3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

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

Al-Mouayed B. Nafeh – PhD Candidate, Scuola Universitaria Superiore IUSS Pavia, Italy, E-mail: mouayed.nafeh@iusspavia.it

Gerard J. O'Reilly – Assistant Professor, Scuola Universitaria Superiore IUSS Pavia, Italy, E-mail: gerard.oreilly@iusspavia.it

Abstract: Past earthquakes have demonstrated the vulnerability of non-ductile reinforced concrete (RC) structures with masonry infills. Damage to said structures has contributed negatively to large economic losses and jeopardised human lives. They represent a relevant portion of the global building stock, particularly in Europe and the Southern Mediterranean region. Seismic risk assessment of existing structures entails the adequate characterisation of hazard and vulnerability. The former is expressed in terms of the annual rates of exceeding a particular intensity measure value, while the latter requires an accurate quantification of a structure's seismic response, expressed as the ground-shaking intensity required to exceed a structure's limit state. To reduce the computational burden associated with characterising seismic vulnerability, a pushover-based method is presented for non-ductile infilled RC buildings. The method uses a simplified approximation of the hazard component and a practice-oriented evaluation of the seismic capacity corresponding to code-based limit state thresholds. The overall performance of the proposed method is highlighted herein within an application carried out on several archetype building models and is validated with results of extensive non-linear time-history analyses. It represents a simple but efficient means to accurately quantify seismic risk in such structures.

Keywords: PBEE, hazard, vulnerability, risk, simplified.

1. Introduction

The seismic risk assessment of reinforced concrete (RC) structures with masonry infills holds paramount importance in modern earthquake engineering and risk mitigation decision-making. Essentially, infilled RC buildings represent a large percentage of the southern European built environment and particularly the Italian building stock (Crowley et al. 2020). Additionally, a significant percentage of infilled RC buildings was constructed before the introduction of adequate seismic guidelines (i.e. around the 1970s) and was typically designed to resist gravity loads only. As such, structural elements were characterised by inadequate seismic detailing and no consideration for ductile failure mechanisms (i.e. capacity design). Additionally, masonry infill panels were not considered in the design process and their effects on the response of the structural system were generally neglected. Past experimental (Basha and Kaushik 2016), analytical (Dolšek and Fajfar 2008; Fardis and Calvi 1994) and field reconnaissance (Parisi et al. 2012) campaigns have highlighted the detrimental effect of infill panels on the global response and their high vulnerability to ground-shaking events.

Generally, the seismic risk is expressed in terms of the mean annual frequency of exceedance (MAFE) and is the result of convolving both seismic hazard and vulnerability. The former requires a proper characterisation of the exceedance probability of a particular intensity measure (IM) level at a given site and return period. Whereas, the latter requires the assessment of the seismic performance through the accurate quantification of the exceedance of structural demand-based performance level or limit-state (LS) for a given intensity level of ground shaking, further denoted as IM_{LS}. According to the recent guidelines on the seismic assessment of existing structures, Pinto *et al.* (2014) infer that risk assessment should be carried out with reference to three methods of analysis: 1) incremental dynamic analyses on detailed numerical models; 2) incremental dynamic analyses on equivalent single-degree-of-freedom (SDOF) oscillators; 3) non-linear static procedures. However, the former two options require performing non-linear time-history analyses (NLTHA) and time-based assessments, which are computationally expensive, for the calculation of seismic risk and would require certain in-depth expertise in the field of earthquake engineers, which are not always available. To this end, practitioners and engineers should be provided with simplified tools for the estimation of seismic risk as it would facilitate the communication of risk to stakeholders and decision-makers for the overall reduction of seismic risk, offer ease of applicability and most importantly overcome the presented limitations. The main scope behind such tools is to aid the quantification and mitigation of seismic risk with respect to different guidelines and procedures (Franchin, Petrini, and Mollaioli 2018; FEMA 2012; CNR 2014).

To reduce the computational burden associated with such analyses, this paper presents a simplified method based on non-linear static procedures for the evaluation of the seismic risk of existing structures, particularly for non-ductile infilled RC frames buildings. The method considers a second-order approximation of the hazard function and a tool-based quantification of the seismic vulnerability. A breakdown of the proposed method along with its application are clearly illustrated. The robustness of the presented methodology is evaluated with respect to results of a more traditional risk-based case study requiring NLTHA. It is conducted using an archetype building model located fictitiously in three different locations: Milano, Napoli and L'Aquila.

2. Proposed Method for Seismic Risk Evaluation

A fast and simple method for the seismic risk evaluation of non-ductile infilled RC frame structures is presented here. Essentially, the method bases itself on high-fidelity mathematical expression to characterise hazard and the application of a response evaluation tool (RET) for vulnerability assessment. Then, results corresponding to both components are integrated using an "IM-based" closed-form solution, derived by Vamvatsikos (2013), corresponding to the risk integral highlighted in Cornell *et al.* (2002). The necessary steps for the application of the proposed method are outlined in Figure 1.

Regarding the hazard component, a full hazard analysis (i.e. probabilistic seismic hazard assessment, or PSHA) should be carried out for the definition of the hazard function (i.e. mean annual rate of exceeding a particular IM value) and then, the application of the mathematical model ensues, as highlighted in Step 1. Considering the vulnerability component, the RET is required for the dynamic performance characterisation of a case study building. RET utilises results from eigenvalue and non-linear static analyses for the interpolation of dynamic capacity curves. It is worth mentioning that the results of RET are solely expressed in terms of the average spectral acceleration for reasons highlighted by O'Reilly (2021) and (Nafeh and O'Reilly 2022). The procedure for which is summarised in Step 2. Subsequently, the two components are then integrated and seismic risk in terms of the MAFE can be derived as outlined in Step 3.

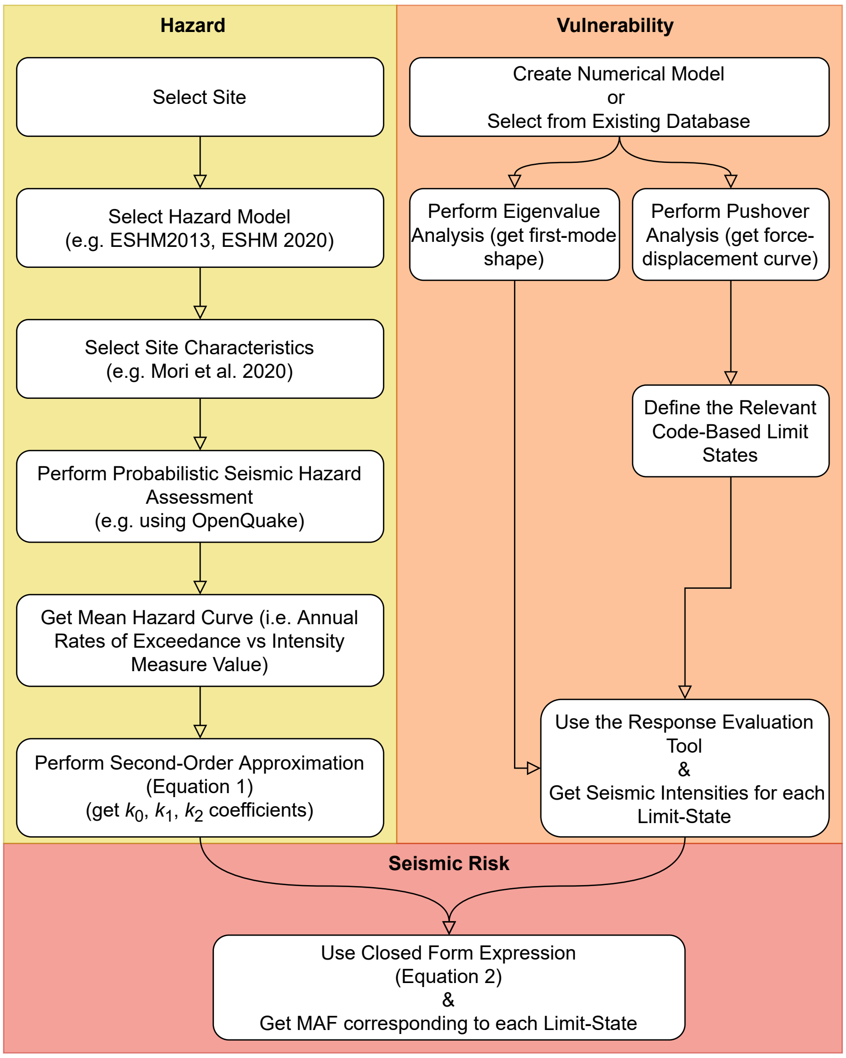


Figure 1: Flowchart illustrating the implementation procedure of the proposed method for the seismic risk estimation of infilled RC frame buildings

2.1. Step 1: Hazard Characterisation

This can be simply described as:

i. Perform PSHA and get mean hazard curve expressing the mean annual rates of exceedance and the intensity measure values.

ii. Fit second-order polynomial to mean hazard curve and obtain fit coefficients (k_0, k_1, k_2) as highlighted in Equation 1:

$$H(s) = k_0 \exp[-k_2 ln^2(s) - k_1\, ln(s)] \tag{1}$$

where $H(s)$ is the hazard function expressing annual rates of exceeding a given intensity measure value equal to s; k_0, k_1 and k_2 are positive real numbers describing the curvature and amplitude of the hazard curve fit.

2.2. Step 2: Vulnerability Assessment

This is carried out as:

i. Build a numerical model or use/edit an existing building model (built in OpenSees) from the database of infilled RC archetype building models. A useful database is available here, for example: https://github.com/gerardjoreilly/Infilled-RC-Building-Database).

ii. Perform eigenvalue analysis and get the first-mode shape ordinate (Φ_i) and mass (m_i) at floor i. Note that the mode shape should be normalised with respect to the roof level's value (i.e. $\Phi_{roof} = 1$)
iii. Perform non-linear static pushover and get the nominal base shear force-roof displacement curve (F-Δ_{roof}). For simplicity, a displacement-controlled inverse triangular pattern can be adopted. If the required analysis is planar, the results corresponding to the in-plane direction of the frame are considered. If the required analysis is three-dimensional, a pushover analysis should be carried out in both principal directions. The results corresponding to the direction exhibiting a less ductile behaviour is considered.
iv. Multi-linearise the F-Δ_{roof} curve with respect to the onset and end of each response branch (i.e. elastic, hardening, softening, residual plateau and strength degradation) (Nafeh and O'Reilly 2022).
v. Define the code-based limit-states and annotate on the pushover curve (i.e. F-Δ_{roof})
vi. Use the response evaluation tool (RET) to estimate the median seismic intensities corresponding to the defined limit-states and the associated dispersion. The tool for infilled RC frames is available here: https://github.com/gerardjoreilly/Infilled-RC-Building-Response-Estimation. The tool considers the average spectral acceleration as the intensity measure for the dynamic strength characterisation. For further details regarding the application of the tool, please refer to: (Nafeh and O'Reilly 2022)

2.3. Step 3: Seismic Risk Evaluation

The seismic risk corresponding to pre-defined limit-state is expressed in terms of λ_{LS} which can be evaluated as shown in Equation 2:

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

$$p = \frac{1}{1+2k_2\beta^2} \tag{3}$$

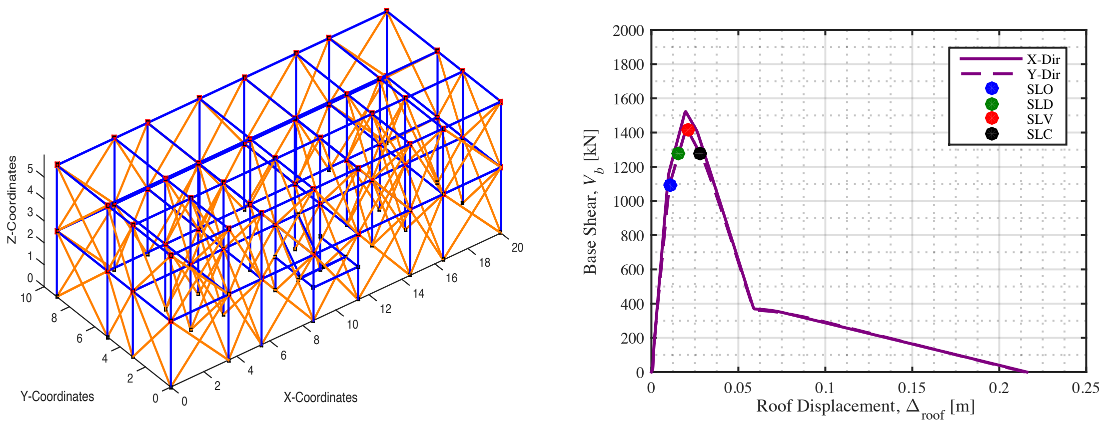
where β corresponds to the record-to-record variability included in Equation 3 and $\beta = 0.27$ for a non-collapse limit-state and $\beta = 0.37$ for the collapse limit-state as outlined in Nafeh and O'Reilly (Nafeh and O'Reilly 2022). $H(\hat{s}_c)$ represents the annual rate of the median intensity measure required to attain a particular demand-based level. For a practical illustration of the proposed method, a case study application on an infilled RC building is presented in the subsequent section.

3. Case Study Application

3.1. Case Study Definition

A two-storey infilled RC building designed for gravity-loads only was adopted for the case study application presented in this section. The numerical modelling of the case study structure was performed in OpenSees (McKenna 2011) using a three-dimensional lumped plasticity approach. The modelling approach of frame members and masonry infill panels considered empirically-calibrated hysteretic models accounting for strength and deformation capacities based on experimental test results (De Risi and Verderame 2017; Verderame et al. 2019; O'Reilly and Sullivan 2019; Hak et al. 2012; Crisafulli and Carr 2007). The case study building was designed using the allowable stress method. With regards to structural detailing, a uniform column section of 20x20 cm was considered corresponding to a reinforcement ratio of 0.89%. For beams, a uniform section of 50x30 cm was considered corresponding to a reinforcement ratio range of 0.21-0.31 %. Transverse reinforcements of $\phi6$ @150mm and $\phi6$ @200mm were considered for the column and beam members, respectively. Smooth rebars (i.e. Aq42) corresponding to an allowable stress of 140 MPa were assumed, whereas an allowable compressive strength of 5 MPa was considered for concrete.

An eigenvalue analysis was conducted to evaluate the first-mode shape ordinates. Furthermore, a non-linear static pushover analysis was carried out to characterise the lateral capacity of the case study building. Considering the results of the SPO analysis, the y-direction was deemed the weakest despite the fact that both directions exhibit similar ductility capacity, yet the assumption was made based on the overall base shear capacity. Additionally, the identification of the code-based demand thresholds or limit-states is necessary for the evaluation of the associated median seismic intensities. The identification of limit-states is typically described in seismic codes and guidelines. As such, the limit-states presented in the Italian national code (NTC 2018) (Ministero delle Infrastrutture e dei Trasporti 2018) were adopted for the comparative case study presented herein. These four limit-states correspond to: "*stato limite di operativita*" or operational limit-state (SLO); "*stato limite di danno*" or damage control limit-state (SLD); "*stato limite di salvaguardia della vita*" or life-safety limit-state (SLV); and "*stato limite di prevenzione del collasso*" or collapse prevention limit-state (SLC).



(a) (b)

Figure 2: (a) Numerical model of the two-storey infilled RC case study building; (b) static pushover analyses curves highlighting the lateral seismic capacity of the case study structure in terms of the base shear and roof displacement

3.2. Seismic Hazard Characterisation

The case study building was selected to be located fictitiously in three different locations: Milano, Napoli and L'Aquila. Then, hazard analyses for the characterisation of the annual hazard and record selection for NLTHA were carried out using the OpenQuake engine (Pagani et al. 2014). Performed analyses considered the average spectral acceleration Sa_{avg} as the intensity measure and accounted for the site characteristics model (i.e. Vs30) for Italy presented in Mori et al. (2020). The mean hazard curves extracted from PSHA in terms of the annual probability of exceedance and the ground-shaking intensity for the three different locations are illustrated in Figure 3. Then, a second-order polynomial was fitted to the mean hazard curves (as per Step 1-ii) for the application of the proposed method following Equation 1. The resulting coefficients of the second-order approximation are summarised in Table 1.

Table 1: Resulting coefficients of the second-order approximation of the hazard function

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

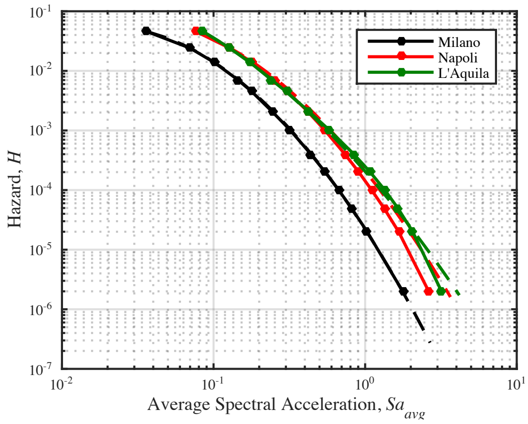
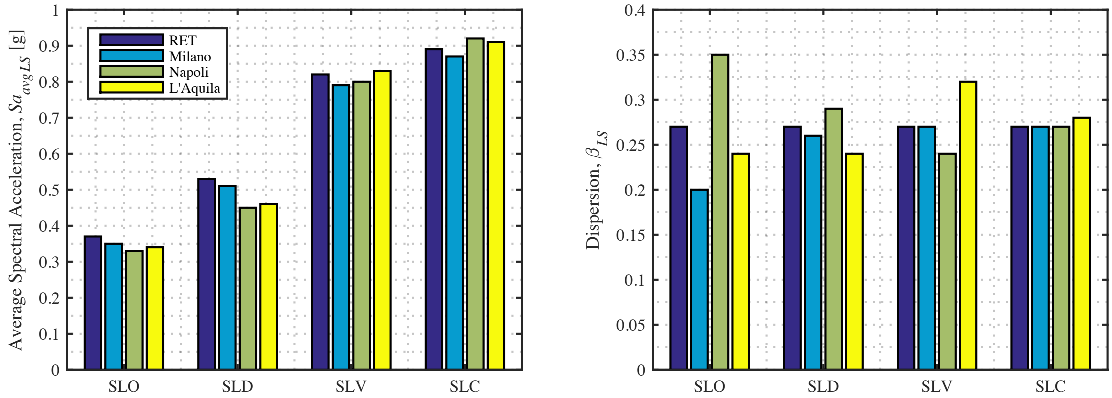


Figure 3: Seismic hazard curves of Milano, Napoli and L'Aquila expressed in terms the average spectral acceleration and the fitted second-order polynomial

3.3. Seismic Vulnerability Assessment

Considering the accurate characterisation of the seismic response of the case study structure, a series of traditional hazard-consistent NLTHA were carried out. To this end, multiple stripe analysis (MSA) was performed. This NLTHA method requires a set of ground motion records to be selected based on the hazard disaggregation at the conditioning period. MSA allows for differences in anticipated properties of low to high-intensity motions to be captured via ground motion selection. Record selection was performed following disaggregation of seismic hazard in terms of the magnitude, M, distance R and epsilon, ε using the EzGM toolbox for record selection and processing developed by Ozsarac *et al.* (Ozsarac, Monteiro, and Calvi 2021). Nine IM levels corresponding to return periods of 22, 42, 72, 140, 224, 475, 975, 2475 and 4975 years were investigated for the characterisation of the structural response in an attempt to cover initial damage of the masonry infill panels up to global structural collapse. The median intensities corresponding to each limit-state previously defined were obtained using maximum likelihood estimation. Furthermore, the response evaluation tool (Step 2.v) was used for the simplified estimation of these intensities. The tool integrates the results of the eigenvalue and non-linear static analyses (i.e. pushover) for the evaluation of the median dynamic capacity. It is worth mentioning that the results of the pushover analysis should be expressed in terms of the base shear and the roof displacement. The results corresponding to NLTHA and RET were derived and presented in Figure 4. It is worth mentioning that the illustrated dispersions correspond to the record-to-record variability only at each demand-based threshold.



(a) (b)

Figure 4: Median seismic intensities and the associated record-to-record variability recorded at the three selected locations corresponding to the code-based limit-states and evaluated following NLTHA and the response evaluation tool (RET).

The results illustrated in Figure 4 suggest a satisfactory overall performance of the proposed method for the seismic vulnerability vis-à-vis the results of NLTHA. When comparing the outcome of the detailed assessment and RET at the three selected locations, it was seen that the tool was able to provide consistently good estimates across the entire range of response considering the four defined limit-states of NTC2018 and across different seismicity levels. This implies the robustness of the statistical model implemented within the response evaluation tool tailored specifically for infilled RC frame structures. Moreover, similar values of the record-to-record uncertainty were obtained despite the tool having fixed values of dispersion as mentioned in Step 3.i.

3.4. Seismic Risk Evaluation

The seismic risk associated with the pre-defined LS can be promptly evaluated once hazard and vulnerability were characterised. To this end, the MAFE (λ_{LS}) was derived with respect to Equation 2 and illustrated in Figure 5. As such, Figure 5 demonstrates that the proposed method yielded relatively good risk estimates when assessed with reference to "traditional" analysis requiring extensive analyses. The main differences, however, with regards to the risk estimates are attributed to the discrepancy in the dispersion values associated with both methods under scrutiny. This is noticeable, particularly for the SLO LS in Napoli and L'Aquila. However, when comparing seismic risk estimates across the complete range of seismic response, it seems that it was fairly well-characterised highlighting once more the robustness of the proposed method. Moreover, the results illustrated in Sections 3.3 and 3.4 can be considered a testimony for an acceptable trade-off level between accuracy and computational effort required where the latter is minimised, rendering it a potential candidate for inclusion is seismic assessment guidelines, particularly for infilled RC frame structures.

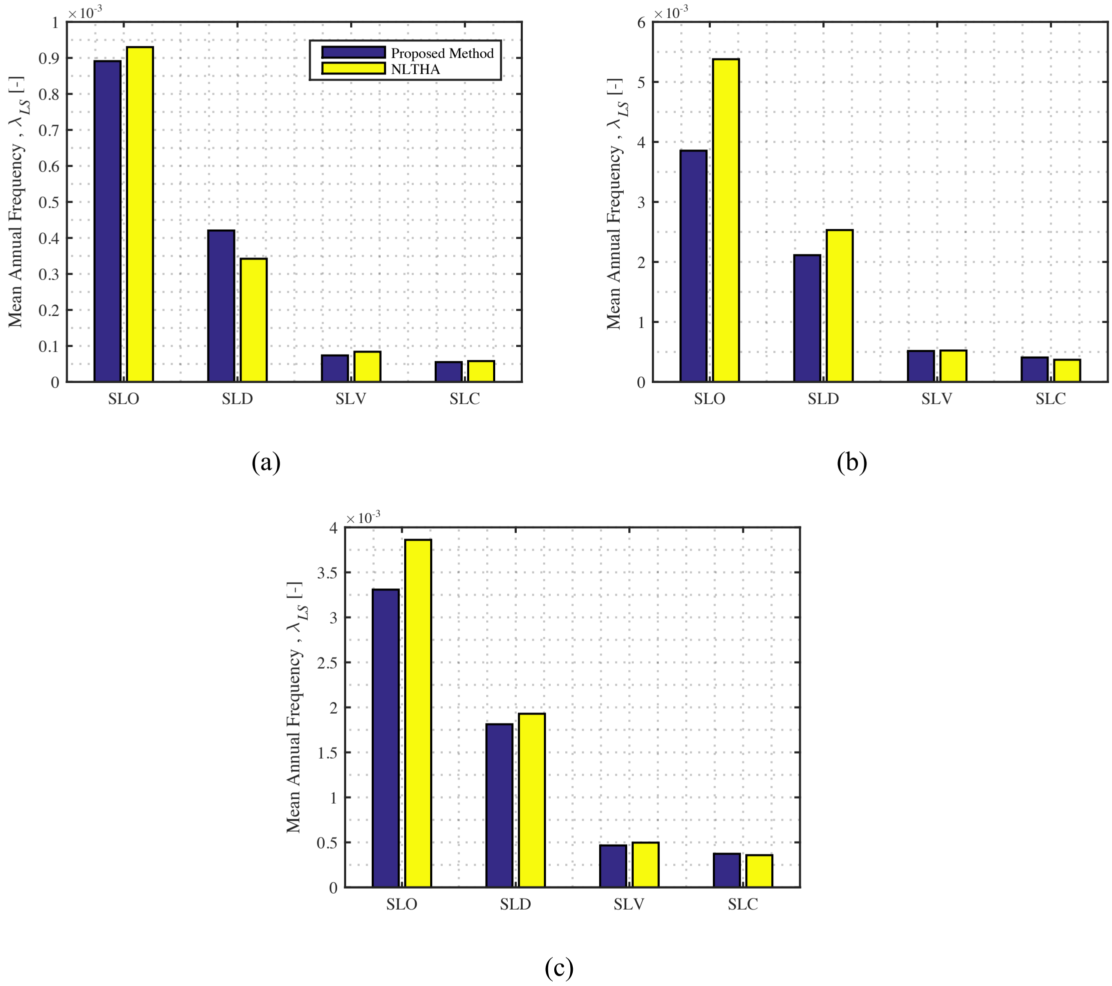


Figure 5: Seismic risk estimates expressed in terms of the mean annual frequency of exceeding the demand-based thresholds corresponding to each limit state (λ_{LS}) evaluated using detailed analysis and the proposed simplified method of assessment for (a) Milano, (b) Napoli and (c) L'Aquila.

4. Conclusions

The accurate seismic risk assessment of reinforced concrete (RC) structures with masonry infills remains an open challenge for practitioners and decision-makers due to their prevalence in the global built-environment and complex behaviour. In risk-based analyses, the proper characterisation of infilled RC buildings based on pre-defined code-based limit-state thresholds is paramount. Furthermore, non-linear time history analyses (NLTHA) methods (e.g. incremental dynamic, multiple stripe and cloud analysis) are computationally expensive in terms of time and effort. To this end, this paper proposed a fast and simple method for the communication of risk in risk mitigation applications for the evaluation of seismic risk which can integrates closed-form expressions for the characterisation of seismic hazard and fragility estimates for risk-based application. The aim of the simplified method is to attempt and facilitate the needs of engineers, and to ease the burden of computationally expensive procedures and address their limitations. Some of the key takeaways of this study are:

- 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.

Acknowledgements

The work presented in this paper has been developed within the framework of the project "Dipartimenti di Eccellenza", funded by the Italian Ministry of Education, University and Research at IUSS Pavia.

References

Basha, Syed Humayun, and Hemant B. Kaushik. 2016. "Behavior and Failure Mechanisms of Masonry-Infilled RC Frames (in Low-Rise Buildings) Subject to Lateral Loading." *Engineering Structures* 111 (March): 233–45. https://doi.org/10.1016/j.engstruct.2015.12.034.

CNR. 2014. "Istruzioni per La Valutazione Affidabilistica Della Sicurezza Sismica Di Edifici Esistenti."

Cornell, C. Allin, Fatemeh Jalayer, Ronald O. Hamburger, and Douglas A. Foutch. 2002. "Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines." *Journal of Structural Engineering* 128 (4): 526–33. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:4(526).

Crisafulli, Francisco J., and Athol J. Carr. 2007. "Proposed Macro-Model for the Analysis of Infilled Frame Structures." *Bulletin of the New Zealand Society for Earthquake Engineering* 40 (2): 69–77. https://doi.org/10.5459/bnzsee.40.2.69-77.

Crowley, Helen, Venetia Despotaki, Daniela Rodrigues, Vitor Silva, Dragos Toma-Danila, Evi Riga, Anna Karatzetzou, et al. 2020. "Exposure Model for European Seismic Risk Assessment." *Earthquake Spectra* 36 (1_suppl): 252–73. https://doi.org/10.1177/8755293020919429.

Dolšek, Matjaž, and Peter Fajfar. 2008. "The Effect of Masonry Infills on the Seismic Response of a Four-Storey Reinforced Concrete Frame - a Deterministic Assessment." *Engineering Structures* 30 (7): 1991–2001. https://doi.org/10.1016/j.engstruct.2008.01.001.

Fardis, M N, and G. M. Calvi. 1994. "Effects of Infills on the Global Response of Reinforced Concrete Frames." In *Proceedings on the 10th European Conference on Earthquake Engineering, Vienna*, 2331–36. Balkema, Rotterdam.

FEMA. 2012. "FEMA P58-1. Seismic Performance Assessment of Buildings: Volume 1 - Methodology (P-58-1). Vol. 1." Washington, DC.

Franchin, Paolo, Francesco Petrini, and Fabrizio Mollaioli. 2018. "Improved Risk-Targeted Performance-Based Seismic Design of Reinforced Concrete Frame Structures." *Earthquake Engineering & Structural Dynamics* 47 (1): 49–67. https://doi.org/10.1002/eqe.2936.

Hak, S., P. Morandi, G. Magenes, and T. J. Sullivan. 2012. "Damage Control for Clay Masonry Infills in the Design of RC Frame Structures." *Journal of Earthquake*

Engineering 16 (SUPPL. 1): 1–35. https://doi.org/10.1080/13632469.2012.670575.

McKenna, Frank. 2011. "OpenSees: A Framework for Earthquake Engineering Simulation." *Computing in Science and Engineering* 13 (4): 58–66. https://doi.org/10.1109/MCSE.2011.66.

Ministero delle Infrastrutture e dei Trasporti. 2018. "D.M Del 17 Gennaio 2018: 'Aggiornamento Delle Norme Tecniche per Le Costruzioni.'" *Supplemento Ordinario Alla "Gazzetta Ufficiale,, n. 42 Del 20 Febbraio 2018- Serie Generale*, 1–198.

Mori, F., A. Mendicelli, M. Moscatelli, G. Romagnoli, E. Peronace, and G. Naso. 2020. "A New Vs30 Map for Italy Based on the Seismic Microzonation Dataset." *Engineering Geology* 275 (September): 105745. https://doi.org/10.1016/j.enggeo.2020.105745.

Nafeh, A.M.B, and Gerard J. O'Reilly. 2022. "Unbiased Simplified Seismic Fragility Estimation of Non-Ductile Infilled RC Structures." *Soil Dynamics and Earthquake Engineering* 157 (June): 107253. https://doi.org/10.1016/j.soildyn.2022.107253.

O'Reilly, Gerard J. 2021. "Limitations of Sa(T 1) as an Intensity Measure When Assessing Non-Ductile Infilled RC Frame Structures." *Bulletin of Earthquake Engineering* 19 (6): 2389–2417. https://doi.org/10.1007/s10518-021-01071-7.

O'Reilly, Gerard J., and Timothy J. Sullivan. 2019. "Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures." *Journal of Earthquake Engineering* 23 (8): 1262–96. https://doi.org/10.1080/13632469.2017.1360224.

Ozsarac, Volkan, Ricardo Monteiro, and Gian Michele Calvi. 2021. "Probabilistic Seismic Assessment of Reinforced Concrete Bridges Using Simulated Records." *Structure and Infrastructure Engineering*, July, 1–21. https://doi.org/10.1080/15732479.2021.1956551.

Pagani, M., D. Monelli, G. Weatherill, L. Danciu, H. Crowley, V. Silva, P. Henshaw, et al. 2014. "Openquake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model." *Seismological Research Letters* 85 (3): 692–702. https://doi.org/10.1785/0220130087.

Parisi, Fulvio, Flavia De Luca, Fabio Petruzzelli, Raffaele De Risi, and Eugenio Chioccarelli. 2012. "Field Inspection after the May 20th and 29th 2012 Emilia-Romagna Earthquakes." http://www.reluis.it.

Pinto, Paolo Emilio, and Paolo Franchin. 2014. "Existing Buildings: The New Italian Provisions for Probabilistic Seismic Assessment." In , 97–130. https://doi.org/10.1007/978-3-319-07118-3_3.

Risi, Maria Teresa De, and Gerardo Mario Verderame. 2017. "Experimental Assessment and Numerical Modelling of Exterior Non-Conforming Beam-Column Joints with Plain Bars." *Engineering Structures* 150: 115–34. https://doi.org/10.1016/j.engstruct.2017.07.039.

Vamvatsikos, Dimitrios. 2013. "Derivation of New SAC/FEMA Performance Evaluation Solutions with Second-Order Hazard Approximation." *Earthquake Engineering & Structural Dynamics* 42 (8): 1171–88. https://doi.org/10.1002/eqe.2265.

Verderame, Gerardo M., Paolo Ricci, Maria Teresa De Risi, and Carlo Del Gaudio. 2019. "Experimental Assessment and Numerical Modelling of Conforming and Non-Conforming RC Frames with and without Infills." *Journal of Earthquake Engineering*. https://doi.org/10.1080/13632469.2019.1692098.