



Seismic Damage Assessment for RC Buildings from SHM Data

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Abstract. In long-term structural health monitoring (SHM), one of the main challenges is to correlate an observed variation in dynamic properties of a structure (i.e., fundamental periods, mode shapes, etc.) to a certain damage level. This correlation is fundamental for an instantaneous damage quantification that can trigger an alert for maintenance works, in the case of minor damage, or for immediate evacuation to protect the life of occupants in the case of a heavy damage. This paper focuses on seismic damage assessment, and adopts a methodology proposed by the authors to quantify the damage experienced in a building from SHM data through numerical analyses. A dataset of 3D existing reinforced concrete buildings representative of structures designed according to non-seismic standards in the Mediterranean region has been selected as a case-study, and non-linear dynamics analyses have been carried out to estimate global damage levels. Modal analyses are performed before and after the dynamic analyses to catch the variation in dynamic properties due to seismic damage. The probability of variation of the fundamental frequency of the structures are assessed for different damage levels.

Keywords: SHM · seismic damage · RC buildings · frequency variation

1 Introduction

Structures may experience slight to severe damage due to extreme events such as earthquakes. A rapid identification of the structural health condition of critical buildings is crucial for timely decision making about interventions, minimizing service disruptions and avoiding economic and societal loss. The use of SHM data for the damage identification and quantification represent a suitable solution for a fast post-emergency management of critical buildings. Several studies in the literature adopted SHM data for the model updating of bridges, churches and towers in order to identify and locate damage [1–7]. Recently, digital twins are proposed as an alternative to FEM models to quickly provide damage information after the occurrence of a seismic event. However, all these procedures require time to develop, train and update such surrogate models for each monitored structure.

The present paper explores the possibility to derive threshold values for the variation of SHM data to be used for a large-scale damage identification and quantification. A dataset of 100 buildings representative of pre-code existing structures in the Mediterranean region is selected for the investigation. For this preliminary study all the buildings in the dataset are governed by a ductile behavior. To quantify the damage, the approach proposed by Lubrano Lobianco et al. [8] is adopted herein. In detail, each 3D building is modelled and subjected to non-linear dynamic analyses with different seismic intensity to simulate slight to severe structural damage. Modal analysis is performed before and after the dynamic analysis to record fundamental frequencies before and after damage. Results in terms of variation of fundamental frequency are analyzed in order to provide the probability of a certain damage level occurrence as a function of the variation in fundamental frequency.

2 Methodology

The approach for the damage quantification through SHM data adopted in this work follows the study of Lubrano Lobianco et al. [8]. In details, the approach consists in correlating a variation in dynamic properties of a structure with a defined damage level. This study is conducted by refined numerical simulations of ground shaking and seismic damage. A FE model is built, and a modal analysis is preliminary performed to record the dynamic properties of the building before damage. Then, the seismic damage is simulated through non-linear dynamic analysis, followed by a modal analysis to record the dynamic properties of the building after damage. In this study, numerical analyses are performed on a dataset of 100 buildings, and variations in fundamental frequencies are recorded before and after damage.

The seismic damage is quantified according to the damage scale proposed by Del Gaudio et al. [9], reported in Table 1. Six seismic structural damage levels are identified, from DL0 to DL5. Each damage level has a qualitative description associated to the EMS98 damage scale for RC buildings. In addition, ranges of maximum interstorey drift ration (MIDR) are associated to each damage level based on the study of Masi et al. [10] for pre-code RC buildings. Structures that experience MIDR lower than 0.10% during the ground shaking are considered undamaged. A MIDR ranging between 0.10% to 0.50% are associated to a slight/moderate damage, whereas MIDRs greater than 0.50% represent a heavy damage or even complete collapse (MIDR < 1.5%).

During each non-linear dynamic analysis, the MIDR experienced by the structure is recorded, along with the fundamental frequencies before and after the ground shaking. Hence, a correlation between the variation in fundamental frequencies due to damage and the selected damage scale is defined.

A previous studies performed by the authors focused on damage quantification for a single building subjected to the L'Aquila earthquake [11]. The present study adopts a probabilistic approach to a dataset of buildings subjected to different ground motions (both in terms of accelerogram and intensity).

Table 1. Seismic damage scale adopted [9, 10].

	EMS 98		MIDR [%]
Damage level	Damage Description		Damage severity
DL0	No damage		<0.10%
DL 1	Slight damage	<i>Fine cracks in plaster over frame members</i>	0.10%-0.25%
DL 2	Moderate damage	<i>Cracks in columns and beams of frames</i>	0.25%-0.50%
DL 3	Heavy damage	<i>Cracks in columns and beams-column joints</i>	0.50%-1.00%
DL 4	Very heavy damage	<i>Large cracks in structural elements; collapse of a few columns</i>	1.00%-1.50%
DL 5	Destruction	<i>Collapse of ground floor or parts of buildings</i>	>1.50%

3 Buildings Dataset Definition

A dataset of 3D RC frame buildings is generated through Latin Hypercube sampling and Monte Carlo simulation. Several parameters are considered as random variables to generate a portfolio of 100 building realizations for each building class. Each realization consists in a combination of random variables representing the geometry of the building, the mechanical properties of materials and the gravity load condition, as summarized in Table 2. In detail, 50 lowrise (2–3 storeys) and 50 highrise (4-storeys) buildings are generated to Monte Carlo simulation. Multi-storey frames with number of bays randomly ranging from 2 to 7 bays are considered in the building portfolios. Geometrical information such as bay span length and interstorey height and infill walls thickness are derived from the knowledge of typical construction practices in the study region.

Typical values of mechanical properties for concrete and steel are taken from the National Group for Earthquake Defence (GNDT) database. Corrective factors to account

Table 2. Random variables.

	Variables	Distribution	Mean (St.Dev)/Range
GEOMETRY	Number of stories	uniform	Low-rise: 2–3 Mid-rise: 4–6
	Number of bays	uniform	2–7
	Bays span	uniform	4–6 m
	Interstorey height	uniform	3 m
MATERIALS	Steel yielding strength	uniform	315–375–430 MPa
	Concrete compressive strength	uniform	15–20–25 MPa
	Factor for concrete compressive strength	normal	1.1 (0.1)
	Factor for steel yielding strength	normal	1.5 (0.1)
LOADS	Dead load – intermediate floor	normal	3.0 (0.5) kN/m ²
	Dead load – roof	normal	2.5 (0.5) kN/m ²
	Live load	constant	3.0 kN/m ²

for uncertainties in concrete and steel strengths are taken from [12]. Statistics for the gravity load are also based on the GNGT data.

For each building realization, consisting in a combination of the random variables reported in Table 2, a structural model is built following a simulated design process. This is needed to derive missing information about the dimension of structural components and the reinforcement details required to perform the structural analyses. This preliminary study focuses on existing buildings built before ‘80s and designed for gravity loads only according to the Italian Regio Decreto 1939 [13]. Columns are dimensioned based on the axial load demand, in order to not exceed the concrete allowable compressive stress. A minimum longitudinal reinforcement ratio (i.e., 0.8% of the gross area) and a light transverse reinforcement are adopted, as commonly found in old existing structures.

4 FE Analyses

The FE models of the 3D buildings dataset are made in *OpenSees* [14]. Both column and beam elements are modelled by using *nonlinearBeamColumn* elements with a Hinge-Radau integration. In the region defined as a plastic hinge, a fibre section with a patch square and a subdivision number equal to 30x30 is assigned for the concrete fibres, while a straight layer with a number of fibres equal to the reinforcing bars present in the cross-section is assigned for the steel fibres. The concrete compressive behavior is modelled with the *Concrete01* model, while the steel is modelled with the *Hysteretic* model. Out of the plastic hinge zones, an elastic material is assigned. The buildings in the dataset are governed by a flexural failure mode, hence the shear behavior of the columns is not modelled. A fixed constrain is considered at the end of ground storey columns, and rigid diaphragms are assigned at intermediate floors. The in-plane response of infill walls is not considered in this preliminary analysis.

Masses are computed based on the dead and live loads in Table 2, and are applied at the centroid of each floor.

Non-linear dynamic analyses are performed using five different accelerograms randomly selected for each building in the dataset. In detail, the following accelerograms are adopted: Central Italy (Mw 6.5), L’Aquila (Mw 6.1), Emilia (Mw 6.0), Friuli (Mw 6.0) and Irpinia (Mw 6.9). Each accelerogram is then scaled to simulate ground shaking of different intensities (i.e., 60%–80%–100%–125%–150%). A total of 500 non-linear dynamic analyses are performed, and results in terms of natural frequencies before and after damage and of MIDRs are collected and further analyzed in the following section.

5 Results and Discussion

Results from numerical simulations have been analyzed in terms of variation of natural frequency before and after damage for each damage level defined in Table 1. The probability of occurrence of a certain damage level over the dataset of buildings is plotted in Fig. 1 for the lowrise (Fig. 1a) and highrise (Fig. 1b) buildings. Probability distributions are depicted as a function of the form factor FF of the building, here defined as the ratio between the two dimensions of the building’s plan. Given the intensity of the selected ground shaking, any building in the dataset experienced a DL0 (i.e., no damage), and very few buildings experienced a DL1 or DL2. Conversely, several records are collected for DL3 to DL5.

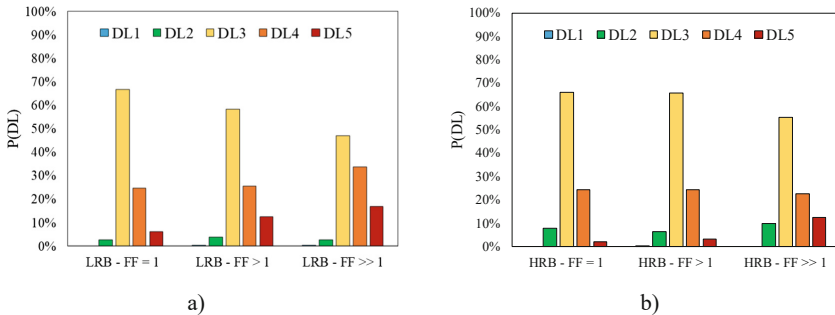


Fig. 1. Probability of occurrence of a certain damage level the lowrise (a) and highrise (b) datasets of buildings.

The variation of the natural frequency of the buildings in the direction of the ground shaking, Δf , is then correlated to the probability of occurrence of each damage level, as shown in Fig. 2 for the full dataset of buildings. The probability function is represented by a lognormal curve which fits the numerical observation according to the Least Square Estimation method. The low number of numerical data for DL1 reduces the accuracy of the probability distribution for this damage level. Conversely, the other curves perfectly match with the numerical observations. The curves attest that, for the dataset of buildings under investigation, a frequency variation greater than 60% can be associated with the collapse of the building. These curves allow a fast estimation of the probability for

monitored buildings to experience a certain damage level during a seismic event in a large-scale approach.

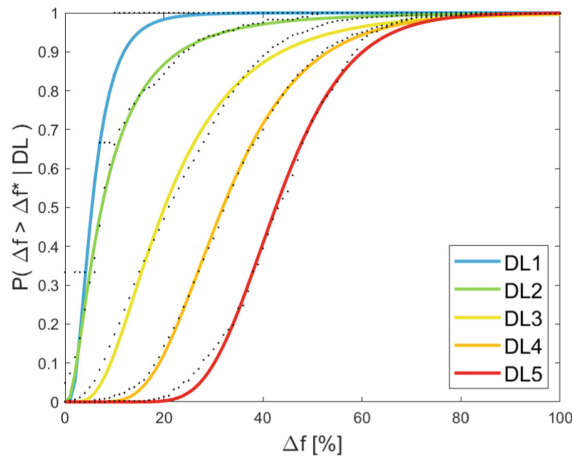


Fig. 2. Probability of occurrence of a certain damage as a function of the fundamental frequency variation Δf for the full dataset of buildings.

Curves are also plotted for the two datasets of lowrise and highrise buildings in Fig. 3 in order to reduce the uncertainties related to the height of the building. The plots show that for the highrise buildings subjected to ground motions compatible with the ones selected for this study, damage levels are achieved for lower variations of natural frequency with respect to the lowrise buildings. For instance, a frequency variation of 20% in a highrise building implies a probability of 26% of DL4, of 60% of DL3 and of 90% of DL 2. Conversely, the same frequency variation in a lowrise building implies a probability of 1% of DL4, of 22% of DL3 and of 64% of DL 2.

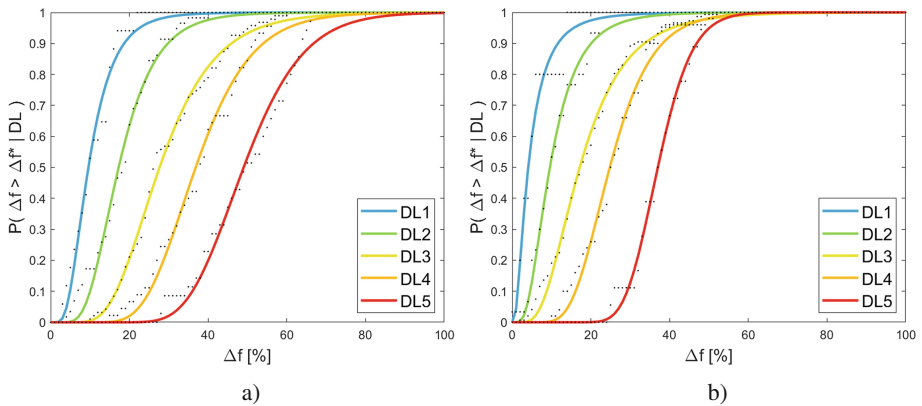


Fig. 3. Probability of occurrence of a certain damage as a function of the fundamental frequency variation Δf for the lowrise (a) and highrise (b) datasets of buildings.

Such probability distributions can be combined with uncertainties related to environmental effects that might cause variations in natural frequencies not correlated to any damage condition in order to provide tools for the fast damage assessment of buildings at urban scale.

6 Conclusions

The present study preliminary explores a large-scale approach for the seismic damage assessment of RC buildings from SHM data. In detail, a dataset of 100 buildings representative of existing structures in the Mediterranean area is generated through Monte Carlo simulations and subjected to non-linear dynamic analyses. Uncertainties in geometrical and mechanical properties as well as in gravity loads and ground motion are considered. The damage level experienced by the buildings in the dataset is assessed following a defined damage scale based on the MIDR. The variation of fundamental frequency before and after damage is recorded in order to provide a correlation between frequency variation and damage level.

Based on the results of this preliminary study, fragility functions correlating the variation of fundamental frequency with the probability of occurrence of a certain damage level are derived for the full database of buildings and for the datasets of lowrise (2–3 storeys) and highrise (4–6 storeys) buildings. Results attest that a variation of fundamental frequency greater than 60% can be associated with the collapse of the structure. Furthermore, damage in highrise buildings occurs for lower frequency variations with respect to lowrise buildings for the seismic scenarios investigated.

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