Vulnerability Assessment of Reinforced Concrete (RC) Structures based on Modal Parameters

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Abstract. During an earthquake, the gradual deterioration of structural components in a building decreases its stiffness. As a result, the overall period of vibration of the entire structure progressively increases. The extent of damage to these components, 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 buildings. The pushover analysis was used to determine the thresholds for a set of DLS 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. The aim is to determine whether the building's period elongation can be a reliable indicator for assessing its damage state after an earthquake.

Keywords: 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. (2006) [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.

In the study by Vidal et al. [12], 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. [13], 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, we perform numerical time-history and pushover analyses on 3-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.

2 Case-study buildings, modeling, and analysis

Three example buildings were considered for this study: 3-storey RC buildings with infill walls with different seismic design coefficients (i.e., 0, 5, and 10 percent), same dimension, and different compressive design strength of concrete and design yielding stress of steel materials. Information about the geometrical and material properties of these archetypes can be found in following table and fig.1.

Table 1. General description of buildings

Structural Type	Length_X(m)	Length_Y(m)	F_{cd} (MPa)	F_{syd} (MPa)
Infilled RC buildings	25.75	12.00	7.0	10.5

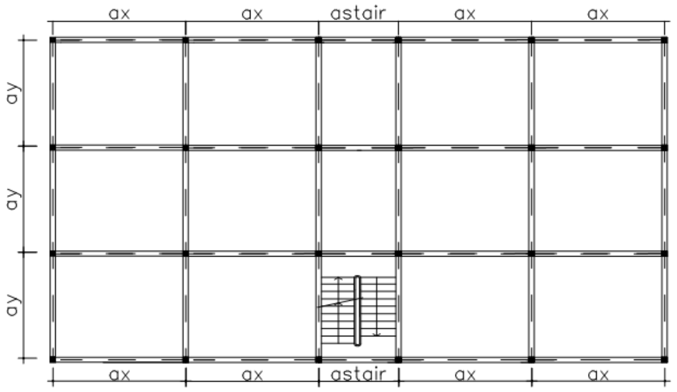

Figure 1. Geometry of case-study building

The non-linear response of buildings was modeled using the OpenSees software (McKenna et al., 2004) by adopting a lumped-plasticity approach. Structural vulnerability assessment is subjected to significant uncertainty due to ground motion, as noted by Shome and Cornell [14]. Therefore, particular attention was paid to the selection of ground motion records. The conditional spectrum method (CSM) proposed by Baker [15] was utilized to select 60 ground motion records used in the numerical analysis. A seismic hazard disaggregation was initially performed to estimate the most probable earthquake scenario's magnitude, distance, and epsilon, 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.

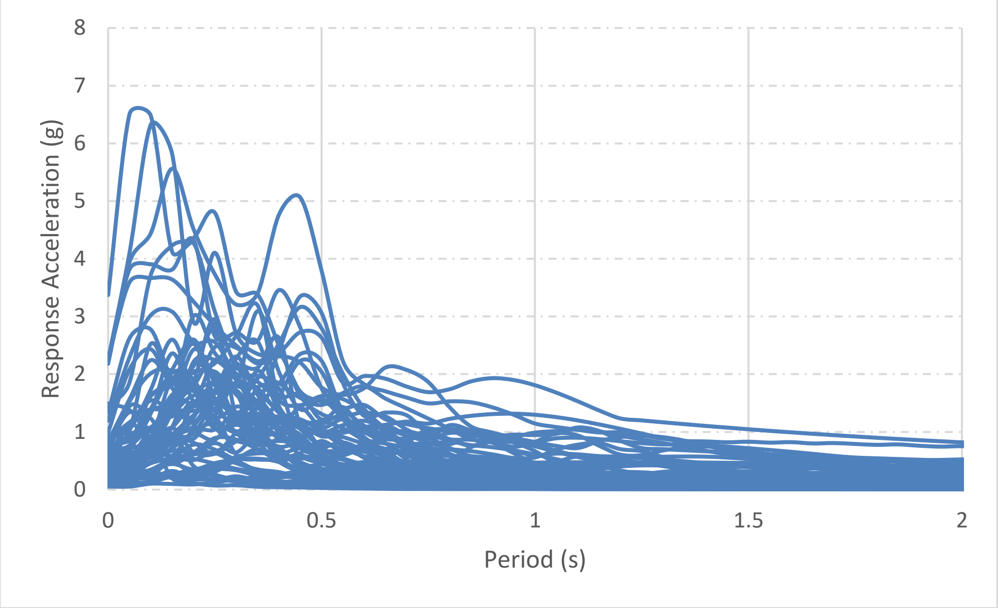

Figure 2. Elastic response spectra of the selected ground motion records conditional to T=0.3s.

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.

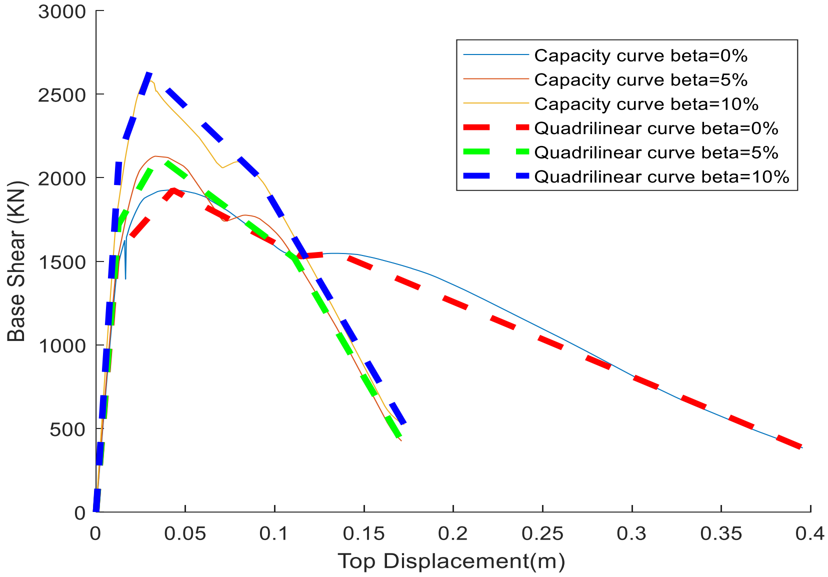

Figure 3. Capacity curve

Typically, vulnerability functions are created by merging fragility models with discrete damage-to-loss models. However, to avoid sudden variations in the loss ratios between different damage states, Silva 2019 [16] proposed to employ continuous distributions of loss ratios between consecutive damage state thresholds, thus allowing correlating directly structural response (i.e., EDPs) to loss ratios. The OpenSees software was chosen due to its capability to perform Eigen value 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 4 using the period elongation as the independent variable on the horizontal axis.

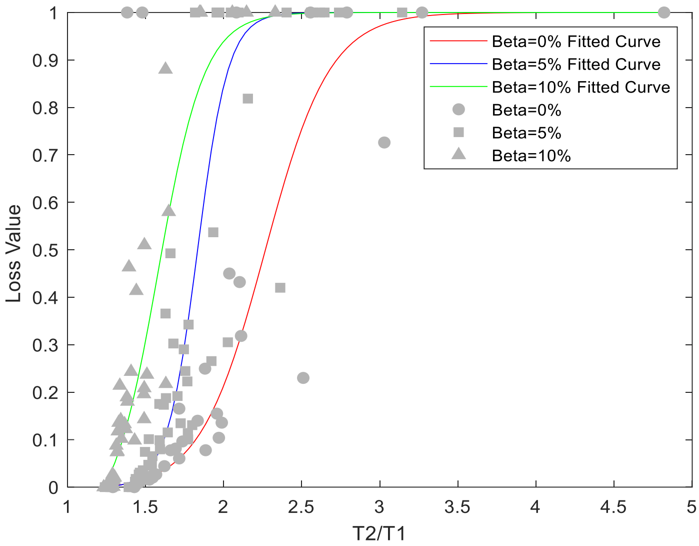

Figure 4. Period elongation versus loss ratio

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. Furthermore, the maximum loss value is reached after the elongated period reaches 2.5 for the structure not designed for seismic loading.

3 Conclusions

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. Three numerical 3D models of reinforced concrete structures, and 3-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.

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