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Influence of the in plane and out-of-plane masonry infill walls' interaction in the structural response of RC buildings

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Abstract

The contribution of infill masonry (IM) walls to the seismic performance of buildings can be favourable or not depending on several phenomena, detailing aspects and mechanical properties such as the relative stiffness and strength between the frames and the masonry walls, the type of connection between masonry and surrounding elements, etc. From survey on damaged and collapsed reinforced concrete (RC) buildings in recent earthquakes a large number of buildings that suffered severe damage or collapse had their poor performance associated with the influence of IM panels, wherein two main mechanisms have been reported. The IM out-of-plane behaviour has been observed as one of the most important critical failures of such type of non-structural elements. This research focuses on the development of a simplified macro-model to account for the out-of-plane behaviour of the IM, including the corresponding interaction between in-plane and out-of-plane, when subjected to seismic loading. That macro-model, implemented in the OpenSees software framework, is an improvement of the commonly adopted equivalent bi-diagonal-strut model, in which the out-of-plane behaviour is considered through the implementation of the element removal algorithm. Additionally it was evaluated the seismic safety assessment of an 8 storey building considering the effect of the IM out-of-plane behaviour in the structural response.

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1. Introduction

The infill masonry (IM) walls contribution to the seismic performance of buildings can be favourable or not depending on several phenomena, detailing aspects and mechanical properties such as the relative stiffness and strength between the frames and the masonry walls, the type of connection between masonry and surrounding elements, etc. From survey on damaged and collapsed reinforced concrete (RC) buildings in recent earthquakes, a large number of buildings that suffered severe damage or collapse had their poor performance associated with the influence of IM panels. The IM out-of-plane behaviour has been observed as one of the most important critical failures of such type of non-structural elements (Fig. 1). One of the major factors that cause the OP instability and poor performance is the deficient/insufficient support-width on the reinforced concrete (RC) beams and/or slabs, normally adopted to minimize the thermal bridges effect, no connection between the interior and the exterior panel and finally no connection to the surrounding RC frames [1, 2]. This type of failure should be studied with particular attention, since it is a type of damage likely to increase significantly the risk of the buildings' users or people on the periphery and contributes for a considerable increase of the repair/rehabilitation interventions required in buildings affected by earthquakes. The numerical modeling of IM walls should take into account this particular behavior, as well as the corresponding interaction between in-plane and out-of-plane behaviour, in order to represent realistically the expected structural response when subjected to earthquakes. In particular, simplified numerical models should be developed to help designers in the design of new buildings or in the evaluation of seismic safety of existing buildings.



Fig. 1. IM walls earthquake damages in L'Aquila (a) Collapse of the external leaf panel; (b) Collapse of the entire IM wall.

For the assessment of infilled RC frame structures, the nonlinear behaviour induced by earthquake demands should be taken into account [3-6]. Different techniques are available in the literature for the simulation of the response of infilled frames, from refined micro-models to simplified macro-models [5-7]. For the non-linear analysis of complex structures, when subjected to earthquakes, in many cases it is not suitable to adopt refined models. Thus, for the response simulation of infilled frame structures, considering IM walls and its interaction with the surrounding frame elements, the adoption of simplified models is unavoidable.

In the present research paper a simplified macro-model which accounts for the in-plane (IP) and out-of-plane (OP) behaviour of IM walls is presented for implementation in the computer software OpenSees [8]. This numerical model takes also into account an element removal algorithm which allows removing elements during an earthquake response simulation and including the IP and OP behaviour interaction.

As an example, an eight storey building was studied mainly aiming at demonstrating the influence of considering the influence of IM walls out-of-plane collapse in the structural response. The building was subjected to non-linear dynamic analysis and the results are compared with three different models: (i) bare frame model, (ii) model with IM walls only with in-plane behaviour and (iii) model with IM walls with the consideration of the IP and OP behaviour.

2. Description of the simplified IM wall macro-model

The IM wall simplified macro-model presented here, to be used in the software framework OpenSees [8], is based on the Rodrigues et al [9] proposal which is an improvement of the commonly used equivalent bidiagonal-strut model. Each masonry infill wall is simulated by four diagonal struts with rigid behavior, and one central element where the non-linearity hysteresis is concentrated. With the main purpose of introduce the out-of-plane behaviour of the IM wall, the panel mass is distributed by the two central nodes.

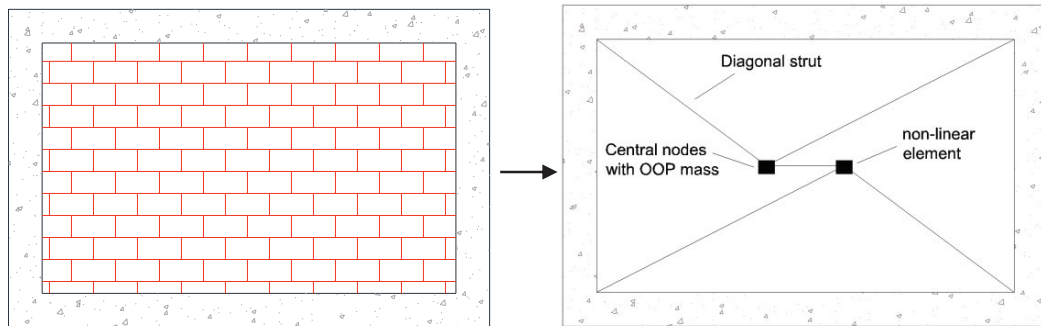


Fig. 2. IM wall simplified macro-model general view.

The numerical model was designed to be composed with the available elements and materials in the OpenSees library [8]; thus, for the five linear elements the BeamWithHinges elements can be adopted or, alternatively, four elastic BeamColumns can be used for the diagonal struts and one nonlinear BeamColumn for the central element as previously studied by some of this paper authors [7].

This numerical model is designed to represent the IM wall non-linear behaviour when subjected to biaxial cyclic loading, such as in-plane and out-of-plane. These two components are defined independently although when subjected to simultaneous in-plane and out-of-plane cyclic actions they interact through an element removal algorithm that was developed by Musalam and Gunay [10]. The following sub-section describes the in-plane and out-of-plane modelling strategy.

2.1. In-plane behaviour

The in-plane behaviour of the infill panel is considered through a central element with non-linear axial behavior, which is characterized by a multi-linear curve that represents the IM in-plane behaviour, defined by eight parameters (Fig. 3a), representing: a) cracking (cracking force F_c and drift d_c); b) yielding (yielding force F_y and drift d_y); c) maximum strength, corresponding to the beginning of crushing (F_{cr} and corresponding drift d_{cr}); d) residual strength (F_u) and corresponding drift (d_u). The hysteretic rules calibrated for infill models are controlled by three additional parameters such: stiffness degradation – α , pinching effect – β and strength degradation – γ . The Pinching 4 uniaxial material model [8], illustrated in Fig. 3b, can be used to represent the in-plane hysteretic behavior of the infill panel and it was ascribed for the central element. This uniaxial material model is used to convey a material that represents a 'pinched' load-deformation response and exhibits degradation under in-plane cyclic loading. Cyclic degradation of strength and stiffness occurs in three ways: unloading stiffness degradation, reloading stiffness degradation, strength degradation.

The proposed model was calibrated for the in-plane response of IM walls and it was observed that represents accurately the global response and energy dissipation during structural response [7]. It should be also referred that this simplified macro-model does not account for the short-column effects. For infilled frames where the short-column effect can be induced, the multiple strut model strategy can be adopted.

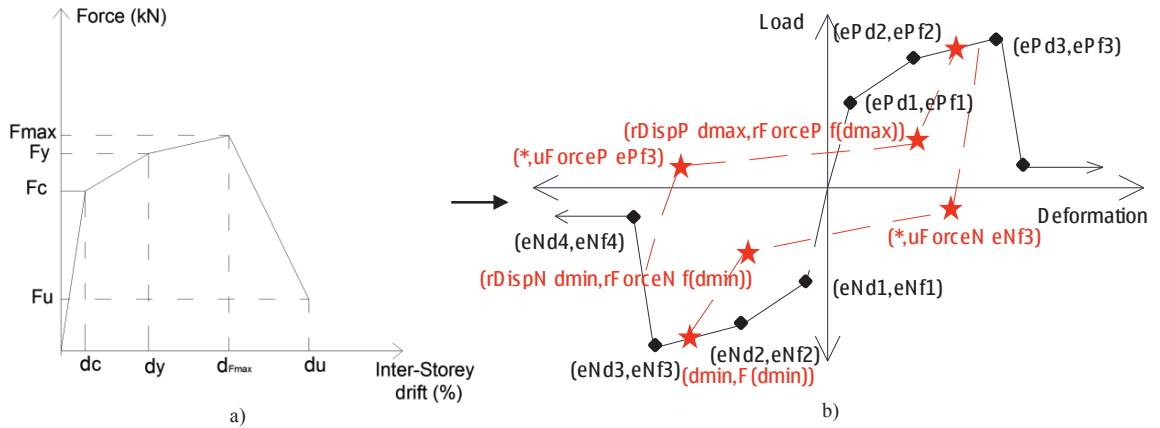


Fig. 3. IM wall simplified macro model a) Hysteretic material in-plane behaviour b) Pinching uniaxial material in OpenSees [8].

2.2. Out-of-plane behaviour

The consideration of this type of particular behavior through simplified macro-models is difficult, for which there is not much information neither about experimental studies relative to the out-of-plane behaviour of IM walls, considering all the relevant parameters, nor about the interaction between in-plane and out-of-plane response. For the present simplified macro-model, the following considerations were taken into account to represent the IM walls out-of-plane behaviour:

- The out-of-plane behaviour is considered to follow a linear elastic curve;
- The numerical representation of this behaviour was implemented through the application of mass at the central nodes, which can be calculated as $0.81M$ (M is the total mass of the infill panel) and equally divided per the two central nodes with $0.405M$ mass each. Assuming the model has the same natural period as the original infill wall, the OP mass and bending stiffness values were considered following the recommendations of FEMA-356 [11] and ASCE-41 [12] and the suggestions of Gunay *et al* [13].
- In order to obtain a realistic representation of the infill panel behavior when subjected to biaxial loadings, it was added an element removal algorithm for masonry walls developed by Musalam *et al* [10]. This algorithm was developed for automated removal of collapsed elements during an ongoing simulation. The IM wall is considered as collapsed when reaching the in-plane and out-of-plane interaction drift limits. Afterwards, the algorithm removes the 5 elements, the corresponding central nodes and respective masses.

The interaction between the IP and OP drift can be defined according to different dispositions, but for the present study this interaction was adopted to follow a linear pattern and the limits can be selected on the basis of previous experimental tests [13, 14]. In the literature a much reduced number of biaxial experimental tests of IM walls can be found, for which further investigations should be performed to quantify this interaction and to better support the definition of displacement limits for the interaction law. In Fig. 4 is explained the consideration of the out-of-plane behaviour in the numerical model.

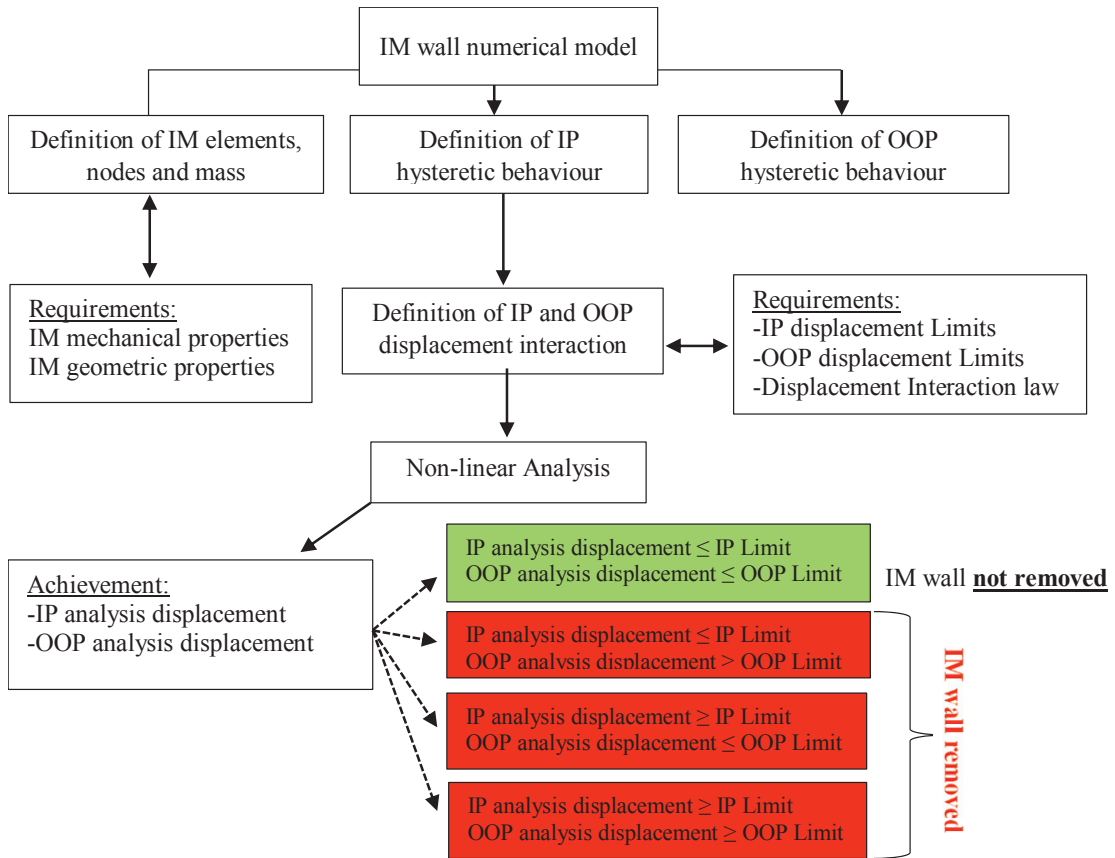


Fig. 4. IM wall numerical model: consideration of the out-of-plane collapse.

3. Influence of the IM out-of-plane response in the structural behaviour of RC buildings - Case study

3.1. General Description

The influence of the IM walls, with and without the consideration of the out-of-plane behaviour in the structural response of RC buildings subjected to seismic actions, was studied taking as an example an eight storey building. The so called PT8 building has in-plan dimension of $20 \times 15 \text{ m}^2$ arranged in $4 \times 5 \text{ m}^2$ modules, with 3m storey height as shown in Fig. 5. The building was designed by the Portuguese Laboratory of Earthquake and Civil Engineering - LNEC as part of a study about the seismic design of buildings, in accordance with the existing code rules in Portugal [15]. For the present study, a 3D model was generated in the computer software OpenSees [8].

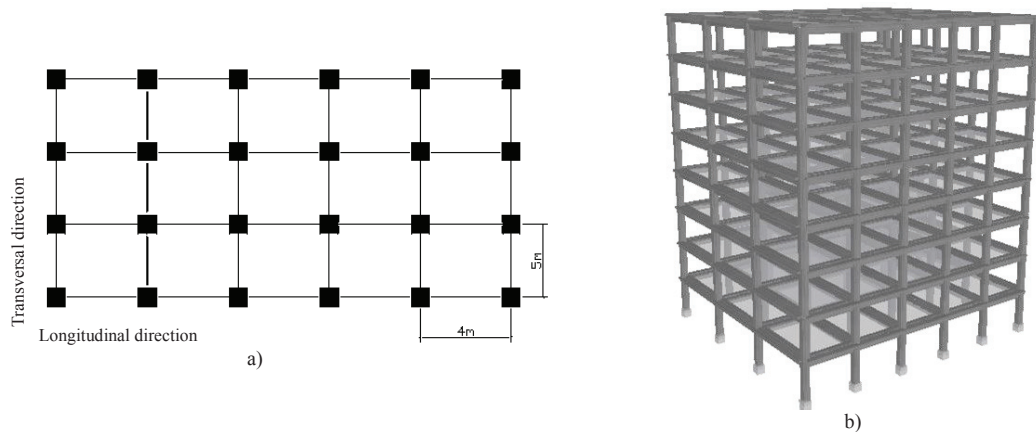


Fig. 5. Case study: a) In plan layout and b), 3D bare frame model.

A set of 3 building configurations was selected according to the adopted IM modelling strategies: (i) Bare Frame model (BF) which does not consider the presence of the IM walls; (ii) In-Plane model (IP) in which the presence of the IM walls is considered in the external building perimeter and the only the IP behaviour is activated; (iii) Out-of-plane model (IP_OOP) which considers the presence of the IM walls in the external perimeter of the building and the in-plane and out-of-plane behaviour interaction with the element removal algorithm.

3.2. Non-linear dynamic time-history analysis

The buildings under study was subjected to non-linear dynamic time-history analysis, particularly to one artificial earthquake that was been generated for a medium/high risk scenario in southern Europe for different return periods. Hazard consistent time series of acceleration (with 90 seconds of duration) were artificially generated yielding a set of seven uniform hazard response spectra for increasing periods. Fig. 6 shows one of such artificial ground motion acceleration time series representing one realization of the seismic action.

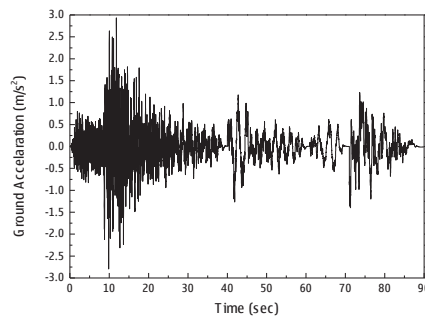


Fig. 6. Ground motion acceleration selected for the non-linear dynamic time-history analysis.

In Fig. 7 it is possible to observe the differences between the drift response obtained with the three numerical models for three inter-storey zones (0 to 1st, 2nd to 3rd and 6th to 7th storeys). It can be found that:

- the inter-storey drift evolution from 0 to 1st floor is higher for the BF model, with a maximum drift of 4.2%, while only 0.7% is reached for the IP and IP_OOP model;
- The inter-storey drift between the 2nd to 3rd floor in the IP_OOP model is more than 4 times higher the BF and IP model, at 74.95sec, as a consequence of the respective IM walls collapse.

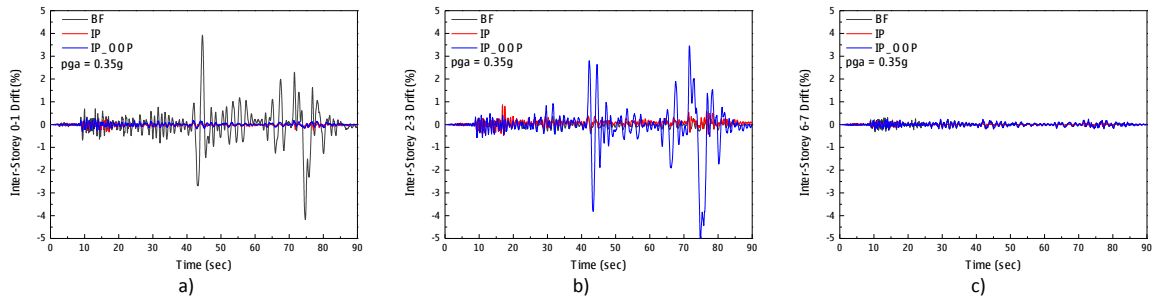


Fig. 7. Evolution of the inter-storey drift for: a) 0-1, b) 2-3 and c) 6-7 storeys.

(a)

(b)

Fig. 8 shows plots of the maximum inter-storey drift against the peak ground acceleration. It can be observed that the BF model has larger maximum inter-storey drifts in both directions and that the transversal direction is the most vulnerable direction of the building as the maximum inter-storey drift increases sharply after 0.14g.

A significant difference between the IP and the IP_OOP models is quite apparent, because:

- For the IP model the infills are protective for peak ground accelerations up to 0.2g, leading to similar response of the building in both directions for larger peak ground accelerations;
- The IP_OOP model exhibits response similar to the BF model in the longitudinal direction. In the transversal direction it can be observed that the inter-storey drift of the IP_OOP model increase significantly for peak ground accelerations upper than 0.2g. This is justified by the out-of-plane collapse of the 5th storey infills' in the transversal direction occurs and, consequently, a soft-storey mechanism forms which largely increases the inter-storey drift value.

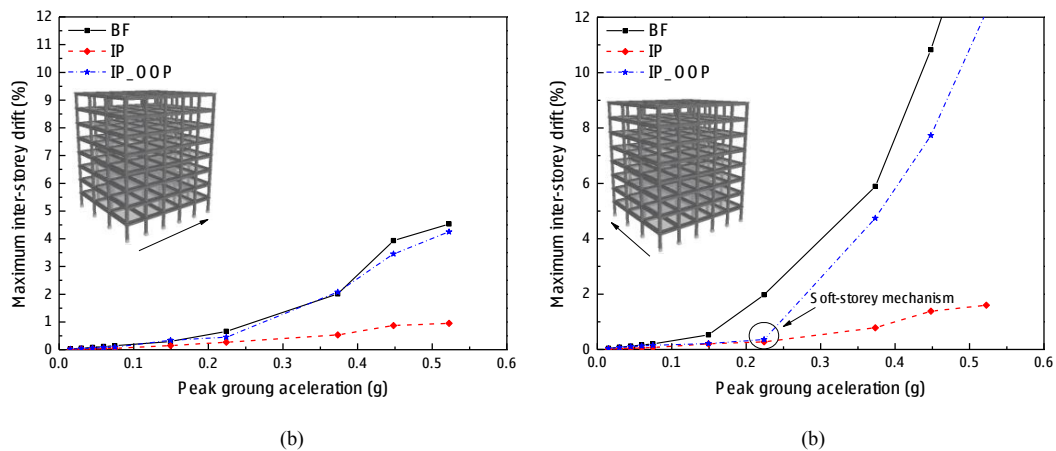


Fig. 8. Evolution maximum inter-storey drift a) Longitudinal direction and b) Transversal direction.

4. Conclusions

This research paper presents a simplified macro-model to simulate the IP and OOP behaviour of IM walls when subjected to seismic loadings. This model is adapted from the typical bi-diagonal strut model, which considers the non-linear behaviour of the infill panel and its contribution to the global response of the RC frames. The OOP behaviour is introduced through the location of the infill mass in two central nodes of the bi-diagonal struts. An OOP elastic behaviour was considered for the numerical model as well as in-plane and out-of-plane interaction. This

interaction mechanism allows considering IM collapse if the IP and/or OOP is reached. Further investigations should be performed to define IP and OOP drift limits according to different types of IM units, with the main goal of approximate the IM wall numerical and response of the IM behaviour subjected to seismic loadings during the last years.

Following a brief presentation of the macro-model, three RC buildings with the same geometric and mechanical properties were numerically modelled and subjected to non-linear static time-history analysis for three different situations: bare frame; with infills considering only IP behaviour and with infills considering IP and OOP behaviour. It was observed that the consideration of the OOP infills' behaviour increased the vulnerability of the building, leading to the collapse of the most vulnerable storeys for peak ground accelerations above 0.3g. A significant difference was observed between the IP and IP_OOP numerical models, which points out to the need of considering the OP behaviour of the IM walls for proper seismic safety assessment of existing RC infilled structures.

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