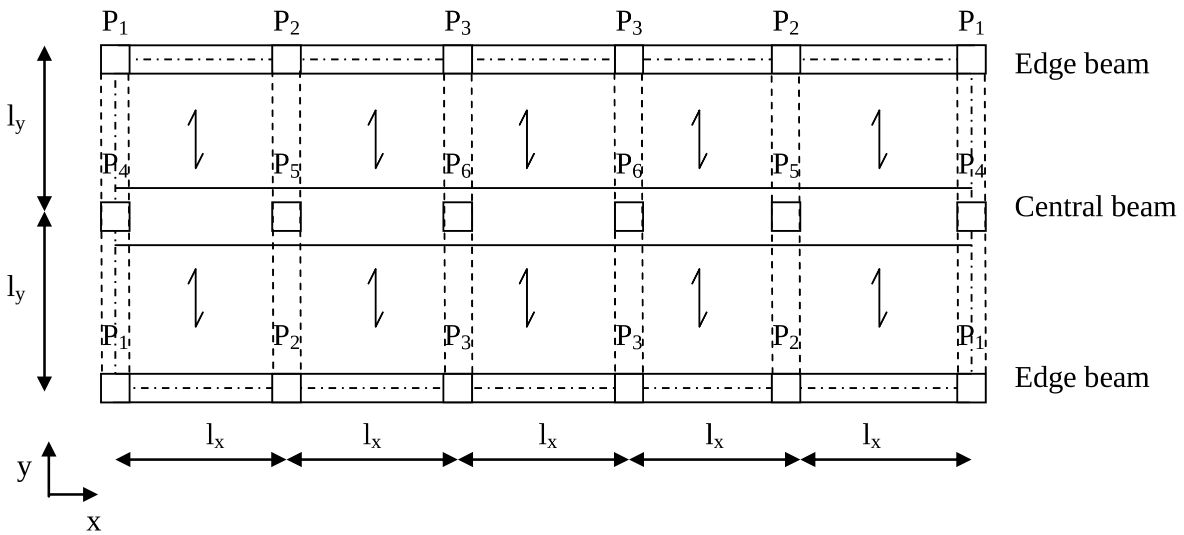



Figure 1 Plan view of the RC frame building assumed as representative of the building structural type for seismically designed buildings.

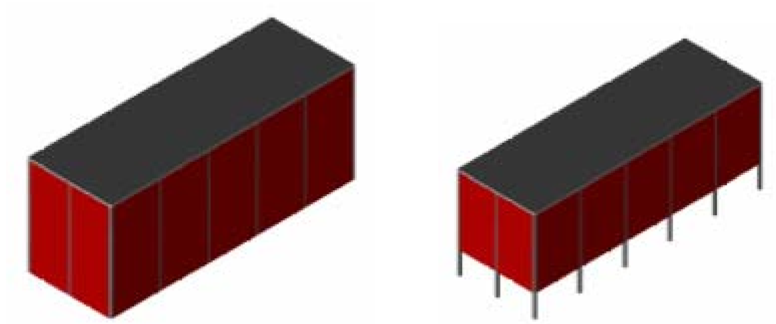


Figure 2 Infill panel distribution: regular (left) and irregular/pilotis (right)

In order to define the base shear resistance of the building in the two orthogonal directions of the building, the frame and the infill panels are considered to act in parallel. The infill panels are modelled through strut elements which have a thickness equal to the wall thickness and an equivalent width which is calculated according to the following relationship (Mainstone, 1971):

$$\frac{b_w}{d_w} = 0.2\sin(2\vartheta)\left(\frac{E_w t_w h_w^3 \sin(2\vartheta)}{E_c I_p}\right)^{-0.1} \tag{2.1}$$

where, $b_w$ is the equivalent width; $d_w$ is the strut length; $t_w$ is the panel thickness chosen as 250 mm in this application; $\vartheta$ is the angle that the strut forms with the horizontal line; $h_w$ is the panel height; $E_w$ is the elastic modulus of the panel, chosen as 2000 MPa; $E_c$ is the elastic modulus of the concrete, chosen as 30000 MPa; and $I_p$ is the second moment of inertia of the columns. It is assumed that the panels have an influence on the lateral resistance of the building up to the yield limit state. Whereas, when the frames evolve into the nonlinear range, the panels are considered to collapse and, therefore, they no longer contribute to the base shear resistance. The collapse multiplier ($\lambda$), that represents the base shear resistance divided by the seismic weight, and the limit state displacement capacities ($\Delta_{LSi}$) are used to calculate the secant stiffness and subsequently the effective period of vibration ($T_{LSi}$), as illustrated in Figure 3.

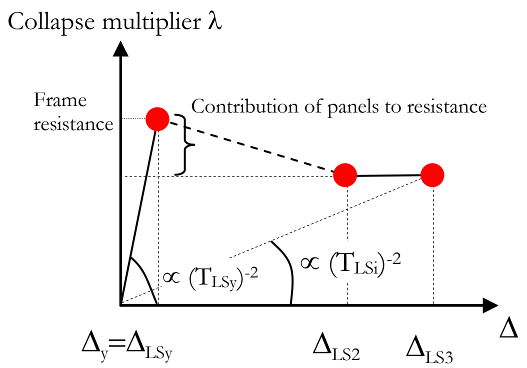


Figure 3 Capacity curve of infilled frame, considering the frames and panels acting in parallel

The influence of the panels is currently not considered in defining the displacement capacity on the pushover curve as the panels are often not perfectly in contact with the frames and they are assumed to play a role on the overall building performance only after the frames have already been deformed beyond their elastic limit. On the other hand, the panels are assumed to collapse before the frames reach the significant damage limit condition.

The displacement capacity is related to damage conditions, which are identifiable through Limit States (LS). Three limit state conditions have been taken into account: light damage, significant damage and collapse. The light damage limit condition refers to the situation where the building can be used after the earthquake without the need for repair and/or strengthening. Beyond the limit condition of significant damage the building cannot be used after the earthquake without strengthening. Furthermore, this level of damage is such that it might not be economically advantageous to repair the building. If the collapse limit condition is achieved, the building becomes unsafe for its occupants, since it is no longer capable of sustaining any further lateral force nor the gravity load for which it has been designed.

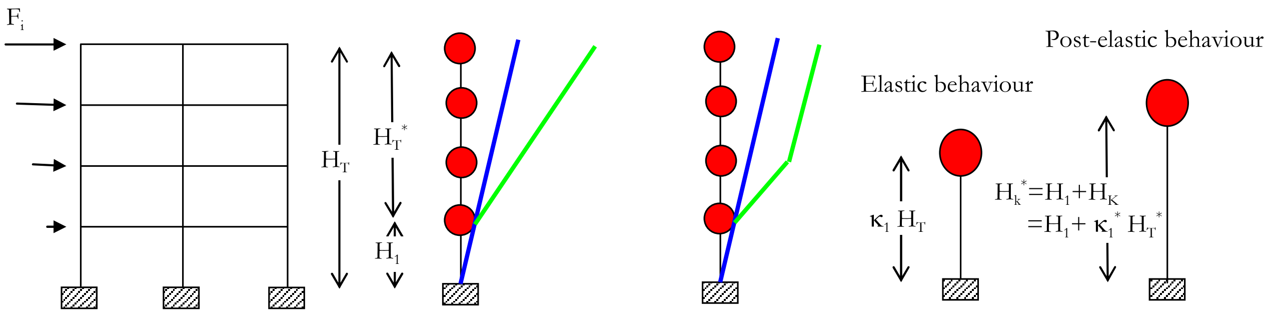


Figure 4 Deformed shape for (centre left) beam-sway and (centre right) column-sway collapse mechanisms activated above the first floor. The black line represents the elastic deformed shape and the grey line the post-yield mechanism.

Limit conditions are related to the rotation requirements imposed on the plastic hinges that lead to the development of a mechanism. Therefore, knowing the collapse mechanism and the rotation capacity of the plastic hinges (using the equations proposed by Panagiotakos and Fardis (2001)), the displacement capacity of the equivalent SDOF system can be calculated, as shown in Figure 4. Figure 4 shows possible mechanisms used in SP-BELA: a beam-sway mechanism caused by plastic hinges forming in all the beams above the first floor and in all of the columns at the base of the second storey whilst the column-sway mechanism forms when plastic hinges form at both ends of the columns in the second storey. Based on the shape of the displaced profile, the displacement capacity of the equivalent SDOF system can be calculated using the elastic displacement and the post-elastic displacement at the height of the SDOF system. The equations used to calculate the displacement capacity in SP-BELA are described in Borzi *et al*. (2008).

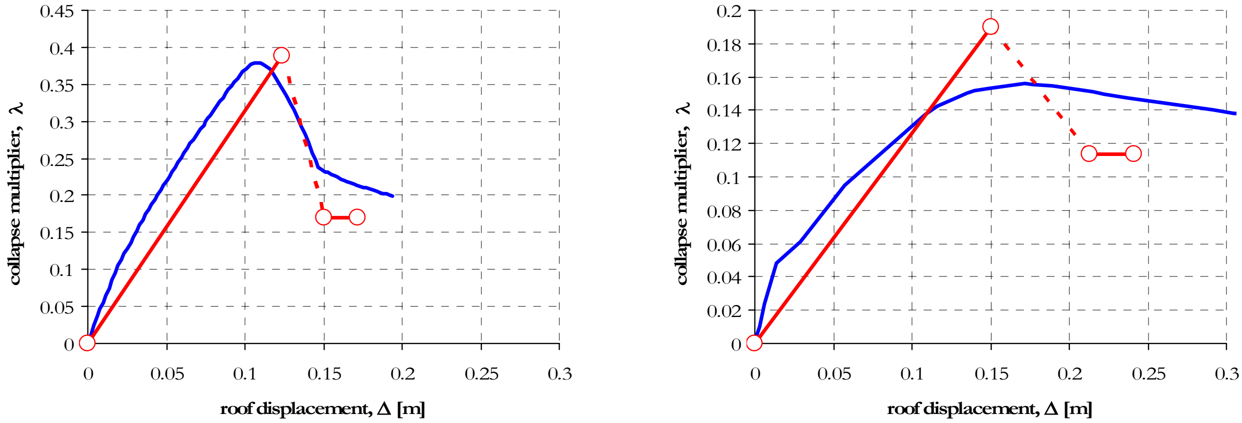
## 3. VALIDATION OF SIMPLIFIED PUSHOVER CURVES

In order to assess the adequacy of the proposed procedure in the computation of simplified pushover curves, comparisons with results obtained from Finite Element (FE) analyses have been carried out. The latter have been conducted with SeismoStruct (SeismoSoft, 2008), a fibre-element based program for seismic analysis of framed structures, which can be freely downloaded from the Internet. The program is capable of predicting the large displacement behaviour and the collapse load of framed structures under static or dynamic loading, duly accounting for geometric nonlinearities and material inelasticity. Its accuracy in predicting the seismic response of reinforced concrete structures has been demonstrated through comparisons with experimental results derived from pseudo-dynamic tests carried out on large-scale models (e.g. López-Menjivar, 2004; Casarotti and Pinho, 2006).

A 4-storey building designed according to the 1992 Italian design code (DM, 1992), considering gravity loads only, and the Decreto Ministeriale 1996 (DM, 1996), considering a seismic load equal to 10% of the seismic weight, have been used in this brief validation study. The possibility of both regularly and irregularly (pilotis) distributed infill panels with height is also taken into account. The building has the same plan as that shown in Figure 1. The span dimensions in the x and y directions are 5 m and 6 m, respectively. It has been loaded with a triangular distribution of lateral forces, and the collapse multiplier $\lambda$ and the displacement capacity at the three limit states have been computed as described in Section 2. In the FE model the panels are represented by strut elements with a softening behaviour after the yield limit condition corresponding to a compression stress equal to 1.2 MPa. A very low residual resistance has been taken into account only to guarantee the numerical stability of the model.

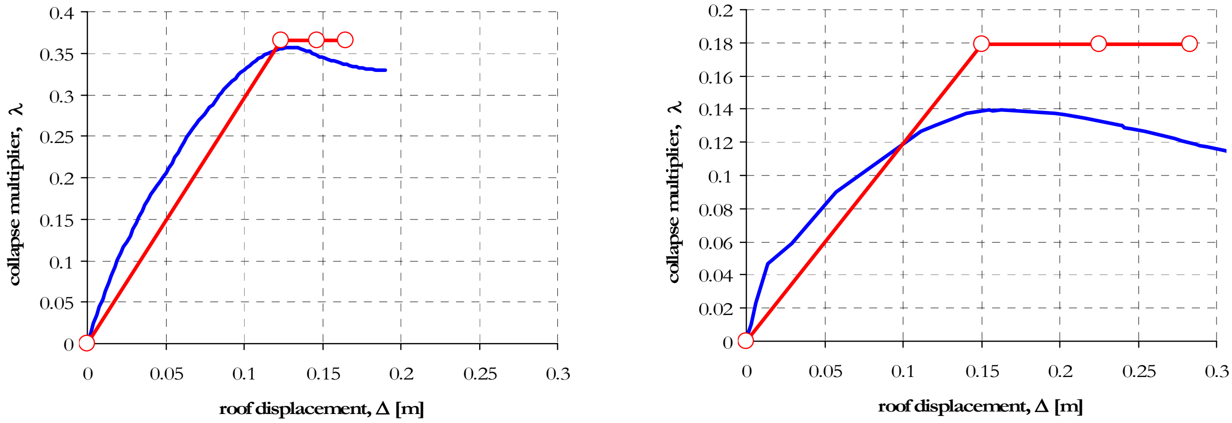
Figure 6 shows the comparison between the simplified and the FE analyses for lateral forces applied along the x and y direction of the RC building designed only considering gravity loads. For the configuration with regularly distributed infill panels, both the FE analysis and the simplified method (SP-BELA) predict the activation of a soft-storey mechanism at the 3rd storey and a global mechanism at the 3rd floor for the x and y directions, respectively. For the non-seismically designed pilotis building, the simplified analysis predicts an average situation between a soft-storey and global mechanism, because the external frames have weaker columns than beams whilst the inner frames have stronger columns than beams; on the other hand, a global failure mechanism is detected in the FE analysis. In the y-direction a global mechanism is predicted by both the simplified and more rigorous nonlinear analysis. In both directions, the comparison in terms of pushover curves is satisfactory, as can be seen Figure 7.

The case of buildings designed accounting for lateral forces (i.e. seismically designed) is shown in Figures 8 and 9 for regularly and irregularly distributed infill panels, respectively. In the case of regularly distributed panels, the building is expected to collapse according to a global mechanism activated at the first storey, whereas with the irregular distribution a soft-storey mechanism is activated at the first storey. In both cases shown in Figures 8 and 9 the same kind of mechanism is expected to be activated in the x and y direction and the results of the FE nonlinear analyses confirm the results of the simplified analysis in terms of prediction of the failure mechanism. Also, the comparison in terms of pushover curves can be considered satisfactory.



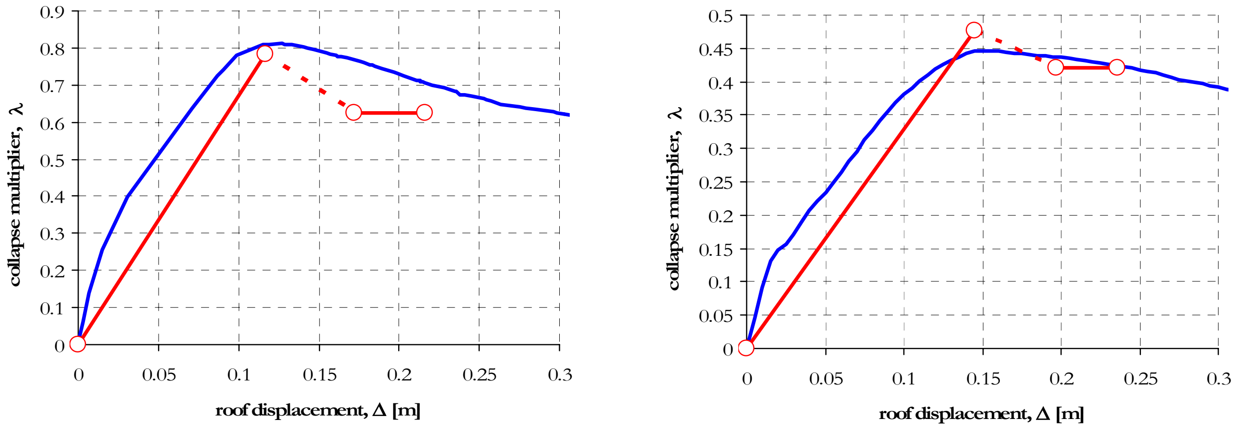

x-direction y-direction

Figure 6 Comparison between pushover curves defined according to rigorous FE analysis (blue curve) and simplified analysis (red curve) for the case of non-seismically designed buildings with regularly distributed panels along the building height.



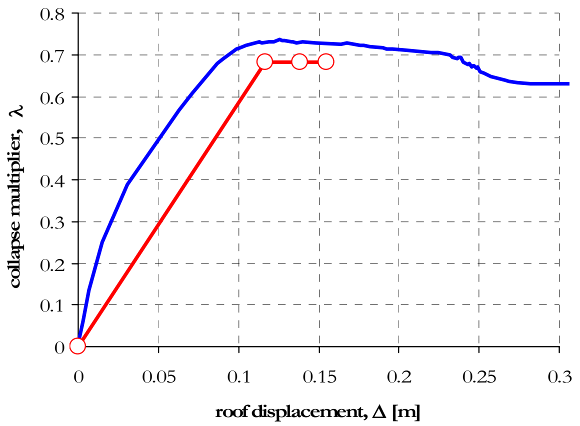

x-direction y-direction

Figure 7 Comparison between pushover curves defined according to rigorous FE analysis (blue curve) and simplified analysis (red curve) for the case of non-seismically designed buildings with irregularly distributed panels along the building height (pilotis).

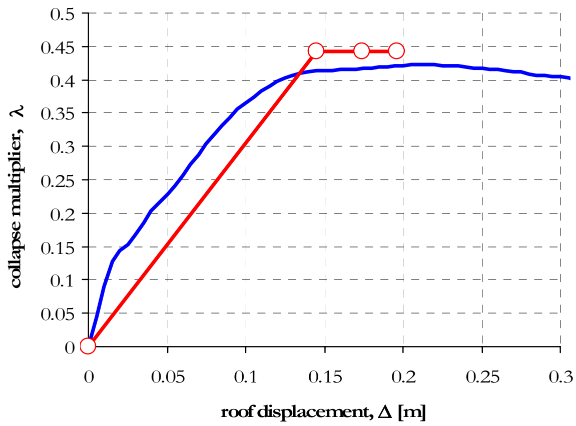



x-direction y-direction

Figure 8 Comparison between pushover curves defined according to rigorous FE analysis (blue curve) and simplified analysis (red curve) for the case of seismically designed buildings (seismic design force, c, equal to 10% of the seismic weight) with regularly distributed panels along the building height.




x-direction




y-direction

Figure 9 Comparison between pushover curves defined according to rigorous FE analysis (blue curve) and simplified analysis (red curve) for the case of seismically designed buildings (seismic design force, c, equal to 10% of seismic weight) with irregularly distributed panels along the building height (pilotis).

Hence, it is possible to state that the simplified procedure is able to capture the collapse multiplier and in most cases to predict the failure mechanism. Some differences might be observed in cases in which the simplified analyses predict a failure mechanism which is a mixture between the soft-storey and global failure, because some columns are more resistant than the connected beams and vice versa. In any case, in general, a good correspondence between the approximate and accurate pushover curve has been observed.

## 4. VULNERABILITY CURVES

For the calculation of vulnerability curves, a random population of buildings is generated using Monte Carlo simulation where random variables are used to describe the beam lengths, storey heights, design loads and material properties of the prototype building. The design of each random building is carried out (to either gravity load or lateral load design) and the simplified pushover curve is generated to obtain the period of vibration and the limit state displacement capacities of each building. The displacement capacity of the randomly generated building is compared with the displacement demand using a displacement response spectrum: the random variables used to describe the variability of the spectrum are the corner periods and the spectral amplification coefficient, as described further in Borzi *et al*. (2008). In order to highlight the influence of infill panels on the vulnerability curves, a 4 storey RC building both seismically and non-seismically designed is presented herein. The seismically designed building has been designed assuming a lateral force equal to 10% of the seismic weight (c=10%). The vulnerability curves for the regularly infilled, irregularly infilled and bare frame buildings for both types of design are presented in Figure 11.

An increase in vulnerability is observed in Figure 11 for non-seismically designed buildings with pilotis as opposed to regularly distributed infill walls. On the other hand, the vulnerability of bare frame is higher than the vulnerability of pilotis buildings. This is due to the fact that in both the aforementioned conditions,100% of the buildings fail due to the activation of a soft-storey mechanism, that for pilotis building is activated at the ground floor storey, but for bare frame in the storey above. Therefore, the soft-storey mechanism of the buildings pilotis has a higher ductility capacity based on columns with larger dimensions. For the seismically designed buildings, it can be seen that the condition of regularly distributed infill panels corresponds to a lower vulnerability, whereas the pilotis buildings are the most vulnerable as a consequence of the high number of buildings that tend to have a soft-storey collapse mechanism. The percentage of buildings that fail according to a soft-storey mechanism has been obtained for all the configurations for which the vulnerability curves have been calculated. Almost all of the buildings of the dataset fail as a consequence of a soft-storey mechanism when the pilotis configuration is assumed, regardless of seismic design. The non-seismically designed bare buildings have a vulnerability very similar to the corresponding pilotis configuration, because, as a consequence of the design only accounting for gravity loads, the dominant failure mechanism is a soft-storey mechanism. However, the regularly distributed infill frame buildings without seismic design have a lower vulnerability than the bare and pilotis frames as a higher proportion respond with a global mechanism. The seismically designed bare and pilotis buildings tend instead to have a vulnerability more similar to the regularly distributed configuration of infill panels. Such buildings have been designed accounting for lateral forces and therefore, the situation of strong columns and weak beams tends to be dominant in all cases, even if the design code does not include a capacity design philosophy.

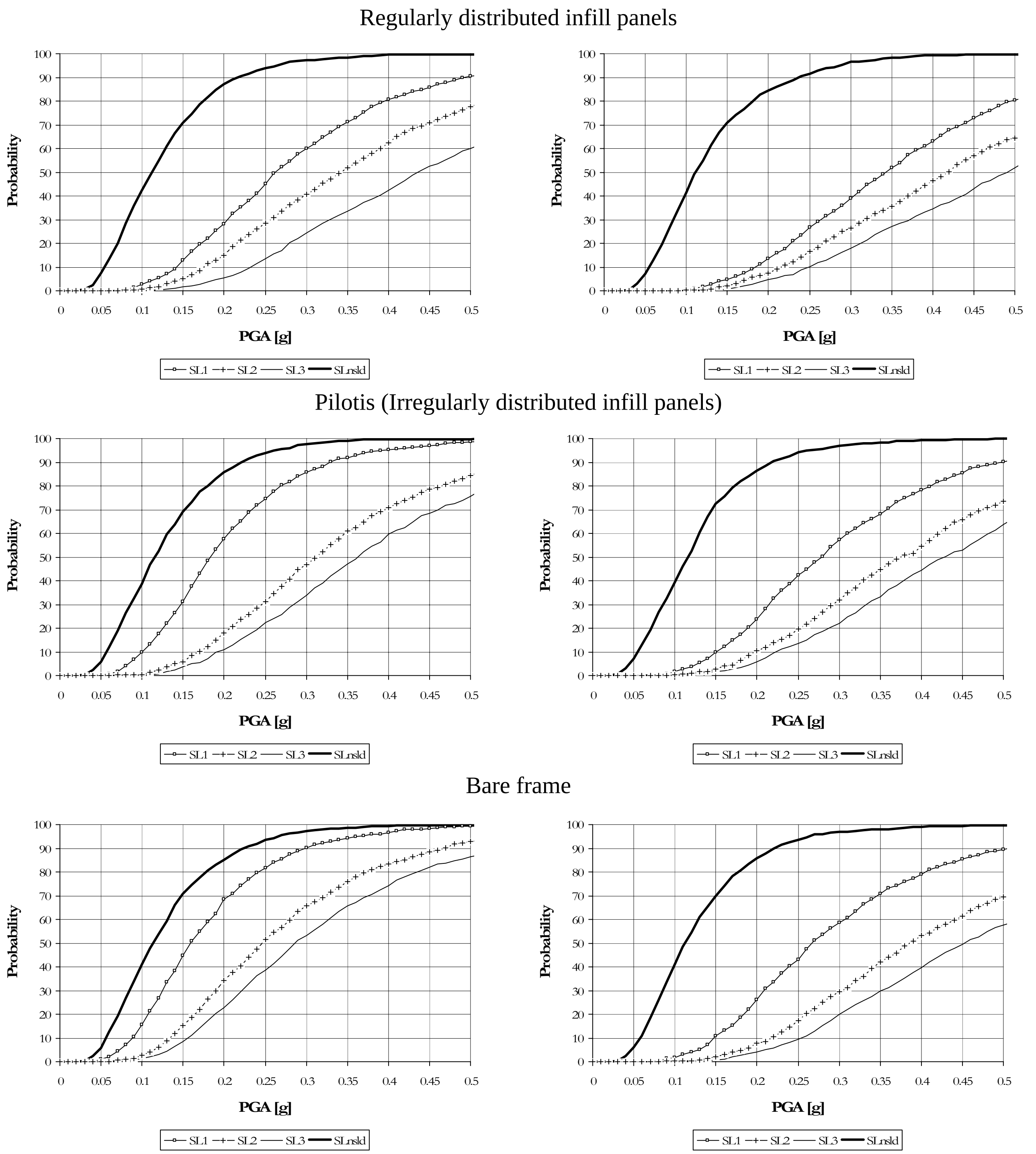



Figure 10 Vulnerability curves for 4 storey RC buildings non-seismically designed (left) and seismically designed, lateral force c=10% (right)

## 5. CONCLUSIONS

A simplified pushover-based method for the definition of vulnerability curves is adopted in this paper to assess the influence of infill panels on the vulnerability of RC buildings. The building capacity has been defined though a pushover curve, which is a valuable tool nowadays and is proposed in modern seismic design codes to capture the global performance of a building subject to earthquake loads with a reasonable level of computational effort. However, a simplified approach to the definition of pushover curves has been adopted such that the analysis of hundreds of randomly-generated buildings can be undertaken within a reasonable time-span. The definition of whether or not a building survives a limit condition is based on displacements, which are known to be well correlated with building damage. Infill walls, especially when not regularly distributed along the building height, tend to govern the failure mechanism that will be activated in the building. Infill panels are rarely considered during the design procedure, but their influence on vulnerability is extremely relevant, especially in the case of seismically designed buildings, because a soft-storey mechanism could be activated instead of a global failure mechanism (which would be forecast for the bare frame) with associated implications on the expected performance of the building. Nevertheless, further research is still required before the methodology is applicable to full-scale loss assessment applications. For example, other elements such as staircases and lift shafts can also significantly modify the building performance and will thus need to be considered in future analyses. Furthermore, not only the regularity in elevation should be studied, but also the regularity in plan should also be taken into account, though this can be easily incorporated through changes to the prototype structure.

## ACKNOWLEDGEMENTS

The authors would also like to acknowledge the support of the Italian Ministry of Research and Higher Education (MIUR – Ministero dell'Università e della Ricerca) through the financing of the project AIRPLANE (Advancing Interdisciplinary Research PLAtform on volcanoes aNd Earthquakes) and of the Italian Department of Civil Protection through the financing of the 2005-2008 framework programme established with the Italian National Network of Earthquake Engineering University Laboratories (RELUIS, Task 10).

## REFERENCES

Borzi, B., Pinho, R. and Crowley, H. (2008). Simplified pushover-based vulnerability analysis for large scale assessment of RC buildings. *Engineering Structures*, **30**, 804-820.

Calvi, G.M. (1999). A displacement-based approach for vulnerability evaluation of classes of buildings. *Journal of Earthquake Engineering*, **3:3**, 411-438.

Casarotti, C. and Pinho, R. 2006. Seismic response of continuous span bridges through fibre-based finite element analysis. *Journal of Earthquake Engineering and Engineering Vibration*, **5:1**, 119-131

Cosenza, E., Manfredi, G., Polese, M. and Verderame, G.M. (2005). A multi-level approach to the capacity assessment of existing RC buildings. *Journal of Earthquake Engineering*, **9:1**, 1-22.

Decreto Ministeriale 14 febbraio 1992 (1992). Norme tecniche per l'esecuzione delle opere in cemento armato normale e precompresso e per le strutture metalliche (*in Italian*).

Decreto Ministeriale 16 gennaio 1996 (1996). Norme tecniche per le costruzioni in zone sismiche. (*in Italian*).

Iervolino, I., Manfredi, G., Polese, M., Verderame, G.M., Fabbrocino, G. (2007). Seismic risk of R.C. building classes. *Engineering Structures*, **29:5**, 813-820.

López-Menjivar, M.A. 2004. Verification of a displacement-based Adaptive Pushover method for assessment of 2-D Reinforced Concrete Buildings. *PhD Thesis*, European School for Advances Studies in Reduction of Seismic Risk (ROSE School), University of Pavia, Italy.

Mainstone, R.J. (1971). On the stiffness and strength of infilled frames. *Proceedings of the Institution of Civil Engineers*, Supplement **IV**, 57-90.

Masi, A. (2004). Seismic vulnerability assessment of gravity load designed R/C frames. *Bulletin of Earthquake Engineering*, **1:3**, 371-395.

Panagiotakos, T. and Fardis, M.N. (2001). Deformation of R.C. members at yielding and ultimate. *ACI Structural Journal*, **98**, 135-148

SeismoSoft (2006). SeismoStruct – A computer program for static and dynamic analysis for framed structures. (online) Avaliable from URL: www.seismosoft.com.