SIMULATION OF REINFORCED CONCRETE FRAMES WITH UNREINFORCED MASONRY INFILL WALLS WITH EMPHASIS ON CRITICAL MODELING ASPECTS

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ABSTRACT

This paper presents an analytical simulation approach which considers the critical modelling aspects in reinforced concrete (RC) buildings with unreinforced masonry (URM) infill walls, e.g. in-plane/out-of-plane interaction, explicit account of infill failure through element removal and consideration of shear damage of the columns due to frame/wall interactions. A commonly configured and code-designed five story RC frame with URM infill walls is analysed under the effect of bi-directional ground motions. The analysis results clearly demonstrate the effect of URM infill walls on the response of RC frames and the necessity for proper modelling in order to represent these effects realistically, even for the cases of code-designed frames.

KEYWORDS: element removal, in-plane/out-of-plane interaction, reinforced concrete frames, unreinforced masonry infill walls

INTRODUCTION

Unreinforced masonry (URM) infill walls are widely used throughout the world, including seismically active regions, as partitions in reinforced concrete (RC) buildings. It is known that such infill walls affect both the structural and nonstructural performance of these buildings. When the seismic vulnerabilities present in the RC system (e.g. lack of confinement at the beam and column ends and the beam-column joints, strong beam-weak column proportions, presence of shear-critical columns, etc.) are combined with the complexity of the interaction between the infill walls and the surrounding frame and the brittleness of the URM materials, non-ductile RC buildings with URM infill walls are considered as the world's most common type of seismically vulnerable buildings. Such buildings have unpredictable damage patterns even if designed according to modern seismic codes without considering the infill walls in the design process. It is recognized that many buildings of this type have performed poorly and even collapsed during recent earthquakes in Turkey, Taiwan, India, Algeria, Pakistan, China, Italy, and Haiti. In many countries with emerging economy, infilled frame buildings continue to be built at a rapid rate in order to keep up with urban population growth. Due to these stated reasons, proper modelling of the infill walls and the frame/infill wall interaction is essential to evaluate the seismic performance and vulnerability of such buildings.

An analytical simulation approach is presented herein, which considers the critical modelling aspects in RC buildings with URM infill walls, e.g. in-plane/out-of-plane (IP/OOP) interaction, explicit account of infill failure by element removal, and shear damage of columns due to frame/wall interactions. A commonly configured and code-designed five story RC frame with URM infill walls is analysed herein under the effect of bi-directional ground motions.

RATIONALE FOR THE CONSIDERED CRITICAL MODELLING ASPECTS

It is a well-known and accepted fact that the RC buildings with URM infill walls are likely to exhibit unacceptable response under earthquake excitations, when their ground stories have no infill walls (weak and/or soft story) and the upper stories have solid infill walls. On the other hand, RC buildings with infill walls along the full height including the ground story are generally considered less vulnerable compared to the open ground story buildings. However, the latter building type possesses an equally important risk of unacceptable behaviour due to the brittle nature of the infill walls. These walls contribute to the lateral stiffness and strength of the primary lateral force resisting system to a degree dependent on the relative stiffness of the infill walls to that of the primary lateral force resisting system. Brittle failure of these infill walls at a story transforms the originally regular building to a weak and/or soft story one during the earthquake excitation. Therefore, the element removal modelling approach explained in the following sections is an essential modelling aspect for RC buildings with URM infill walls.

For low- to mid-rise URM infilled RC buildings, ground story infill walls are expected to be damaged first since they are subjected to the highest IP shear forces. However, under the effect of bidirectional loading, where the two components of a ground motion are equally significant, infill walls of the upper stories may fail under the combination of OOP and IP effects. The magnitude of IP forces reduces at the upper stories, while that of OOP forces increases due to the increase of accelerations. Therefore, proper consideration of IP/OOP interaction of URM infill walls is an essential modelling aspect which complements the use of the element removal.

Before failure of infill walls during earthquake excitation, the non-integral infill walls (i.e. absence of shear connecters) partially separate from the frame because of the difference in the deformation patterns, where the frame deforms in a flexural mode and the infill wall deforms in shear, Figure 1. As a result of this separation, the infill wall transfers axial force along the diagonal. Therefore, diagonal strut modelling of infill walls is the most common modelling approach. However, there is another consequence of the mentioned separation which is not as commonly considered, that is the explicit consideration of the shear forces exerted on the column as a result of the horizontal component of the diagonal strut force. These additional shear forces may lead to premature shear failures of the columns depending on the strength of the infill wall.

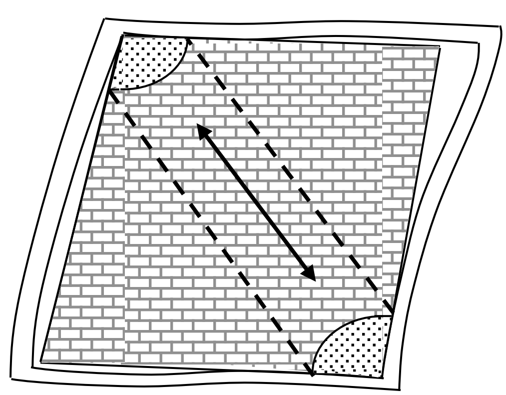

Figure 1: Partial infill wall/frame separation and resulting force transfer mechanism

IN-PLANE/OUT-OF-PLANE INTERACTION

The analytical model employed for considering the IP/OOP interaction of infill walls is a practical model previously developed in [1]. In this model, each infill wall panel is represented by a single diagonal idealization (Figure 2), composing of two beam-column elements connected at the midpoint node which is assigned a lumped mass in the OOP direction. The cross-section of the beam-column elements is modelled by strategically locating a collection of nonlinear fibres, located along a line in the OOP direction (Figure 2). By this way, the beam-column element acts as truss and flexural elements in the IP and OOP directions, respectively. The model considers the interaction between the IP axial strength and the OOP bending strength. Location of the fibres and the nonlinear material properties assigned to them are set such that the intended strength interaction and the IP axial and OOP bending stiffness values are properly simulated. FEMA-356 [2] equations are used for calculating the axial stiffness and unidirectional strength in the IP direction. The OOP mass, stiffness and unidirectional bending strength are calculated such that: (a) the model has the same natural frequency as the original infill wall, (b) it produces the same support reactions, where it is attached to the surrounding frame, for a given support motion (story acceleration) and (c) it initiates yielding at the same level of support motion that causes the original infill wall to yield. Relevant equations and their derivation can be found in [1]. The IP axial and OOP bending strength interaction curve is a 3/2-power curve, Equation 1.

$$\left(\frac{P_{IP}}{P_{IP0}}\right)^{3/2} + \left(\frac{M_{OOP}}{M_{OOP0}}\right)^{3/2} \leq 1.0 \qquad (1)$$

where P_{IP} is the IP axial strength in the presence of OOP force, P_{IP0} is the IP axial strength without OOP force, M_{OOP} is the OOP bending strength in the presence of IP force, and M_{OOP0} is the OOP bending strength without IP force. Equation 1 matches the finite element results in [3].

Since only one diagonal element is considered in the model, it has both tension and compression strengths. Therefore, the fibres have the same absolute value for the tensile and compression yield strengths. A bilinear relationship with a very small strain hardening is assumed for the stress-strain relationship.

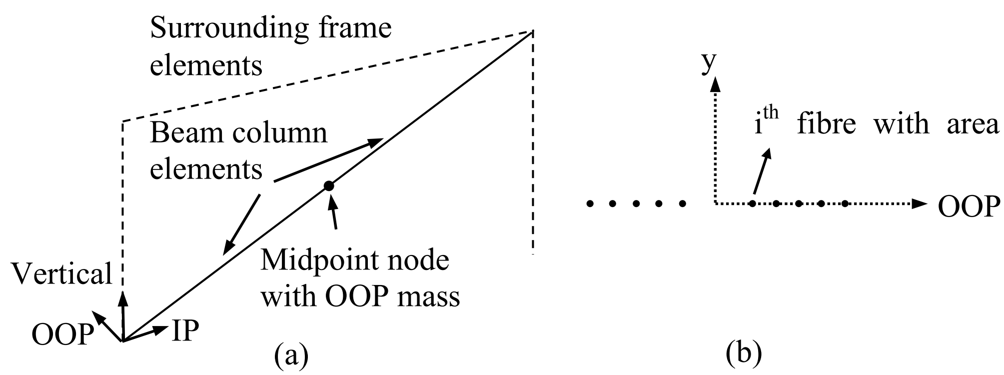

Figure 2: (a) Infill wall model for IP/OOP interaction, (b) Fibre layout in the cross-section

EXPLICIT ACCOUNT OF INFILL FAILURE THROUGH ELEMENT REMOVAL

In order to account for the failure of URM infill walls during earthquake excitations under combined IP and OOP effects, the analytical infill wall model described in the previous section is implemented in a previously developed progressive collapse algorithm [4]. This algorithm was developed by using element removal based on dynamic equilibrium and the resulting transient change in system kinematics, the underlying theory of which can be found in [4, 5]. It was implemented for automated removal of collapsed elements during an on-going simulation, Figure 3. The implementation was carried out as a new OpenSees (Open System for Earthquake Engineering Simulation [6]) module, designed to be called by the main analysis module after each converged integration time step to check each element for possible violation of its respective removal criteria. A violation of a pre-defined removal criterion triggers the activation of the element removal algorithm on the violating element before returning to the main analysis module. This activation includes updating nodal masses, checking if the removal of the collapsed element results in leaving behind dangling nodes or floating elements, which must be removed together with all associated element and nodal forces, imposed displacements, and constraints. Removal criteria were defined for force-based and displacement-based distributed plasticity fibre elements and lumped plasticity beam–column elements with fibre-discretized plastic hinges in OpenSees [6]. These criteria were based on the material-level damage indices for a confined RC cross-section model [4].

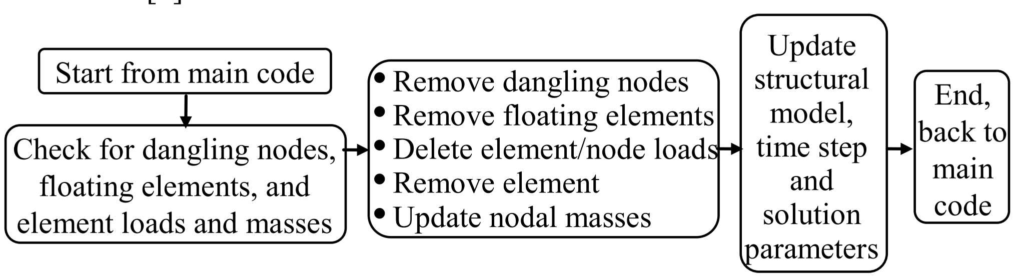

Figure 3: Considered element removal algorithm

Implementation of the removal of the infill wall analytical model in the progressive collapse algorithm is achieved through defining a new criterion for the beam-column elements [7]. The new criterion is based on the interaction between the IP and OOP displacements. IP displacement is the relative horizontal displacement between the top and bottom nodes of the diagonal. OOP displacement is that of the middle node (where the OOP mass is attached) with respect to the chord which connects the top and bottom nodes in OOP direction. The same equation used for the strength interaction is adopted for the displacement interaction. When the combination of displacements from the analysis exceeds the envelope curve (Figure 4), the two beam-column elements and the middle node representing the URM infill wall are removed, which directly corresponds to the failure of the physical URM infill wall. IP and OOP displacement capacities in the presence of zero displacement in the other direction are obtained from FEMA-356 for collapse prevention level. The algorithm for the removal of an infill wall is presented in Figure 5.

SHEAR DAMAGE OF COLUMNS DUE TO FRAME/INFILL WALL INTERACTION

For explicit consideration of the horizontal forces transferred by the infill wall to the column and the consequent potential of shear damage, nonlinear shear springs are modelled at the ends of the columns and the diagonal elements (Figure 2) are connected to these shear springs, Figure 6. In addition to the realistic representation of the additional shear forces, realistic representation of shear strength is sought to be achieved. For this purpose, the change of shear strength as a function of the axial force is considered by implementing the ACI 318 [8] shear strength equations in OpenSees as a uniaxial material [9]. This uniaxial material is used as a nonlinear shear spring at the column ends as shown in Figure 6, where the shear strength changes as a function of the axial force variation due to overturning moments during earthquake excitation.

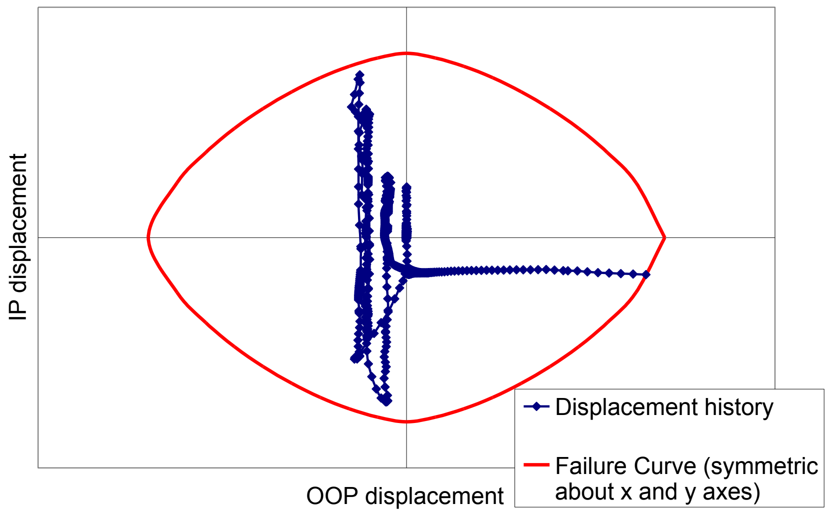

Figure 4: Removal criterion for the URM infill wall considering IP/OOP interaction

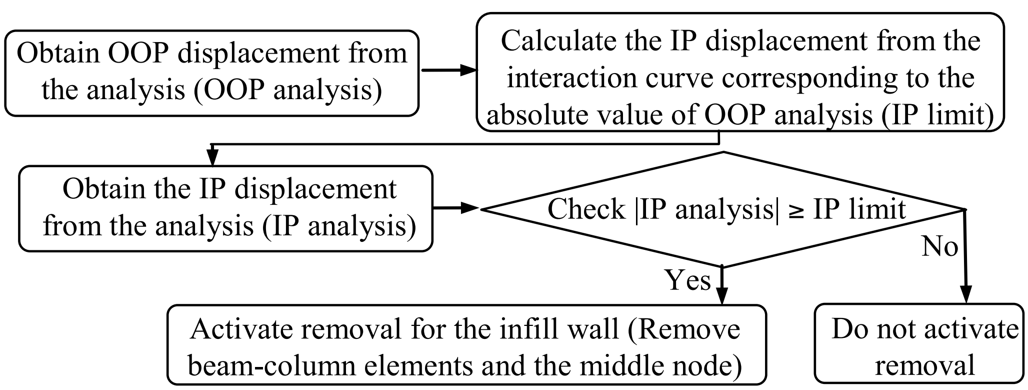

Figure 5: Algorithm for the URM infill wall removal

Figure 6: Nonlinear shear springs modelled at the column ends

ANALYSES OF A FIVE STORY CODE-DESIGNED BUILDING

For the application of the analytical simulation approach which considers the critical modelling aspects mentioned above, a hypothetical five-story, three-bay by two-bay RC building containing URM infill walls is employed. Typical story height is 3.65 m (144"), whereas the bay widths are 5.50 m (216") and 4.90 m (192") in the directions with three and two bays, respectively, Figure 7. The building is designed according to ACI-318 [8] and NEHRP seismic design recommendations [10] with its exterior columns as the primary lateral load-resisting system [3], where the infill walls are not considered as structural elements in the design process. It is to be noted that the infill walls in this study are non-integral walls without shear connecters. Cross-section sizes and reinforcement detailing of the columns and beams are summarized in Table 1.

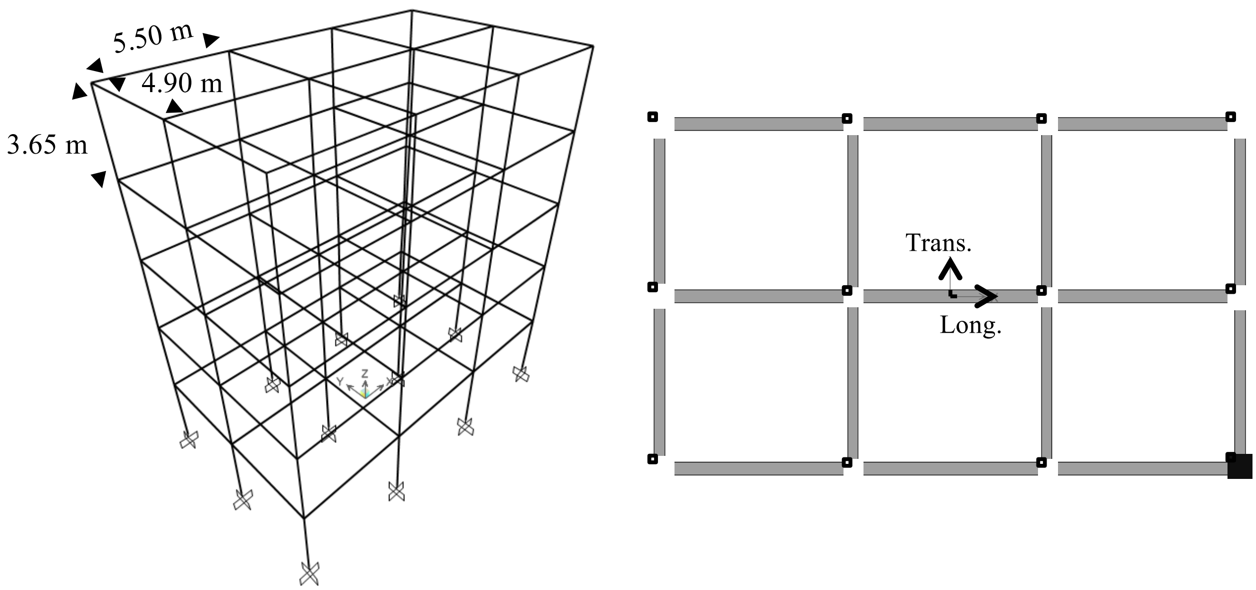

Figure 7: 3D configuration and plan view of the application building

Analyses are conducted using OpenSees, where most of the critical modelling aspects are implemented as mentioned above. In addition to these modelling aspects, other considered modelling features are as follows. To model the beams and columns, force-based beam-column element is employed with five integration points. Material models designated as Concrete02 and Steel02 are used to respectively model concrete and steel uniaxial behaviours. The following values are used in concrete modelling: strength (f'_c) = 37 MPa (5.4 ksi), strain corresponding to peak stress (ε_c) = 0.002 and ultimate strain (ε_{cu}) = 0.006 for cover concrete, f'_c = 45 MPa (6.5 ksi), ε_c = 0.004 and ε_{cu} = 0.020 for core concrete. The compressive strength and strain properties for the core concrete are calculated based on Mander's model [11] using the confinement provided by the transverse reinforcement. Yield strength and strain-hardening ratio of steel are defined as 458 MPa (66.5 ksi) and 0.01, respectively. Mass and tangential stiffness proportional Rayleigh damping (5% of critical) is used with constants calculated by using the periods of the dominant modes of the building in the longitudinal (0.46 sec.) and transverse (0.37 sec.) directions, Figure 7.

Two horizontal components of the ground motion recorded in Los Gatos station during 1989 Loma Prieta earthquake [12] is used in the analysis. Acceleration, velocity and displacement histories of this pulse-type ground motion are shown in Figure 8. Analyses are conducted on two different configurations of the application building: (a) bare frame without any infill walls and (b) infill walls placed in all the bays along the perimeter. For the infill wall case, URM infill walls with 135 mm (5.3") thickness are employed with modulus of elasticity 6190 MPa (900 ksi), compressive strength 17.0 MPa (2.46 ksi), and shear strength 1.81 MPa (263 ksi).

Table 1: Cross-sections and reinforcement of members of the application building

Element	**Dimensions**	**Longitudinal Reinforcement†**	**Transverse Reinforcement*†**
Outer Columns	710 mm × 710 mm (28" × 28")	12#8	#4@100 mm (4")
Inner Columns	535 mm × 535 mm (21" × 21")	8#8	#4@125 mm (5")
X Dir. Beams	455 mm × 355 mm (18" × 14")	3#8 top & bottom	#4@100 mm (4")
Y Dir. Beams	405 mm × 305 mm (16" × 12")	2#8 top & bottom	#4@100 mm (4")

*Included in the confinement zone at the member ends only.
†#8 and #4 bars have cross-sectional areas of 0.79 in^2 (509 mm^2) and 0.2 in^2 (129 mm^2), respectively.

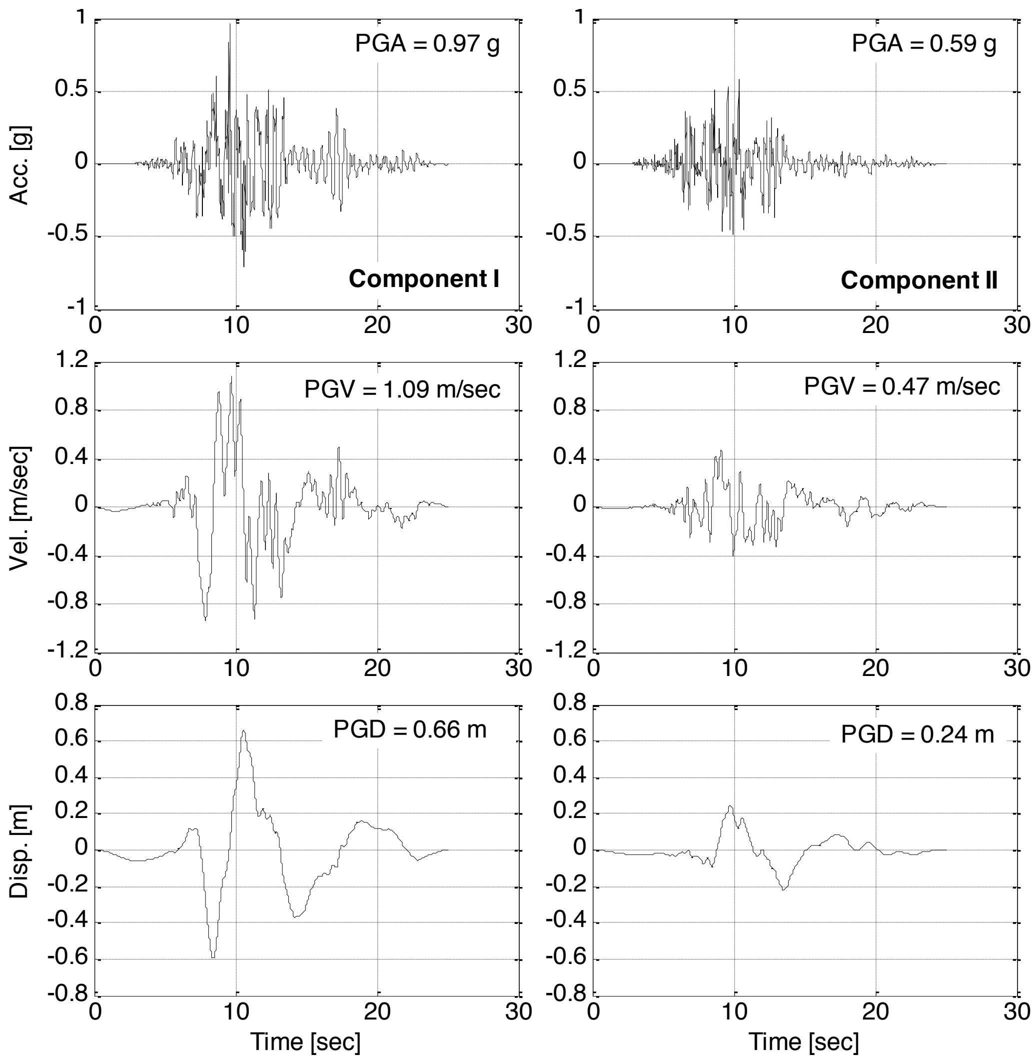

Figure 8: Acceleration, velocity and displacement traces of Los Gatos ground motion [12]

The displacement envelopes of one of the corner columns, marked with a solid black square in Figure 7, in the longitudinal and transverse directions are plotted in Figure 9 for both of the analysed configurations. It can be observed that the displacement envelope of the bare frame is as expected from a code-design [3, 8, 10]. However, in the case with infill walls, second story becomes a soft story during the ground motion excitation after the failure of infill walls as shown in Figure 10. This result supports the necessity of using the above mentioned critical modelling aspects to estimate the behaviour of RC frames with URM infill walls realistically in analytical simulations. It would not be possible to detect the presence of a soft story if the element removal algorithm was not used and the soft story location would probably be misleadingly determined as the first story if the IP/OOP interaction was not considered. It should be mentioned that these types of intermediate soft/weak story mechanisms have been observed in recent earthquakes, e.g., 2009 L'Aquila earthquake [13]. Shear failure of columns due to the effect of additional horizontal forces transferred from the infill walls is not observed for this particular case.

It should be noted that the above results may be specific to this frame, i.e. infill wall and ground motion combination. Hence, further analyses should be conducted with different ground motions characteristics and intensities. Resulting fragility curves could be used for more generalized conclusions. However, the limited analyses conducted herein with the two components of the selected ground motion is beneficial to demonstrate the necessity of proper modelling of RC frames with URM infill walls. It is also beneficial to show that prescriptive code design requirements may not be necessarily sufficient to be indicative of satisfactory performance. Therefore, the observed behaviour herein is an evidence of the requirement of performance-based earthquake engineering (PBEE) and design methods, e.g. PEER PBEE methodology [14], for more realistic performance estimations and realization of the corresponding designs.

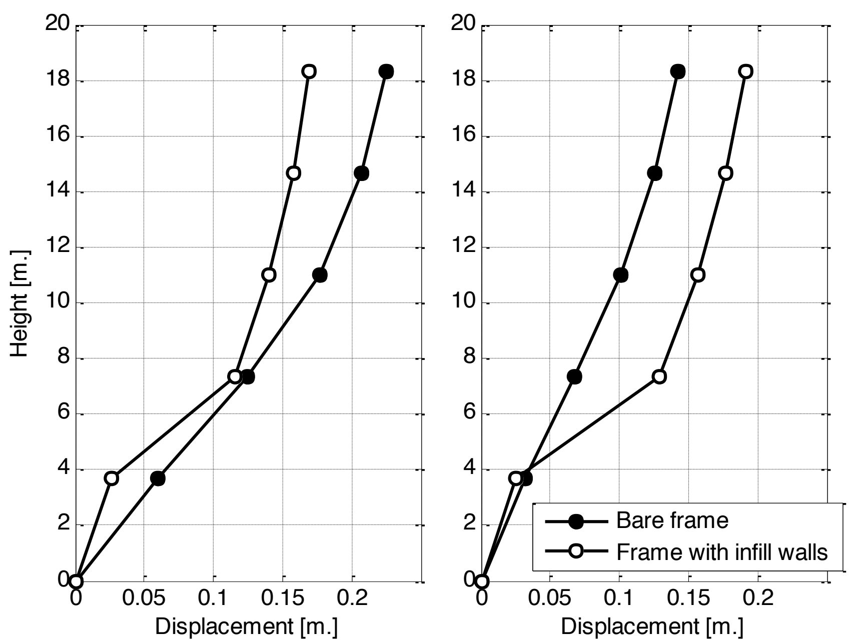

Figure 9: Peak displacement profile of a corner column in longitudinal (left) and transverse (right) directions

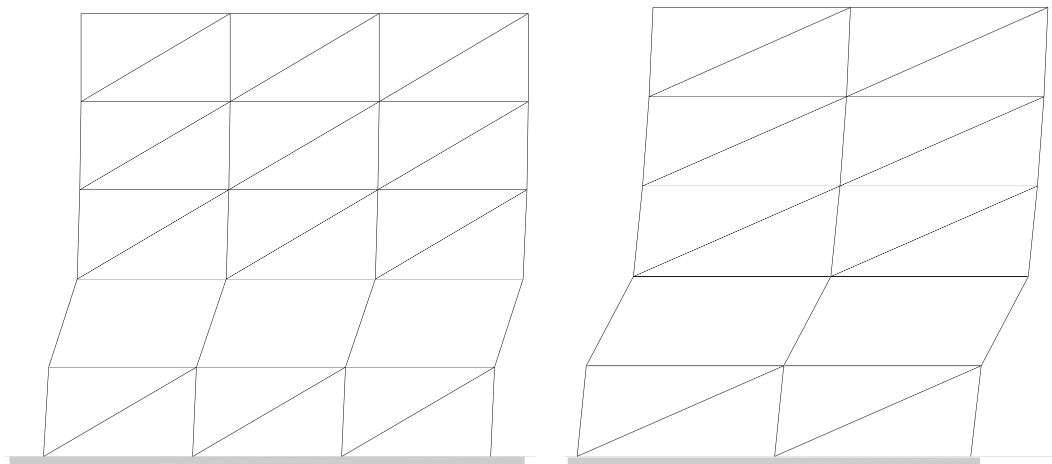

Figure 10: Deformed shapes of the infilled perimeter frames in longitudinal (left) and transverse (right) directions at the time of peak roof displacements

SUMMARY AND CONLUDING REMARKS

An analytical simulation approach is presented, which considers the critical modelling aspects in reinforced concrete (RC) buildings with unreinforced masonry (URM) infill walls. These modelling aspects include in-plane/out-of-plane interaction, explicit account of infill failure through element removal, and consideration of shear damage of the columns due to frame/wall interactions, where modelling of the last two aspects are achieved with new implementations in OpenSees source code. A commonly configured and code-designed five story RC frame with URM infill walls is analysed using the mentioned approach under the effect of bi-directional ground motions. The main concluding remarks are listed as follows:

- The structural response of the bare frame agrees with the requirements of a code-design.
- In the configuration of the frame with infill walls, second story becomes a soft story during the ground motion excitation after the failure of infill walls.
- The responses obtained from the bare frame and the frame with infill walls support the necessity of using the mentioned critical modelling aspects to realistically estimate the behaviour of RC frames with URM infill walls.
- The responses obtained from the bare frame and the frame with infill walls show that prescriptive code-design requirements may not be necessarily sufficient to be indicative of satisfactory performance. In other words, these results serve as an evidence of the requirement of performance-based earthquake engineering for realistic performance estimations and corresponding designs.

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