Simplified Seismic Risk Assessment of Non-Ductile Infilled RC Frame Buildings

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Outline

- Motivation
- Proposed Method for Seismic Risk Evaluation
  - Hazard Characterisation
  - Vulnerability Assessment
  - Seismic Risk Evaluation
- Case Study Application
- Conclusions
- Downloadable Content

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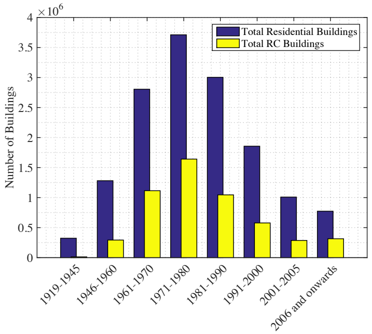
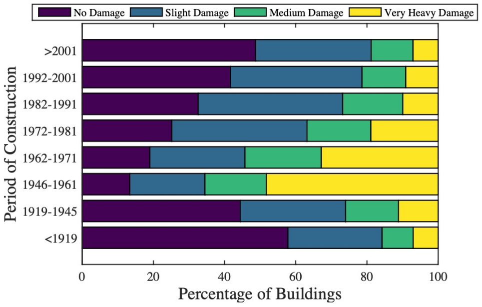
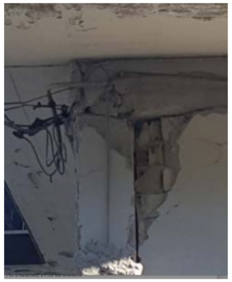
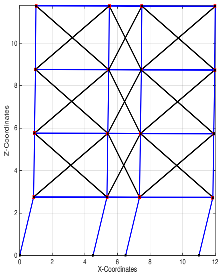
Motivation

- The prevalence of RC-URM structures in Italian/Southern European building stock and observed damage.
- Insufficient or poor detailing of structural members, inadequate solution to the frame-panel interaction problem.
- The global effect of URM infill panels addition: increase in initial stiffness and sudden drop in lateral strength capacity after the rupture of infills.
- The necessity for simplified tools for vulnerability assessment and seismic risk evaluation.









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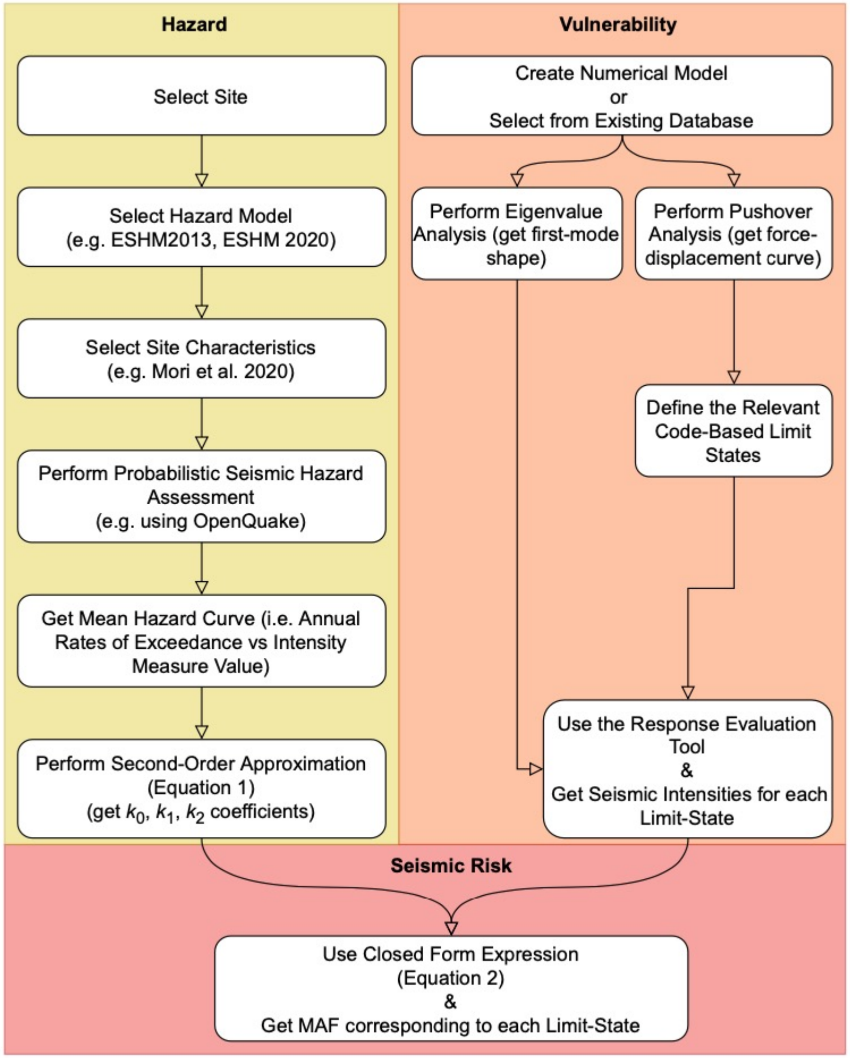
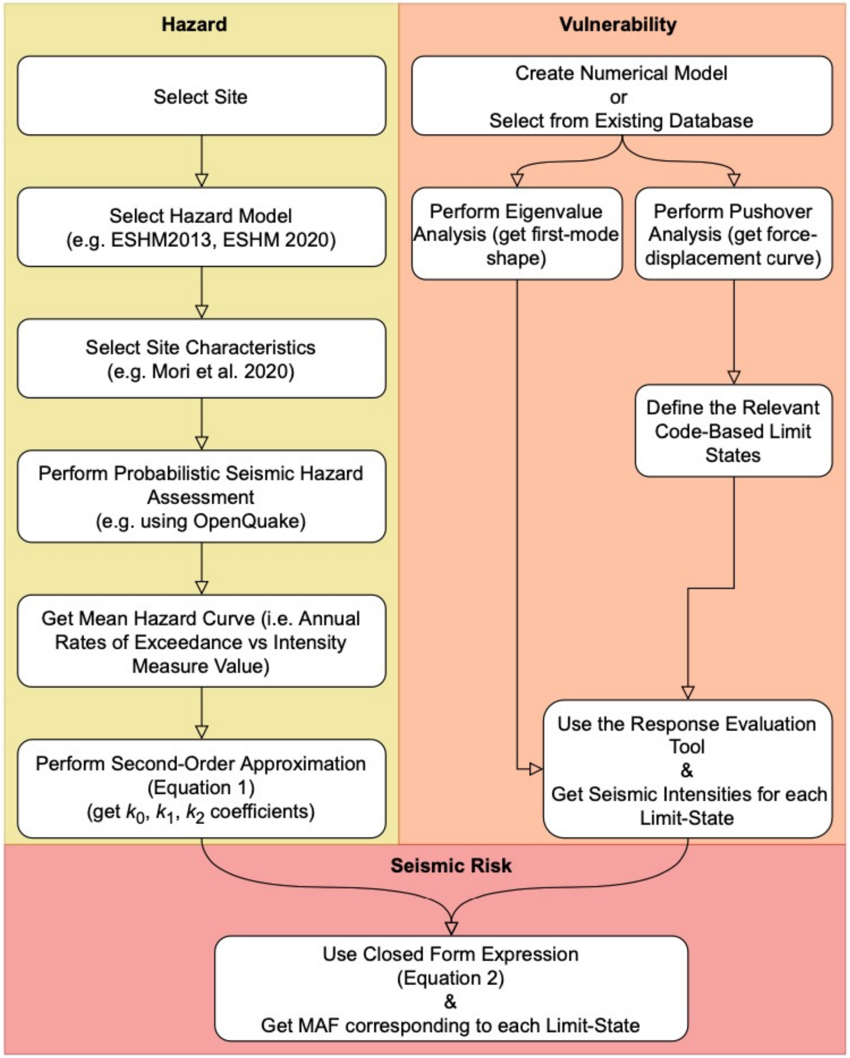
Proposed Method



- A relatively fast and simple method for the seismic risk estimation of non-ductile infilled RC structures.
- Integration of high-fidelity mathematical expression and statistical models for the characterization of hazard and vulnerability.
- “IM-based” closed-form solution (Vamvatsikos, 2013) to the risk integral (Cornell *et al.* 2002) for the derivation of risk expressed in terms of the mean annual frequency of exceedance.

Proposed Method



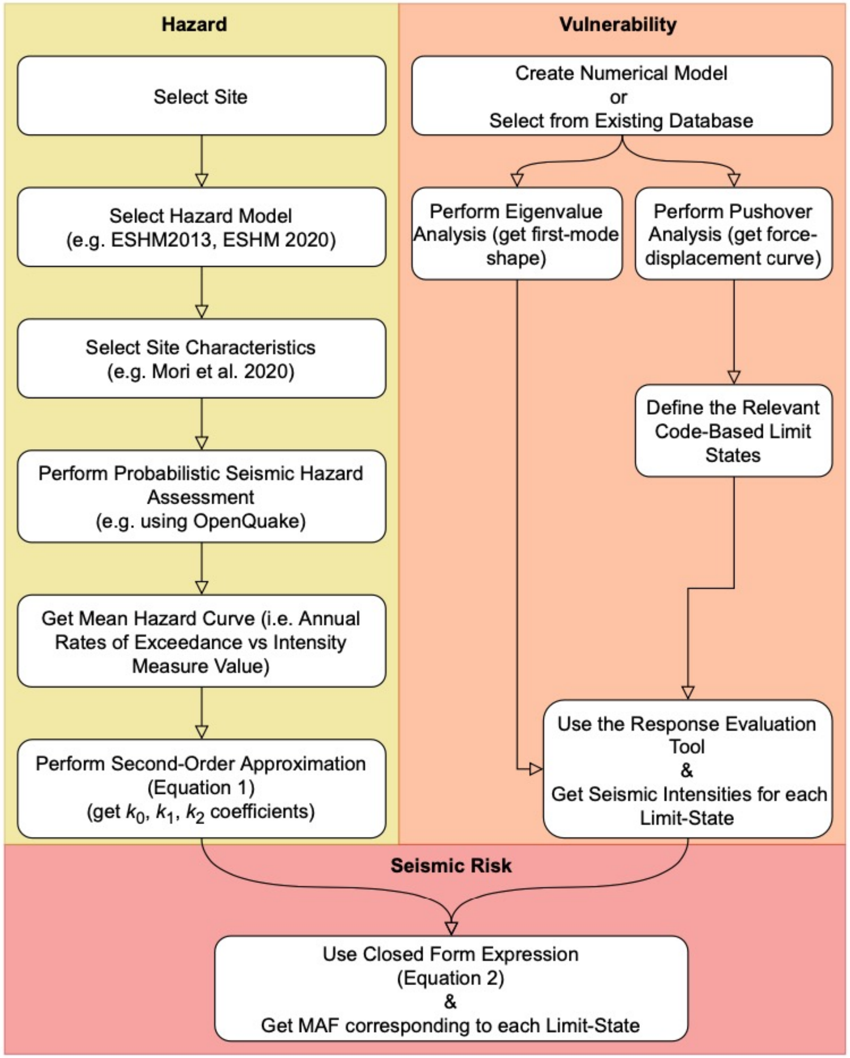
- Hazard

1. Perform probabilistic seismic hazard assessment at the location of interest and get mean hazard curves.
2. Fit second-order polynomial to mean hazard and obtain fit coefficients (k_0, k_1, k_2).

$$H(s) = k_0 \exp[-k_2 ln^2(s) - k_1 ln(s)] \quad \text{(Eq. 1)}$$

Where $H(s)$ is the hazard function and s is a given intensity measure value. k_0, k_1 and k_2 are positive real numbers describing the curvature and amplitude of the hazard curve fit.

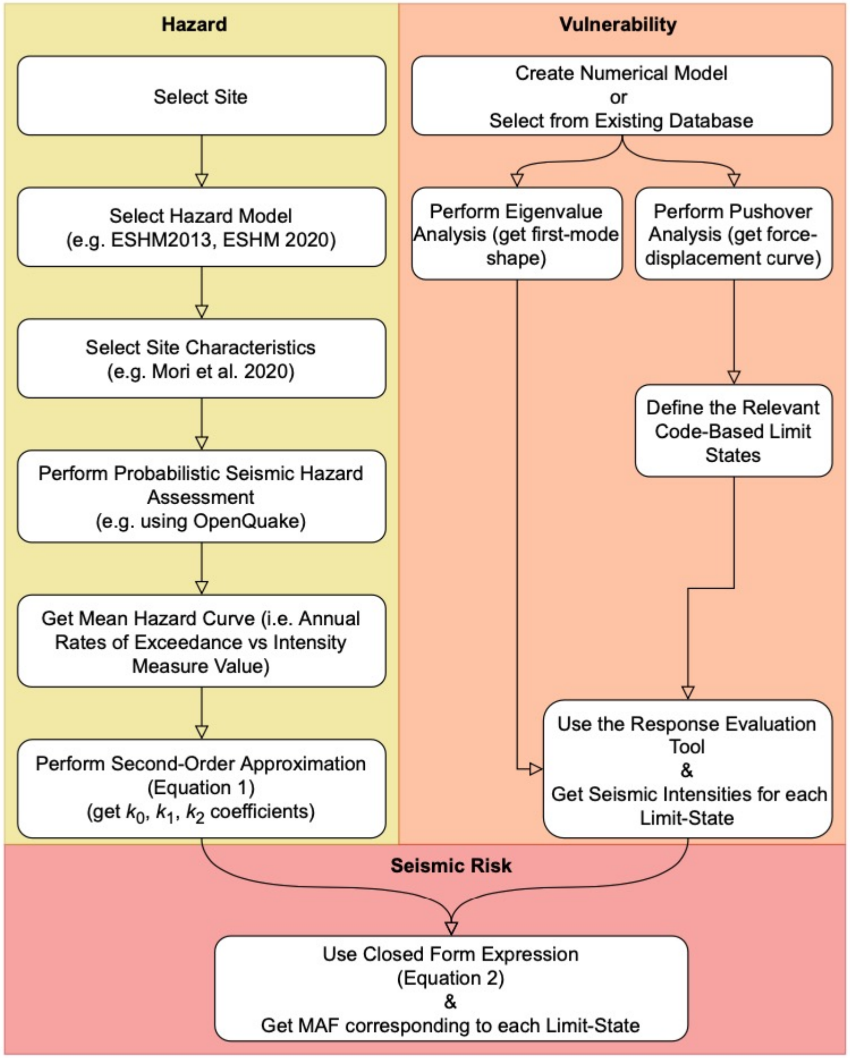
Proposed Method



- Vulnerability

1. Build numerical model or use/edit an existing building model from the database of infilled RC archetype building models (link provided).
2. Perform eigenvalue analysis and get the first-mode shape ordinate (Φ_i) and mass (m_i) at floor i.
3. Perform non-linear static analysis (i.e. Pushover) and get the nominal base shear force and roof displacement curve (*F-Δ*).
4. Multi-linearise the *F-Δ* with respect to the onset and end of each response branch.
5. Define the code-based limit-states and annotate on the pushover curve *F-Δ.*
6. Use the response estimation tool (link provided) to estimate the median seismic intensities and the associated dispersions.

Proposed Method



- Seismic Risk

$$\lambda_{LS} = \sqrt{p}k_0^{1-p}[H(\hat{s}_c)]^p \exp[\frac{k_1^2}{4k_2}(1-p)] \text{ (Eq. 2)}$$

$$p = \frac{1}{1+2k_2\beta^2} \text{ (Eq. 3)}$$

Where β corresponds to the record-to-record variability. $\beta = 0.27$ for non-collapse limit-states and 0.37 for the collapse limit-state. $H(\hat{s}_c)$ represents the annual rate of the median intensity measure required to attain a particular demand-based level.

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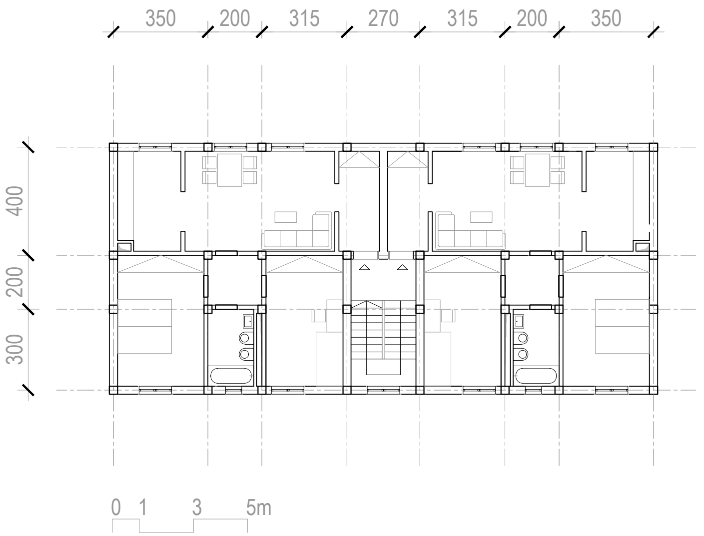
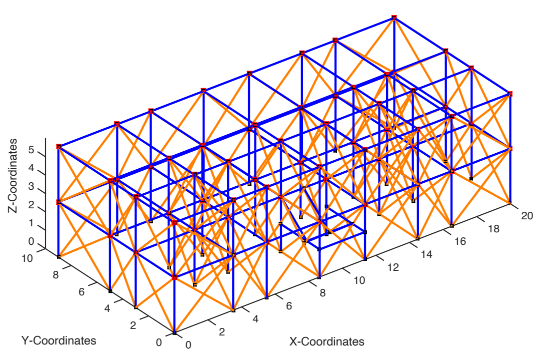
Case Study Building Description



Case Study Building Layout

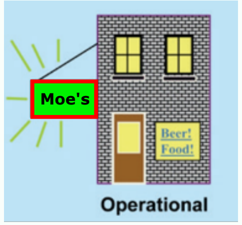
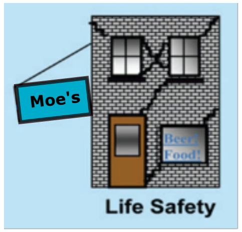
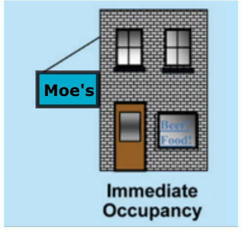
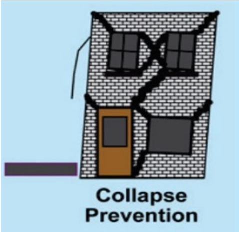


OpenSees Numerical Model

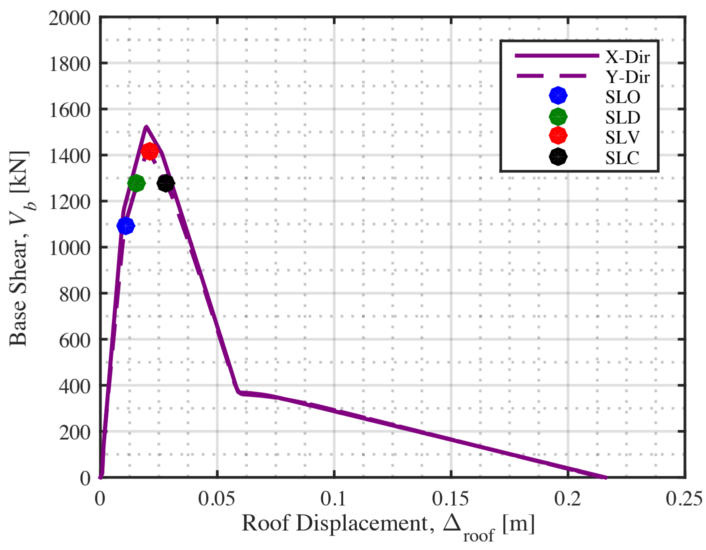
- Design Method: Allowable Stress Method (Pre-1970s)
- Column Section: 20x20 cm
- Column Reinforcement Ratio: 0.89%
- Beam Section: 50x30 cm
- Beam Longitudinal Reinforcement Ratio: 0.21-0.31%
- Beam Transverse Reinforcement: Φ6 @ 150-200 mm
- Concrete Allowable Stress: 5 MPa
- Steel Rebars Allowable Stress: 140 MPa (Type Aq42)

- Lumped Plasticity Model
- BC Elements: Rotational and shear hinges with empirically calibrated hysteretic models (De Risi et al. (2019))
- Interior and Exterior BC Joints: Scissor model (O'Reilly et al. (2017))
- Masonry Infill Panels: Compression-only single and double strut models (Crisafulli et al. (2000))

Identification of Code-Based Limit-States

Limit-State	Description	Illustration
Stato Limite di Operatività 'Operational' (SLO)	Structural and non-structural elements maintain functionality without suffering damage and significant interruption of usage. Moderate damage to infill panels is foreseen at low levels of drift. The deformation capacity is equivalent to 2/3 of the deformation capacity at SLD.	
Stato Limite di Danno 'Damage Control' (SLD)	Structural and non-structural elements suffer moderate damage. Structure remains under immediate occupancy without jeopardizing human life. The overall capacity and stiffness of the structure is not compromised. The deformation capacity corresponds to the elastic limit of the bilinear equivalent model or reaching the yield chord rotation (θ_y) in a supporting column.	
Stato Limite di salvaguardia della Vita 'Life Safety' (SLV)	Structure sustains heavy damage to its structural elements resulting in a significant loss of lateral stiffness. The structure retains its gravity load carrying capacity with a margin of safety against collapse. Failure of non-structural elements is a direct consequence of attaining SLV. The ultimate displacement at SLV is defined as ¾ of the roof displacement at SLC or achieving 75% of the ultimate chord rotation (θ_u) in any component.	
Stato Limite di prevenzione del Collasso 'Collapse Prevention' (SLC)	Structural and non-structural elements suffer heavy damage. The structure maintains gravity-load carrying capacity with a slender margin of safety against collapse due to the full exploitation of the strength and deformation capacity. The SLC limit-state is defined as the point on the bilinear capacity curve where a residual capacity of 80% of the maximum base shear is achieved or the ultimate chord rotation (θ_u) is reached corresponding to any component	

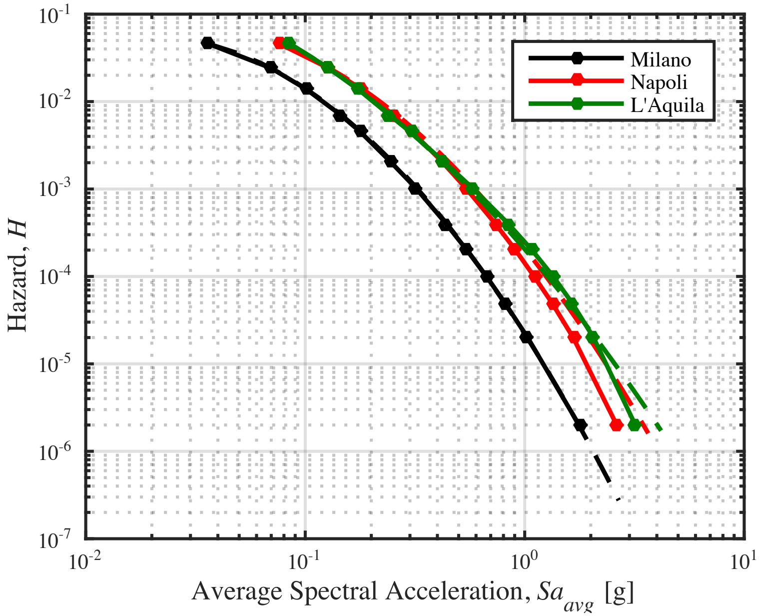
Nonlinear Static Analysis (Pushover)



- Displacement-controlled static pushover analysis with inverse triangular load pattern was carried out.
- Static pushover analysis was performed in both principal directions of the case study structure.
- NTC 2018 limit states were identified on the force-displacement curve.
- The Y-direction was considered for the remainder of the assessment.

Case Study Application

Seismic Hazard Characterisation

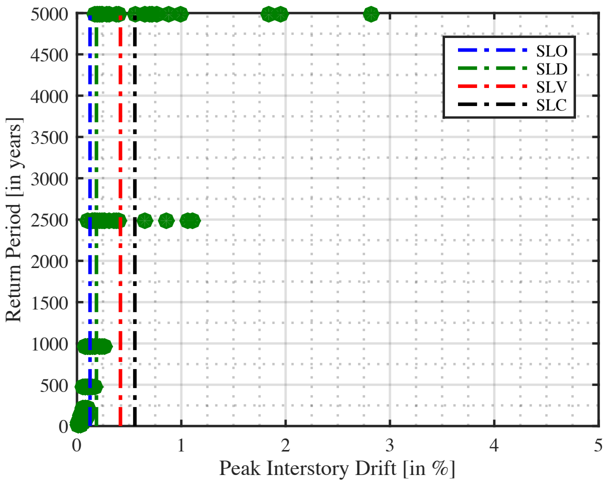


Site	Second-Order Approximation Coefficients		
	k_0	k_1	k_2
Milano	2.20e-05	3.95	0.50
Napoli	2.09e-05	3.20	0.43
L'Aquila	2.04e-05	2.92	0.29

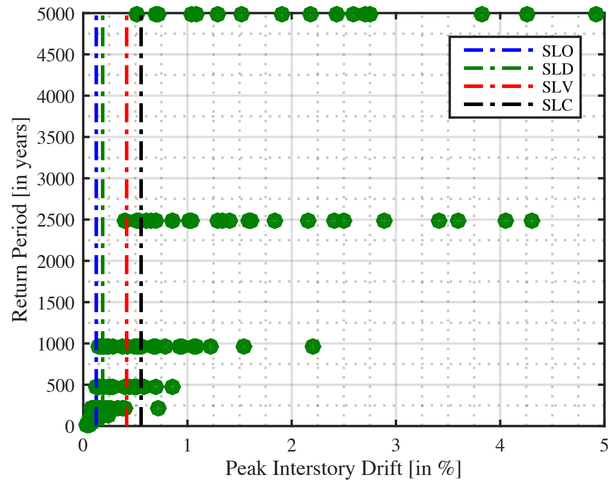
- Three locations were considered: Milano, Napoli, L'Aquila.
- Hazard analysis was carried out using the OpenQuake engine.
- The average spectral acceleration (Sa_{avg}) as the intensity measure.
- The mean hazard curves were extracted and second-order polynomial was fitted (Eq. 1).

Case Study Application

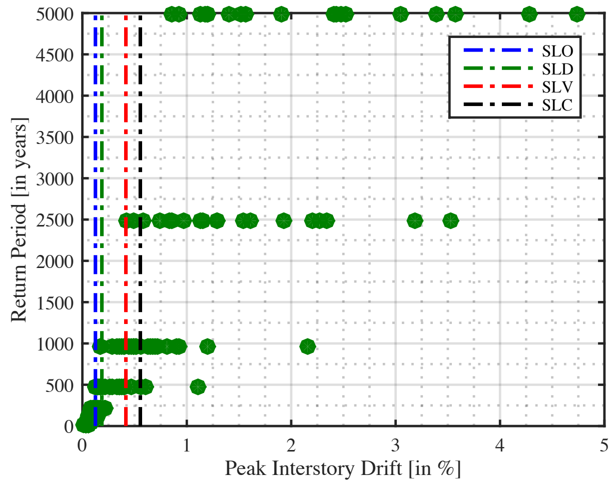
Multiple Stripe Analyses



Milano



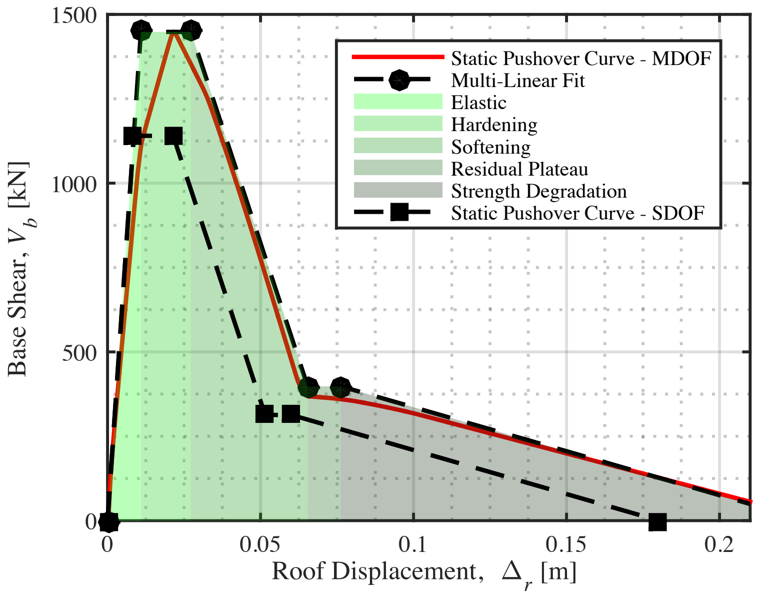
Napoli

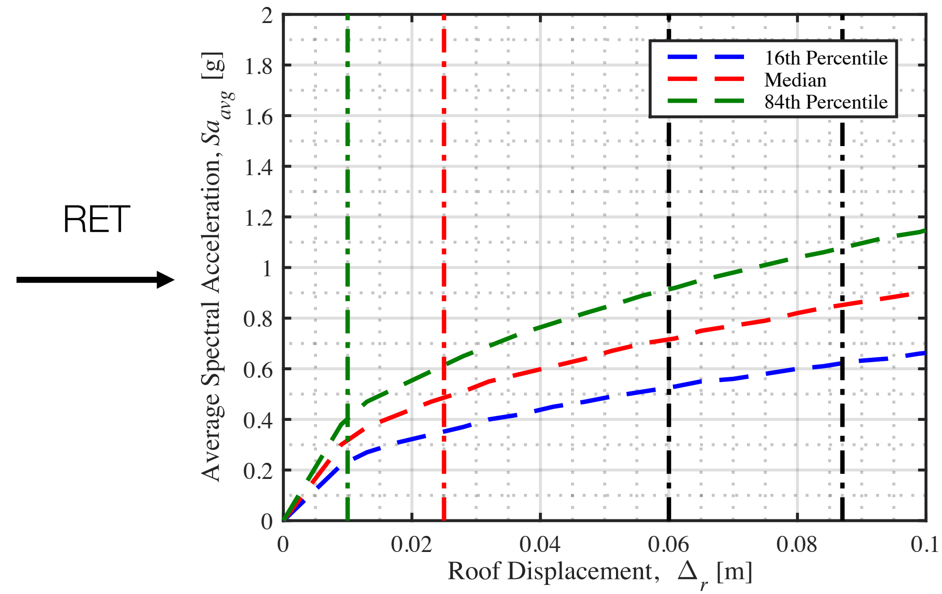


L'Aquila

- Nine return periods: 22, 42, 72, 140, 224, 475, 975, 2475 and 4975 years.
- Ground-motion record sets of 25x2 per stripe.
- Increasing intensity measure levels to characterize the structural response up to collapse.
- Maximum likelihood method for the estimation of the median intensities and associated dispersions corresponding to each limit-state demand-based threshold.

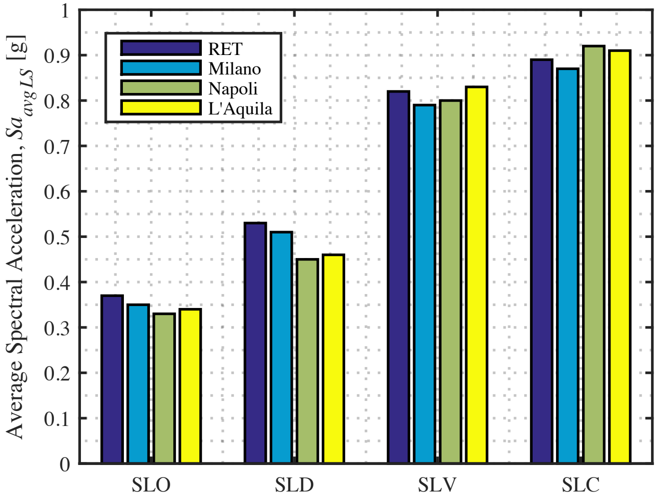
Simplified Analyses



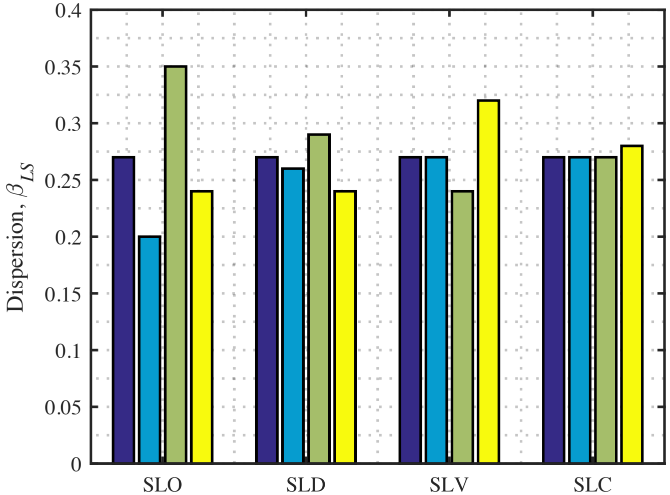


- Multi-linearised SPO curve using the response estimation tool for Infilled RC frames.
- Median and quantiles (16th and 84th) dynamic capacity curve were interpolated.
- Median intensities and associated dispersions were computed at the demand-based thresholds for the NTC2018 limit-states.

Comparison of Median Seismic Intensities and Associated Dispersions



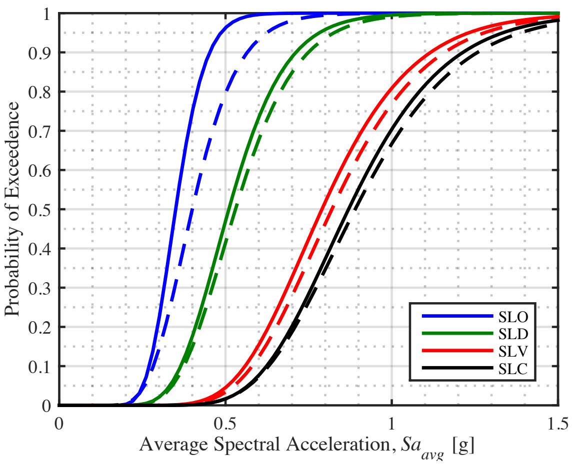
Median Seismic Intensities ($Sa_{avg,LS}$)



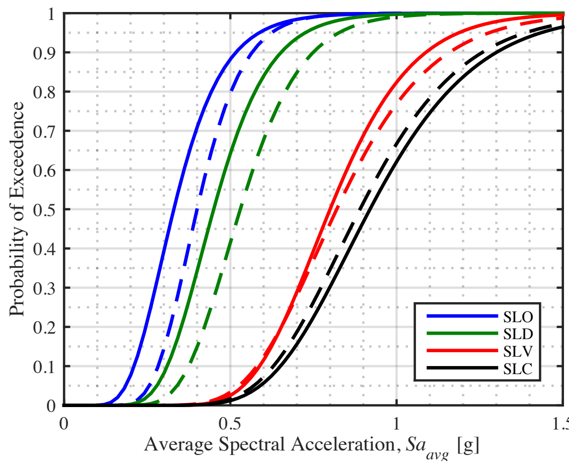
Record-to-Record Variability (β_{RTR})

- Satisfactory overall performance of the proposed tool for the seismic fragility estimation vis-à-vis NLTHA.
- Consistently good estimates across the entire range of response considering the four limit-states of the NTC2018 and across different seismicity levels.
- Robustness of the statistical model implemented within the response evaluation tool tailored specifically for the concerned typology.

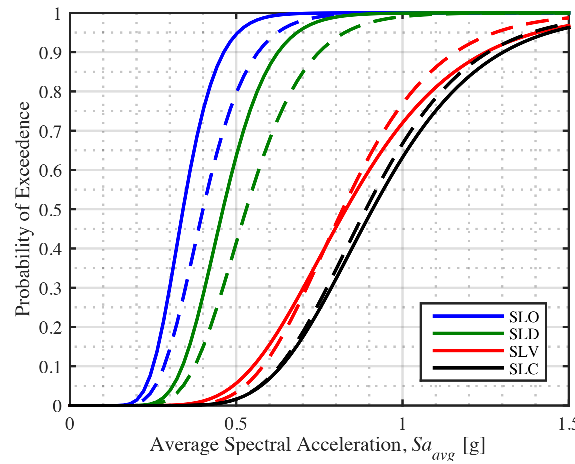
Comparison of Median Seismic Intensities and Associated Dispersions (Fragility Functions)



Milano



Napoli



L'Aquila

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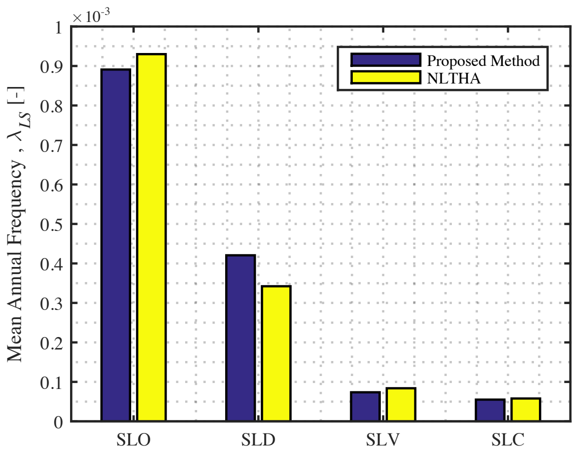
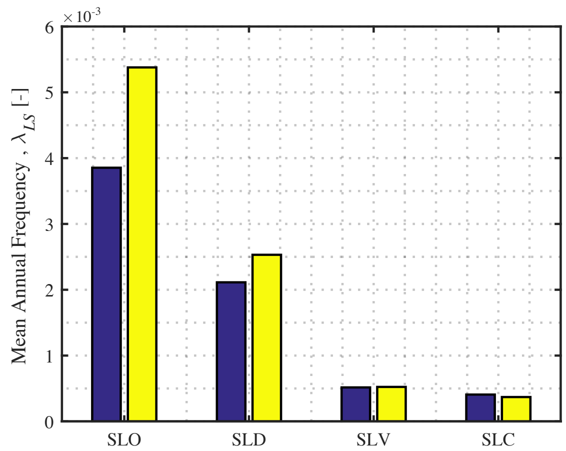
Case Study Application

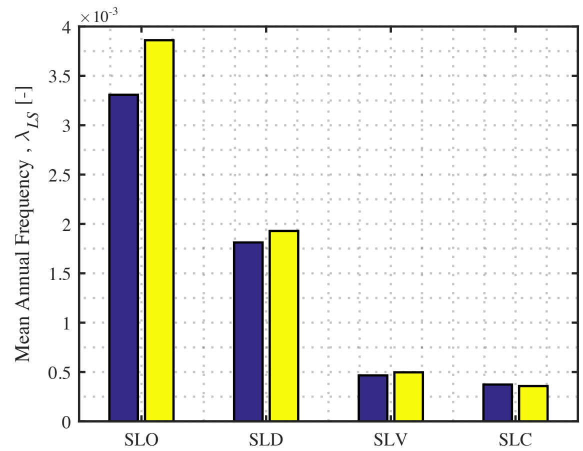
Seismic Risk Estimates: Mean Annual Frequency of Limit-State Exceedance (λ_{LS})



Milano



Napoli



L'Aquila

- The proposed method yielded relatively good risk estimates when compared to traditional analyses.
- Main differences in risk estimates can be attributed to the discrepancy in the dispersion values (i.e. fixed values for the response evaluation tool vs maximum likelihood estimates for MSA)
- Across the entire range of response, seismic risk is fairly well-characterized highlighting the robustness of the method.
- Acceptable trade-off level between accuracy and computational effort.

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- A fast and simple method for the seismic risk evaluation of non-ductile infilled RC frame buildings was presented.
- The method bases itself on closed-form approximations for the characterisation of hazard and risk and a pushover-based seismic response estimation tool for the quantification of vulnerability parameters.
- The performance of the proposed method in accurately defining vulnerability and seismic risk was validated within a comparative case study application which applies NLTHA.
- The results highlighted the reliability and consistency of the proposed method in the evaluation of seismic risk when compared to results of NLTHA.
- The capability of the tool in accurately quantifying the seismic demand associated to prescribed limit-states and subsequently the related seismic risk-based applications render it a good improvement to be implemented in seismic assessment guidelines.

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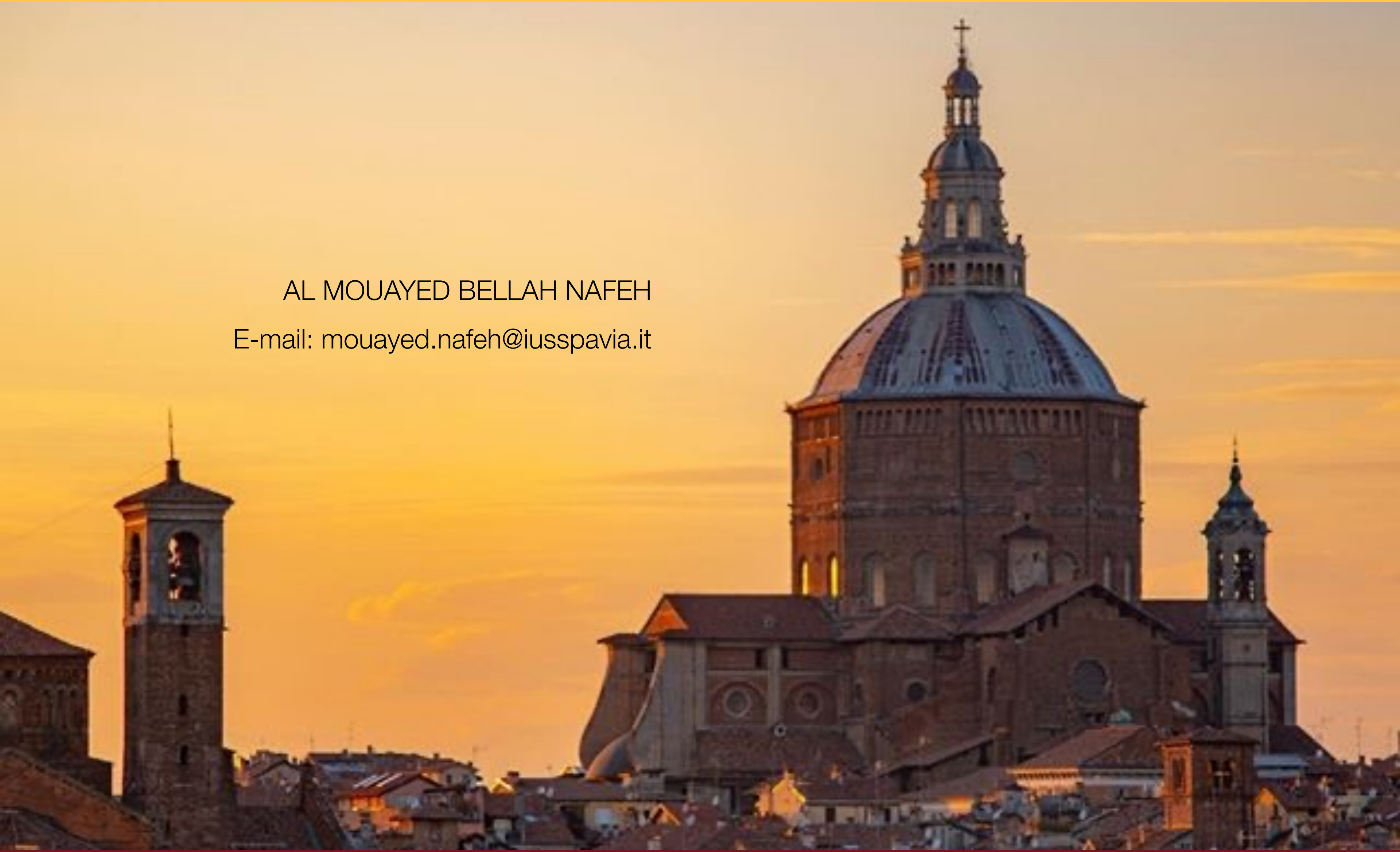
Downloadable Content

- Database of 315 Archetype Three-Dimensional Building Numerical Models in OpenSees (Tcl).
    - Typologies: Bare, Infilled, Pilotis RC Buildings.
    - Stories: 2, 3, 4, 5 and 6 Storey Buildings.
    - Design Practice and Temporal Consideration: gravity-loads only (GLD), sub-standard design using equivalent lateral force method (SSD), high-seismic design using response spectrum analysis (HSD).
    - Repository contains also: Master files for running static and cyclic pushover analyses, incremental dynamic analysis and multiple-stripe analysis.
    - Link: https://github.com/gerardjoreilly/Infilled-RC-Building-Database

- Infilled RC Building Response Estimation Tool.
    - Link: https://github.com/gerardjoreilly/Infilled-RC-Building-Response-Estimation



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