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# Assessment of the mainshock-aftershock collapse vulnerability of RC structures considering the infills in-plane and out-of-plane behaviour

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## Abstract

One major challenge of earthquake risk mitigation is the assessment of existing buildings not designed with modern codes and the development of effective strengthening techniques. Particular attention should be given to reinforced concrete (RC) frame structures with infill masonry (IM) panels, as proved by their poor performance in recent earthquakes. From surveys on damaged and collapsed RC buildings, many buildings suffered severe damage or collapse due to the IM panels presence. It is observed that in-plane (IP) behaviour of IM can prevent the development of out-of-plane (OOP) strength mechanisms by arching effect. By contrast, in most cases the major damages were found in non-structural elements, particularly in clay IM, including diagonal cracking, OOP collapse or detachment of surrounding RC frames (the latter taking place in early earthquake instants) due to absence of or deficient connection to that frames. In a seismically active region, structures are subjected to multiple earthquakes, due to mainshock–aftershock phenomena or other sequences, leaving no time for rehabilitation of the buildings or rescue of the injured people between the events. This research pretends to assess the mainshock-aftershocks effects on an eight storey RC building. For this, different numerical models (considering different IM walls modelling strategies) were subjected to several non-linear dynamic analyses. The structure damage level was evaluated for different intensity levels of the aftershock-mainshock by the comparison between the maximum inter-storey drifts with drift limits suggested by international codes.

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## 1. Introduction

Cities located in zones of high seismic hazard throughout the World contain a large number of buildings having reinforced concrete (RC) resisting moment frames with infill masonry (IM) walls that share common characteristics and seismic vulnerabilities. Collapses of such structures during recent earthquakes have killed tens of thousands of people in the last decade. The presence of IM walls in RC buildings is very common. However, in the design of new buildings, as well as in the assessment of existing ones, infills are usually considered to be non-structural elements and their influence on the structural response is normally disregarded [1, 2]. The construction evolution presents both critical issues and opportunities, forcing the need to apply modern performance-based earthquake engineering criteria and new methods that account for the influence of infill walls together with upgrading and strengthening strategies for buildings to represent more rigorously the structural behaviour and reduce damage in future seismic events.

Two main failure mechanisms are reported due to the IM walls presence. One is the short column mechanism, where IM walls leave a short portion of the column clear, concentrating larger demands in a short element; the other is related with the absence of IM panels on the ground floor, inducing a sudden change in the storey stiffness and strength in height, leading to a soft-storey mechanism [3, 4]. Moreover, the non-balanced in-plane distribution of IM panels can introduce global torsion in buildings, which can induce larger demands in columns that were not considered in the original design [5-8]. The IM out-of-plane (OOP) collapse is also observed as one of the most important critical failures of this type of non-structural element. Some of the factors that can increase the OOP instability and poor performance are: high slenderness of the panel, previous in-plane (IP) damage, deficient/insufficient support-width on the RC beams and/or slabs, no connection between the interior and the exterior panel (in the case of double-leaf IM walls and finally no connection between the panels and the surrounding RC frame elements [2]).

Recently, some experimental studies were carried out in order to characterize the OOP performance of the infill panels considering and not considering previous IP damage [9, 10]. It was observed that the OOP capacity of the IM walls is reduced with the increasing IP demands, which allow to conclude that it must be considered the infill panel OOP behaviour on the numerical modelling and the respective interaction with the IP behaviour. It is possible to find in the literature numerical studies that concluded that the OOP behaviour and in particular the IP and OOP interaction during an earthquake must be considered on the numerical analyses and during the seismic safety assessment of the building.

Major earthquakes, considered ‘mainshocks’ (MS), are typically followed by smaller magnitude earthquakes known as ‘aftershocks’ (AS), which originate at or near the rupture zone of the larger earthquake. Foreshocks, which can be smaller than and precede the MS, also originate at or near the rupture. For example, On May 12th of 2015, a powerful AS struck with a magnitude of 7.3M<sub>w</sub> occurred in the district of Dolakha following the MS of 25<sup>th</sup> April 2015, with 7.8M<sub>w</sub> and epicenter located in Barpark, Gorkha’s district. The powerful shock resulted around 200 deaths and 2500 injuries, and increased the previous number of collapses of buildings. More than 400 AS with magnitude larger than 4M<sub>w</sub> including another one of 6.6M<sub>w</sub> in Ghorka district, were registered during the following two months.

The main goal of this research is to evaluate the MS-AS effects on an eight storey RC building considering different IM walls modelling strategies. Three numerical models were built in the software OpenSees [11] considering different strategies: i) Bare frame structure; ii) infilled RC frame considering only the infills IP behaviour; c) infilled RC frame considering the infills IP and OOP. Both numerical models were subjected to several non-linear dynamic analyses and the results of the AS consequences and the effect of the IM walls will be evaluated in terms of maximum inter-storey drift for the different levels of peak ground accelerations.

## 2. Case study

### 2.1. General description and modelling strategy

With the aim of evaluate the MS-AS effect on the structural response of a reinforced concrete structure and the influence of the IM walls with and without considering the OOP behaviour it was built an eight storey building which plant dimensions are 20 m x 15 m, that consists in modules of 4 x 5m, with a storey height of 3 m. The building was designed by the Portuguese Laboratory of Earthquake and Civil Engineering (LNEC) as part of a study on the seismic design of buildings, in accordance with the existing code rules in Portugal [12]. A 3D model (Fig. 1a) was generated in the computer software OpenSees [11]. A set of three building configurations was selected according to the IM

modelling strategies adopted: (i) bare frame model (BF) which does not consider the presence of the IM walls; (ii) in-plane model (IP) which considers the presence of the IM walls in the external perimeter of the building, and only the IP behaviour is considered; (iii) out-of-plane model (IP\_OOP) which considers the presence of the IM walls in the external perimeter of the building and both the in-plane and out-of-plane behaviour interaction with the element removal algorithm. It was adopted the same infills distribution and the same IM walls properties as adopted by Furtado *et al* [13]. The RC elements were modelled by using force-based elements with 5 integration points and 200 fibres per each section. Regarding the IM walls modelling it was adopted the Furtado *et al* [13] proposal, which is represented as an equivalent double-strut model (Fig. 1b) that take into account the IP-OOP behaviour of the infill masonry walls during the analysis. In this model, each masonry infill wall is simulated by four diagonal struts with rigid behaviour, and a central element where the non-linearity hysteresis is concentrated (Fig. 1b), and the two central nodes with panel mass. The numerical model was defined with the available elements and materials in the OpenSees library [28], namely the five elements adopted were BeamWithHinges elements. This numerical model is designed to represent the IM wall's non-linear behaviour when subjected to biaxial cyclic loading, such as in-plane and out-of-plane. These two components are modelled independently although when subjected to this biaxial cyclic action they interact through an element removal algorithm that is implemented.

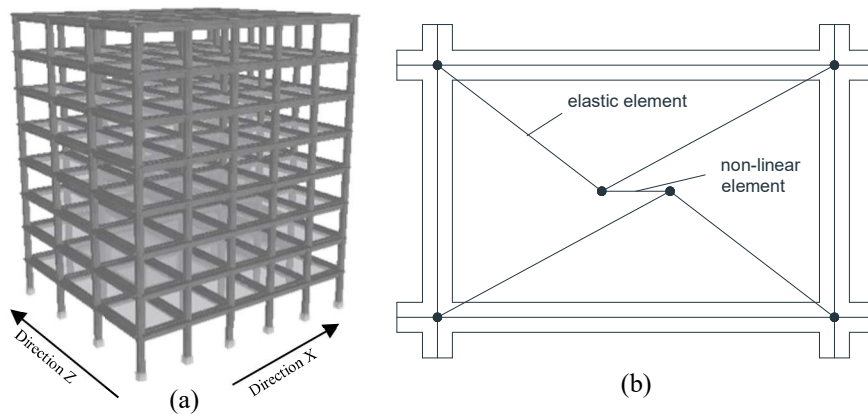


Fig. 1. Case study: (a) 3D frame general view; (b) Numerical modelling strategy adopted to represent an infilled RC frame using OpenSees.

## 2.2. Aftershock incremental dynamic analysis - Methodology

In AS analysis, the building is subjected to a MS-AS sequence, as shown in Fig. 2. The building was firstly subjected to a MS ground motion with the same peak ground acceleration throughout the analyses. The MS record was scaled and, subsequently, apply as an AS record that was applied to the MS-damaged structure. The scale factor considered of the AS record was varied to capture different damage levels of the building, and the same scale was applied for ground motions in both directions. A period of 10 seconds is added between the MS and AS ground motions to represent the situation in which the structure comes to rest after the first event, but is not repaired. The AS analysis is repeated considering the same structure and MS-AS sequence, increasing the intensity of the AS ground motions (by scaling the AS record) until the MS-AS sequence introduce to the structure inter-storey drift higher than 5% which corresponds to collapse state of the building. The intensity of the scaled AS ground motion in the sequence quantifies the collapse capacity of the mainshock-damaged building.

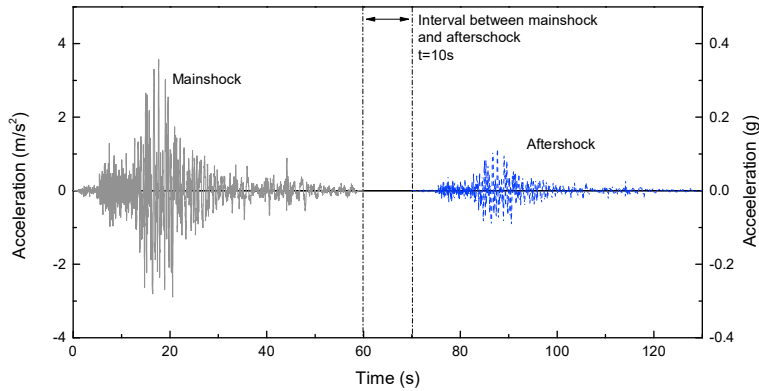


Fig. 2. Methodology adopted for the MS-AS sequence applied to analyze a MS-damaged building.

### 3. Numerical Results

Along the present section, it will be presented the results obtained from the non-linear dynamic analysis. A MS with peak ground acceleration of 0.423g was considered followed by one AS with different increasing peak ground accelerations that were obtained by the scale of the mainshock. The results from the different analysis are plotted in Fig. 3 and 4. It is presented the results for both directions X and Z (red and blue respectively) of the structure and is plotted the maximum inter-storey drift reached during the MS (Cross line) and the evolution of the AS maximum inter-storey drift as a solid line.

From the evolution of the maximum inter-storey drift obtained for the different AS pga it can be observed high differences between the responses of the three numerical models. As observed by Furtado *et al* [13], the consideration of the IM walls OOP behaviour modify the expected response of the structure, due to the collapse of the infill walls. It is observed that the most vulnerable model was the IP\_OOP reaching drifts more than 2 times higher than those observed with the IP model. It is observed that in the model IP the infill walls protected the structural behaviour, reduction the maximum drift for values below 1%. Regarding the BF model it was obtained a different response compared with the remaining two models, which allow to understand the importance of consider the presence of the IM walls in the seismic response of RC structures and in particular the consideration of the IP-OOP interaction.

Regarding the damage induced by the AS in the structure it can be observed that only the IP model did not reach inter-storey drift levels higher than those observed in the MS (Fig. 3b). The BF model shows that for AS with pga higher than 0.35g the maximum inter-storey drift is higher than the values obtained following the MS. In particular it can be observed that the direction Z reaches 1.5-2 times higher maximum inter-storey drift for that pga range values (Fig. 3a). Finally, the most vulnerable case the model IP\_OOP shows that in direction X the AS with pga higher than 0.2g causes more damage to the structure than the MS ones. In direction Z it is observed that only AS with pga higher than 0.3g have additional contribution in terms of damage to the structure (Fig. 3c).

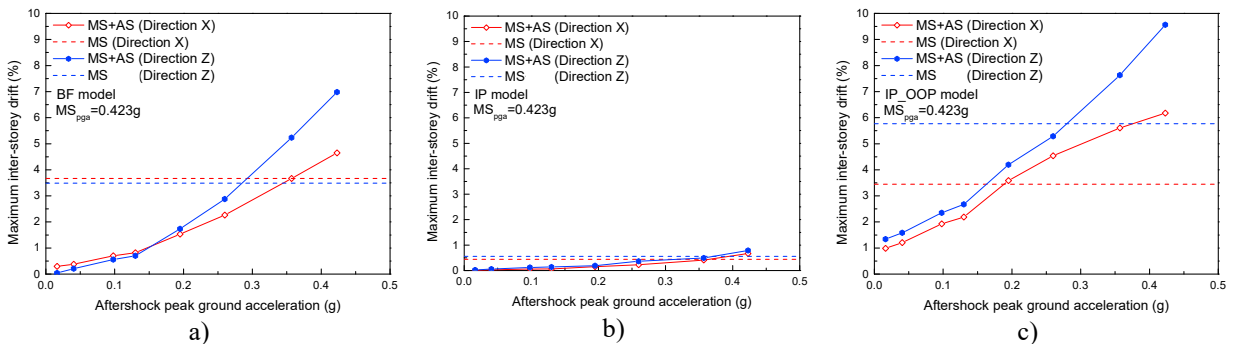


Fig. 3. Numerical results: Maximum inter-storey drift a) BF model; b) IP model; and c) IP\_OOP model.

The inter-storey drift profile for the MS of 0.423g and for an AS with peak ground acceleration of 0.357g for both directions (X and Z) of the numerical models and from the results it can be observed differences between the seismic responses of the three numerical models. In model IP\_OOP it is observed a particular increase of the maximum drift caused by the AS, when compared with the response of the MS. In fact it was obtained for storey three and five 1.5 and 4 times higher drift. In model BF the increase of the drift caused by the AS was only higher in storey 1 with an increase of 5%. Regarding the response of the model IP it is notorious that the numerical response of the AS is lower than the one observed for the MS.

Following the seismic response of the model IP\_OOP it is observed that due to the MS-AS sequence the infill panels from the storey 3 and 5 collapsed during the analysis and caused a soft-storey mechanism that concentrated the deformation in this levels of the structure. This concentration of the deformation on the 3<sup>rd</sup> and 5<sup>th</sup> storey of the structure is due to the vertical irregularity of the columns section. This particular mechanism is typically observed throughout recent earthquakes and is pointed as responsible of the collapse of RC structures.

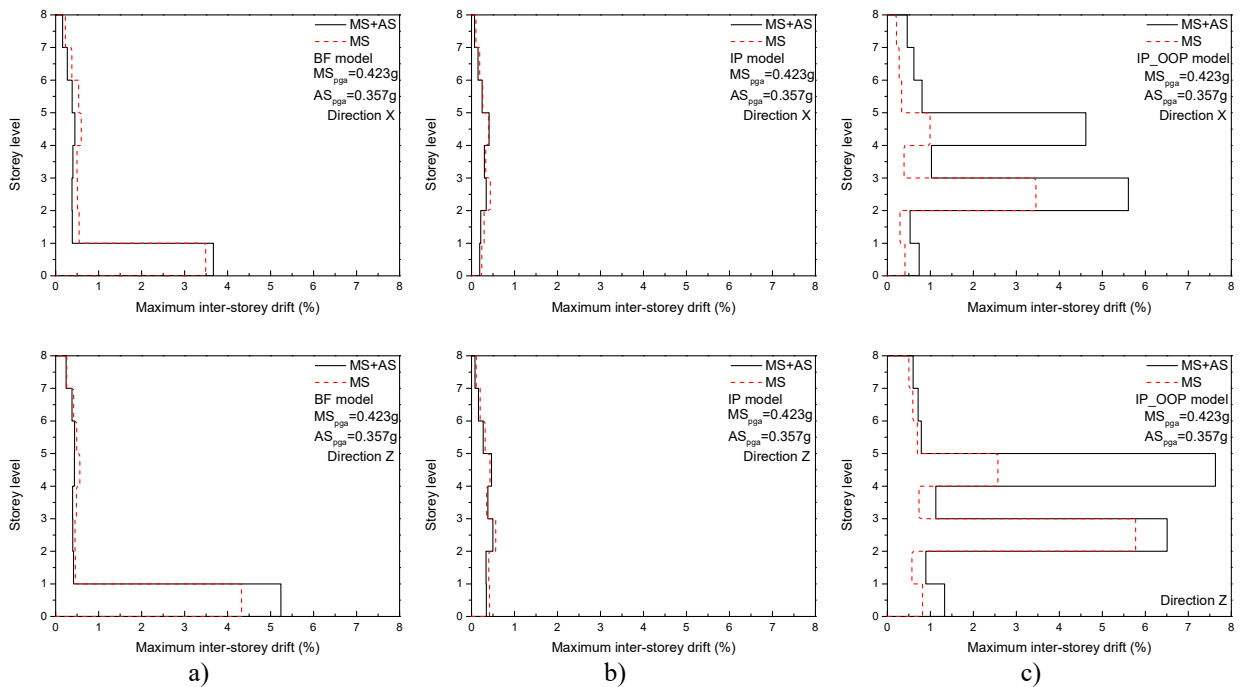


Fig. 4. Numerical results: Inter-storey drift profiles for MS=0.423g followed by an AS=0.357g a) BF model; b) IP model; and c) IP\_OOP model.

#### 4. Conclusions

This research paper presents a numerical study that was carried with the aim of evaluate the effect of the MS-AS sequence in the structural response of RC buildings considering and not the presence of the IM walls and in particular taking into account and not the IP-OOP interaction. For this, three numerical models with the same geometric and mechanical properties were subjected to MS ground motions followed by AS with different levels of peak ground accelerations for three different situations: bare frame, with infills with only IP behaviour, and with infills with both IP and OOP behaviour. It was observed that consideration of the infills OOP behaviour increased the vulnerability of the building, namely with the collapse of the most vulnerable storeys for peak ground accelerations greater than 0.3 g. The results revealed different seismic responses from MS and AS sequences for both numerical models. The model with the consideration of the OOP behaviour reached higher maximum inter-storey drifts than the ones obtained by the MS for AS with peak ground acceleration higher than 0.2g. The AS maximum inter-storey drifts obtained by the model that consider only the in-plane behaviour of the infill walls were lower than the ones obtained during the MS ground motion. This particular difference observed in this study is important to evaluate the seismic vulnerability of

the existent RC buildings, and to highlight the importance of the consider the IM walls OOP behaviour during a seismic event. This research presents only one case study, which needs furthermore cases to reinforce general conclusions regarding this topic.

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## References

- [1] X. Romão, A.A.Costa, E. Paupério, H. Rodrigues, R. Vicente, H. Varum, *et al.*, "Field observations and interpretation of the structural performance of constructions after the 11 May 2011 Lorca earthquake," *Engineering Failure Analysis*, vol. 34, pp. 670-692, 2013.
- [2] R. Vicente, H. Rodrigues, H. Varum, A. Costa, and J. M. Silva, "Performance of masonry enclosure walls: lessons learned from recent earthquakes," *Earthquake Engineering and Engineering Vibration*, vol. 11, 2012.
- [3] H. Alinouri, F. Danesh, and S. Bharam, "Effect of soft-storey mechanism caused by infill elimination on displacement demand in nonlinear static procedure using coefficient method," *The Structural Design of Tall and Special Buildings*, vol. 22, pp. 1269-1309, 2013.
- [4] A. Furtado, H. Rodrigues, H. Varum, and A. Costa, "Assessment and strengthening strategies of existing buildings with potential soft-storey response," presented at the 9<sup>th</sup> International Masonry Conference, Portugal, 2014.
- [5] T. Paulay and M. J. N. Priestley, *Seismic design of RC and masonry buildings - John Wiley - ISBN 0-471-54915-0*, 1992.
- [6] H. Rodrigues, "Biaxial seismic behaviour of reinforced concrete columns," PhD Thesis, Departamento de Engenharia, Universidade de Aveiro, Aveiro, 2012.
- [7] H. Rodrigues, A. Arêde, H. Varum, and A. Costa, "Damage evolution in reinforced concrete columns subjected to biaxial loading " *Earthquake Engineering and Structural Vibration*, vol. 42, pp. 239-259, 2013.
- [8] H. Rodrigues, A. Arêde, H. Varum, and A. Costa, "Experimental evaluation of rectangular reinforced concrete column behaviour under biaxial cyclic loading," *Earthquake Engineering and Structural Dynamics*, vol. 42, pp. 239-259, 2013.
- [9] G. Calvi and D. Bolognini, "Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels," *Journal of Earthquake Engineering*, vol. 5, pp. 153-185, 2001.
- [10] S. Hak, P. Morandi, and G. Magenes, "Out-of-plane experimental response of strong masonry infills," presented at the Second European Conference on Earthquake Engineering and Seismology, Istanbul, 2014.
- [11] F. Mckenna, G. Fenves, M. Scott, and B. Jeremic, "Open System for Earthquake Engineering Simulation (OpenSees)," ed. Berkley, CA, 2000.
- [12] E. Carvalho and E. Coelho, *Análise Sísmica de estruturas de edifícios segundo a nova regulamentação - Análise Estrutural de um conjunto de 22 edifícios* vol. II. Lisboa, Portugal, 1984.
- [13] A. Furtado, H. Rodrigues, A. Arêde, and H. Varum, "Simplified macro-model for infill masonry walls considering the out-of-plane behaviour," *Earthquake Engineering & Structural Dynamics*, vol. 45, pp. 507-524, 2016.