Evaluation of the seismic retrofitting of an unreinforced masonry building using numerical modeling and ambient vibration measurements

Clotaire Michel\textsuperscript{a,⁎}, Amin Karbassib, Pierino Lestuzzi\textsuperscript{b}

\textsuperscript{a} Swiss Federal Institute of Technology Zurich (ETHZ), Sonneggstrasse 5, 8092 Zürich, Switzerland
\textsuperscript{b} École Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland

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A B S T R A C T

Ambient vibration measurements and 3-D nonlinear time-history numerical modeling are used to assess the retrofitting measures conducted in a 6-story unreinforced masonry building (URM) built in the end of the 19th century in Switzerland. Retrofitting measures were taken in order to improve the soundproofing and possibly the seismic performance of the building. Reinforced concrete (RC) footings were added under the walls and horizontal steel beams were added to link the walls together with a RC slab at each floor, though the wooden beams were left in place. Several ambient vibration recordings were performed before, during and after the retrofitting work in order to monitor the evolution of the dynamic behavior of the structure. Moreover, numerical models representing the state of the building before and after the retrofit work have been developed to perform nonlinear dynamic analyses using various ground motion records. The change in the modal vibration frequencies, mode shapes, and failure mechanism are presented and discussed in further details. According to ambient vibration measurements, the performed retrofitting resulted in an increase of about 25% of the fundamental frequency. From the results of both the numerical modeling and the ambient vibration measurements, it is confirmed that the in-plane behavior of the slabs evolved from non-rigid floors with in-plane deformation to rigid floors with diaphragm effects. The ambient vibration measurements show that the new stiff slabs could lead to torsion behavior in the building as the result of the diaphragm effect and to higher seismic demand. However, the numerical models show that the displacement capacity of the building increases as a result of those new stiff slabs. Consequently, higher deformation capacity, indicated by the inter-story drift values, on average, are observed for all the damage grades in the post-retrofit state of the building. Finally, the overall seismic safety was only slightly improved.

1. Introduction

Since a large part of buildings around the World and especially in Northern Europe, were built without or with insufficient seismic provisions, seismic assessment of existing buildings is a critical and endless issue to be solved by earthquake engineering [1]. Cost-benefit approaches for the assessment and retrofit of existing buildings in Switzerland started to be used on a day-to-day basis in 2004 with the Pre-standard SIA2018 [2]. This Pre-standard provides guidelines on the measures to undertake to improve the seismic safety of a building taking into account the seismic risk, and in case, if retrofitting measures are commensurate. The results provided by the prescribed method are, however, quite rough, and the effects of an eventual retrofit needs to be more finely quantified.

Different seismic retrofitting measures have been proposed for unreinforced masonry (URM) buildings. Examples are: adding sandwich columns to partition brick walls [3], jacketing of columns, adding structural walls, and construction of a mat foundation [4], reinforced cement jacketing of the main load carrying walls [5] and using Fiber-Reinforced Polymers [6,7]. The effect of those retrofitting measures has been assessed using a variety of methods including Finite Element numerical modeling [8,9] and vibration measurements [9]. One of the common measures to retrofit existing URM buildings in Europe is to create composite slabs by adding a reinforced-concrete (RC) layer over the existing wooden floor or even to replace it by a RC floor. This measure is generally proposed to improve the comfort and the soundproofing of the building, and is thought to be beneficial for the seismic behavior, as well. As a result, the masonry walls are linked together creating a diaphragm effect, which also prevents out-of-plane collapse of the walls [10,11].

This paper presents the evaluation of the retrofitting measures on a typical residential building in Switzerland [12]. The studied building is...
a 6-story simple stone unreinforced masonry building located in Lausanne Switzerland (Fig. 1) built in the end of the 19th century. The quality of masonry is poor since different bloc sizes and materials were used. The width of the walls varies from 25 to 70 cm, and its average story height is 3 m (Fig. 2). The mortar quality was also observed to be poor as it would crumble in hand under fingers’ pressure. The structure is regular and not surrounded by any other building. The structural plan is rectangular (14 m by 12 m), with wooden attics at the top (6th floor) and thinner walls at the 5th floor. Originally, no rigid diaphragm existed in the building, as shown in Fig. 3a. Retrofitting measures were taken primarily in order to improve the soundproofing of the building. Qualitatively, these measures also aimed at improving the seismic safety. Horizontal steel beams were added at each floor to link the walls, together with a mixed slab, connecting the original wooden beams to a 7 cm thick RC slab (Fig. 3). Moreover, one longitudinal wall that had not been fully connected to the wooden slab was carefully connected to the new RC slab. RC footings were added under the walls. The foundation ground is made of a layer of moraine of likely 10–20 m thickness laying on weathered Molasse rock [13]. The precise ground profile is unknown since the closest available profile is located 200 m away.

The method to assess the retrofitting work is based on two complementary techniques. Several ambient vibration recordings were performed before, during and after the retrofitting work in order to monitor the evolution of the dynamic behavior of the structure. Moreover, numerical models representing the state of the building before and after the retrofit work have been developed to perform nonlinear dynamic analyses using various ground motion records. Changes in the dynamic behavior should prove the effectiveness of the retrofitting, especially a change in the diaphragm effect. Using ambient vibrations, properties of the soil and features regarding soil-structure interaction can be evaluated, as well. These qualitative observations at low amplitudes are then used to validate [14,15], as realistic as possible, a non-linear numerical model using the Applied Element Method [16]. The numerical model provides the failure modes of the structure subjected to various ground motion records. Moreover, using many scenario earthquakes before and after the retrofitting measures, the safety of the structure is evaluated in both stages. It should be noted that, due to the simplifications in the numerical models and other uncertainties in the dynamic properties of structures, especially for URM buildings, no model updating (e.g. [15]) is undertaken in this study.

The objectives of this paper are to assess the effect of the retrofitting measures and to quantify the improvement in the seismic vulnerability of the building, which leads to the quantification of the gain in seismic safety. It aims at evaluating this retrofitting solution but does not provide a performance-based analysis for this particular case, i.e. for the local hazard. To this end, an original evaluation methodology is proposed based on in situ ambient vibration recordings and advanced nonlinear 3-D numerical modeling using Applied Element Method.

2. Experimental modal analysis

In order to evaluate in situ effect of the retrofit work in the URM building, we propose to compare the building’s pre- and post-retrofit modal properties. Modal frequencies of civil engineering structures are synthetic measurable parameters that characterize the ratio of the stiffness of the structure over its mass. Since the mass of structure does not generally change much, they are used in Structural Health Monitoring to follow variations of the structural stiffness [17]. For retrofitting works, mass is generally added to the system (new RC slabs here), which complicates the interpretation. Moreover, modal shapes are directly sampling the structural behavior under a dynamic loading. Understanding this behavior (diaphragm effect, torsion, dominance of bending or shear) is crucial to validate hypotheses of numerical modeling.

For that purpose, operational modal analysis, based on ambient vibration (AV) recordings, is selected as it is easy to implement. Ambient vibrations result mainly from human activities (e.g., industrial machines, traffic) at frequencies above 1 Hz [18]. In addition to the quasi-stationary signals from those sources, transients such as footsteps close to a sensor could affect the stationary properties of the signals, and should be avoided in the analysis. Simultaneous recordings in the building, using a reference in a corner of the last floor and rover sensors are performed, as well as recordings on the ground, outside the building. Datasets of 15 to 30 mins are recorded at different steps before, during and after the works.

The easiest way to obtain modal information from ambient vibration recordings is to calculate the Power Spectral Density (PSD), for instance using Welch method [19]. First, to make sure that only stationary signals are used, 50% overlapping tapered time windows of the data are selected using an anti-triggering Short Time Average Long Time Average (STA/LTA) algorithm. Then, the Fourier Transforms of those windows are averaged and squared. The peaks in the spectra can be either due to ambient loading, internal sources or structural modes. Very sharp peaks can be ignored in the interpretation since they are due to un-damped forced motions that cannot be structural modes.

In order to extract the modal parameters of the structure (resonance
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