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REALISTIC SEISMIC ASSESSMENT OF RC BUILDINGS WITH MASONRY INFILLS USING 3D HIGH-FIDELITY SIMULATIONS

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Abstract. This paper presents a high fidelity nonlinear modelling strategy for accurate response predictions of reinforced concrete (RC) framed buildings subjected to earthquakes. The proposed numerical approach is employed to investigate the seismic performance of a 10-storey building, which is representative of many existing RC structures designed with no consideration of earthquake loading by following design strategies typically used in Italy before the introduction of the first seismic regulations. The seismic response of the representative building is investigated through detailed nonlinear dynamic simulations using ADAPTIC, an advanced finite element code for nonlinear analysis of structures under extreme loading. The analysed structure is described by 3D models, where beam-column and shell elements, both allowing for geometric and material nonlinearity, are employed to represent RC beams, columns and floor slabs respectively. Furthermore, in order to model the influence of non-structural components interacting with the main frame elements, masonry infill panels are described using a novel 2D discrete macro-element representation, which has been purposely developed within a FE framework and implemented in ADAPTIC. The nonlinear dynamic simulations are performed considering sets of natural accelerograms acting simultaneously along the two main horizontal and the vertical directions and compatible with the design spectrum for the Near Collapse Limit State (NCLS). To improve computational efficiency, which is critical when investigating the nonlinear dynamic response of large structures, a partitioning approach, previously developed at Imperial College, has been adopted. The numerical results, obtained from the accurate 3D nonlinear dynamic simulations, have shown an extremely poor seismic performance of the building, for which collapse is predicted for seismic events characterized by lower magnitude compared to the expected more catastrophic earthquake. The comparison of the results obtained for the bare frame building or allowing for non-structural infills contribution shows significant variation in the dynamic responses. This confirms the need to consider the influence of masonry infill panels for a realistic description of existing RC building structures not designed to resist earthquakes.

1 INTRODUCTION

The assessment of the Seismic Vulnerability of existing non-ductile RC buildings, designed only for gravity loads and built before the introduction of the first seismic design codes in different countries, is nowadays an important field of research. These buildings are generally characterised by different sources of structural weakness that make difficult a rigorous seismic assessment as well as the identification and the design of efficient and reliable seismic retrofitting measures. This paper presents a high fidelity numerical model developed to investigate the seismic performance of a 10-storey reinforced concrete (RC) framed building designed to be representative of many similar residential buildings built in Europe before the introduction of seismic codes. In particular, the prototype building has been designed by considering the architectural features of many typical existing RC buildings built in the city of Catania, in Sicily, according to old standards considering gravity and wind loading but not earthquakes. The proposed numerical description adopts beam-column elements [1,2] for beams and columns and detailed shell elements [3] for modelling RC floor slabs, both allowing for geometric and material nonlinearity. In order to model the influence of masonry infill, a novel macro-element has been developed within a FE framework based on a discrete formulation proposed in previous research [4, 5]. 3D nonlinear dynamic simulations are performed considering sets of natural accelerograms acting simultaneously along the two horizontal and the vertical directions and compatible with the design spectrum for the Near Collapse Limit State (NCLS) [6,7]. To improve computational efficiency, which is critical when investigating the nonlinear dynamic response of large structures, the partitioning approach previously developed at Imperial College [8] is adopted, enabling effective parallelisation on HPC systems. The numerical results obtained from the 3D nonlinear dynamic simulations are presented and discussed, focusing on the variation in time of the deformed shape, inter-storey drifts, plastic deformations and internal force distribution, considering or neglecting the infill panel contribution. The numerical results confirm that seismic performance of the original structure is very poor, where collapse is predicted also for seismic events characterized by low magnitude compared to the more catastrophic earthquake expected in Catania. The comparison of the analyses performed with and without non-structural infill panels show significant variation in the dynamic responses highlighting the need to consider masonry infill contribution for obtaining a realistic modelling of existing RC building structures not designed to resist earthquakes.

2 TEN-STOREY TYPICAL RC BUILDING

The prototype building has been designed with the aim to be representative of many residential buildings constructed in several areas of the south of Italy before the introduction of the national seismic code, in 1981, that classified these areas as seismic prone regions.

The analysed structure is a typical multi-storey RC frame building, with non-structural masonry infills, designed according to old standards to resist gravity and wind loading but not earthquakes. The structure was selected considering the results of an extensive survey on many existing multi-storey RC buildings built in Catania, in the oriental Sicily, in the seventies. The prototype building has been designed by a research group at the University of Catania within a research project funded by the Catania section of the National Association of Builders (ANCE Catania) [9]. Although the structure does not correspond to a real building, it can be considered as representative of several multi-storey residential buildings built in Italy before the introduction of a specific seismic codes. The number of storeys of these buildings, which are made up of low-ductility reinforced concrete frames, generally ranges from three to twelve, where the first floor is typically used for commercial purposes. The floor plans are 300-450 m^2 large and accommodate from two to five apartments. As these structures are characterised by very low lateral stiffness and resistance, as a consequence non-structural masonry infills greatly influence their nonlinear dynamic behaviour when the structures are subjected to earthquake loading and may represent a further source of vulnerability.

The analysis of the design drawings of many existing buildings, the evidence obtained by developers, builders and structural engineers operating in the 1970s, provided critical information leading to a detailed design of a typical building based on the standards adopted in Italy in the early ‘70s [10, 11]. The ten-storey residential building possesses a symmetric plan as shown Figure 1. The main structural system includes four RC frames, arranged along the longitudinal direction supporting RC ridded floor slabs, and four RC frames along the transversal direction located at the perimeter and in central position close to the staircase. The geometric details of the typical building can be found in [8,9], where further information on the loading and the material properties are reported.

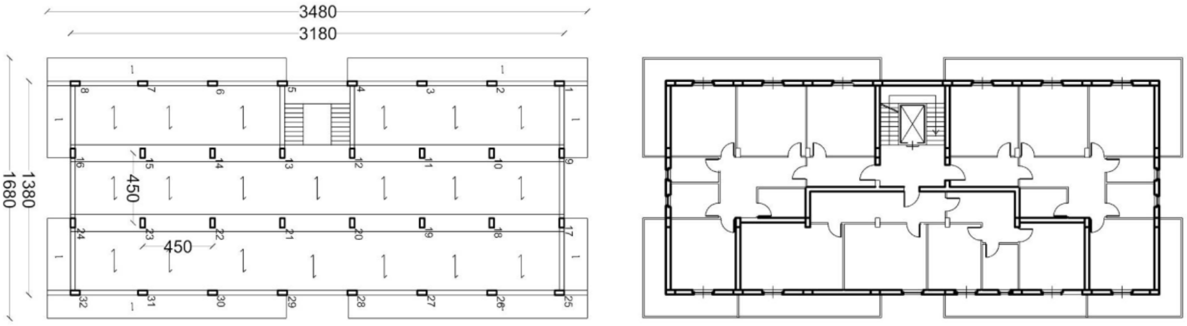


Figure 1: Architectural (a) and structural (b) plan of the typical building.

In Figures 2 and 3 the typical steel reinforcement distributions in the beams and in the columns are illustrated, all the details regarding the typical buildings are reported in references [6, 9].

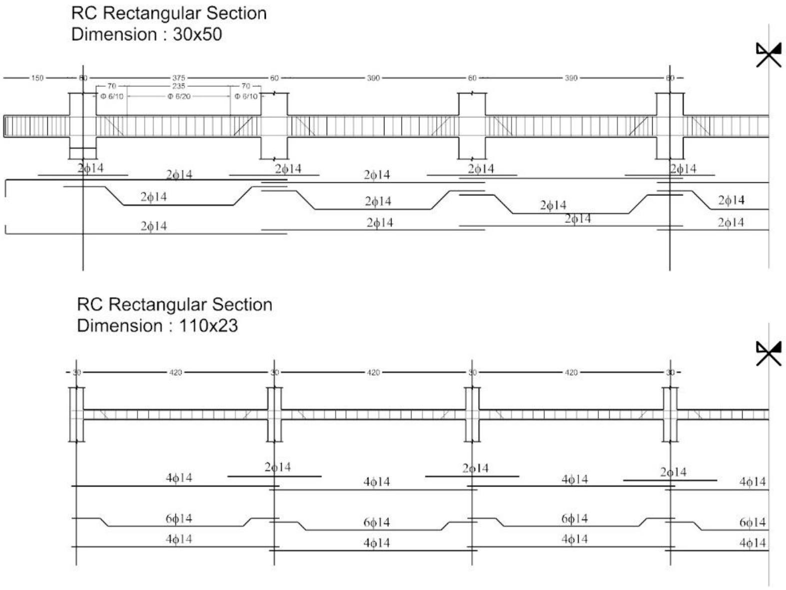


Figure 2: Example of the typical steel reinforcement distributions in the beams.

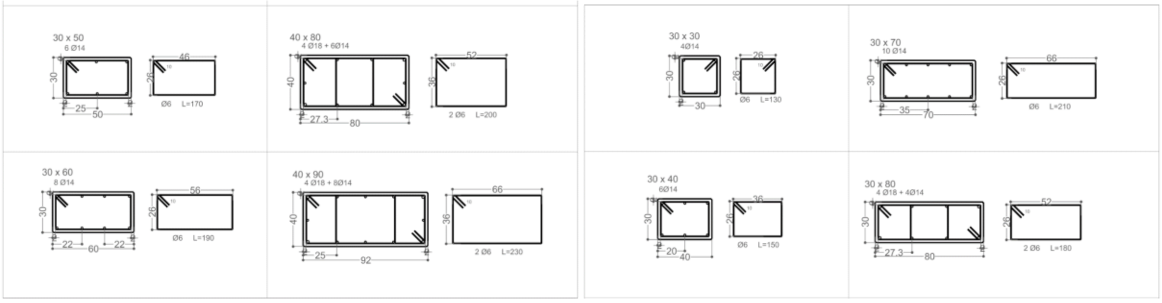
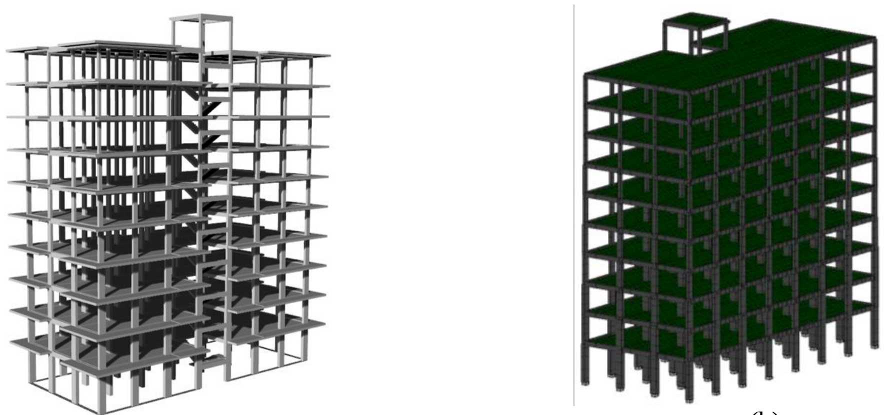


Figure 3: Typical steel reinforcement distributions in the columns.

3 THE HIGH FIDELITY MODELLING OF THE ANALYSED BUILDING

Two different high fidelity 3D models for the analysed building have been developed in ADAPTIC [1] and used in nonlinear dynamic simulations. These include i) a 3D bare frame (BF) model representing the contribution of all RC components (e.g. beams, columns and floor system) but disregarding non-structural elements, ii) an infilled frame (IF) model where all the structural and the main non-structural components (e.g. masonry cladding) are explicitly modelled. Concerning the BF model, each RC beam and column is modelled using a number of 1D elastic-plastic cubic beam-column elements [2] developed according to the distributed plasticity approach, where the influence of large displacements is considered by using a co-rotational formulation. The cross-section of a generic RC beam element at the integration points along the element length is discretised into a number of monitoring points (Figure 5), where strains in concrete and steel reinforcement are determined and then used within specific material relationships to obtain the associated stresses. In this respect, accurate nonlinear material laws for the two materials are used.



(a) (b)

Figure 4: The 3D view of the Reinforced Concrete Frame. (b) the high fidelity model in ADAPTIC.

These allow for yielding and strain hardening of steel reinforcement, cracking in tension and crushing in compression of concrete and the specific hysteretic behaviour of the two materials. In the numerical description for the multi-storey building, particular attention has been paid to representing the contribution of the floor systems which consist of one-way RC ribbed slabs spanning in the direction perpendicular to the main frames, Figure 6.

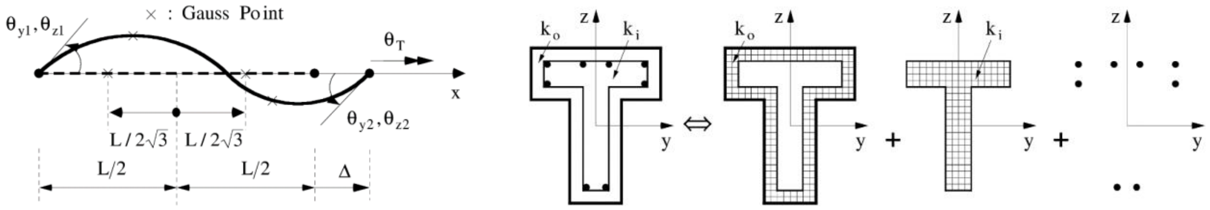


Figure 5: Sketch of the fibre elements with nonlinear material models.

In the numerical description in ADAPTIC, each floor rib is modelled by a discretization of 1D elasto-plastic beam-column elements which are connected to upper 2D nonlinear slab elements representing the top thin solid reinforced concrete slab.

Table 1: Concrete material properties

Material property	cover region	core region
Cylinder Compressive strength (MPa)	20.75	23.25
Young's modulus (MPa)	27386	27386
Strain at maximum strength	2×10^{-3}	2×10^{-3}
Strain at crushing	4×10^{-3}	50×10^{-3}
Tensile strength in tension	1.04 MPa	1.04 MPa

The RC slab elements [3] consider material nonlinearity in both concrete and steel reinforcement, and account for both bending and membrane effects as well as geometric nonlinearity. Tables 1 and 2 report the main material properties for concrete and steel reinforcement that have been considered in the nonlinear 3D models.

Table 2: Steel material properties

Material property	Rebars
Yielding strength (MPa)	375
Young's modulus (MPa)	210000
Strain-hardening ratio	0.01

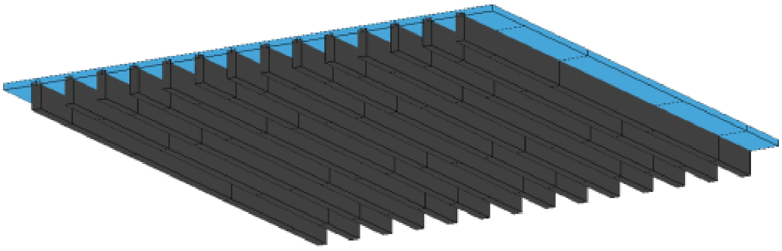


Figure 6: The high fidelity model of the floor system in ADAPTIC.

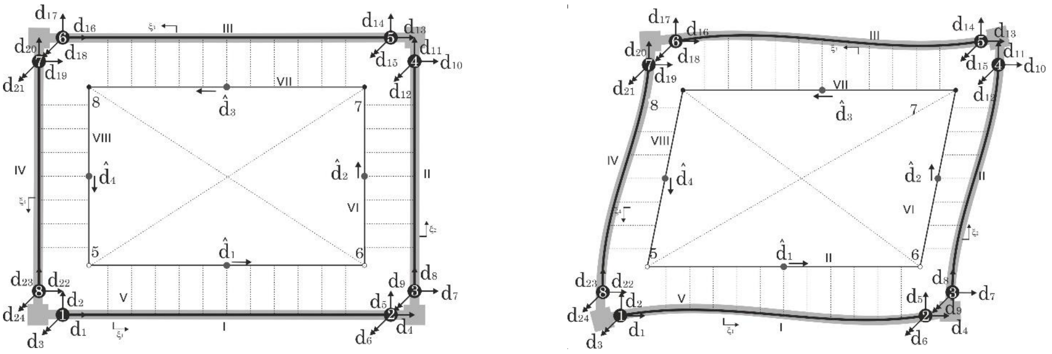
3.1 The macro-modeling of the non-structural masonry infills

As mentioned before, in the Infilled Frame (IF) model, exterior masonry infill panels are explicitly modelled within the 3D building description. Namely, a novel macro-element formulation, purposely developed and implemented in ADAPTIC, has been used (Figure 7). This is effectively a finite element implementation of a discrete modelling approach previous developed at the University of Catania [5] and incorporated in the 3DMacro software [12]. The new ADAPTIC macro-element has been verified against 3DMacro and experimental results for monotonic and cyclic loading.

The basic macro-element has been initially conceived for the simulation of the nonlinear in-plane behavior of unreinforced masonry walls [4]. This element is characterised by a simple mechanical description, Figure 7, constituted by an articulated quadrilateral with rigid edges connected by four hinges and two diagonal nonlinear springs. Each side of the quadrilateral can interact with other elements or supports by means of a discrete distribution of nonlinear springs, denoted as interface. In spite of its simplicity, such a basic mechanical representation is able to simulate the main in-plane failure mechanisms of a masonry wall portion subjected to in-plane horizontal and vertical loads.

The proposed nonlinear plane discrete macro-element is here re-defined according to an original approach that allows its implementation in any displacement based finite element code. In the FEM implementation the mechanical response of the element is governed by zero-thickness interfaces whose general behavior is controlled by 28 degrees of freedom associated to eight nodes of external edges and 4 degrees of freedom ruling the macro-element kinematics. The location and the corresponding orientation of the 24 degrees of freedoms of the 8-nodes and of 4 degrees of the quadrilateral are reported in Figure 7a. The 24 degrees of freedom

$d_1,...d_{24}$ associated to the 8 external nodes are identified as *external degrees of freedom* while the 4 degrees of freedom $\hat{d}_1,...\hat{d}_4$, related to the kinematics of the articulated quadrilateral, are identified as *internal degrees of freedom*.



(a) (b)

Figure 7: The plane macro-element and its degrees of freedom. (a) undeformed configuration; (b) deformed configuration.

The interface forces are related to the relative motion between the rigid edges of the quadrilateral which is described by using polynomial shape functions to represent external edge displacements which are associated to the external degrees of freedom.

It is worth noticing that, according to the adopted macro-element, the zero thickness interfaces incorporate the deformability of the infill panel assumed as a homogeneous orthotropic medium. The flexural and sliding kinematic is associated to the interface relative displacements controlled by the interface mechanical response while the shear-diagonal deformability is related to the diagonal nonlinear links. All the nonlinearities are lumped in the Gauss point of the interfaces and in the diagonal nonlinear links.

In the implementation here adopted, the interfaces have been calibrated according to a uniform distribution of Gauss points that leads to a uniform fiber discretization similar to that proposed in [5]. The typical macro-element discretization adopted in the ADAPTIC models is represented in Figure 8.

This formulation is intended to represent the nonlinear elastic response of the masonry infills by following a simplified approach based on an asymmetric constitutive law for the mechanical representation of the interfaces. Standard finite element technique is used for obtaining the local nodal forces F and the local stiffness matrix K at the element level.

The material properties for the masonry macro-elements representing hollow clay brick-masonry panels with 120 mm thickness are provided in Table 3 which include material parameters for the flexural and shear behavior, where the softening behavior is governed by the fracture energies. Additionally, potential plastic sliding along the mortar joints has been modelled by considering a rigid-plastic Coulomb frictional behavior with cohesion c = 0.4 MPa and friction angle tangent $\tan(\phi)=0.7$.

Furthermore, to avoid unrealistic stress distributions in infill masonry panels, a new capability in ADAPTIC for staged construction analysis has been developed and used in the IF models. It allows a realistic representation of the contribution of non-structural components.

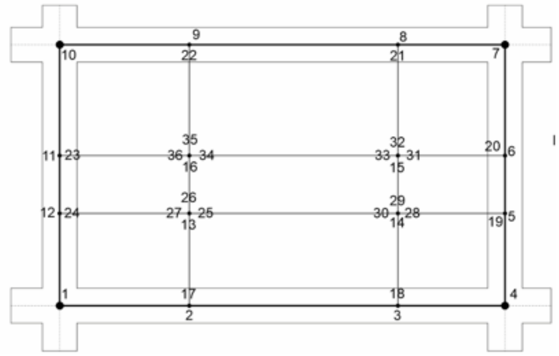


Figure 8: ADAPTIC adopted macro-element discretization for masonry infill

Table 3: Masonry infill material properties

Flexural behaviour					Shear behaviour			
Young's modulus E [Mpa]	Tensile strength σ_t [Mpa]	Compr. strength σ_c [Mpa]	Fract.en. (tens.) G_t [N/mm]	Fract. en. (compr.) G_c [N/mm]	Shear modulus G [Mpa]	Cohesion f_{v0} [Mpa]	Friction angle ϕ	Fract.en. (shear) G_s [N/mm]
1580	0.1	1	0.02	1	700	0.07	0.58	0.10

More specifically, this capability ensures that masonry infills do not take dead and imposed loads from the original building structure, and that they contribute mainly to resisting seismic action.

3.2 The partitioned modelling capability in ADAPTIC

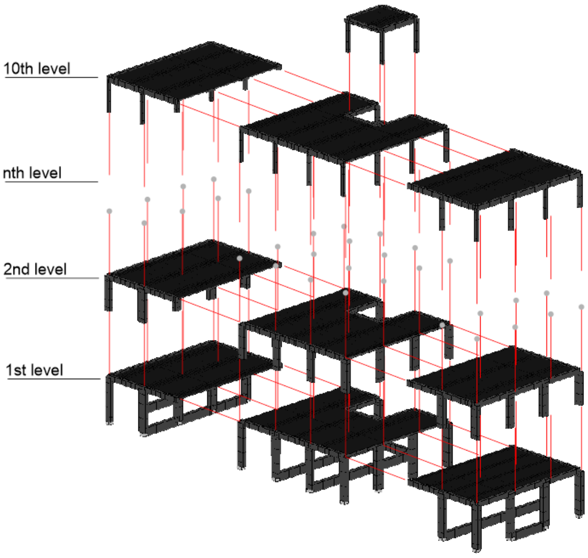


Figure 9: Partition strategy with 31 partitions for the analysed building

To enhance computational efficiency, all the large high fidelity models with 35896 nodes and 215184 degree of freedoms have been coupled with unique partitioned modelling capability in ADAPTIC [8], which allows efficient analysis on High Performance Computing systems. Thus each 3D building model has been divided in 31 partitions communicating with 1 parent structure (Figure 9) increasing the computational efficiency and dramatically reducing the computation time. This procedure allows adopting a scalable hierarchic distributed memory. Using this enhanced solution strategy, the typical nonlinear dynamic analysis took an average time of less of one days, much less than a conventional monolithic model that would have taken several weeks.

4 SEISMIC ASSESSMENT OF THE TYPICAL BUILDING WITH HIGH FIDELITY MODELS

Seven nonlinear dynamic simulations (NLDA1 to NLDA7), each using a different set of ground motion acceleration records acting simultaneously along the 3 perpendicular directions (e.g. two horizontal and the vertical directions) [6, 7, 13] were carried out using the high fidelity 3D models. The assessment has been conducted according to the Italian Seismic Code, D.M. 14 Gennaio 2008 and Circolare 2 -02-2009, 617. In particular, the following response characteristics have been analysed: 1) horizontal displacements, 2) inter-storey drifts, 3) ductile mechanisms (chord rotation) and 4) brittle mechanisms (shear failure). The horizontal displacements and inter-storeys drifts have been considered to evaluate the displacement demand at each floor level and for the whole building. On the other hand for a specific floor level, inter-storey drift capacity have been related to the ultimate chord rotation capacities of the RC columns.

4.1 Typical RC building

Some results of the global seismic response determined using the BF model, neglecting the infills contribution, is illustrated in Figure 10. The Figure reports the deformed shapes at the last step of the analyses, corresponding to the beginning of the strong phase of the accelerogram. All the colour maps have the same scale, in which the maximum value is the maximum displacement for all seven analyses. The displacements, except those for analyses NLDA5-6, are magnified 10 times. The average drift values in the two planar direction and the vertical displacements are shown in Figure 11. These results reveal that the seismic response of the original building, neglecting the infill panel contribution, is not satisfactory. Very large drift values indicating the development of soft storey collapse mechanisms (e.g. seventh and eighth storeys) can be seen.

The more realistic results, obtained employing the IF model (Figure 11) show a less significant drift demand at the top floors. In these cases the average maximum drifts in the two directions show large values at the first and the eighth floor, both smaller than the maximum drift predicted by the BF model as reported in Table 4. The results clearly indicate that the presence of unreinforced masonry panels strongly influences the seismic response of the building structure. The complete absence of panels at the ground floor leads to a concentration of the drift demand at that level, where a soft storey collapse is clearly predicted. At the same time, the analyses on this structural configuration show less localised but still significant drift demand at the eighth level. This is related, as in the BF model, to the variation of column size with a substantial section reduction of the column cross-section at the last three levels. This is due to the gravity loading-based optimisation of the column sections considered in the design of the prototype building, according to standard practice before the application of seismic design code in Eastern Sicily.

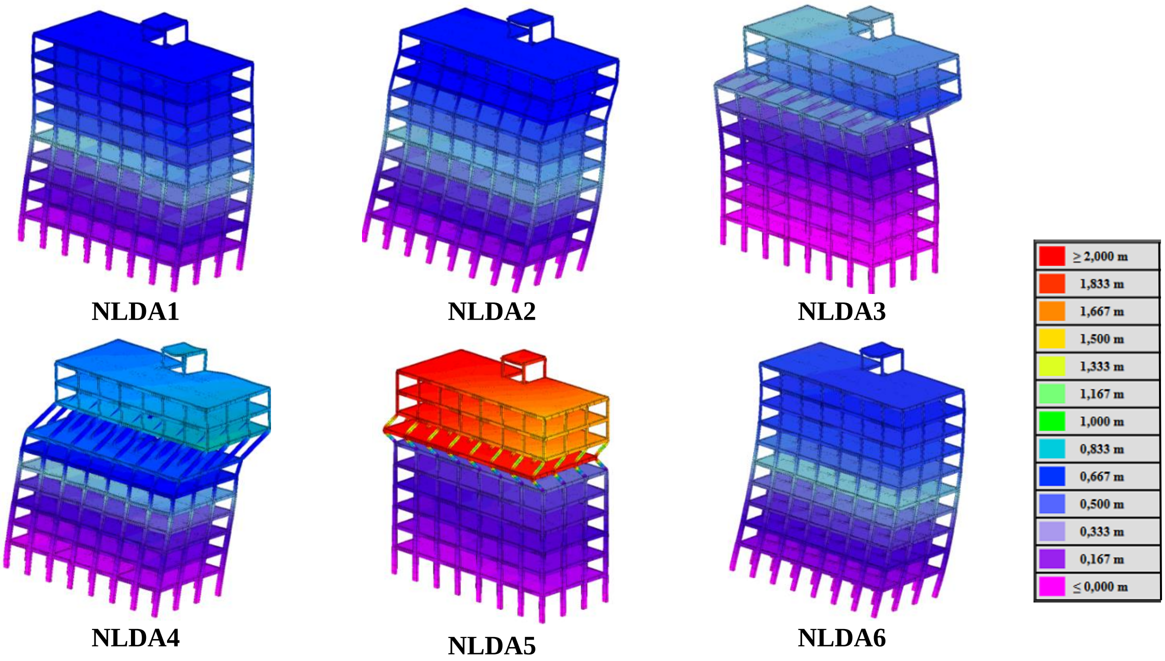
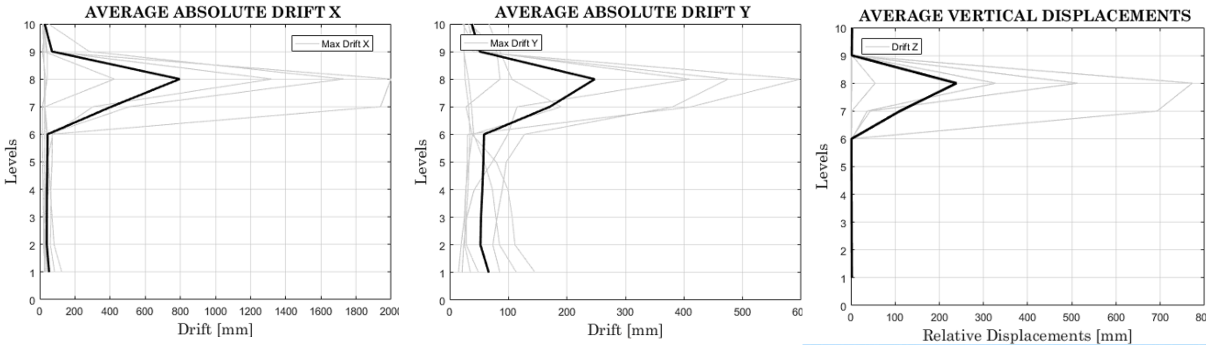


Figure 10: Global response of the BF model for the first six accelerograms



(a) (b) (c)

Figure 11: Average drift values for the BF model in the two planar (a,b) and vertical displacements (c)

Time-history results have shown that several columns fail due to the large demand in rotations and shear forces. More specifically, when considering the BF model neglecting infill panel contribution large chord rotations develop at the end of the beam which are related to the large inter-storey drifts. On the other hand, the IF model, allowing for masonry infills, achieves smaller rotations but higher shear forces in the columns which are induced by the local interaction with the masonry cladding.

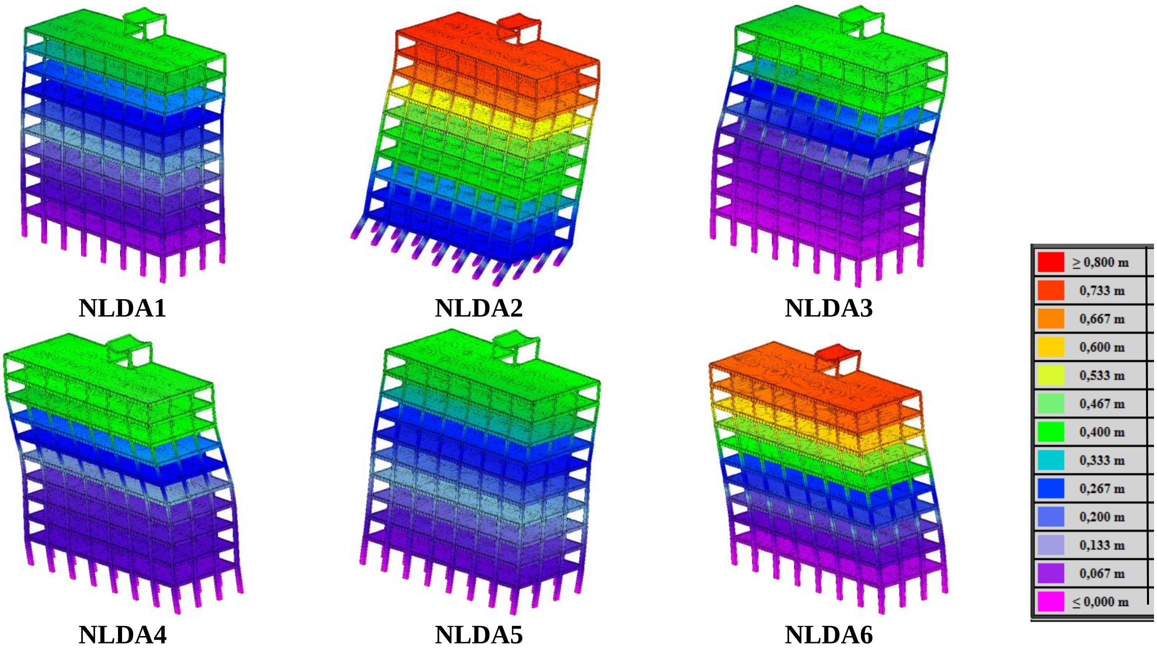
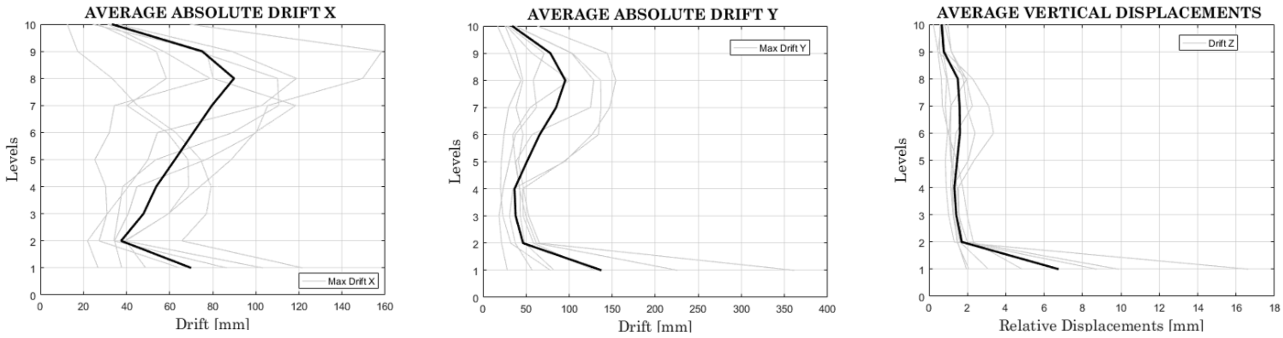


Figure 12: Global response of the IF model for the first six accelerograms



(a) (b) (c)

Figure 13: Average drift values for the IF model in the two planar (a, b) and vertical displacements (c)

Table 4: Maximum drifts determined by the BF and IF models

Model	Average absolute Drift X [mm]	Average absolute Drift Y [mm]	Average Vertical Displacements [mm]
BF	~800	~230	~210
IF	~90	~170	~8

Both numerical descriptions clearly indicate local failures in a significant number of RC components under the design ground motion.

5 CONCLUSION

The seismic performance of a typical multi-storey RC building, which is representative of residential structures designed and built in the earthquake-prone urban area of Catania (Italy) in the early ‘70s without consideration of earthquake loading, has been investigated using nonlinear dynamic analysis. Detailed 3D numerical descriptions have been developed allowing for the main structural and non-structural components of the framed building including RC beams and columns, ribbed floor slabs and masonry infills. In order to model the influence of masonry infill, a novel discrete macro-element has been developed and implemented in ADAPTIC. The results achieved confirm the very poor seismic performance of the existing structure, where the presence of masonry infill strongly influences the dynamic behavior. The comparison of the analyses performed with and without non-structural infills contribution shows significant variation in the dynamic responses, thus highlighting the critical role played by these non-structural components which should be properly taken into account for a realistic description of existing RC building structures not designed to resist earthquakes.

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