SEISMIC DAMAGE ASSESSMENT OF BUILDINGS USING MODAL PARAMETERS

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ABSTRACT

During an earthquake, a building's overall vibration period generally increases due to alterations in its structural stiffness. The extent of damage, known as the Damage Limit State (DLS), can be assessed either visually or through numerical analyses. These analyses correlate the surpassing of a specific Engineering Demand Parameter (EDP) threshold with reaching a particular DLS for a given earthquake scenario. Evaluating the DLS after an earthquake is essential for determining whether a building remains serviceable.
This study involves the use of numerical time history and pushover analyses on reinforced concrete residential buildings to explore their behavior during seismic events. Pushover analysis was particularly useful in identifying the thresholds associated with various Damage States in infilled RC structures. The primary objective of this research is to establish an initial link between two key factors: first, the damage a building sustains from a specific earthquake scenario, which impacts its serviceability; and second, the elongation of its vibration period, which can be accurately measured using finite element methods (FEM).
The study aims to investigate whether the elongation of a building's vibration period can reliably indicate its damage state and usability after an earthquake. By understanding this relationship, the research seeks to provide a more effective means of assessing post-earthquake building conditions, potentially improving the process of determining whether a structure remains safe for continued use.

Key words: Period Elongation; Damage Detection; Earthquake Engineering; Reinforced Concrete Building;

1. INTRODUCTION

The period of vibration of a structure is mostly influenced by its total mass and stiffness. During an earthquake, damage affects both structural and non-structural elements, leading to a decrease in their stiffness. This phenomenon is known as "period elongation", and essentially, the more severe the damage, the more significant the increase in the period compared to the undamaged state.

The extent of period elongation is a helpful indicator of the building's damage state: higher elongation implies more significant damage. Numerous studies have been conducted on this subject, involving numerical and experimental research [1-16]. However, the relationship between the period elongation and vulnerability assessment of RC buildings with infill walls has yet to be established. In a more

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detailed context, Zembaty et al. [2] conducted experiments using shaking tables on reinforced concrete (RC) frames. Their research illustrated that as damage progressed, there was a noticeable decrease in the effective stiffness of the structures, accompanied by a corresponding decrease in the fundamental frequency. Additionally, Mucciarelli et al. [9] documented the initial strong motion of a European building during the Molise earthquake in Italy in 2002. This building sustained significant damage, and a substantial reduction in frequency, approximately 50%, was observed. Furthermore, Calvi et al. [11] reported that a fundamental period elongation of roughly 150%, equivalent to a 60% drop in frequency, is indicative of an extensively damaged RC building that is nearing a state of collapse.

Nonlinear elasticity of materials has been recently observed by researchers [12-13] in RC buildings under dynamic loading, through real-time monitoring. This phenomenon is due to the nonlinear response of concrete (σ-ε relationship) under low deformations, which results in temporary frequency shifts (period elongation) and is followed by slow dynamics. The latter is a process during which the elastic properties of the material (e.g. elastic modulus) recover fully or partially after the end of an excitation or loading. Nevertheless, in the typical bilinear capacity curve models used for vulnerability modeling, such frequency shift is still considered elastic. Recently, Mori and Spina [15] developed an analytical methodology for estimating the vulnerability of buildings regarding their operational limit state, based on experimental ambient vibration data. The authors also suggested a reduction coefficient for each estimated natural frequency, in order to take into account, the difference between ambient vibration and seismic frequencies, which for the first mode is approximately 0.6.

In the study by Vidal et al. [16], which focused on 34 damaged reinforced concrete (RC) buildings following the Lorca earthquake in Spain in 2011, the authors investigated alterations in the fundamental period and damping ratio. They identified a significant correlation between an elongation in the period and the extent of structural damage. Additionally, the study found that a period elongation of 10-20% could occur even when there was no visually apparent evidence of damage. In a separate study by Ditommaso et al. [17], 68 damaged RC buildings following the L'Aquila earthquake in Italy in 2009 were examined. The research compared the observed fundamental periods to the period-height relationship outlined in the Italian building code. The findings revealed that the highest levels of damage were associated with a maximum period elongation of 100%, while lower damage levels exhibited an elongation of approximately 60%.

This study, it was performed numerical time-history and pushover analyses on 4-story reinforced concrete residential buildings with infills. The results from the pushover analyses were used to determine the thresholds of a set of Damage States (DLSs), while the time-history analyses were employed to evaluate the variation of the period of vibration with increasing ground shaking intensities. The goal is to establish a preliminary relationship between a) the vulnerability of a building under groups of specific earthquake intensity and b) its corresponding period elongation. In the paper's last part, a novel experimental damage detection method will be presented, which is deemed compatible through numerical analysis for identifying seismic damage by analyzing modal parameters.

2. DESIGN, MODELLING AND ANALYSIS OF ARCHETYPE BUILDINGS

4-story RC buildings with infill walls with different seismic design coefficients (i.e., 20 and 10 percent) were considered for this study. This number of stories is common in Portugal. Information about the geometrical and material properties of these archetypes can be found in Table 1 and Fig. 1.

Table 1. Archetype buildings properties.

Structural Type	*Length_X* [m]	*Length_Y* [m]	*fcd* [MPa]	*fsyd* [MPa]
Reinforced Concrete Moment Resisting Frame	25.75	12	7	10.5

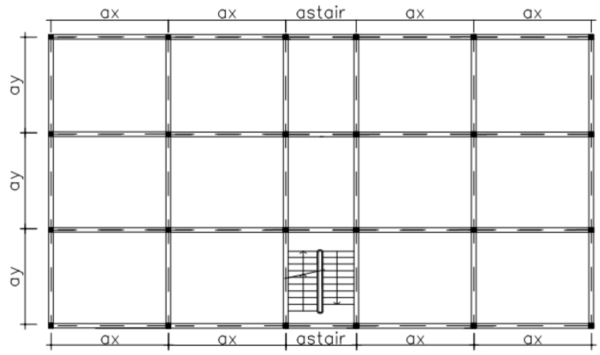

Figure 1. Geometry of buildings under study.

The non-linear behavior of buildings was simulated using the OpenSees software [21], employing a lumped-plasticity model. Structural vulnerability assessment involves significant uncertainty due to variability in ground motion, as highlighted by Shome and Cornell [18]. To address this, careful consideration was given to selecting appropriate ground motion records. The Conditional Spectrum Method (CSM), introduced by Baker [19], was employed to select 180 ground motion records for the numerical analysis. Initially, seismic hazard disaggregation was conducted to estimate the characteristics of the most likely earthquake scenario, followed by the calculation of the mean conditional spectrum. Records that closely matched the mean conditional spectrum were then selected for each intensity level. The response spectra of these selected records are illustrated in Fig. 2.

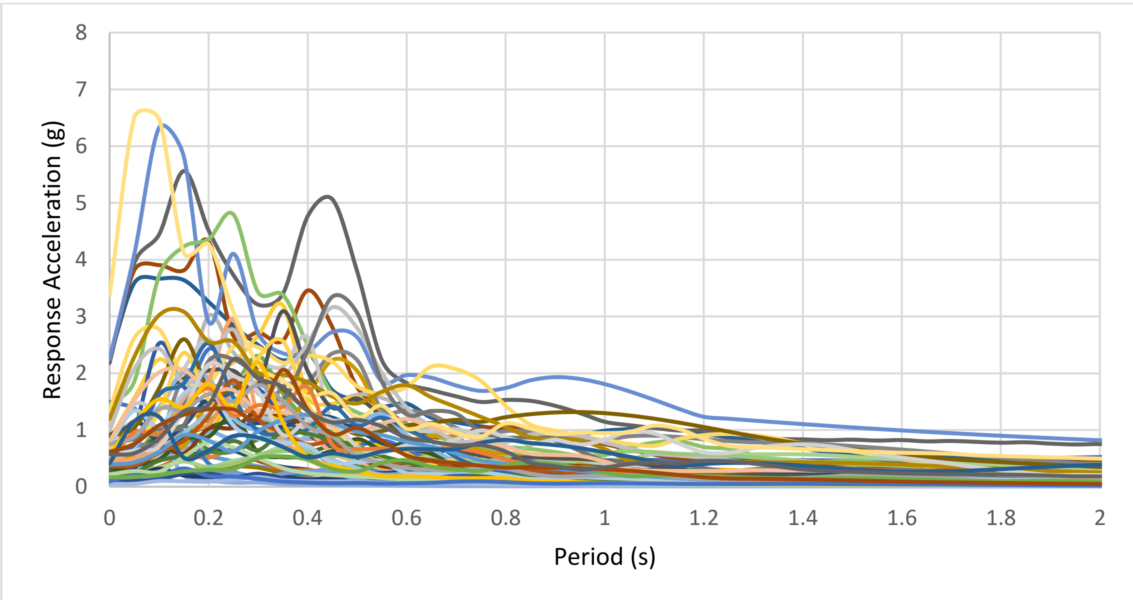

Figure 2. Elastic response spectra of the selected ground motion records conditional to T=0.3s.

Seismic loads were applied to the structure's foundation, oriented perpendicularly to its length. Structural damage was classified into four distinct damage states: slight, moderate, extensive, and complete. The threshold values for each damage state were established based on the expected yield and ultimate displacements.

Traditionally, vulnerability functions were developed from the convolution between fragility models and discrete damage-to-loss models. However, to preserve the variability in the loss estimates, the methodology followed herein, proposed by Silva [20], correlates the expected loss ratio (LR) at different damage states directly with an engineering demand parameter (see example in Table 2).

The maximum displacement of each building was utilized to evaluate the anticipated loss fraction according to the damage model proposed by Silva [20]. Damage states (DS)—ranging from slight to complete—are defined based on the yielding (Sdy) and ultimate (Sdu) displacements derived from the capacity curves. Table 2 outlines the thresholds for each DS and the corresponding average loss ratio (LR). Additional criteria, such as maximum shear capacity, maximum inter-story drift ratio (ISDR), or strain in concrete or steel, can also be employed to define the DS.

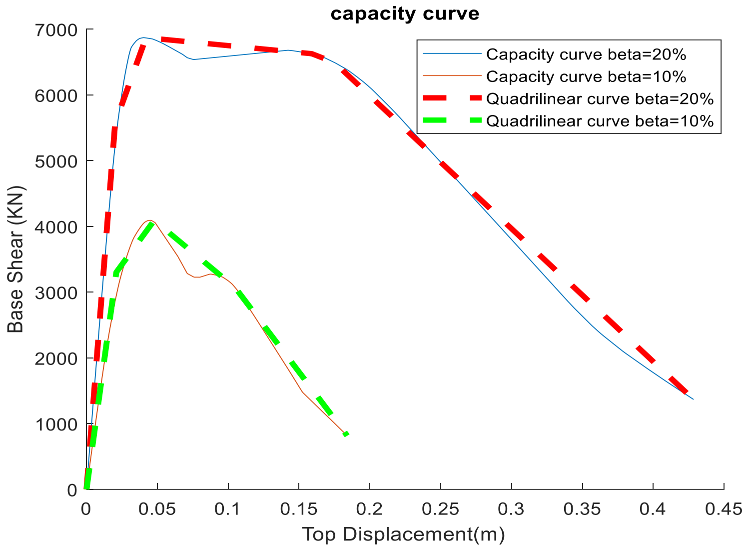

Figure 3. Capacity curve.

Each structure was allocated in a damage state based on the estimated maximum displacement. Then the level of damage could be converted into a fraction of loss based on the assumed average loss ratio. Some damage-to-loss models propose uniform or beta distributions to model the possible range of loss ratios within each damage state. However, within each damage state, such an approach leads to no correlation between the resulting loss ratio and the estimated engineering demand parameter. For this reason, the average loss ratios in this study were assumed as the central value for each damage state, and a linear increase in the loss ratio with the maximum displacement was assumed, as depicted in Figure 4 by the black line. An exception was imposed for complete damage, in which a loss ratio equal to 1 was assumed for a maximum spectral displacement equal to the ultimate point (Sdu). This damage model implies that damage starts when the displacement reaches 75% of Sdy, increases linearly according to the average loss ratio (as defined in Table 2) at the central displacements per damage state, and reaches a total loss when Sdy is reached.

As previously mentioned, these limit state thresholds can also be characterized by significant uncertainty. However, it should be noted that in this study, these thresholds are defined based on the notable points of the capacity curves (Sdy and Sdu) as opposed to assuming a set of pre-established displacements or drifts for all of the building classes [21]. This approach ensures a correlation between the actual structural capacity of each structure and the displacements that mark the initiation of each level of damage.

Combining the damage thresholds computed from the capacity curve (Fig. 3) with the damage-to-loss model in Table 2 produced a discrete relationship between the structural performance and expected loss (depicted in Fig.4 as vertical bars). Connecting the mean damage threshold with linear segments (see Fig. 4) generates a continuous relationship between top displacement and loss used to estimate the expected loss for each ground motion record.

Table 2. Discrete damage to loss model.

Damage State	*Threshold*	*Loss Ratio* [%]
Slight Damage (DS1)	$0.75Sd_y$	5
Moderate Damage (DS2)	$(2Sd_y + Sd_u)/3$	20
Extensive Damage (DS3)	$(Sd_y + 2Sd_u)/3$	60
Complete Damage (DS4)	Sd_u	100

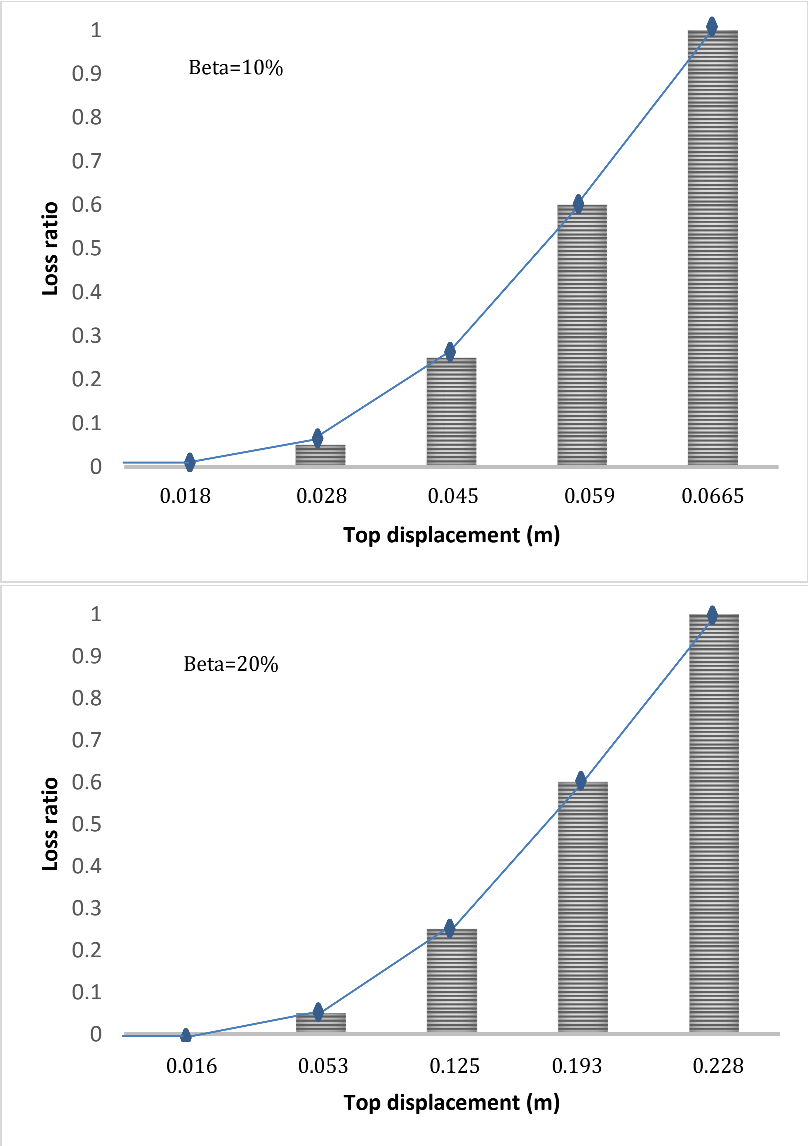

Figure 4. Relation between the LR (Loss Ratio) and Sd (Sdu and Sdy) for each building with

For the case study structures this procedure generated the Associated dispersion between loss values and each ground motion depicted in Figure 5. At each intensity level, the loss ratio was computed and will be used to estimate the vulnerability curve and correlate the period of vibration under different ground motion intensities to the loss ratio.

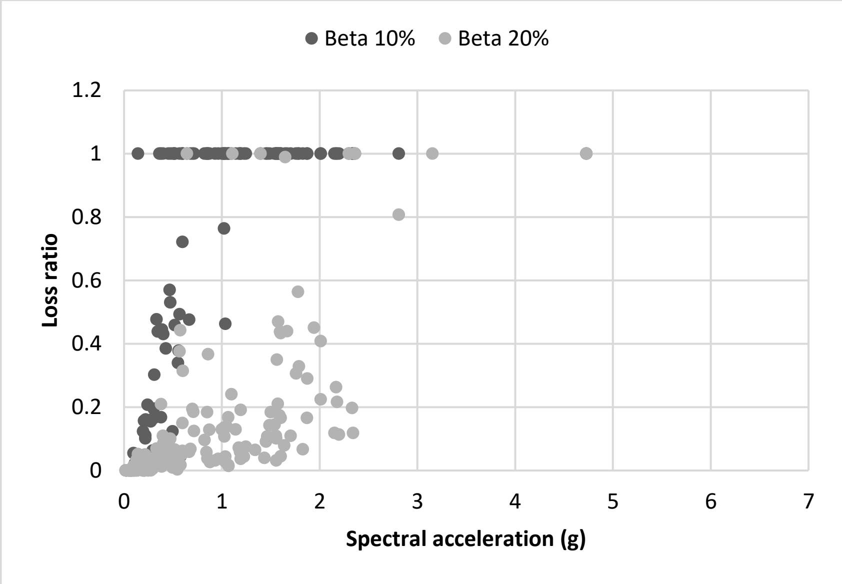

Figure 5. Associated dispersion of ground motion intensity versus loss ratio.

The OpenSees [22] software was chosen due to its capability to perform Eigenvalue analysis to determine the period of vibration of the structure at any step. We estimated the period elongation by comparing the original period (T1) with the period of vibration at the final time step (T2).

After the estimation of the period elongation and the expected loss ratio for each ground motion record, a new vulnerability function was derived, as presented in Figure 6 using the period elongation as the independent variable on the horizontal axis.

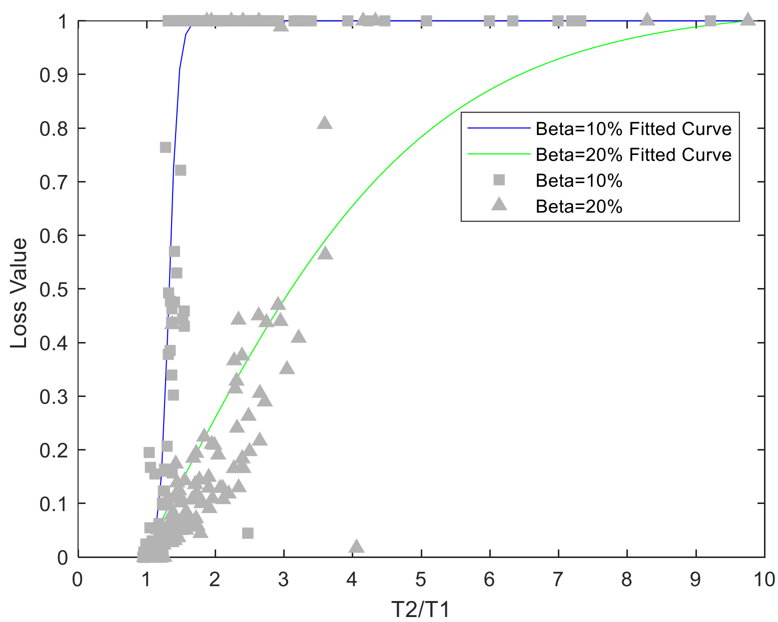

Figure 6. Period elongation versus loss ratio.

Based on the vulnerability results (Figure 6), it is possible to observe that the loss value increased with different values of period elongation depending on the seismic coefficient that the structure was designed for it. Both structures are modeled with infill walls, therefore, the results are near to the actual value. Furthermore, the maximum loss value is reached after the elongated period reaches 2 for the structure not designed for seismic loading (beta=10%), and for the structure that was designed for seismic resistance (beta=20%) the maximum loss ratio happened at high values of period elongation (which shows high stiffness of building and high ductility of infill walls). The period elongation of the structure starts to have loss depending on the stiffness and ductility of the infill panels, and in this paper, the infill panels data arrived from experimental data on the structures in Portugal. This methodology provides a practical tool for rapid damage assessment of structures based on their period elongation to make decisions about the stability of buildings. This numerical analysis was done just for two buildings; however, with more numerical analysis with different buildings, the results will be more comprehensive.

3. INTEGRATING THE PROPOSED NUMERICAL METHODOLOGY FOR DAMAGE ASSESSMENT OF REAL STRUCTURES

The methodology proposed in section 2 has the potential to be integrated into existing engineering practices. In this part, the possibility of using proposed methods through monitoring of the natural period of buildings will be explained. Some sensors (Figure 7) provide long-term vibration based SHM systems information about damages that are not detectable by a mere visual inspection. As an example of these sensors could be mentioned to the Safe hub sensors which is the first IoT-based analytics platform that remotely monitors structural health and provides actionable damage alerts and detailed, building-specific data in minutes that expediting emergency response and recovery based on the period elongation of buildings. Predominant features in damage detection based on period elongation is damage alerts in minutes, expediate emergency response and recovery, prevent unnecessary financial loss, and incidence simulation features. Through these sensors, the period elongation of buildings will be calculated, and based on the values obtained from the sensors, the loss value of the structure will be stimulated based on proposed methodology in section 2.

The method that was proposed in the numerical part (part 2) will estimate the real value of the loss ratio and send an alarm to the buildings with a high level of loss value, which is the conversion of the structural period to the damage alarm of the buildings.

Figure 7. Safe-hub sensor for damage detection of structures based on modal parameters.

Accuracy of the measured frequencies by these sensors is important in damage detection methods and is possible for buildings that are not too stiff. The weakness of the sensors is for buildings with very stiff lateral load resisting systems, and in this case, the accuracy of measured frequency should be checked through accelerometers.

CONCLUSION

This paper delves into how structural monitoring can affect seismic risk assessment and loss estimation by introducing an innovative vulnerability modeling technique that relies on the elongation of the structural vibration period. To explore this concept, the study developed two detailed 3D numerical models of reinforced concrete structures, specifically 4-story buildings situated in Portugal. The researchers conducted nonlinear dynamic analyses to estimate how these structures would respond to seismic events.

This study directly predicts the expected loss for each ground motion record by examining changes in the modal parameters of the structures. Based on the vulnerability results, it is possible to observe that the loss value increased with different values of period elongation depending on the seismic coefficient that the structure was designed for it. Both structures are modeled with infill walls, therefore, the results are near to the actual value. The maximum loss value is reached after the elongated period reaches 2 for the structure with less seismic coefficient, and for the structure that was designed for high seismic coefficient the maximum loss ratio happened at high values of period elongation. The period elongation of the structure starts to have loss depending on the stiffness and ductility of the infill panels. This methodology provides a practical tool for rapid damage assessment of structures based on their period elongation to make decisions about the stability of buildings. This numerical analysis was done just for two buildings; however, with more numerical analysis with different buildings, the results will be more comprehensive.

This novel methodology that was offered by the numerical analysis for calculating the damage and financial losses for structures, could be practical for buildings equipped with specific sensors. These sensors can measure the elongation of the vibration period shortly after the occurrence of significant earthquakes, thereby providing immediate and actionable insights into the extent of damage and associated losses Which was verified by numerical analysis.

ACKNOWLEDGEMENTS

This work is financially supported by national funds through the FCT/MCTES (PIDDAC), under the project PTDC/ECI-EGC/7244/2020 - ASSIMILATE – Assessment of Seismic Safety Integrated with Machine Learning and Tremors, and by: Base Funding - UIDB/04708/2020 with DOI 10.54499/UIDB/04708/2020 (https://doi.org/10.54499/UIDB/04708/2020) and Programmatic Funding - UIDP/04708/2020 with DOI 10.54499/UIDP/04708/2020 (https://doi.org/10.54499/UIDP/04708/2020) of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).

REFERENCES

[1] Arezzo, D., Nicoletti, V., Carbonari, S., & Gara, F. (2021). The tracking of modal parameters for a reinforced concrete building during low-medium intensity earthquakes. In 8th ECCOMAS thematic conference on computational methods in structural dynamics and earthquake engineering. Athens, Greece.

[2] Zembaty, Z., Kowalski, M., & Pospisil, S. (2006). Dynamic identification of a reinforced concrete frame in progressive states of damage. Engineering Structures, 28(5), 668-681.

[3] Di Sarno, L. (2013). Effects of multiple earthquakes on inelastic structural response. Engineering Structures, 56, 673-681

[4] Di Sarno, L., & Amiri, S. (2019). Period elongation of deteriorating structures under mainshock-aftershock sequences. Engineering Structures, 196, 109341.

[5] Gallipoli, M. R., Stabile, T. A., Guéguen, P., Mucciarelli, M., Comelli, P., & Bertoni, M. (2016). Fundamental period elongation of a RC building during the Pollino seismic swarm sequence. Case Studies in Structural Engineering, 6, 45-52.

[6] Katsanos, E. I., Sextos, A. G., & Elnashai, A. S. (2014). Prediction of inelastic response periods of buildings based on intensity measures and analytical model parameters. Engineering Structures, 71, 161-177.

[7] Lin, L., Naumoski, N., Foo, S., & Saatcioglu, M. (2008). Elongation of the fundamental periods of reinforced concrete frame buildings during nonlinear seismic response. In 14th World conference on earthquake engineering. Beijing, China.

[8] Masi, A., & Vona, M. (2010). Experimental and numerical evaluation of the fundamental period of undamaged and damaged RC framed buildings. Bulletin of Earthquake Engineering, 8, 643-656.

[9] Mucciarelli, M., Masi, A., Gallipoli, M. R., Harabaglia, P., Vona, M., Ponzo, F., & Dolce, M. (2004). Analysis of RC building dynamic response and soil-building resonance based on data recorded during a damaging earthquake (Molise, Italy, 2002). Bulletin of the Seismological Society of America, 94(5), 1943-1953.

[10] Trifunac, M. D., Ivanović, S. S., & Todorovska, M. I. (2001). Apparent periods of a building. II: Time-frequency analysis. Journal of Structural Engineering, 127(5), 527-537.

[11] Calvi, G. M., Pinho, R., & Crowley, H. (2006, September). State-of-the-knowledge on the period elongation of RC buildings during strong ground shaking. In Proceedings of the 1st European conference of earthquake engineering and seismology, Geneva, Switzerland, paper (Vol. 1535).

[12] Guéguen, P., Johnson, P., & Roux, P. (2016). Nonlinear dynamics induced in a structure by seismic and environmental loading. The Journal of the Acoustical Society of America, 140(1), 582-590.

[13] Astorga, A., Guéguen, P., & Kashima, T. (2017). Nonlinear elasticity in buildings: a prospective way to monitor structural health. Procedia engineering, 199, 2008-2013.

[14] Astorga, A., Guéguen, P., & Kashima, T. (2018). Nonlinear elasticity observed in buildings during a long sequence of earthquakes. Bulletin of the Seismological Society of America, 108(3A), 1185-1198.

[15] Mori, F., & Spina, D. (2015). Vulnerability assessment of strategic buildings based on ambient vibrations measurements. Struct. Monit. Maint, 2(2), 115-132.

[16] Vidal, Francisco, Manuel Navarro, Carolina Aranda Caballero, and Takahisa Enomoto. Changes in Dynamic Characteristics of Lorca Rc Buildings from Pre- and Post-Earthquake Ambient Vibration Data. Vol. 12, 2014. doi:10.1007/s10518-013-9489-5.

[17] Ditommaso, R., Vona, M., Gallipoli, M. R., & Mucciarelli, M. (2013). Evaluation and considerations about fundamental periods of damaged reinforced concrete buildings. Natural Hazards and Earth System Sciences, 13(7), 1903-1912.

[18] Shome, N. (1999). Probabilistic seismic demand analysis of nonlinear structures. Stanford University.

[19] Baker, J. W. (2011). Conditional mean spectrum: Tool for ground-motion selection. Journal of Structural Engineering, 137(3), 322-331.

[20] Silva, V. (2019). Uncertainty and correlation in seismic vulnerability functions of building classes. Earthquake Spectra, 35(4), 1515-1539.

[21] Ghobarah, A. (2004, June). On drift limits associated with different damage levels. In International workshop on performance-based seismic design (Vol. 28). Ontario, Canada: Department of Civil Engineering, McMaster University.

[22] McKenna, F., Fenves, G., Scott, M. and Jeremic, B. (2000) Open System for Earthquake Engineering Simulation (OpenSees). Pacific Earthquake Engineering Research Center. University of California, Berkeley, CA.