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RAPID SEISMIC DAMAGE ASSESSMENT OF REINFORCED CONCRETE (RC) STRUCTURES BASED ON MODAL PARAMETERS

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ABSTRACT

During an earthquake, the overall period of vibration of the entire structure progressively increases due to the structural stiffness. The extent of damage to the elements, commonly termed as a Damage Limit State (DLS), can be assessed either through visual inspection or by using numerical analyses that correlate the exceeding of a certain Engineering Demand Parameter (EDP) threshold with the attainment of a specific DLS for a specific earthquake scenario. Evaluating the DLS in a building after an earthquake serves as the basis for determining its serviceability. This study conducted numerical time history and pushover analyses on reinforced concrete residential buildings to examine their behaviour during earthquakes. The pushover analysis was used to determine the thresholds for a set of Damage States of infilled RC structures. The main objective of this study is to establish a preliminary relationship between two factors: a) the damages that a building experiences due to a specific earthquake scenario, which determines its serviceability, and b) its period elongation, which can be analytically measured using finite elements methods (FEM). The aim is to determine whether the building's period elongation can be a reliable indicator for assessing its damage state and usability after an earthquake.

KEY WORDS: Period elongation, damage detection, earthquake engineering.

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 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 into temporary frequency shifts (period elongation) and 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 modelling, such frequency shift is still considered as 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%.

In 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. CASE-STUDY BUILDINGS, MODELING, AND ANALYSIS

Two example buildings were considered for this study: 4-story RC buildings with infill walls with different seismic design coefficients (i.e., 20 and 10 percent). Information about the geometrical and material properties of these archetypes can be found in Table 1 and Figure 1.

Table 1. General description of buildings

Structure Type	Length_X (m)	Length_Y (m)	F_{cd} (MPa)	F_{syd} (MPa)
concrete structures	25.75	12	7	10.5

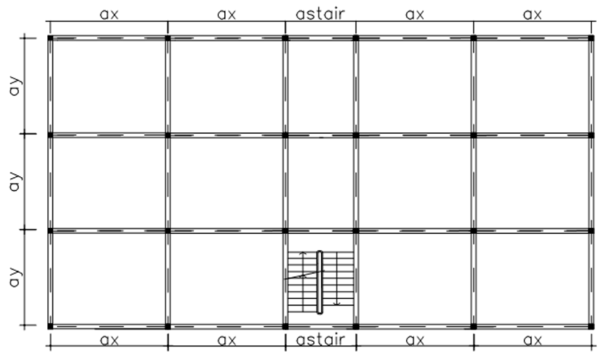

Figure 1. Geometry of case-study building

The non-linear response of buildings was modeled using the OpenSees [21] software by adopting a lumped-plasticity approach. Structural vulnerability assessment is subjected to significant uncertainty due to ground motion, as noted by Shome and Cornell [18]. Therefore, particular attention was paid to the selection of ground motion records. The conditional spectrum method (CSM) proposed by Baker [19] was utilized to select 180 ground motion records used in the numerical analysis. A seismic hazard disaggregation was initially performed to estimate the most probable earthquake scenario's features, followed by an assessment of the mean conditional spectrum. Subsequently, some records with the smallest distance to the mean conditional spectrum were selected for each intensity level. The response spectra of the chosen records are displayed in Figure 2.

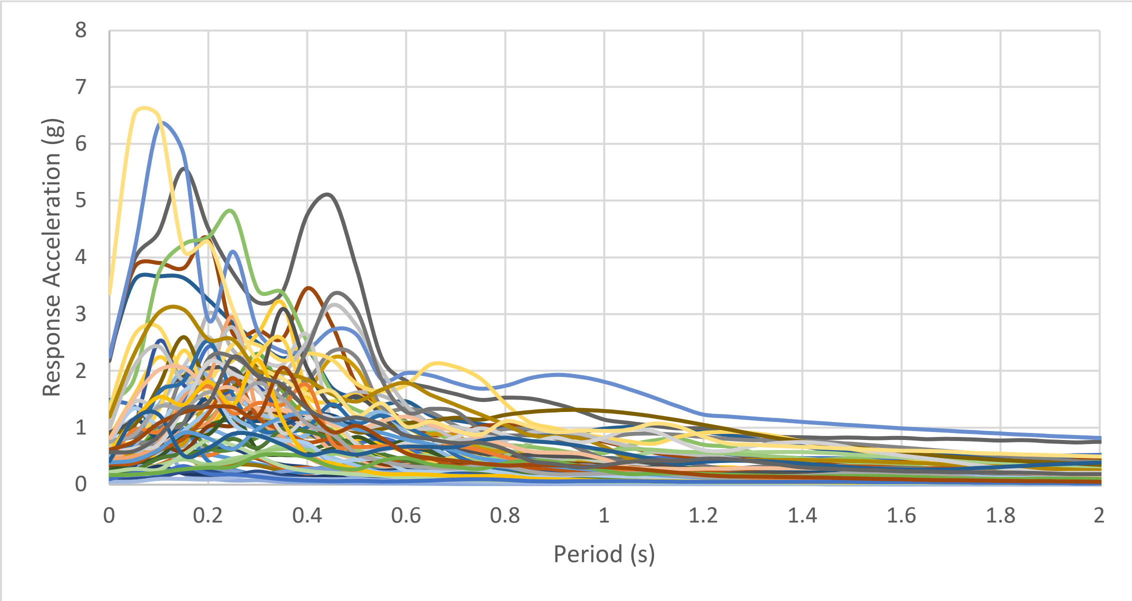

Figure 2. Elastic response spectra of the selected ground motion records conditional to T=0.3s.

The seismic loads were applied to the structure's foundation, perpendicular to its length. The structural damage was categorized into four damage states: slight, moderate, extensive, and complete damage. The threshold values for each damage state were determined based on the anticipated yield and ultimate displacements.

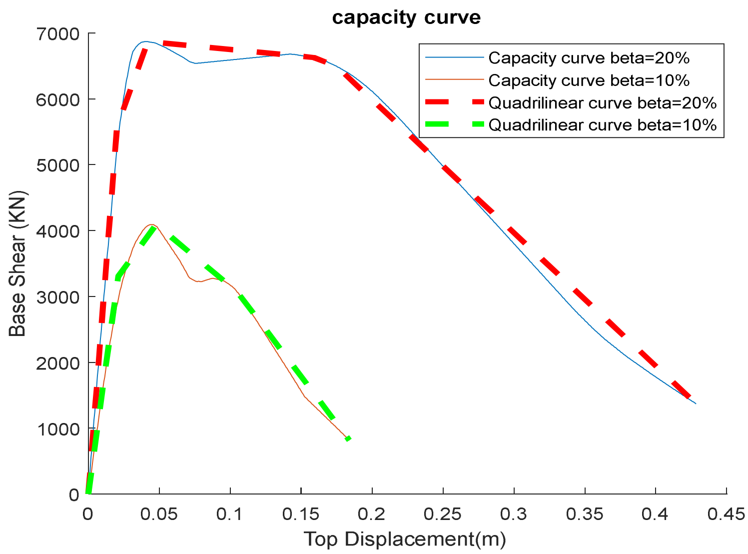

Figure 3. Capacity curve

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 used to assess the expected fraction of loss following the damage model proposed by Silva [20]. A number of damage states (DS; slight, moderate, extensive, and complete) are defined based on the yielding (Sdy) and ultimate (Sdu) displacements from the capacity curves. Table 1 describes the thresholds for each DS and the assumed average LR. Other criteria for the definition of the DS (e.g., maximum shear capacity, maximum inter-story drift ratio (ISDR), strain in the concrete or steel; can also be used.

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 states; However, within each damage state, such 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 a 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 (Figure 3) with the damage-to-loss model in Table 2 produced a discrete relationship between the structural performance and expected loss (depicted in Figure 4 as vertical bars). Connecting the mean damage threshold with linear segments (see Figure 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

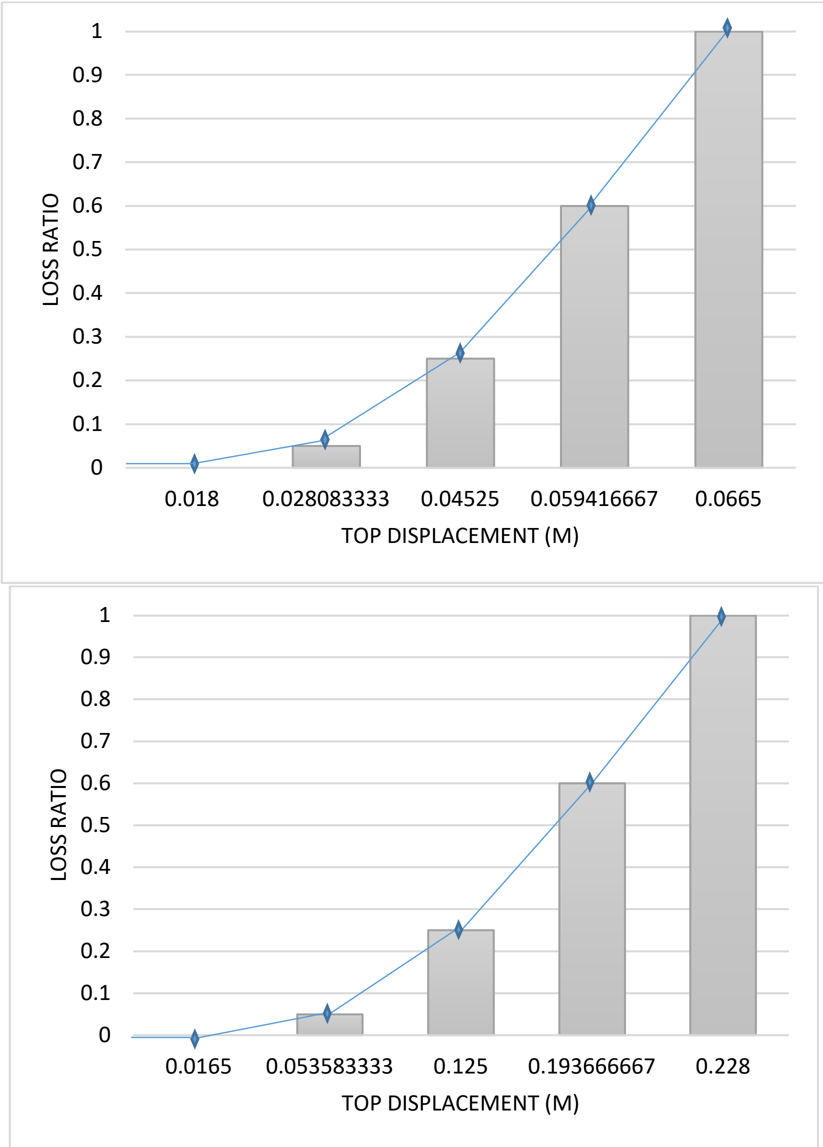

Figure 4. Relation between the LR (Loss Ratio) and Sd (Sdu and Sdy) for each building with; beta=10% (above) and 20% (below)

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 intensity to loss ratio.

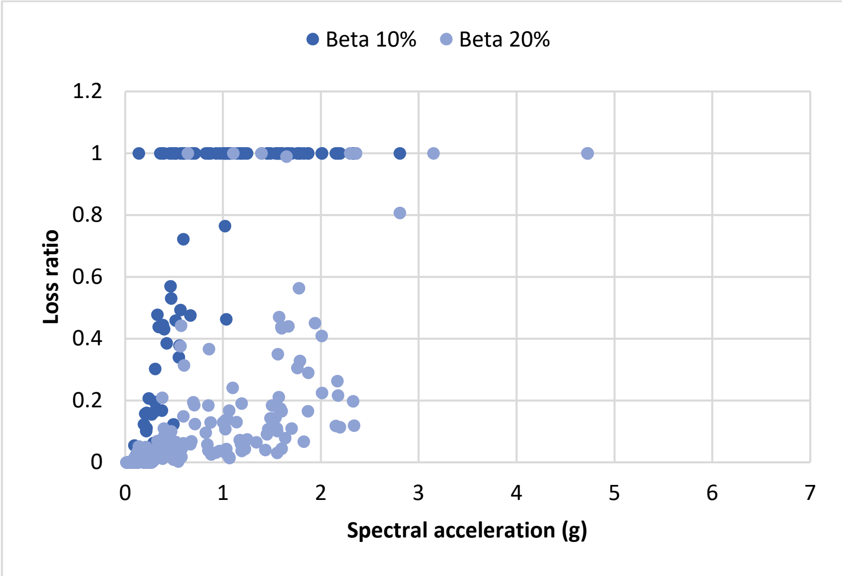

Figure 5. Associated dispersion of ground motion intensity versus loss ratio

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 (T_1) with the period of vibration at the final time step (T_2).

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.

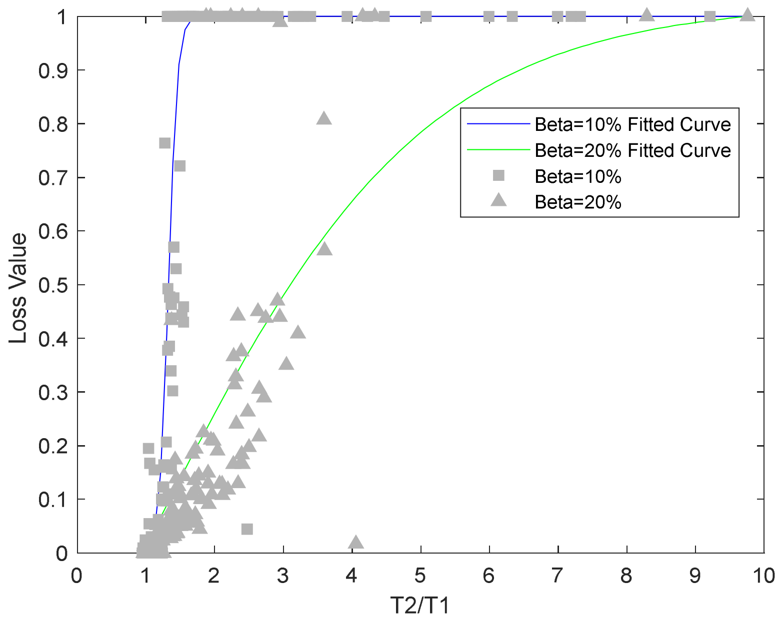

Figure 6. Period elongation versus loss ratio

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 that structure start to have loss depends on the stiffness and ductility of the infill panels and in this paper the infill panels data was 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 decision 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 PROPOSED METHODOLOGY FOR DAMAGE ASSESSMENT OF REAL STRUCTURES BASED ON PERIOD ELONGATION AND ITS CHALLANGES

The methodology proposed in section 2 can be integrated into existing engineering practices through the structural health monitoring methods. Safe hub sensors (figure 7) provide long-term vibration-based SHM systems information about damages that are not detectable by a mere visual inspection. Safehub is first IoT-based analytics platform by remotely monitoring structural health that provides actionable damage alerts and detailed, building-specific data in minutes — expediting emergency response and recovery based on period elongation of buildings.

SafeHub predominant features in damage detection based on period elongation: Damage alerts in minutes, Expediate emergency response and recovery, Prevent unnecessary financial loss, Incidence simulation features.

Through these sensos, the period elongation of buildings will be calculated and based on the values obtained from the sensors the loss value of structure will be stimulated. The method that was proposed in the numerical part (part 2) will be estimated the real value of loss ratio and send alarm to the buildings with high level of loss value which is the conversion of 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 are important in damage detection methods and are possible for buildings that are not too much 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.

4. CONCLUSION

This paper explores the influence of structural monitoring on seismic risk assessment and loss estimation by proposing a novel vulnerability modeling technique based on structural period elongation. Two numerical 3D models of reinforced concrete structures, and 4-story buildings located in Portugal were developed for this purpose. Nonlinear dynamic analyses were performed to estimate the seismic response of the structures. In contrast to the traditional approach of developing fragility models and combining them with a damage-to-loss model to determine vulnerability curves, this study directly predicted the expected loss for each ground motion record based on the changes in the modal parameters. Such model can be used to rapidly calculate damage and losses in structures with sensors, that can calculate the elongation in the period of vibration shortly after the occurrence of destructive earthquakes.

5. ACKNOWLEDGEMENTS

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