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FRAGILITY CURVES FOR RETROFITTED RC BUILDINGS DESIGNED ACCORDING TO OBSOLETE SEISMIC CODES VIA STICK MODEL

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Abstract

Existing Reinforced Concrete (RC) buildings, designed to withstand only gravity loads or according to outdated code provisions, are particularly vulnerable to damage during strong earthquakes. To improve their seismic performance, preventive retrofit strategies can be implemented at both local and global levels, significantly reducing structural vulnerability. In this context, analytical fragility curves for specific building classes in both as-built and retrofitted configurations are essential tools for quantifying the benefits of these strategies on a large scale.
The generation of comprehensive fragility curves, however, requires a robust probabilistic framework that accounts for key uncertainties, including inter-building and intra-building variability, record-to-record differences, and damage level definitions. Addressing these uncertainties within a fully probabilistic framework introduces significant computational challenges, necessitating simplified yet reliable analytical models to assess seismic performance effectively.
To this end, the authors have proposed a simplified analytical model, STICK, which efficiently simulates the behavior of masonry-infilled RC buildings. The model captures key features of existing buildings, explicitly accounting for typical failure modes of non-conforming RC elements and brittle failures induced by local infill-frame interaction, in both as-built and ret-refitted configurations [1]. STICK has recently enabled the generation of analytical fragility curves for as-built building typologies within a cloud-based probabilistic framework [2].
The present work extends these findings by incorporating both local and global retrofit strategies. The effectiveness of retrofitting is evaluated in terms of vulnerability reduction across increasing damage states, demonstrating the role of different retrofit strategies in enhancing seismic resilience at a regional scale.

Keywords: Reduced-order model, RC frame, infills, shear-type.

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1 INTRODUCTION

Earthquakes are among the most devastating natural disasters, often causing significant losses even at moderate intensities. To mitigate the possible consequences of earthquakes, the adoption of retrofit intervention is generally preferred to demolition and reconstruction due to economic and environmental considerations, especially in Mediterranean regions.

Various retrofitting techniques exist, ranging from highly invasive methods (e.g., such as the addition of shear walls, external exoskeletons, or buckling-restrained braces) to less intrusive approaches like the adoption fiber-reinforced polymer (FRP) wrapping, or reinforced concrete (RC) jacketing. While invasive methods often require partial demolition, prolonged downtime, and architectural modifications, local retrofit interventions such as FRP wrapping or RC jacketing are frequently adopted due to their ability to improve both strength and ductility with minimal disruption ([3], [4]).

To evaluate the effectiveness of retrofitting strategies at a large scale, fragility models are essential for assessing seismic performance improvements. While previous studies have developed fragility curves for existing infilled RC buildings in as-built configuration (e.g., [5], [6]), systematic studies quantifying the improvements due to the implementation of retrofitting techniques remain limited. Most research focuses on single or limited sets of case-study buildings, often applying simplified retrofit design criteria (e.g., [7], [8]).

Recently, Gaetani d'Aragona et al. [2] generated analytical damage fragility curves for different masonry-infilled RC building typologies representative of the Italian building stock. Specifically, a probabilistic framework was applied to account and propagate main aleatory and epistemic uncertainties related to the building capacity, the seismic demand, and the definition of damage states [9]. To enhance the computational efficiency, the authors employed a reduced-order model, named STICK [10], adapted [1] to capture typical structural and non-structural deficiencies in non-conforming structure. A total of 32 building classes was considered. These classes were identified based on construction years ranging from 1950s to 1980s, two possible design levels (i.e., gravity-load and outdated seismic design), number of stories ranging from 2 to 8, and different masonry infill consistency (weak, medium, strong) in order to cover the majority of the existing Italian building stock.

Beyond modeling as-built conditions, the STICK model has the potentiality of accounting non only for the behavior of buildings in as-built configuration, but also for the possible implementation of both local and global retrofit interventions. Indeed, in Gaetani d'Aragona a calibration procedure [1] was presented to account for the implementation of two among the most common retrofitting strategies: (1) local strengthening using carbon-FRP wrapping, to prevent brittle failures in relevant structural members, and (2) a global strategy consisting of the RC jacketing of the perimeter columns.

This paper builds upon previous studies by introducing the impact of two retrofit strategies on damage fragility curves for a specific building class consisting of six-storey buildings constructed in the 1980s according to outdated seismic code provisions. The findings highlight the effectiveness of these strategies across distinct damage states, offering valuable insights into mitigation strategies that can be implemented at the community level.

2 PROBABILISTIC FRAMEWORK

A comprehensive probabilistic framework (Figure 1) is developed to derive damage fragility curves for infilled RC building typologies, both in their as-built and retrofitted configurations, while accounting for key aleatory and epistemic uncertainties. The proposed methodology systematically captures and propagates uncertainties related to variations between buildings, intra-building variability, capacity models, and the definition of damage thresholds in a straightforward yet rigorous manner. The assessment employs a fully stochastic approach based on Monte Carlo simulations, enabling uncertainty propagation through repeated sampling of input variables. To enhance computational efficiency, a stratified Latin Hypercube Sampling (LHS) technique with a median-based sampling scheme is implemented. This approach incorporates predefined probability distributions while maintaining correlations among variables through the simulated annealing technique, ensuring a robust and reliable fragility assessment.

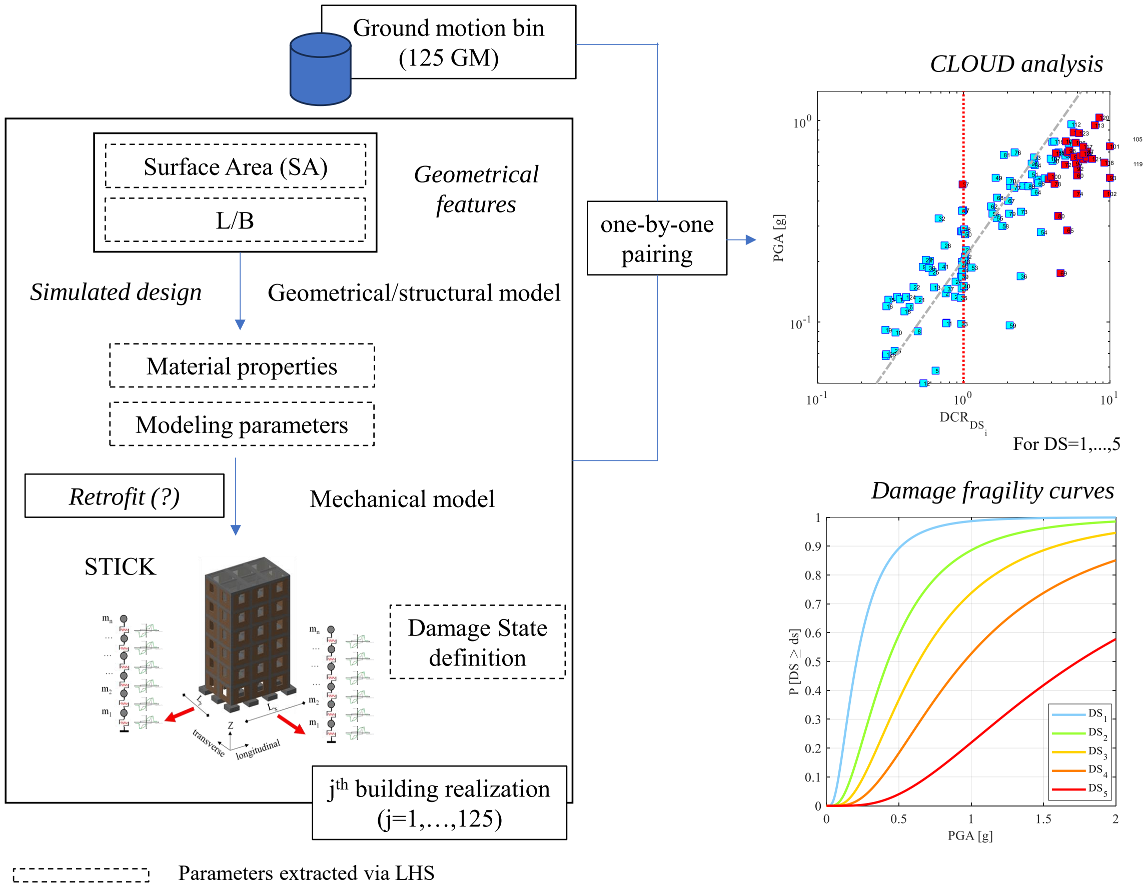

Figure 1: Probabilistic framework for the generation of damage fragility curves for a building class

The seismic response of each single building class - defined by the (a) number of storeys (a) age of construction, (b) design level, and (c) infill consistency - is analyzed by generating a virtual set of "n" building models. These models are generated through random variable extraction based on assigned statistical distributions, ensuring representation of geometric and structural variability within each class. The initial step involves defining geometric-typological parameters (e.g., surface area, shape ratio, opening percentage, and mass distribution), followed by the creation of corresponding geometric/structural models. Further variability in material properties and modeling parameters is accounted for through additional stochastic sampling, ultimately resulting in the generation of analytical STICK models for structural analysis. In case of the implementation of structural retrofit, a simplified design procedure is employed to dimensioning the retrofit intervention and applied during the generation of the analytical STICK model. For each building class, a total of n=125 building models is generated.

Each model is then paired with an unscaled seismic record from a selected dataset, ensuring a one-to-one match between building realizations and ground motion inputs. In this study, 125 model-realization-to-record pairings are considered. Seismic performance is evaluated via nonlinear time-history analyses using the STICK model, capturing structural responses in terms of relevant engineering demand parameters. These parameters are then compared against structural capacities both at the component-level and at the system-level to compute Demand-to-Capacity Ratios (DCRs), which indicate the exceedance of specific Damage States (DS). The DS definitions, aligned with the EMS-98 damage scale, incorporate an additional layer of uncertainty through randomized threshold extractions.

Finally, the simulation outputs are statistically processed using cloud analysis techniques to derive fragility curves for each damage state. This approach enables a robust estimation of the probability of exceeding various damage levels under given seismic intensities, contributing to an enhanced understanding of the seismic vulnerability of infilled RC buildings. For further details, the reader is referred to the original work by the authors [2].

2.1 Stick model

A reduced-order model introduced for the rapid assessment of engineering demand parameters The Stick model is a Multi-Degree-of-Freedom (MDOF) system that represents structural behavior at the story level, with lumped masses connected by nonlinear springs. It simulates building response along principal directions and can be applied in 3D analyses if torsional effects are negligible. The model core lies in defining the envelope of nonlinear springs through backbone curves and hysteretic rules (sketched in Figure 2).

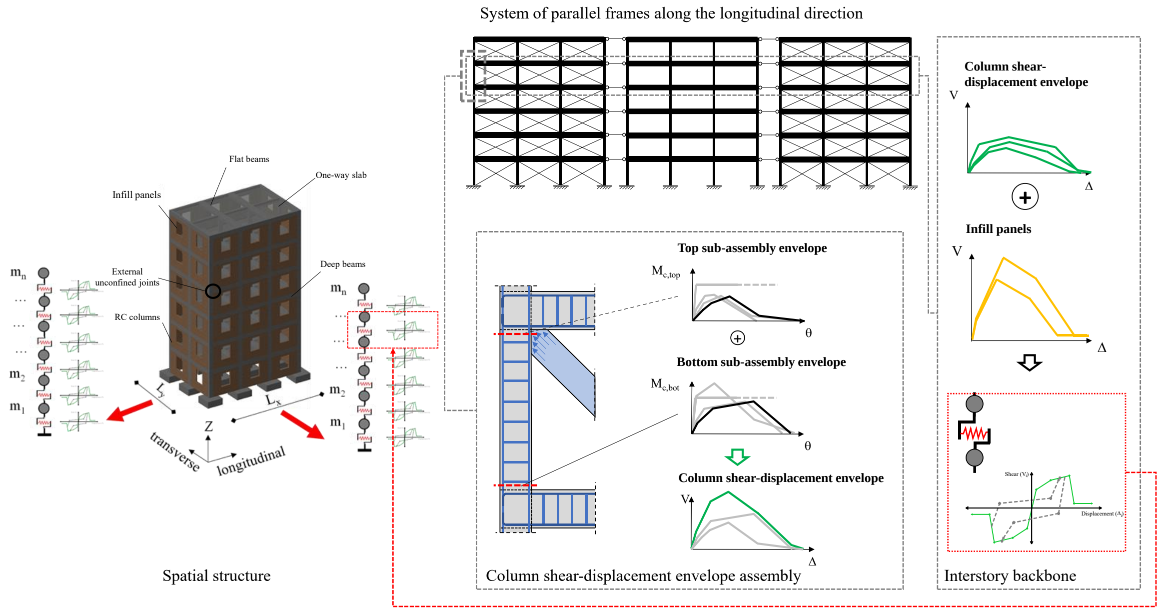

Figure 2: Calibration of the STICK model spring envelope (adapted from [1])

Initially developed for gravity-load-designed infilled RC frames [10], it allows the generation of interstory backbone curves based on key parameters like story number, infill opening percentage, and plan dimensions. It has been validated at both individual building and large-scale levels ([11], [12]). More recently, Gaetani d'Aragona et al. [1] introduced a MATLAB®-based calibration procedure assuming shear-type behavior, and accounting for main structural (columns, beams, joints) and non-structural (infill panels) interactions both at the local and global. The model also integrates retrofit strategies, including FRP wrapping of RC members and RC jacketing of perimeter columns.

2.2 Uncertainty quantification

The generation of analytical fragility curves considers three primary sources of uncertainty: seismic demand, building capacity, and damage state definitions. Unlike conventional approaches that often estimate only one or two uncertainty sources while approximating the others through dispersion inflation, this study explicitly quantifies all three sources. Geometric, typological, material, and modeling uncertainties are explicitly simulated through predefined probabilities, and the uncertainty in damage state threshold definition is accounted too. Finally, record-to-record variability is incorporated via nonlinear time-history analyses using a suite of 125 ground motion pairs. In the following, main sources or uncertainty are clarified:

Geometric and typological features
Building typologies are defined based on key characteristics such as the number of stories, construction era, and infill panel properties, which are treated as deterministic. Other parameters, including surface area, in-plan ratio, and infill opening percentage, are considered random variables to account for inter-building variability.

Material properties
Material properties vary based on construction period and design standards. Concrete and steel classes are assigned accordingly, with compressive strength and yielding strength modeled as random variables following probability distributions from literature. For masonry infill panels, mechanical parameters such as shear strength, shear modulus, and Young Modulus are assumed as random variables depending on the infill consistency.

Modeling parameter
Modeling uncertainties primarily affect nonlinear behavior characterization of columns, beam-column joints, and infill panels. For RC columns, key parameters depend on reinforcement type and failure mode. Ductility parameters (e.g., plastic rotations) follow literature distributions depending on the type of reinforcement bars (i.e., smooth and deformed). Shear failure is considered by comparing shear strength with demand, properly modifying the ductile envelope to account for the development of brittle failure. Beam-column joint behavior is defined by envelope models with strength capacity treated as a random variable depending on the position of the joint in the frame (e.g., exterior, interior, knee), the type of reinforcement bars. Infill panel backbone parameters (e.g., cracking strength, peak strength, stiffness values) are also probabilitically characterized.

Damage threshold
Damage states thresholds are defined in terms of suitable engineering demand parameters both at the member and the system-level according to the EMS98 damage scale [13]. DS1-DS3 are defined at the member-level for both structural and non-structural members, while DS5 is defined represents global collapse, either Side-Sway Collapse or Gravity-Load Collapse defined according to Gaetani d'Aragona et al. [14].

Record-to-record
To account for the record-to-record variability, a bin consisting of 125 ground motion pairs, selected by Manfredi et al. [15] to ensure site-independent fragility curves and cover a broad intensity range, has been adopted.

3 FRAGILITY CURVES FOR AS-BUILT AND RETROFITTED BUILDING

For the selected building class corresponding to 6-storey buildings with Medium infill consistency designed in the 1980s according to obsolete code provisions, a set of nonlinear time-history analysis is performed by randomly coupling each building realization with a ground motion record. Considering a one-to-one coupling, a cloud of points D={($PGA_{max,i}$, $DCR_{DS,i}$), i=1:125} is obtained for different damage states (DS=1,…,4). Where PGA_{max} is the maximum PGA along the two main directions, and DCR_{DS} is the critical Demand to Capacity Ratio. It represents the maximum ratio between the recorded IDR and the threshold IDR corresponding to the selected DS. For each DS it is calculated as the maximum considering each story and direction. The Damage State DS_5 is managed separately as considered as system-level collapse (C). By performing a linear interpolation in the log-log space for the simulations for which collapse not occurred and using the Total Probability theorem to include collapse cases, the fragility curve can be obtained for DSs ranging from 1 to 4 considering lognormal distributions according to the procedure outlined in Jalayer et al. [16] (the C condition is represented by a logit distribution). The statistical elaboration of data points allowed the generation of damage fragility curves for the case-study building (Figure 3). The fragilities are reported for the as-built configuration (Figure 3(a)), considering RC members retrofitted with FRP and SRP stripes to avoid the development of brittle failures in RC columns and beam-column joints (Figure 3(b)), and including the effect of retrofit at the global level via the RC jacketing of perimeter frame columns. The latter retrofit solution includes two possible alternatives. Since the retrofit intervention is designed according to a performance-based criterion (i.e., for a seismic intensity corresponding to Damage Limit State defined consistently with current Italian seismic design regulations [17], the maximum lateral deformation should be limited to a threshold value), two possible thresholds are considered. The first is according to the Italian seismic code (i.e., 5‰, Figure 3(c)), while the second is more restrictive (i.e., 2‰, Figure 3(d)).

It is important to note that seismically designed buildings generally exhibit lower vulnerability compared to those designed solely for gravity loads. In Gaetani d'Aragona et al. [2] the ground motion bin selected in Manfredi et al. [15] was deemed not sufficient to explore the full spectrum of building responses from lower to higher damage states, especially for low-rise buildings. Thus, to address this limitation and minimize the risk of extrapolation, in addition to the original set of 125 ground motions, a second set consisting of the same 125 ground motions, scaled twice, was considered. In this study, due to the presence of retrofit interventions, a third set of ground motions, scaled three times, was included to comprehensively investigate the nonlinear response of the buildings.

From Figure 3, it can be observed that FRP wrapping has minimal impact on damage states DS1 to DS2. This outcome aligns with expectations, as FRP wrapping does not significantly alter the lateral stiffness of the frame but primarily enhances the ultimate deformation capacity of reinforced concrete (RC) members. Since DS1 and DS2 are primarily governed by damage to infill walls, their behavior remains largely unchanged. The effect of FRP wrapping becomes slightly more noticeable in DS3, where both structural and non-structural components contribute to damage accumulation. However, the intervention is only effective in cases where shear failure of columns was a critical factor. In most cases, once shear failure was mitigated, the next limiting factor was damage to infill panels, which occurred shortly thereafter in terms of peak ground acceleration (PGA). The most significant improvements were observed at higher damage states (DS4 and DS5), where the PGA capacity increased by 48% and 49%, respectively.

For RC jacketing designed with a 5‰ deformation threshold, most of the 125 building realization indicated that the retrofit was unnecessary for 1980s seismically designed buildings, as the inherent lateral stiffness of these frames was already sufficient to meet design requirements. Consequently, no improvement was observed for DS1 to DS3, and only modest increases of 6.7% and 7.9% were recorded for DS4 and DS5, respectively. Notably, in low-rise buildings (≤5 stories), the high lateral stiffness of the original frame often rendered retrofitting at the 5‰ threshold unnecessary at the Damage Limit State. In such cases, a more stringent threshold (2‰) should be considered. Instead, for buildings originally designed for gravity loads only, the 5‰ threshold was generally sufficient to justify the retrofit intervention [18].

For RC jacketing designed to achieve a maximum lateral deformation of 2‰, the impact on seismic performance is more pronounced across all damage states due to enhancements in both strength and stiffness. The increases in PGA capacity relative to the as-built configuration were 50% for DS1, 46% for DS2, 48% for DS3, 123% for DS4, and 267% for DS5.

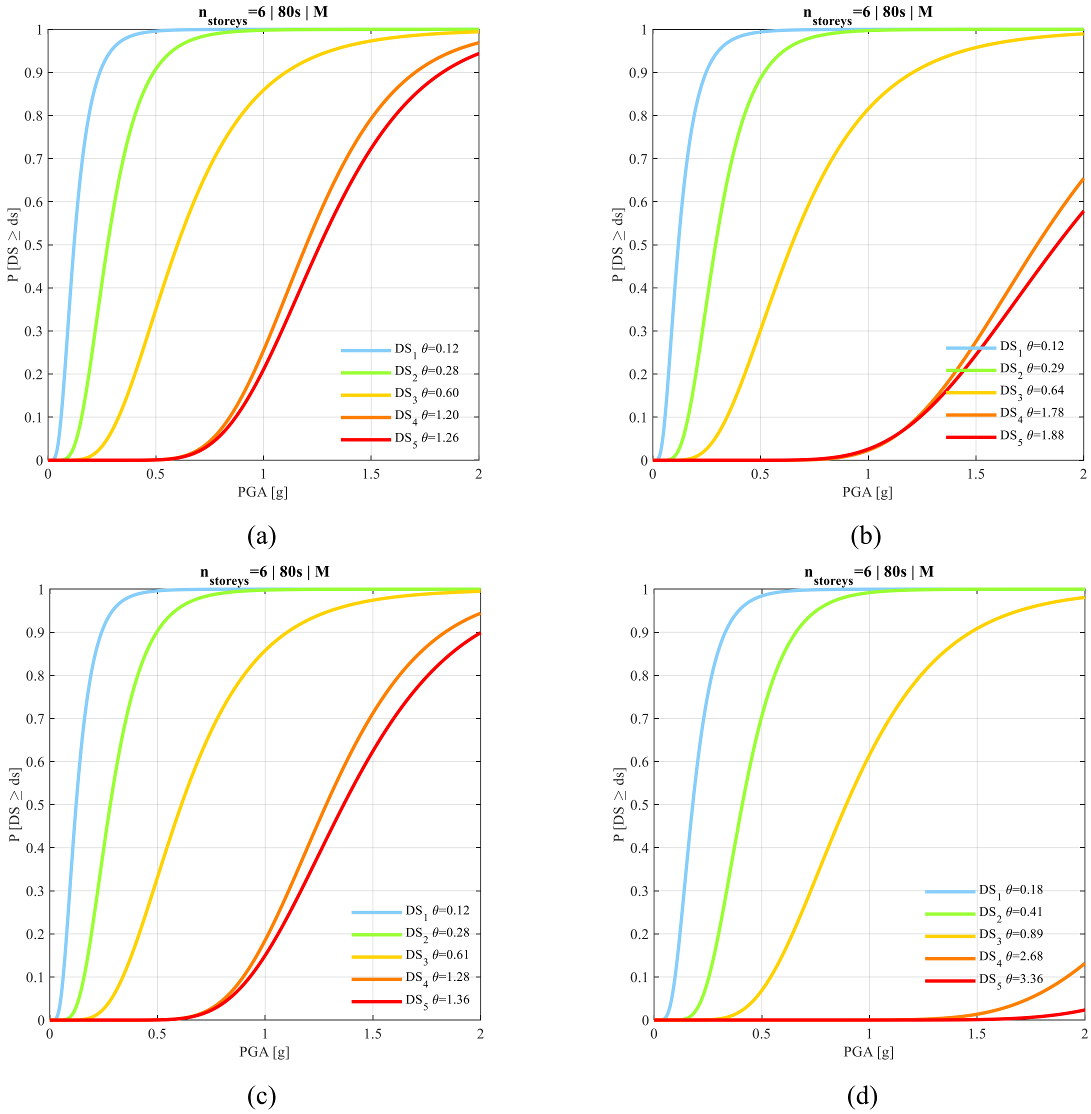

Figure 2: Damage fragility curves for 6-storey building seismically designed in 1980s with Medium masonry infills, in (a) as-built, (b) retrofitted with FRP, retrofitted with RC jacketing designed considering the threshold of (c) 5‰ and (d) 2‰ for design of retrofit intervention at the Damage Limit State.

4 CONCLUSIONS

This paper summarized first results of the probabilistic framework proposed in Gaetani d'Aragona et al. (2024) for developing analytical damage fragility curves for retrofitted RC buildings. The framework allows to account and propagate the main uncertainties related to seismic capacity, demand, and damage state thresholds, as well as uncertainties related to the record-to-record variability. The framework is based on the use of a reduced-order model proposed by the authors named STICK, which allows to simulate the response of infilled RC buildings in as-built and retrofitted configurations with a reduced computational burden still providing reliable results. The STICK model is automatically generated within a Matlab routine starting from basic geometric and mechanical features.

The application of the proposed framework is demonstrated via the construction of damage fragility curves for a 6-storey building designed and constructed in the 1980's according to outdated seismic design codes. Two retrofit strategies, one at the local level, corresponding to the FRP wrapping of relevant structural members, and one at the global level, consisting of the RC jacketing of perimeter frame columns is applied. The latter retrofit strategy has been designed considering two levels of design.

The present study is a part of a larger study performed within the RELUIS project 2022-2024 an 2024-2026 performed by the authors. The original work refers to the generation of damage fragility curves for classes of buildings as-built configuration, considering different number of storeys, age of construction and design elevel, number of storeys and infill consistency.

This study highlights the importance of selecting appropriate ground motion scaling strategies and retrofitting techniques to accurately assess the seismic response of buildings. The initial set of ground motions was insufficient for capturing the full range of damage states, particularly for low-rise structures designed according to outdated seismic codes. To address this, two additional sets of scaled ground motions were introduced, allowing for a more comprehensive analysis of nonlinear building responses, especially in cases involving retrofit interventions.

The effectiveness of FRP wrapping was found to be limited in the lower damage states (DS1–DS3) since it does not influence lateral stiffness but only enhances the deformation capacity of reinforced concrete members. Improvements were only observed in cases where shear failure of columns was the governing factor. At higher damage states (DS4–DS5), FRP wrapping significantly increased PGA capacity by 48% and 49%, respectively.

RC jacketing showed a more substantial impact, particularly when designed with a 2‰ deformation threshold, leading to progressive improvements across all damage states, with PGA capacity increasing by up to 267% in DS5. However, when a 5‰ threshold was used, the retrofit had little to no effect in DS1–DS3, as the inherent lateral stiffness of 1980s seismically designed buildings was already sufficient. Only minor improvements (6.7% and 7.9%) were observed in DS4 and DS5. Additionally, for buildings with five stories or fewer, RC jacketing at 5‰ was often unnecessary, whereas a 2‰ threshold was more appropriate.

FRP wrapping provides limited benefits in lower damage states but is more effective at higher levels of structural degradation. RC jacketing, particularly with a 2‰ deformation threshold, proves to be a more effective retrofitting solution. These findings emphasize the need to tailor retrofit interventions based on existing lateral stiffness and structural characteristics, ensuring optimal performance under seismic excitations.

5 ACKNOWLEDGEMENTS

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