Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 1685-1699

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

REALISTIC 3D NONLINEAR DYNAMIC ANALYSIS OF EXISTING AND RETROFITTED MULTI-STOREY RC BUILDINGS SUBJECT TO EARTHQUAKE LOADING

G. Occhipinti[1], B. Izzuddin[2], I. Calio'[1] and L. Macorini[2]

[1] Department of Civil and Environmental Engineering University of Catania, Catania, Italy
e-mails: giuseppe.occhipinti@dica.unict.it, icalio@dica.unict.it

[2] Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
e-mails: b.izzuddin@imperial.ac.uk, l.macorini@imperial.ac.uk

Keywords: 3D nonlinear dynamic analysis, seismic assessment of RC building, retrofitting strategies, eccentric steel bracings

Abstract. *This paper presents a high fidelity numerical model developed to investigate the seismic performance of an original and retrofitted 10-storey reinforced concrete (RC) framed building. The analysed structure represents a typical existing building in Catania, Italy, which was designed according to old standards to resist gravity and wind loading but not earthquakes. The proposed numerical description adopts beam-column elements for beams and columns and special purpose shell elements 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 is developed within a FE framework based on a discrete formulation. 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). To improve computational efficiency, which is critical when investigating the nonlinear dynamic behaviour of large structures, the partitioning approach previously developed at Imperial College 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 original structure showed a very poor seismic performance, where the consideration of the infill panel contribution leads to significant variation in the response. An effective strengthening solution utilising eccentric steel bracings with dissipative shear links is also illustrated and employed to retrofit the original structure. A detailed model of the retrofitting components is also proposed and implemented within the detailed model for the original building. The results of numerical simulations for the retrofitted structure confirm that the proposed solution significantly enhances the response under earthquake loading, allowing the structure to resist the design earthquake with only limited damage in the original RC beams and columns, highlighting the feasibility of retrofitting for this typical multi-storey RC building structure.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5522.18445

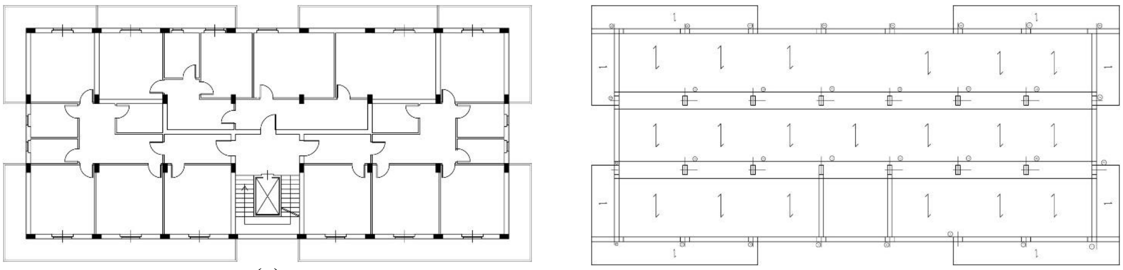
1 INTRODUCTION

A large number of multi-storey reinforced concrete (RC) framed buildings, designed to resist gravity and wind loading but not earthquakes, are located in seismic regions. At present these structures need to be assessed and potentially strengthened to avoid future failures. This paper presents a numerical investigation on a typical multi-storey RC building designed according to old standards. High fidelity 3D models developed in ADAPTIC [1], an advanced finite element code for nonlinear analysis of structures under extreme loading, have been used for detailed nonlinear dynamic simulations to investigate the seismic performance of the original building structure and address the design of an effective retrofitting solution enhancing its seismic performance. The use of a 3D approach in ADAPTIC allows for the consideration of the real seismic action which acts in 3 directions (e.g. 2 horizontal and the vertical directions) as well as the interaction of different planar frames within the building. In this way, torsional effects, due to initial or damage induced structural irregularities, can be automatically captured. According to the adopted modelling strategy, the combined response of the 3D frames, floor slabs, infill panels, retrofitting system, and any other structural/non-structural component are accurately modelled allowing for geometric and material nonlinearity. The use of realistic nonlinear 3D models in fully dynamic time-history analysis enables also to take into account potential deterioration in column resistance which may eventually lead to disproportionate collapse. The detailed 3D numerical descriptions have been used in combination with a unique partitioned modelling capability in ADAPTIC which allows efficient analysis on High Performance Computing systems [2]. This is critical to reduce the computational time required in nonlinear dynamic analysis of large structures represented by high fidelity models. In the following, the analysed structure and the main characteristics of the models used in the numerical simulations are presented. Subsequently, the results achieved in nonlinear dynamic analyses of the original multi-storey building are illustrated. Finally, the proposed strengthening solution is detailed, and the results of numerical analyses on the strengthened structure subjected to earthquake loading are presented and discussed.

2 THE RC BUILDING AND THE PROPOSED RETROFITTING SOLUTION

The analysed structure is a multi-storey RC frame building with masonry infills, which was 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 existing multi-storey RC buildings in Catania conducted by the University of Catania [3] within a project funded by the Catania section of the National Association of Builders (ANCE Catania). Although the structure does not correspond to a real building, it can be considered as representative of many multi-storey residential buildings built in Italy before the introduction of specific seismic codes. The number of storeys of these buildings, which are made up of low-ductility reinforced concrete frames, generally ranges from five to twelve, where the first floor is typically used for commercial purposes. The floor plans are 300 to 450 m^2 large and accommodate from two to five apartments. As these structures are characterised by low lateral stiffness and resistance, 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. This is because their interaction with the RC frames may induce local failures.

The analysis of the design drawings of many existing buildings, as well as evidence obtained from 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 [4]. It is a ten-storey residential building with 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 geometrical details of the typical building can be found in [3], where further information on the loading and the material properties are reported.



(a) (b)

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

To enhance the seismic performance of the original building, a retrofitting solution has been developed. It considers a set of eccentric steel bracings with dissipative shear links used in combination with traditional concentric steel bracings which are connected to the original structure providing significant additional hysteretic energy dissipation capacity and higher lateral stiffness. It is important to point out that, according to the authors' knowledge, the geometrical layout proposed for the eccentric steel bracings has never been adopted before and it allows the concentration of damage in the shear links without transferring high shear forces to the original reinforced concrete beams. Thus significant plastic damage is expected to develop in the shear links which can be easily removed and substituted after a strong earthquake. Figure 2 shows the distribution in plan of the strengthening elements, where the red marks indicate the position of the concentric steel bracings and the blue marks the eccentric dissipative bracings.

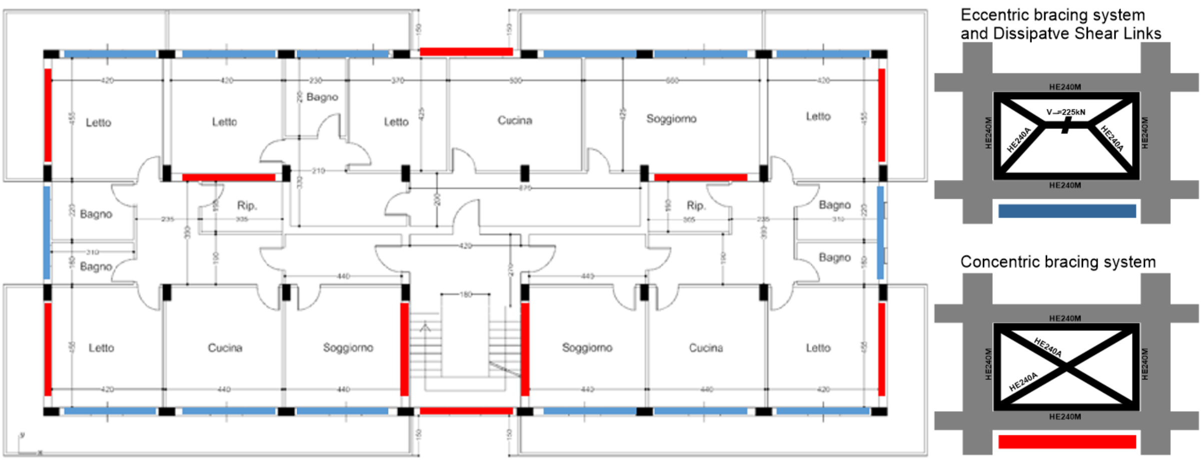
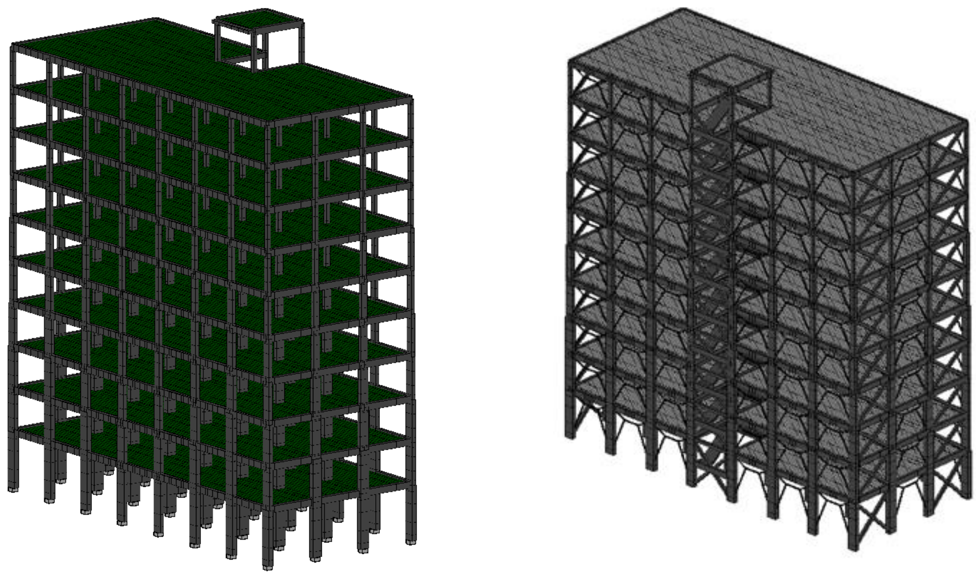


Figure 2: Distribution in plan of the strengthening components.

3 3D NUMERICAL DESCRIPTIONS FOR THE ORIGINAL AND RETROFITTED BUILDINGS

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 (Figure 3a), ii) an infilled frame (IF) model where all the structural and the main non-structural components (e.g. masonry cladding) are explicitly modelled, and iii) a retrofitted infilled frame model (RIF) where properly designed strengthening steel components are incorporated into the model (Figure 3b). Concerning the BF model, each RC beam and column is modelled using a number of 1D elastic-plastic cubic beam-column elements [6] utilising a fibre 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 4), 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. 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. In the numerical description in ADAPTIC, each floor rib is modelled by a number of 1D elasto-plastic beam-column elements which are rigidly connected to upper 2D slab elements representing the top thin solid slab. The RC slab elements [7] consider material nonlinearity in both concrete and steel reinforcement, and account for both bending and membrane effects and 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.



(a) (b)

Figure 3: 3D models in ADAPTIC for the original building (a) and the strengthened structure (b).

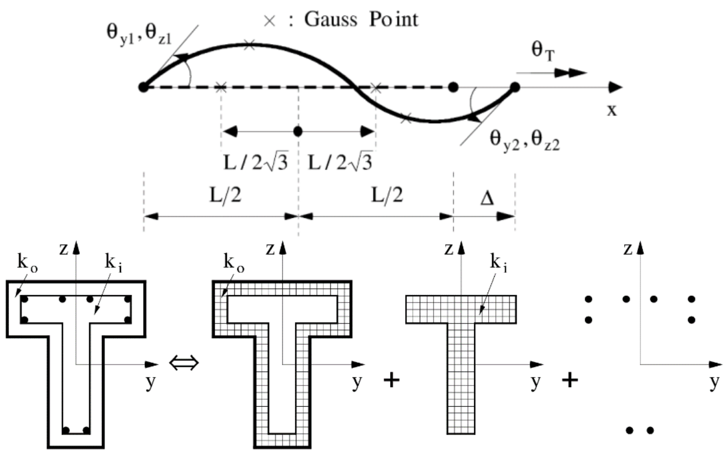


Figure 4: Sketch of the fibre elements with nonlinear material models.

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 (MPa)	1.04	1.04

Table 1: Concrete material properties.

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

Table 2: Steel material properties.

As mentioned before, in the IF model, exterior masonry infill panels are explicitly modelled within the 3D building description. A novel macro-element formulation purposely developed and implemented in ADAPTIC has been used (Figure 5). This is effectively a finite element implementation of a modelling approach previous developed at the University of Catania [8] and incorporated in the 3DMacro software [10]. The new ADAPTIC macro-element has been verified against 3DMacro and experimental results for monotonic and cyclic loading. 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(ϕ)=0.7.

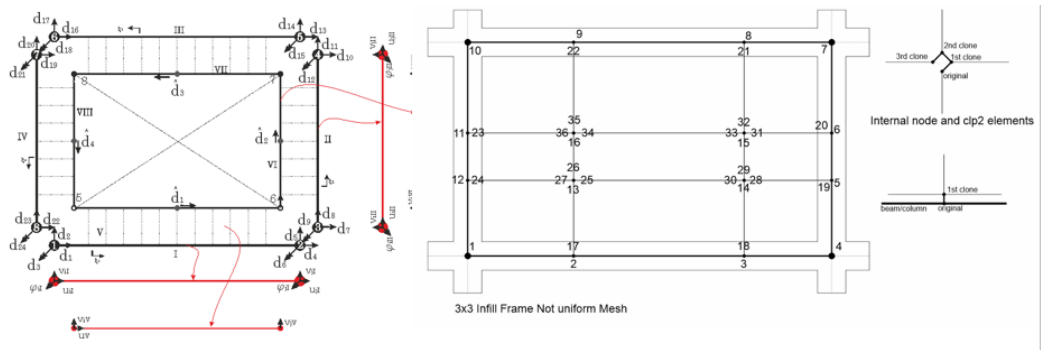


Figure 5: ADAPTIC macroelement for masonry infill.

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

Table 3: Material parameters for infill macroelements.

In the RIF model (Figure 3b), the steel elements of the strengthening system, encompassing eccentric bracings with dissipative shear links along with traditional concentric bracings and (Figure 6), are modelled using 1D elasto-plastic beam-column elements and nonlinear joint elements.

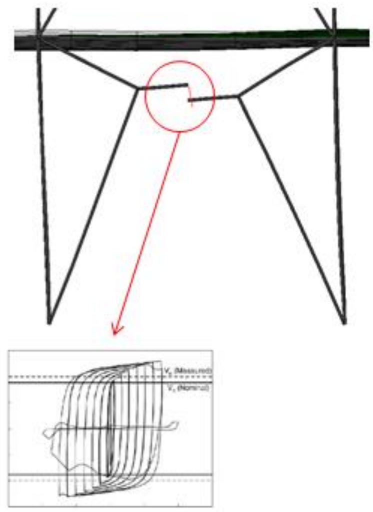


Figure 6: Modelling of an eccentric bracing with a dissipative shear link.

Finally, to avoid unrealistic stress distributions in infill masonry panels and the steel bracing systems, a new capability in ADAPTIC for staged construction has been developed and used in the IF and RIF models. It allows a realistic representation of the contribution of non-structural components and retrofitting systems. More specifically, this capability ensures that retrofitting systems do not take dead and imposed loads from the original building structure, and that they contribute mainly to resisting seismic action. To enhance computational efficiency, all the large high fidelity models with 35896 nodes and 215184 degree of freedoms have been considered with a unique partitioned modelling capability in ADAPTIC [2], which allows efficient analysis on High Performance Computing systems. Thus, each 3D building model has been divided into 31 partitions communicating with 1 parent structure (Figure 7) 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 2-3 days, much less than a conventional monolithic model that would have taken several weeks.

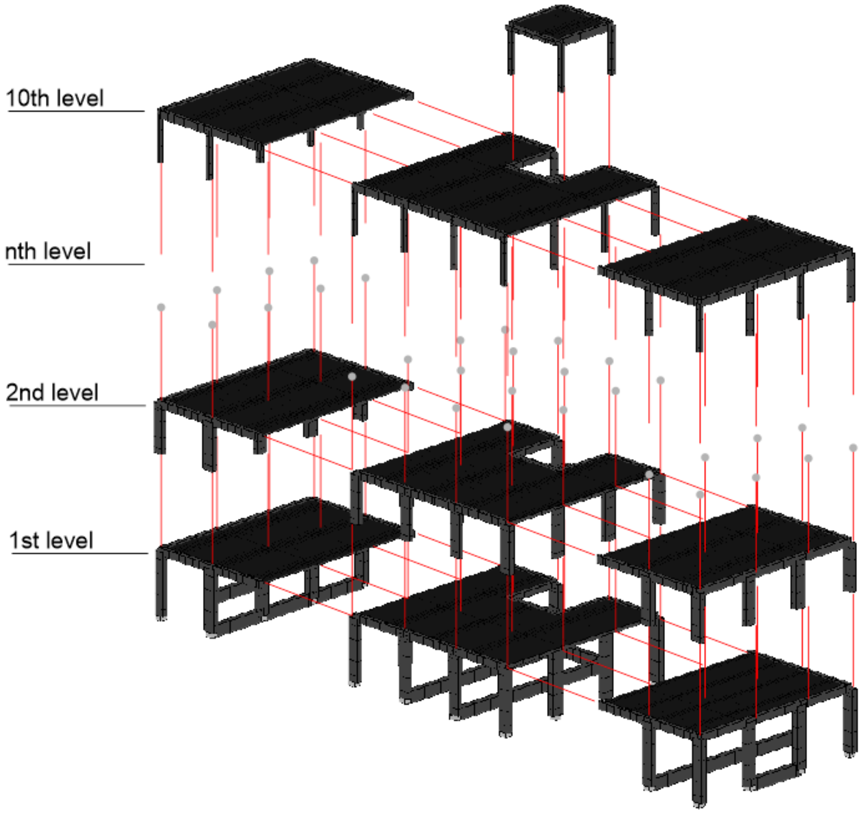


Figure 7: Partition strategy with 31 partitions for the analysed building.

4 SEISMIC ASSESSMENT 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) [11] were carried out using the high fidelity 3D models. The results achieved have been used to assess the seismic performance of the typical RC multi-storey building and the strengthened structure. 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-storey 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 can be related to the ultimate chord rotation capacities of the RC columns.

4.1 Typical RC building

The global seismic response determined using the BF model is illustrated in Figure 8, where the deformed shapes at the last step of the analyses are shown. 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 directions and the vertical displacements are shown in Figure 9. These results reveal that the seismic response of the original building, neglecting the infill panel contribution, is not satisfactory. Large drift values indicating the development of soft storey collapse mechanisms at the top levels (e.g. seventh and eighth storeys) can be seen. The results obtained employing the IF model (Figure 10) show a less significant drift demand at the top floors. The average maximum drifts in the two directions show notable 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 show 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 concentrates the drift demand at that level, where a soft storey collapse is predicted. At the same time, the analyses on this structural configuration show less localized, 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 optimisation of the column sections considered in the design of the prototype building, according to standard practice before the application of seismic design principles in the Catania area.

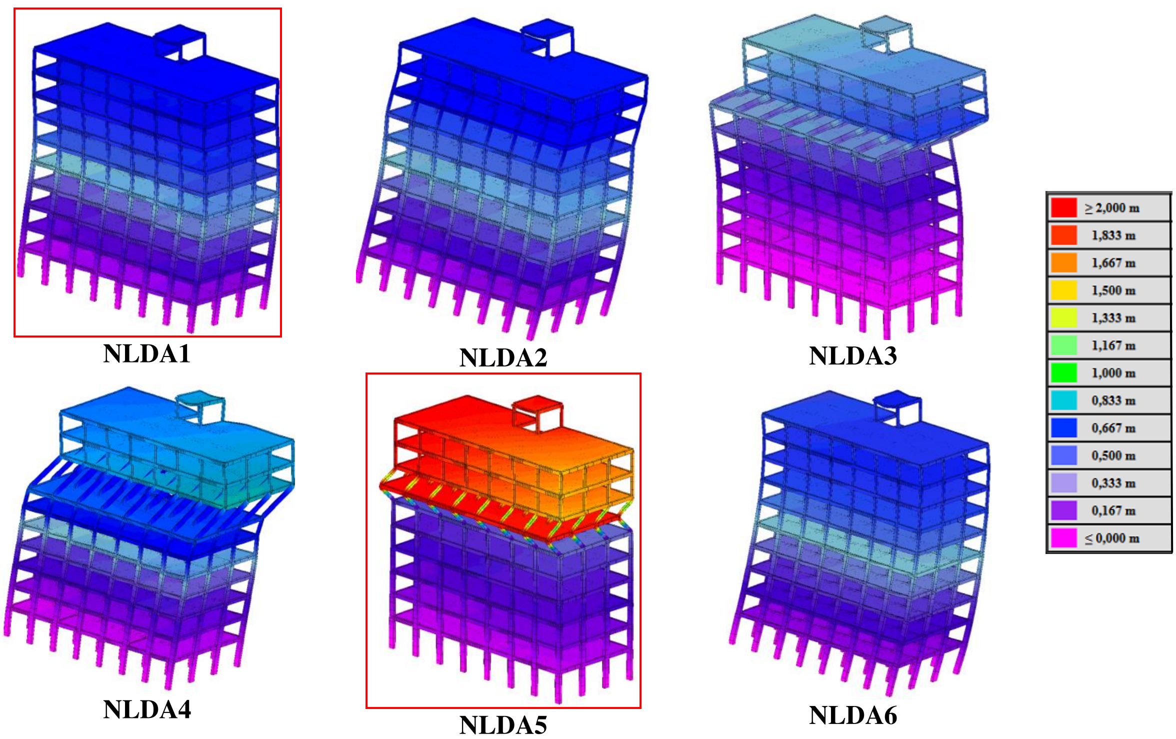
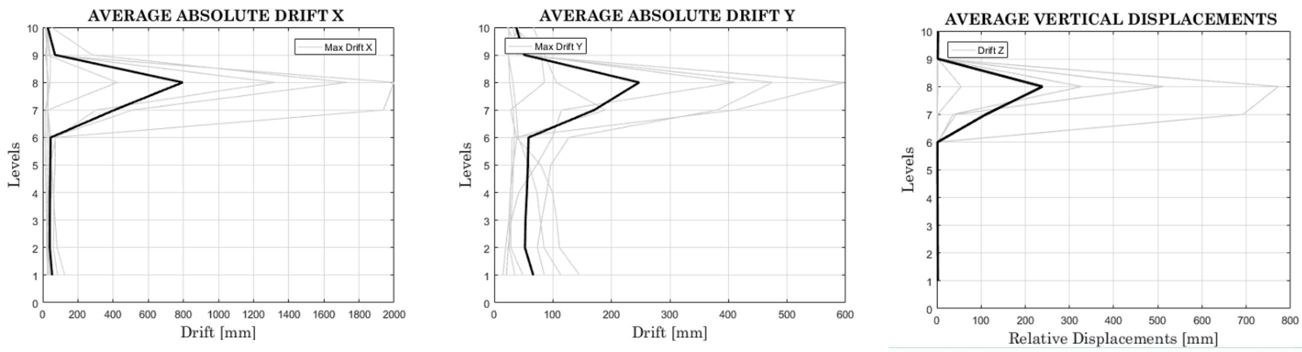
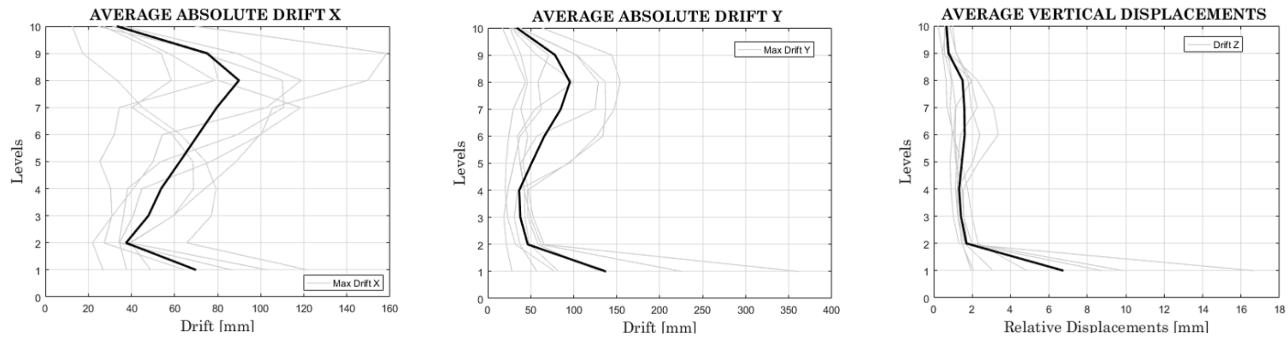


Figure 8: Global response of the BF model for the seven accelerograms.



(a) (b) (c)

Figure 9: Average drift values for the BF model in the two planar (a,b) and vertical displacements (c).



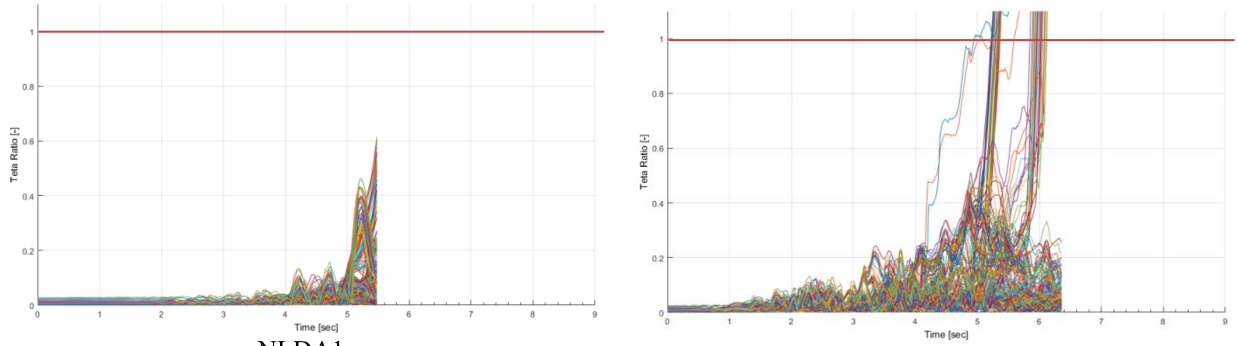
(a) (b) (c)

Figure 10: Average drift values for the IF model in the two planar (a, b) and vertical displacements (c).

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

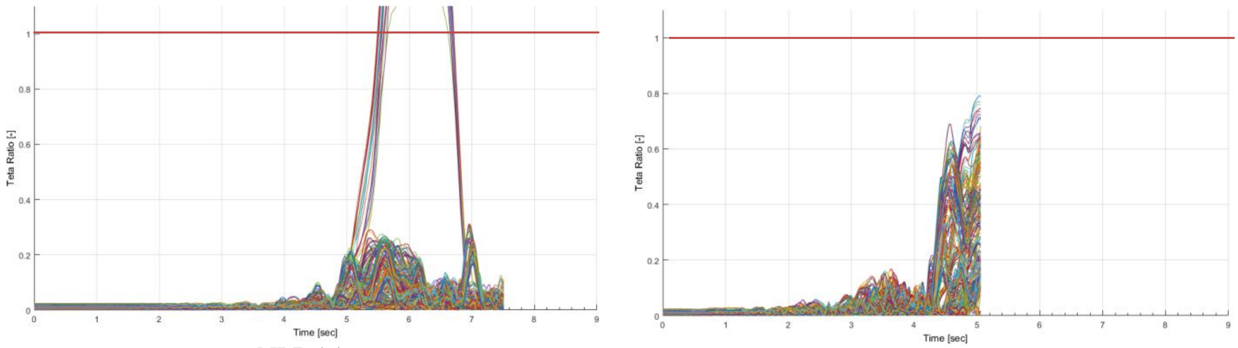
Table 4: Maximum drifts determined by the BF and IF models.

Some results of the checks for the ductile and brittle local failure mechanisms for the BF model are presented in Figures 11 and 13 and for the IF model in Figures 12 and 14. It can be seen 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 infill achieves smaller rotations but higher shear forces in the columns which are induced by the local interaction with the masonry cladding. Both numerical descriptions clearly indicate local failures in a significant number of RC components under the design ground motion.



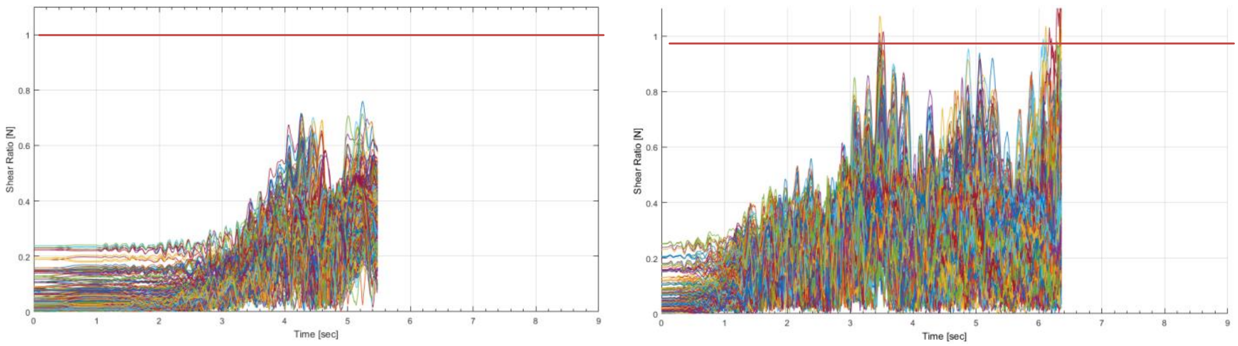
NLDA1 NLDA6

Figure 11: Column chord rotation ratios for the BF model in the NLDA1 and NLDA6 analyses.



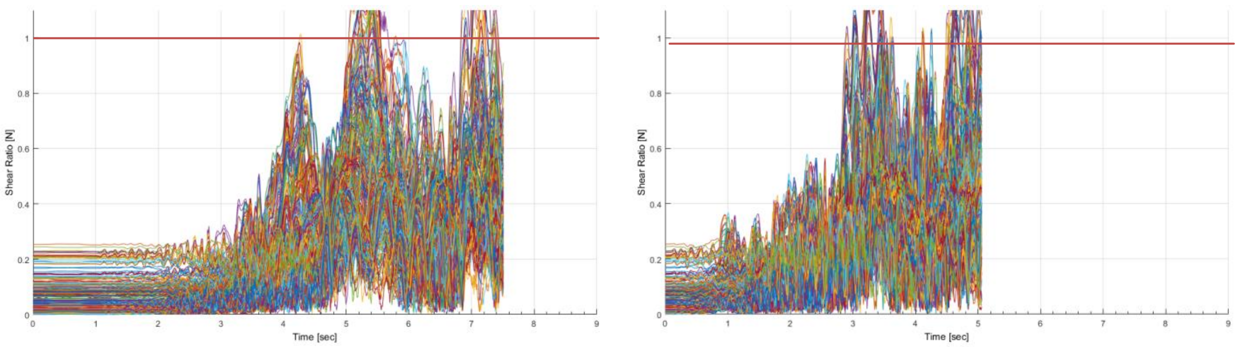
NLDA1 NLDA6

Figure 12: Column chord rotation ratios for the IF model in the NLDA1 and NLDA6 analyses.



NLDA1 NLDA6

Figure 13: Column shear demand/capacity ratio for the BF model in the NLDA1 and NLDA6 analyses.



NLDA1 NLDA6

Figure 14: Column shear demand/capacity ratio for the IF model in the NLDA1 and NLDA6 analyses.

4.2 Retrofitted building

The results obtained in the assessment of the RC building have directed the design of the retrofitting solution. In the design stage, the software 3DMacro [10] with implemented code-based checks, has been used to explore different retrofitting strategies. Traditional and more innovative retrofitting systems have been modelled, analysed and compared. As mentioned before, the chosen solution considers a set of eccentric steel bracings with dissipative shear links along with traditional concentric steel bracings.

Nonlinear dynamic simulations have been carried out using the RIF model in ADAPTIC. The results achieved confirm the effectiveness of the proposed retrofitting strategy, as horizontal displacements are significantly reduced limiting damage in the original RC elements. Figures 15 and 16 show the deformed shapes and the horizontal displacement profiles of the retrofitted building obtained in two nonlinear simulations (e.g. NLDA1 and NLDA 6). It can be seen that there is no longer a concentration of deformations at a specific floor level and the distribution of horizontal displacements in the two planar directions increases monotonically with almost uniform gradient along the height of the building. Notably, the importance of 3D modelling is clearly evident in Figure 16, where a torsional mode is induced due to asymmetric inelastic deformations which cannot be represented using simplified 2D modelling approaches. The different response of the original structure and the retrofitted building can be observed in Figure 17 where the horizontal displacements obtained in the simulations for the two structures are compared. The maximum displacement and drift values are reported in Tables 5 and 6. It can be seen that the maximum values for the retrofitted structure are within acceptable limits, e.g. around 1% maximum drift for the Near Collapse Limit State. It is important to point out that the results for the original building depict the response in the early part of the analysis, since, unlike the simulations of the retrofitted building, the original building simulations stopped well before the end of the time-history analysis because of unrealistically large displacements and local drifts (e.g. 2m drift for NLDA6) which indicate global collapse of the original building. On the other hand, the results for the strengthened structure refer to the response to the end of the dynamic analysis. This confirms that the proposed retrofitting solution enables the strengthened building to survive the design earthquakes, also preventing the development of significant damage in the RC columns potentially leading to progressive collapse of the whole structure or a significant portion of it. Even though progressive collapse is avoided for this retrofitted building, the potential of progressive collapse should be an important consideration when it comes to the application of the proposed retrofitting measures to other existing buildings.

Analysis	IF Model [mm]	RIF Model [mm]
NLDA1	Δ_{max} = ~515	Δ_{max} =~305
NLDA6	Δ_{max} =~2000	Δ_{max} =~280

Table 5: Maxima drifts demands.

Analysis	IF Model [rad]	RIF Model [rad]
NLDA1	$\Delta_{max} = \sim 0.026$	$\Delta_{max} = \sim 0.011$
NLDA6	$\Delta_{max} = \sim 0.6$	$\Delta_{max} = \sim 0.01$

Table 7: Maximum normalised drifts demands.

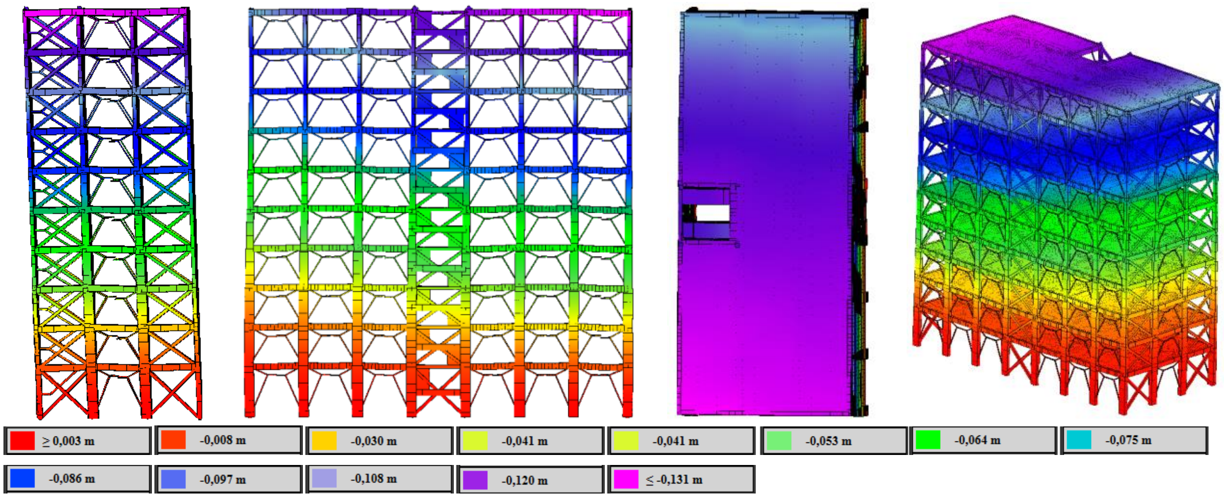


Figure 15: Deformed shape and displacements at the last step of the NLDA1 analysis.

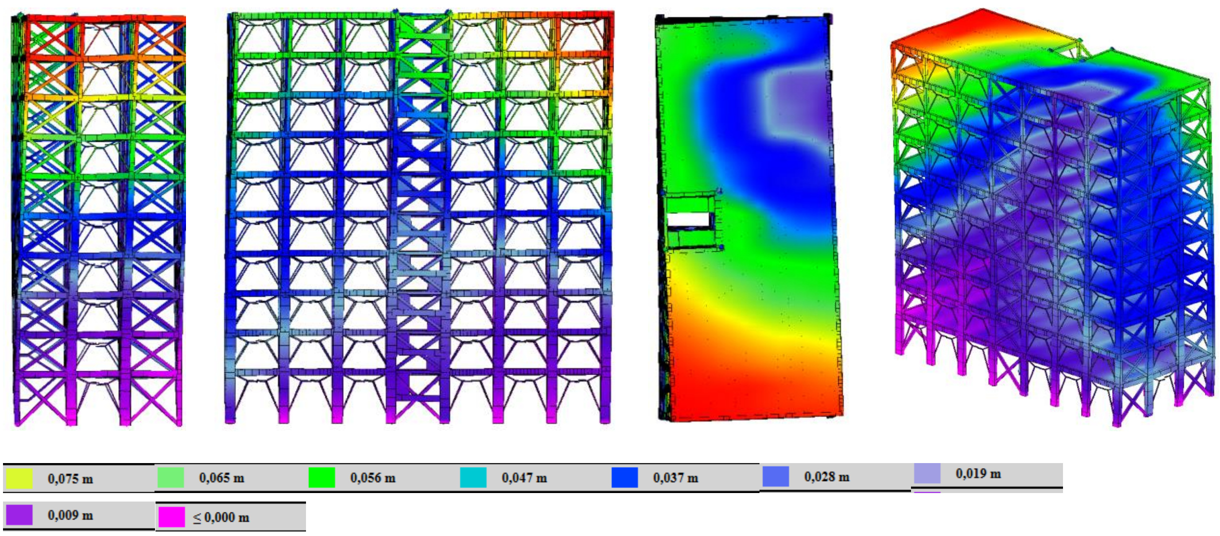
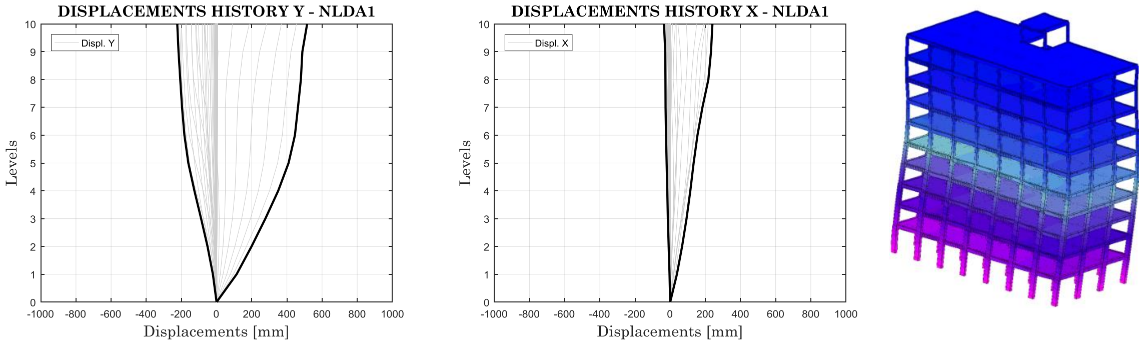
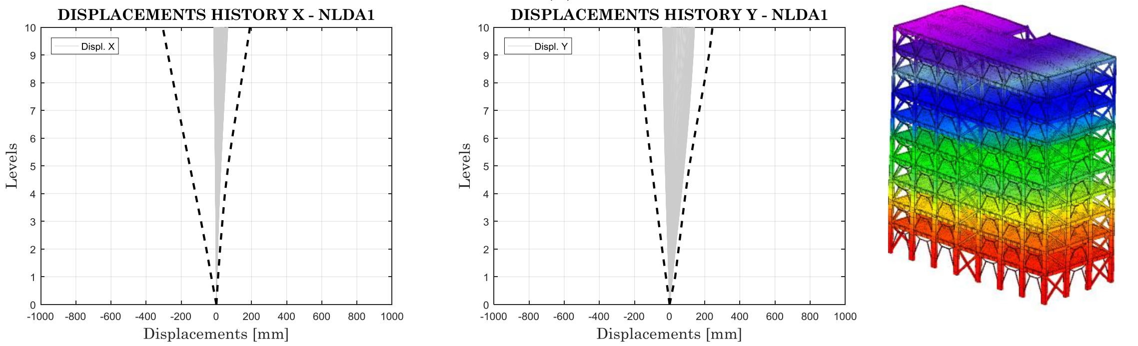


Figure 16: Deformed shape and displacements at the last step of the NLDA6 analysis.

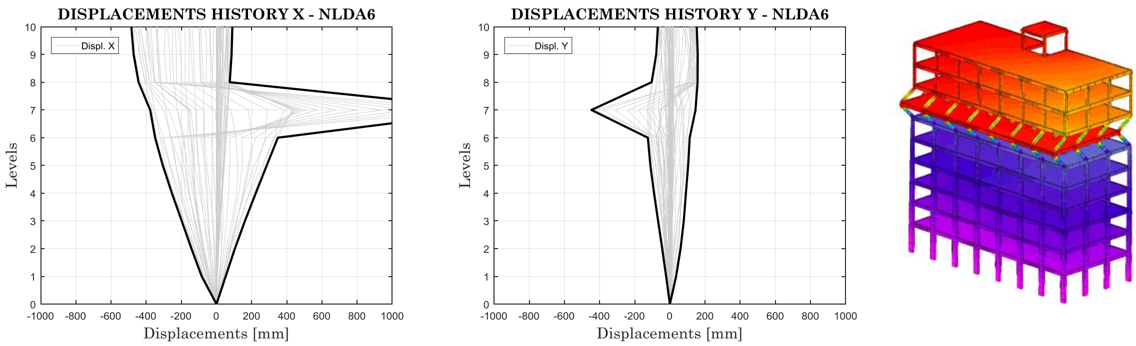


(a)

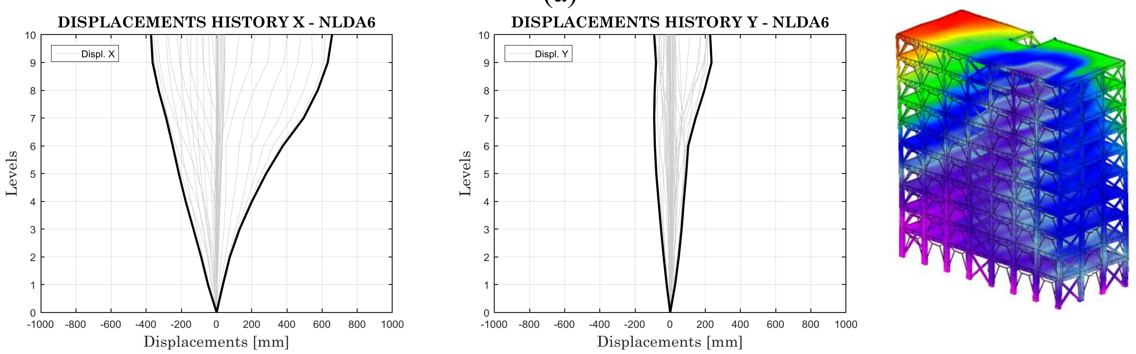


(b)

Figure 17: Displacement history of the BF (a) and RIF (b) models during the NLDA1 analysis.



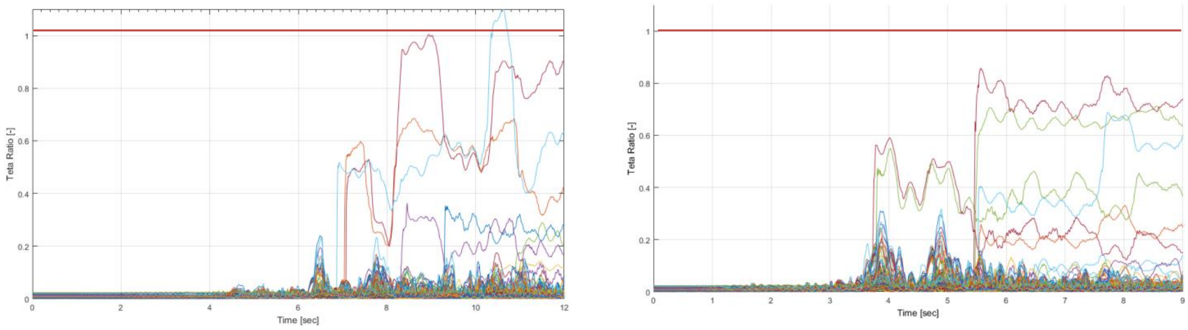
(a)



(b)

Figure 18: Displacement history of the BF (a) and RIF (b) models during the NLDA6 analysis.

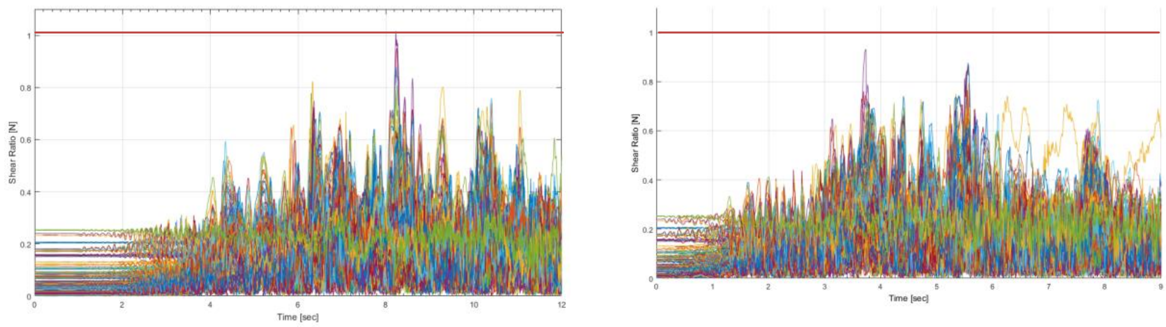
Local checks for all the RC components (e.g. beams and columns) have been conducted considering local brittle and ductile failure. In particular, the demand chord rotations have been obtained from the results of the nonlinear time-history analyses while the capacity values have been calculated based on the ultimate chord rotation equation proposed by Italian Seismic Code. Figure 19 shows the results for all the columns obtained in two different nonlinear dynamic simulations, where it can be observed that only one column presents a chord rotation ratio (e.g. demand/capacity) larger than 1 indicating the need for limited local strengthening.



NLDA1 NLDA6

Figure 19: Chord rotation ratios of all the concrete columns for NLDA1 and NLDA6 analyses.

Similar results have been obtained in the checks for the brittle mechanisms, where the shear demand/capacity ratios calculated according to a circular interaction relationship were smaller than 1 for all the columns (Figure 20). This confirms the effectiveness of the proposed retrofitting solution in protecting the RC building also when subjected to strong earthquakes.



NLDA1 NLDA6

Figure 20: Shear demand/capacity ratio of the concrete columns for NLDA1 and NLDA6 analyses.

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 high-fidelity 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. The results achieved confirm the poor seismic performance of the original structure, where the presence of masonry infill strongly influences the dynamic behavior. The initial findings on the original RC building response have been used to direct the design of effective strengthening solutions utilising traditional and innovative steel bracings. In particular, a novel configuration for eccentric bracings with shear links has been developed and applied to the original structure enhancing its seismic behavior, where lateral drifts, chord rotations and maximum shear forces in original beams and columns are significantly reduced. The findings confirm the applicability of the proposed system as an effective retrofitting solution for typical RC buildings in the Catania region.

REFERENCES

[1] B.A Izzuddin, Nonlinear dynamic analysis of framed structures, Imperial College of London, London, 1991.

[2] GA Jokhio, BA Izzuddin, A dual super-element domain decomposition approach for parallel nonlinear finite element analysis, *International Journal for Computational Methods in Engineering Science and Mechanics*, **16**(3), 188-212. 2015.

[3] ANCE|Catania Project, Final Report 11/1/2017, *Seismic Assessment and Rehabilitation of multi-storey RC Buildings not designed to withstand earthquakes*.

[4] Italian Ministry of Public Works: Law n. 1086, 5/11/1971, *Norme per la disciplina delle opere in conglomerato cementizio normale e precompresso ed a struttura metallica*.

[5] Italian Ministry of Public Works: Ministry Decree, 22/07/1971, *Norme tecniche alle quali devono uniformarsi le costruzioni in conglomerate cementizio armato normale e precompresso ed a struttura metallica*.

[6] B.A. Izzuddin, D. Lloyd Smith, Efficient Nonlinear Analysis of Elasto-Plastic 3D R/C Frames Using Adaptive Techniques, *Computers & Structures*, **78**(4), 549-573, 2000.

[7] BA Izzuddin, XY Tao, AY Elghazouli, Realistic Modelling of Composite and R/C Floor Slabs under Extreme Loading – Part I: Analytical Method, *Journal of Structural Engineering*, ASCE, **130**(12), 1972-1984, 2004.

[8] I Caliò, M Marletta, B Pantò, A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings, *Engineering Structures*, **40**, 327–338, 2012.

[9] Caliò, I., Pantò, B. A macro-element modelling approach of Infilled Frame Structures *Computers & Structures*, **143**, 91-107, 2014.

[10] Caliò, I., Cannizzaro, F., Marletta, M. Pantò, B. 3DMacro: a 3D Computer Program for the Seismic Assessment of Masonry Buildings", Gruppo Sismica s.r.l. Catania, Italy. Release 3.0, November 2012..

[11] I Iervollino, C Galasso and E Cosenza, 2010 REXEL: computer aided record selection for code-based seismic structural analysis, *Bull Earthquake Eng,* **8**(2), 339-362, 2010.