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Seismic Retrofitting of a RC case-study structure: preliminary evaluation of the behaviour of structural and non-structural elements for seismic loss assessment

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Abstract

Italy's long seismic history continues to offer important lessons in preparedness, response, and recovery. However, both past and recent events have revealed the poor seismic performance of many buildings, highlighting the severe consequences of inadequate resilience to seismic hazards. This situation often leads to post-earthquake scenarios where, due to extensive damage, structures are difficult to repair or in need of demolition/reconstruction, causing considerable socio-economic losses. In addition, such damage requires extensive repair operations, leading to large CO_2 emissions, tons of debris, relocation and reconstruction, significantly impacting the environment. In this context, structural safety and environmental sustainability are crucial in reducing the losses associated with both seismic and climate change impacts. Although the need for integrated rehabilitation/retrofit strategies increasingly emerged in recent years, there is still the need for implementation of technologies for combined seismic and energy loss reduction. Within this context, the SMART project aims at developing a methodology to assess integrated seismic and energy losses. To achieve these objectives, an existing case-study Reinforced Concrete (RC) structure, representative of the widespread RC buildings in Italy built prior to modern seismic codes, was selected. Two contextual scenarios are defined to simulate different seismic and thermal response conditions and various retrofitting solutions are compared with the aim of minimizing combined seismic and energy losses. As a preliminary step, this paper presents the design and modelling of the case-study structure and provides an initial assessment of its seismic performance in two

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contextual scenarios (i.e., low and high seismicity). Finite Element (FE) models are developed in SeismoStruct and SAP2000, including the contribution of both structural and non-structural elements. Non-linear static and dynamic analyses are performed and compared to evaluate the seismic performance of the structure, both its original state and after the application of two retrofitted strategies. Subsequently, the Expected Annual Losses (EAL) are assessed and compared to provide a preliminary probabilistic comparison of the results.

Keywords: Estimated Annual Losses, Seismic retrofitting, Reinforced Concrete Structures, Non-Linear Static Analysis, Incremental Dynamic Analysis.

1. Introduction

Earthquakes rank among the most destructive and costly natural disasters worldwide. In earthquake-prone countries like Italy, past events, such as the L'Aquila-2009 (*e.g.,* Ricci et al. (2011)) and Central Italy-2016 earthquakes (*e.g.,* De Luca et al. (2018)) have highlighted widespread structural vulnerabilities and resulted in substantial economic losses, offering critical lessons for improving resilience. Earthquakes not only result in direct physical damage but also in indirect impacts such as business interruption and environmental harm, for both structural and non-structural elements. Repair efforts often involve high CO_2 emissions, large amounts of debris, and land usage, highlighting the need for resilient and sustainable building systems. Structural safety and environmental sustainability are closely linked, and although much research has been done to improve innovative strategies for the reduction of seismic losses (*e.g.,* Sorace et al. (2008), Rizzano et al. (2009), Pampanin et al. (2012), Bencardino et al. (2018)), it is often treated separately from environmental concerns. Therefore, there is an emerging need of integrating damage mitigation with energy efficiency strategies (*e.g.,* Bianchi et al. (2021), Menna et al. (2021)) for achieving greater resilience and long-term resource savings.

Within this context, the SMART (Sustainable Mitigation and Adaptation techniques for loss Reduction of sTructures and non-structural elements) aims at developing a methodology to assess integrated seismic and energy losses for multi-storey Reinforced Concrete (RC) structures aiming at promoting strategies for reducing both seismic and energy-relate economic losses. To meet the objectives, the project will design and numerically model a case-study structure simulating the characteristics of the wide stock of multistorey RC buildings built in Italy before the release of modern Technical Standards (e.g., NTC 2018), as they generally highlight poor seismic performance due to outdated construction practices and the absence of seismic design considerations. Following the design of the case-study structures, the focus will be given to the evaluation and comparison of possible retrofitting design solutions aimed at reducing the integrated seismic and energy losses. Such methodology will be reliable in predicting the probability of exceedance of a multi-performance (seismic and energy) buildings level. SMART will provide a method to facilitate decision-making by using simple design rules enabling innovative structures to address effectively and concurrently the following objectives: *1)* to encourage building owners to invest in seismic retrofitting to meet modern seismic standards; *2)* to implement adaptive strategies for changing environmental conditions, promoting structures' sustainability and energy efficiency; *3)* to develop a methodology for the integrated seismic and energy economic loss reduction.

The present paper presents the design and modelling of the RC case-study structure and provides an initial assessment of its seismic performance. Finite Element (FE) models are developed in SeismoStruct and SAP2000 including both structural and non-structural elements. Subsequently, the structure is retrofitted using two different strategies for structural and non-structural elements. Non-linear static and dynamic analyses are performed to evaluate the seismic performance of the structure, following the Italian guidelines (*i.e.,* NTC 2018 and DM2017). Successively, Incremental Dynamic Analyses (IDAs) (Vamvatsikos et al. (2002)) are performed to account for the record-to-record variability. The results of non-linear static and dynamic analyses are analysed and compared in terms of Peak Ground Acceleration (PGA) capacity. The Expected Annual Losses (EAL) parameter is then calculated to provide a probabilistic comparison of the structure's performance before and after retrofitting. The preliminary outcomes of this paper offer valuable insights into the effectiveness of each retrofitting approach, supporting the development of integrated strategies to reduce both seismic vulnerability and energy inefficiency in existing RC buildings.

2. Case-Study RC Prototype Structure

The case-study RC building is characterised by a plan of dimensions of 20 ×15 meters, a ground floor and five floors in elevation, with a practicable flat roof. Fig. 1 shows the first-floor plan and one elevation views of the building. The design is performed according to the Italian regulations adopted during the 1960s (*i.e.,* Regio Decreto 1939). The structural system comprises beams categorized into dropped and hidden beams, both exhibiting variable cross-sections along their spans. The columns are tapered along the building's vertical elevation. The floor systems are RC slabs combined with hollow clay blocks, with an overall thickness of approximately 20 cm (*i.e.,* 10 cm deep joists and 4 cm concrete topping). The non-structural elements are infill walls composed of double-layer masonry with an overall thickness of 30 cm. The material characterization indicates that the concrete exhibits mechanical properties consistent with the C20/25 strength class, as defined by current standards (NTC 2018). The reinforcing steel corresponds to the AQ50 grade, which was commonly used in Italy during the 1960s.

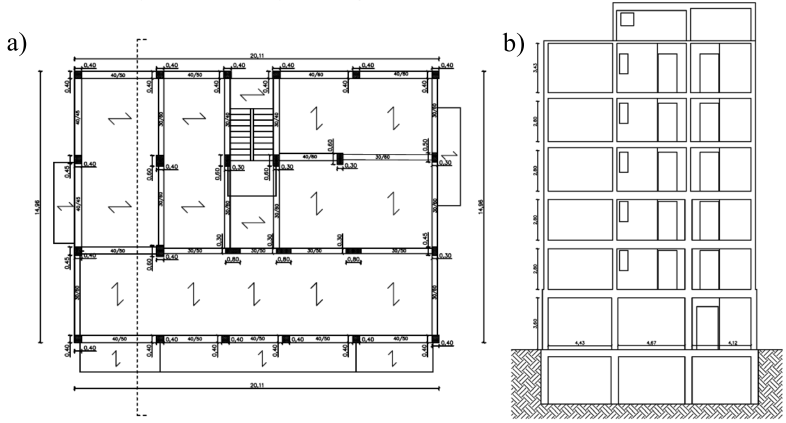

Fig. 1 (a) First floor plan and (b) Elevation view of case-study RC building

Two contextual scenarios were defined to simulate different seismic and thermal response conditions as follows: *i)* two seismic hazard with different levels of seismicity, a low-seismicity (*i.e.,* Salerno) and a high-seismicity area (*i.e.,* Tolmezzo (UD)), *ii)* climatic conditions characterized by two different average annual temperatures. For the sake of brevity, this paper discusses the preliminary seismic assessment only, while the results of the energy performance analysis will not be discussed herein. Fig. 2 shows the elastic response spectra for both the selected seismic zones. In both cases, the soil type considered is B and class II (*i.e.,* $C_U = 1$) is considered for the definition of the Ultimate Limit State (*i.e.,* ULS, $T_R = 475$).

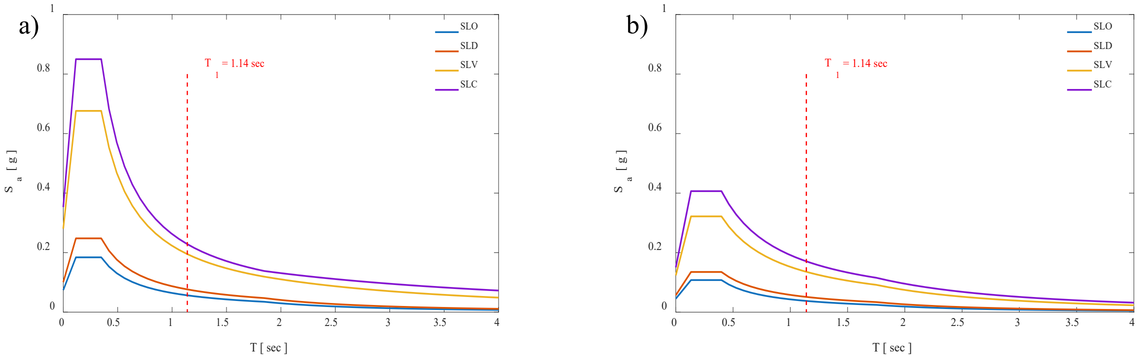

Fig. 2. Elastic Spectra for high (a) and low (b) seismicity

3. Retrofitting strategies

Two retrofitting strategies have been proposed and analysed: *i)* the use of Fiber Reinforced Polymer (FRP) for structural elements, and *ii)* the application of glass-Fiber Reinforced Cementitious Matrix (FRCM) for non-structural elements. Local strengthening with FRP (SikaWrap 300C or 530C) is adopted for shear reinforcement of beams and for shear/confinement enhancement of columns. The design of FRP wraps is guided by the building's seismic safety level (*i.e.,* ζ_E factor in NTC2018) and its risk classification. For non-structural elements, the retrofitting strategy involves applying glass-FRCM on both sides of each infill wall.

4. Finite Element (FE) Models

Fig. 3(a) shows the FE model developed in SeismoStruct (SeismoSoft 2025), representing the bare frame configuration without accounting for masonry infills. Beams and columns are modelled by 3D inelastic force-based elements '*infrmrFBPH*' with plastic hinges, following Scott and Fenves (2006) formulations. Concrete confinement is modelled based on the approach indicated by Mander et al. (1988), with confinement factors calculated from the section and reinforcement layout. Slabs are assumed as infinitely rigid in its plane and rigid diaphragms are implemented using multipoint constraints.

Fig. 3(b) presents the corresponding FE model built in SAP2000NL (CSI 2025), where the non-structural elements are incorporated to simulate the in-plane stiffness contribution of masonry infill panels. Beams and columns are modelled as elastic frame-type elements connected by non-linear link '*NLLink*' elements as plastic hinges at both ends. These links are characterized by a bilinear moment-rotation law identified by the yielding and ultimate response points of the RC members sections, and isotropic hysteretic behaviour. A tri-linear axial force-displacement law was assigned to the compression-only struts adopted as substitute elements for the masonry panels consistently with Bertholdi et al. (1993). The equivalent struts were modeled using '*NLLink*' elements too, with a degrading '*Concrete-type*' hysteretic behaviour. As illustrated in Fig. 3 (c), the trilinear backbone curve is divided into eight segments, (*i.e.,* S1 to S8), representing progressive seismic performance levels of infills, marked by eight values of the Interstorey Drift Ratio (IDR). Additional details are provided in Sorace at al. (2023).

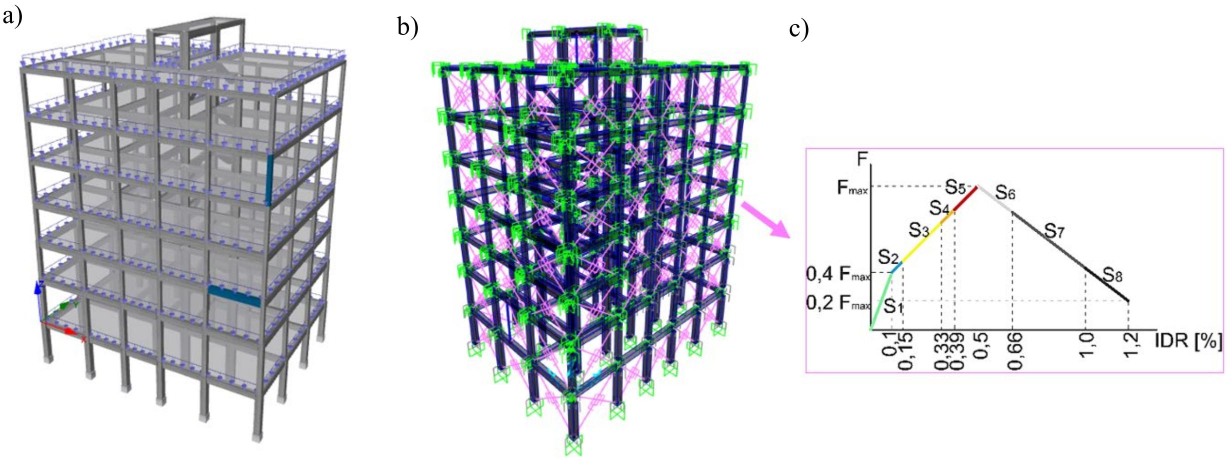

Fig. 3. FE modelling strategies: a) *SeismoStruct* model for structural elements; b) SAP2000NL model including non-structural elements; c) Backbone curve assumed for the analysis of infills

5. Pushover analysis

Non-linear static analyses are performed with a distribution of lateral forces applied proportionally to the storeys (for buildings with less than 75% of participant seismic masses according to NTC 2018). Fig. 4 (a) shows the results of non-linear static analyses in terms of base shear (V_{Base}) *vs* top storey displacement. In addition, the equivalent system single degree of freedom (SDOF) capacity curve (*i.e.,* evaluated with N2 method following NTC 2018), the bi-linear capacity curve and the system at multiple degrees of freedom (MDOF) capacity curve are represented to simplify the evaluation of the seismic demand displacement. Given the displacement demand, it is possible to evaluate the EAL starting from the PGA capacity of the structure ($PGAc$), comparing it with the PGA demand ($PGAd$), as follows:

$$\lambda_{LS} = \frac{1}{T_{rC}}\ ;\ T_{rC} = T_{rD}\left(\frac{PGAc}{PGAd}\right)^{\eta} \tag{1}$$

where λ_{LS} is the Mean Annual Frequency (MAF), T_{rC} is return period related to the capacity of the structure, T_{rD} is the return period as stated in NTC2018. It is highlighted that the value of PGA capacity is estimated starting from the weakest fragile (shear)\ductile (chord rotation) mechanisms on beams and columns, consistently with the NTC 2018 provisions. Fig. 4 (b) shows the Restore Cost (CR%) *vs* λ (MAF), evaluated for the low seismicity. The area under the curve is the EAL, allowing the assignment of a seismic class from A+ to G. For the low-seismic zone, the case-study structure is classified as E with an EAL of 3.54%. Conversely, for the high-seismic zone, the case-study structure is classified as F with an EAL of 5.11%.

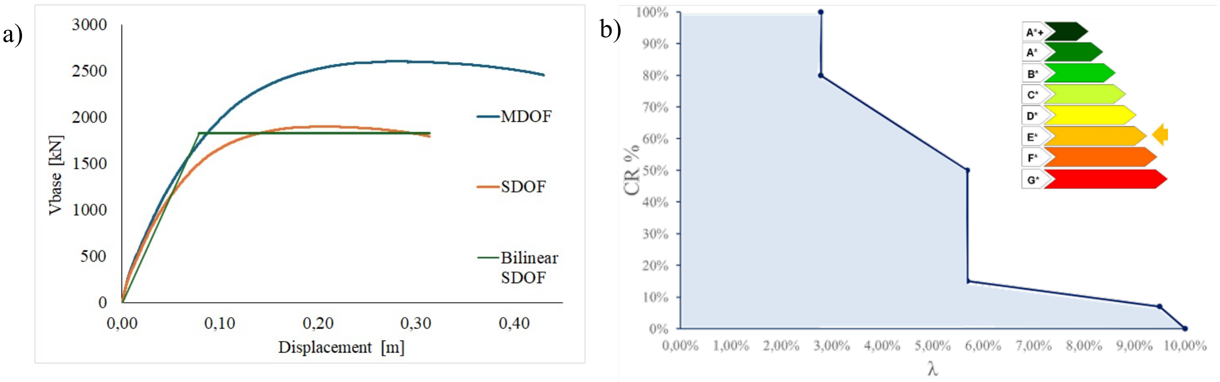

Fig. 4 Pushover analysis results: (a) Pushover curve; (b) EAL estimation for low seismicity

Fig. 5 (a) shows the Restore Cost (CR%) *vs* λ (MAF), considering various retrofitting strategies with FRP wraps aimed at progressively increasing the ζ_E parameter from 25% to 100%, in line with seismic retrofitting standards. Each curve corresponds to a different ζ_E level (25%, 50%, 75%, and 100%). As expected, increasing ζ_E leads to a reduction of the EAL, confirming that the retrofit strategies effectively decrease the seismic risk. Based on these results, the retrofit strategy corresponding to $\zeta_E = 50\%$ has been selected for comparative purposes. The resulting damage scenario is illustrated in Fig. 5 (b).

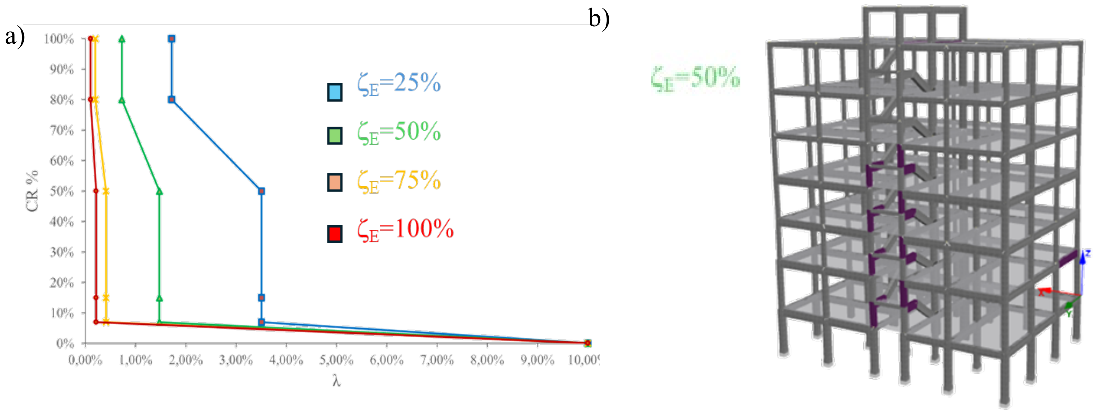

Fig. 5. (a) EAL considering various retrofitting levels with increasing of ζ_E parameter; (b) Damage scenario corresponding to $\zeta_E = 50\%$

6. Incremental Dynamic Analysis (IDA)

6.1 Analysis for structural elements

IDAs (Vamvatsikos et al. 2002) are performed by considering a suite of 30 ground motion records, selected from the ITALIAN Database (Iervolino et al. 2010) and scaled to increasing Intensity Measure (IM) values to cover the range from elastic to non-linear seismic response. The spectral acceleration corresponding to the first vibration mode ($Sa(T_1)$) is used as IM where $T_1 = 1.14$ sec. The records have been selected such that their mean elastic spectrum is kept between 90% and 130% of the design spectrum at the SLV (Fig. 2).

Fig. 6 (a) compares the results of the IDAs in terms of PGA capacity ($PGAc$) for the structure as built *vs* the retrofitted structure with $\zeta_E = 50\%$, for each individual record (numbered 1–30). The average value is then calculated among the 30 values. The black dashed line shows the average $PGAc$ value for the retrofitted structure, equal to 0.080. The red dashed line represents the previous value, which is 0.044 before retrofitting. As it is possible to observe, the results show an increase in the average $PGAc$ after retrofitting, demonstrating enhanced seismic performance, as expected. Subsequently, using the formula reported in Eq. (1), the EAL has been calculated from the average value of all PGA capacities as in Fig. 6 (a). Fig. 6 (b) displays the corresponding Restore Cost (CR%) vs λ (MAF) for the structure as built *vs* the retrofitted structure for the low-seismic zone. The results show that the EAL reduced from 3.54% to 0.97%, indicating that the retrofitting method significantly improved the resilience of the structure.

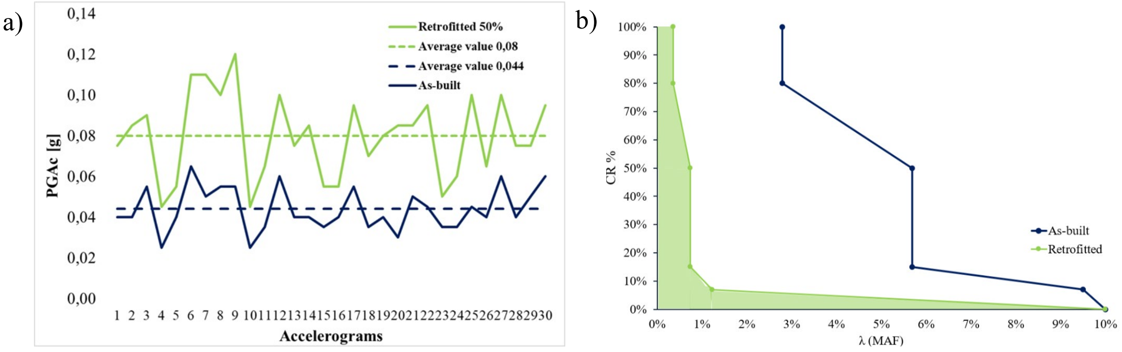

Fig. 6. Comparison of results of the structure before/after retrofitting in low seismicity with $\zeta_E = 50\%$: (a) PGA capacity; (b) EAL comparison

Additional insights can be made regarding the comparison between the results of non-linear static and IDAs. Fig. 7 presents a comparison of $PGAc$ obtained from the results of non-linear static and IDAs for three structural configurations: the as-built structure and two retrofitted cases using FRP wraps designed for damage thresholds of $\zeta_E = 50\%$ and 100%. The bar chart shows that for the as-built structure, the PGA capacity from both IDA and pushover analysis are closely aligned, indicating consistent results between the two methods. A similar level of agreement is observed for the structure retrofitted with FRP designed for $\zeta_E = 50\%$. Conversely, when the structure is retrofitted with a higher reinforcement level ($\zeta_E = 100\%$), the results begin to diverge significantly, suggesting that the static method may overestimate performance for heavily retrofitted structures.

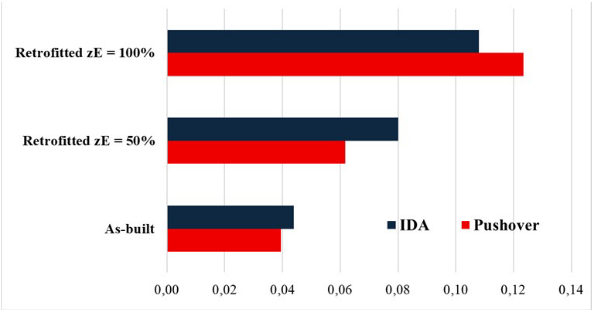

Fig. 7. PGA values comparison between ID Analysis and Pushover analysis

6.2 Analysis for non-structural elements

The seismic performance of the infills was assessed via IDAs, by assuming the full set of seismic hazard levels provided for by the NTC2018, identified by 81%, 63%, 50%, 39%, 22%, 10%, 5% and 2% probabilities (p_{VR}) of being exceeded over the reference structural lifespan, V_R, of the building. For both high- and low-seismicity sites, as well as for all nine hazard levels, seven groups of three accelerograms each were applied as input to the time-history analyses. The artificial ground motions were generated from the elastic pseudo-acceleration response spectra at linear viscous damping ratio of 0.05. For each group, one accelerogram was applied in X direction, one in Y and one in Z. For the sake of brevity, the results of the IDA analysis are summarized below only for the action with p_{VR}/V_R equal to 63% and 10%, corresponding to the Serviceability Design Earthquake (SDE) and Basic Design Earthquake (BDE) levels of the Italian Standards, respectively.

For the low-seismicity site, at the SDE the response of the structure is elastic, and the peak IDR values are constrained within the S4 branch of the backbone curve of infills, identifying very low damage conditions. At the BDE, the most stressed infills belonging to the first and second storey reach the S7 branch, assessing irreparable damage conditions in 8.7% of the total of panels. Furthermore, 1.5% of structural members achieve plastic response conditions, but none of them collapse. Concerning the high-seismicity site, a full elastic structural response is surveyed at the SDE in this case too, with maximum IDR values below 0.5%, i.e. the NTC2018 IO-related threshold. At the BDE, several beams and columns achieve collapse conditions. In particular, the number of plastic hinges formed in the columns determines a soft-storey mechanism on the first and second storeys.

Fig. 8 (a) shows the infills of the as-built structure by the color maps corresponding to the chromatic scale used for the backbone curve in Fig. 3 (c). As highlighted by the results, the response of over 20% of infills is situated in the S8 branch, and 34.8% in the S7 branch, for a total of 57.4% of panels reaching an irreparable damage state. Conversely, Fig. 8 (b) shows the color maps of the corresponding retrofitted structure with glass-FRCM strengthening intervention on both sides of each infill. According to Akhoundi et al. (2018), this solution was simulated by increasing the resisting lateral force values at the three characteristic points of the backbone curve, for the same IDR values. The results show that no black-filled panel is present, and only 19% of infills is in irreparable condition (dark grey-filled elements). Notable benefits are observed also for structural members, whose number in plastic conditions is significantly reduced, with only a few first-storey columns reaching collapse.

Fig. 8. Colour maps assessing the response of infills at the BDE: a) as-built; b) after FCRM-based retrofit

7. Conclusions

The present paper presents the design and modelling of a Reinforced Concrete (RC) case-study structure representative of the wide stock of multistorey RC buildings built in Italy before the release of modern seismic codes. Finite Element (FE) models are developed in SeismoStruct and SAP2000 including both structural and non-structural elements.

Subsequently, the structure is retrofitted using two different strategies for structural (*i.e.,* Fiber Reinforced Polymer (FRP)) and non-structural elements (*i.e.,* glass-Fiber Reinforced Cementitious Matrix (FRCM)). Non-linear static and dynamic analyses are performed to evaluate the seismic performance of the structure, following the Italian guidelines. Successively, Incremental Dynamic Analyses (IDAs) are performed to account for the record-to-record variability. The results of non-linear static and dynamic analyses are analysed and compared in terms of Peak Ground Acceleration (PGA) capacity. The Expected Annual Losses (EAL) parameter is then calculated to provide a probabilistic comparison of the structure's performance before and after retrofitting. The preliminary conclusions can be drawn as follows:

- The introduction of the FRP with ζ_E = 50% for structural elements allows a reduction of the EAL from 3.54% to 0.97%, significantly enhancing the structure's resilience;
- The use of the glass-FRCM decreases the percentage of panels reaching an irreparable damage state from 57.4% to 19%. It also benefits structural members by greatly reducing plastic deformations.
- The comparison between non-linear static and dynamic analyses leads to consistent results, indicating a good agreement between the two methods in estimating the PGA capacity.

References

Akhoundi, F., Vasconcelos, G., Lourenço, P. B., Silva, L. M., Cunha, F., Fangueiro R., 2018. In-plane behavior of cavity masonry infills and strengthening with textile reinforced mortar. Engineering Structures 156, 145–160.

Bencardino F, Carloni C, Condello A, Focacci F, Napoli A, Realfonzo R, Flexural behaviour of RC members strengthened with FRCM: State-of-the-art and predictive formulas, Composites Part B: Engineering, 148, 2018, 132 -148, https://doi.org/10.1016/j.compositesb.2018.04.051

Bertholdi, S. H., Decanini, L. D., Gavarini, C., 1993. Telai tamponati soggetti ad azione sismica, un modello semplificato: confronto sperimentale e numerico. In: Borri ,A., Parducci, A. (eds.), Proceedings of the VI Italian National Conference on Earthquake Engineering, Vol. 2, pp. 815–824 (in Italian).

Bianchi S, Ciurlanti J, Overend M, Pampanin S, A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings, Engineering Structures, 269, 2022,114852, https://doi.org/10.1016/j.engstruct.2022.114852

CSI, 2025. SAP2000NL. Theoretical and user's manual. Release 26.01. Computers & Structures Inc., Berkeley, CA, USA.

De Luca, F., Woods, G.E.D., Galasso, C. et al. RC infilled building performance against the evidence of the 2016 EEFIT Central Italy post-earthquake reconnaissance mission: empirical fragilities and comparison with the FAST method. Bull Earthquake Eng 16, 2943–2969 (2018). https://doi.org/10.1007/s10518-017-0289-1

Iervolino, I., Galasso, C., Cosenza, E., 2010, REXEL: Computer aided record selection for code-based seismic structural analysis, Bullettin of Earthquake Engineering, no. 8, pp. 339-362

Mander, J. B., Priestley, M. J. N., & Park, R. (1988). Theoretical stress–strain model for confined concrete. Journal of Structural Engineering, 114(8), 1804–1826. https://doi.org/10.1061/(ASCE)0733-9445(1988)114:8(1804)

Ministero dell'Istruzione, dell'Università e della Ricerca. Decreto Ministeriale n. 58 – 28/02/2017

Menna C, Del Vecchio C, Di Ludovico M, Mauro GM, Ascione F, Prota A, Conceptual design of integrated seismic and energy retrofit interventions, Journal of Building Engineering, 38, 2021,102190, https://doi.org/10.1016/j.jobe.2021.102190

NTC2018—Ministry of Infrastructure Decree, DM 17 gennaio 2018: Aggiornamento delle Norme tecniche per le costruzioni, Suppl. or. n.30 alla G.U. n.29 del 4/2/2008, 2018

Pampanin S. Reality-check and Renewed challenges in Earthquake Engineering:Implementing low-damage structural Systems – from theory to practice. Bull NZ Soc Earthq Eng 2012;45(4):137–60. https://doi.org/10.5459/bnzsee.45.4.137-160.

Regio Decreto 16 novembre 1939, n. 2229. Norme per l'esecuzione delle opere in conglomerato cementizio armato. Gazzetta Ufficiale del Regno d'Italia, n. 92, 18 aprile 1940.

Ricci, P., De Luca, F. & Verderame, G.M. 6th April 2009 L'Aquila earthquake, Italy: reinforced concrete building performance. Bull Earthquake Eng 9, 285–305 (2011). https://doi.org/10.1007/s10518-010-9204-8

Rizzano G, Tolone I, Seismic Assessment of Existing RC Frames: Probabilistic Approach, Journal of Structural Engineering, 2009, 135 (7): 836-852

Seismosoft 2025 - SeismoStruct - A computer program for static and dynamic nonlinear analysis of framed structures

Scott, M. H., Fenves, G. L. (2006). Plastic hinge integration methods for force-based beam–column elements. Journal of Structural Engineering, 132(2), 244–252. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:2(244)

Sorace, S., Terenzi, G., 2008. Seismic protection of frame structures by fluid viscous damped braces. ASCE Journal of Structural Engineering 134, 45–55

Sorace, S., Costoli, I., Terenzi, G., 2023. Seismic assessment and dissipative bracing retrofit-based protection of infills and partitions in RC structures. Engineering Structures 281, 115781.

Vamvatsikos, D., Cornell, C.A., 2002. Incremental Dynamic Analysis, Earthquake Engineering and Structural Dynamics, no. 3, pp. 491-514