16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

AMBIENT VIBRATION TESTS ON A BUILDING BEFORE AND AFTER THE 2012 EMILIA (ITALY) EARTHQUAKE

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ABSTRACT

Structural monitoring of strategic buildings is an important tool for the identification of dynamic characteristics changes caused by an earthquake, of primary interest to prevent potential damage due to future seismic events or even to assess the capability of a seismic retrofit to the damaged structure. Recent studies have shown how these variations can be assessed with special focus on the permanent and transient decrease of the main frequency during ground shaking. In this work, we analyzed three data set acquired on one building of the University of Ferrara (Emilia Romagna Region, Northern Italy). Ambient noise surveys were performed at each floor of the building: the first data set was acquired few months before the earthquake that struck the Emilia region on May 20, 2012; the second was acquired right after the earthquake, when the building showed slight damage; finally, the third data set was acquired in 2016, after the repair of seismic damage occurred to non-structural components. The analysis of those data sets highlighted the permanent drop of the building main frequency after the earthquake due to damage, with its partial recovery after the repair of seismic damage. This study demonstrates that building monitoring, even with low-cost instruments, allows understanding if and how the building main frequency changes due to an earthquake, providing a preliminary assessment of possible damage. Low-cost monitoring systems can therefore be considered a valuable prevention and monitoring tool for structures.

Keywords: Structural health monitoring; Microtremors; HVSR; Emilia earthquake; Non-structural damage

1. INTRODUCTION

The structural monitoring of a building is an important tool for the identification of its dynamic characteristics and the estimation of their possible changes over time as a result of structural degradation due to earthquakes, aging and/or long-term, intense, operational demands. In seismic engineering, the assessment of the damage caused by an earthquake and the subsequent structural monitoring is of primary interest to prevent potential damage due to future seismic events or even to assess the capability of a seismic retrofit to the damaged structure. Actually, particular attention is paid to safety of public/strategic building for Civil Protection authorities to gain useful information in

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deciding if a building is safe for use, requires inspections or has to be abandoned, according to the three thresholds usually adopted after earthquake crisis for building inventory. Permanent instrumentation can then provide relevant detection of changes based on frequency drop observation. This requires a continuous recording, also because the frequency recovery may be long, and can therefore provide false alarm situation if the interpretation of the frequency drop is not complete.
The physical meaning of instantaneous frequency variation is a crucial point that must be explored in depth since the monitoring of the building frequency is certainly the easiest way for the assessment of the building behavior and its structural health monitoring. Recent studies (e.g., Mucciarelli et al., 2004; Clinton et al., 2006; Dunand et al., 2006; Pai et al., 2008) have shown how these variations can be monitored for structural health monitoring with special focus on the permanent and transient decrease of the frequency value during ground shaking. Therefore, the important issue is to know how the fundamental frequency drop observed during the occurrence of weak to strong earthquakes could be considered as a proxy of the damage. Observations about the fundamental frequency variation due to damage can be traced back both to Clinton et al. (2006), for the Millikan Library buildings which has experienced several earthquakes, and to Dunand et al. (2006) who studied some buildings during the 2003 Boumerdès earthquake. From weak to strong motion, Hans et al. (2005) and Michel et al. (2008, 2010) have reported the variation of the fundamental frequency of buildings related to the opening of cracks in the elastic domain. Such nonlinearities may produce a recoverable frequency decrease of about 35% during excitation. On the other hand, it seems that a 60% permanent drop in frequency is a limit before the collapse according to data compiled by Calvi et al. (2006). During the most recent Italian earthquakes particular attention was paid to study and assess the permanent and/or transient frequency drop in more detail in R.C. buildings. For example, the earthquakes recorded in the Navelli town hall during the 2009 Abruzzo earthquake revealed multiple temporary period elongations which did not correspond to an increase of damage (see for example Mucciarelli et al., 2011); similarly, during Pollino seismic swarm sequence in September 2011- October 2012, the temporary variation of the fundamental period of the Rotonda school was observed for different levels of motion of earthquakes,but any damage has been reported (Gallipoli et al., 2016). A permanent period shift accompanied by damage was observed during Molise earthquake, 2002 (Mucciarelli et al., 2002), and Emilia earthquake, 2012 (Masi et al., 2014); in both the above-mentioned cases the buildings had already suffered damage before the installation of the monitoring system.
In this work, we analyzed three data set acquired on one building of the University of Ferrara (Emilia Romagna Region, Northern Italy). The first data set was acquired by seismic ambient noise recordings in different points of the building few months before the earthquake that struck the Emilia region on May 20, 2012. The second was acquired also by seismic ambient noise recordings, right after the earthquake when the building showed slight damage. Finally, the third data set was acquired two years after the repair of seismic damage occurred tonon-structural components.
The building of the University of Ferrara represents an important case study for two aspects:

- The main frequency has been estimated before any damage, so the frequency drop has been monitored before and after the strong motion due to the May 20, 2012, Emilia earthquake;
- The monitoring had permitted to estimate how the repair of damage has impacted to the building main frequency.

2.THE BUILDING OF THE UNIVERSITY OF FERRARA DAMAGED BY THE MAY 20, 2012, EMILIA EARTHQUAKE

The investigated building belongs to the scientific pole of the University of Ferrara. From the geological and seismo-tectonic point of view, the city of Ferrara is located in a tectonically active area characterized by low to medium hazard, with an expected maximum acceleration for an exceedance probability of 10% in 50 years within 0.125 and 0.150 g. In 2012, the area was affected by the Emilia seismic sequence (Galli et al., 2012; Tertulliani et al., 2012; Govoni et al., 2014) characterized by two main events occurring on May 20 and May 29 with local magnitude (Ml) respectively equal to 5.9 and 5.8, and with each event followed by several aftershocks (Fig. 1). The seismic sequence is related to the buried active front of the Romagna and Ferrara fold and thrust belt, which represents the advanced northern rim of the Apennines mountains (Priolo et al, 2012). It is overlain by a thick succession of Pliocene and Quaternary sediments forming a wedge-like shape of sediments underlying the Po Plain. The two major events caused 27 fatalities as well as the most of the damage to residential buildings, industrial facilities and public buildings. During the seismic sequence the epicentres migrated westward for about 15 km. For example, the urban centre of Ferrara was 27 km epicentral distance from the May 20 shock and 42 km epicentral distance from the May 29 shock. The earthquakes caused heavy damage in several villages mainly located in Emilia region, where MCS (Mercalli–Cancani–Sieberg) intensity values ranging from V to VII–VIII degree were observed (Galli et al. 2012). In the city of Ferrara, the final MSC intensity was V degree (Galli et al. 2012).

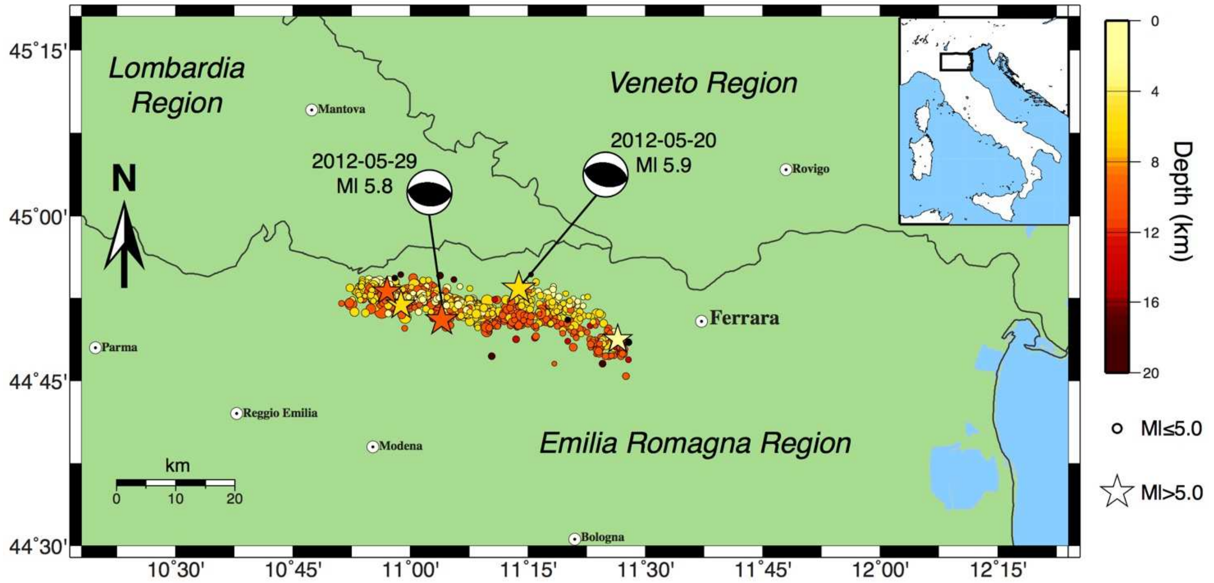
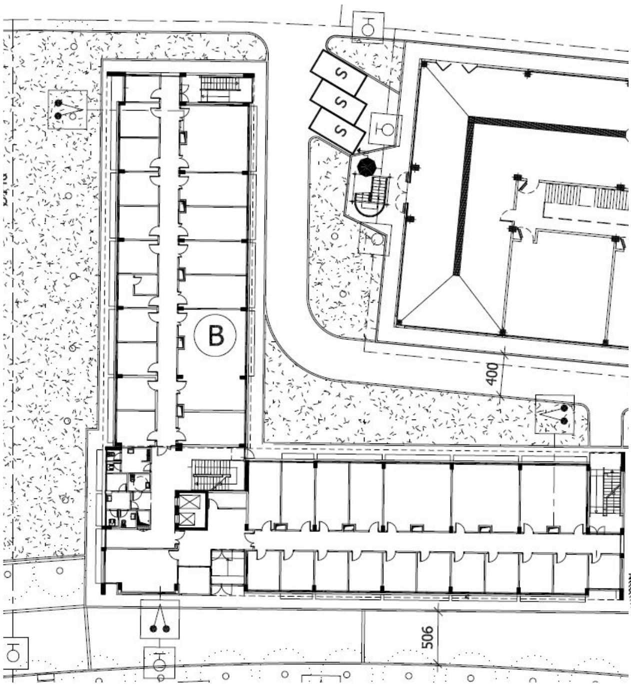


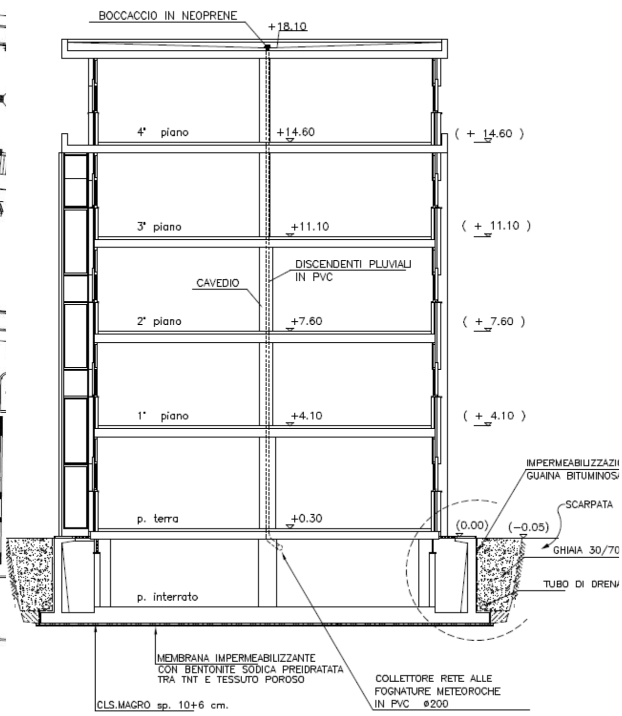
Figure 1 – The Emilia seismic sequence of May 2012 (from Govoni et al., 2014) and the location of Ferrara. The focal mechanisms of the two main events occurred on May 20 and May 29 are also displayed.

The investigated structure is a reinforced concrete frame, L-shaped, 5 floors building with a basement built in 2002. The two sides of the L, called from now on CFR (ConsorzioFuturo in Ricerca, 50m x 14.5 m) and SDT (Scienze Della Terra, 36 m x 14.5 m), are separated by a seismic joint (Figure 2). The building soil foundation is composed mainly of clay and silty clay sediments with some thin layers of organic clay that extends to 18 m depth. The average shear wave velocity in the first 30 m below the foundations placed the site in Class C (Vs=200±4 m/s) according to the Italian Building Code (NTC08).
After the May 20 earthquake, the SDT side incurred damage effects presenting few diagonal cracks on the curtain walls of the ground floor and slightly of the first and second floors (Figure 3). On May 21, 2012, the day after the seismic event, a diagnostic inspection was performed according to the Civil Protection procedures (Baggio et al., 2014). In the inspection form, a slight damage (D1) on infill walls, extended to the 2/3 of the structure, and a medium to severe damage (D2-D3) on infill walls, extended to 1/3 of the structure, were reported. Additionally, other typology of non-structural damage was also collected particularly concerning plaster fall off and internal or external objects falling. Considering the inspection results, the building was declared temporarily not usable, until safety intervention took place, and parking outside the building was temporarily forbidden. Obviously, being a public building, with a high number of users (around a hundred), this resulted in a high level of inconvenience. The proposed intervention included repairing the infill walls and restoring the plasters as measures extended to a large part of the building. Moreover, as a high priority action, on the first and ground floors of the east side of the building it was prescribed to tie service ducts. An inspection on laboratories instruments (and to tie them on the wall) was also demanded. As prescribed, the damage to the walls was repaired through traditional construction works. Moreover, the doors of the

two partition walls of the first floor of the SDT side (in the NW-SE direction) were reinforced with a metallic support.The ducts (130 cm wide) were also reinforced through metallic bars along all the floors, both in the CFR than in the SDT sides. The damage repair intervention was concluded in October 2012.

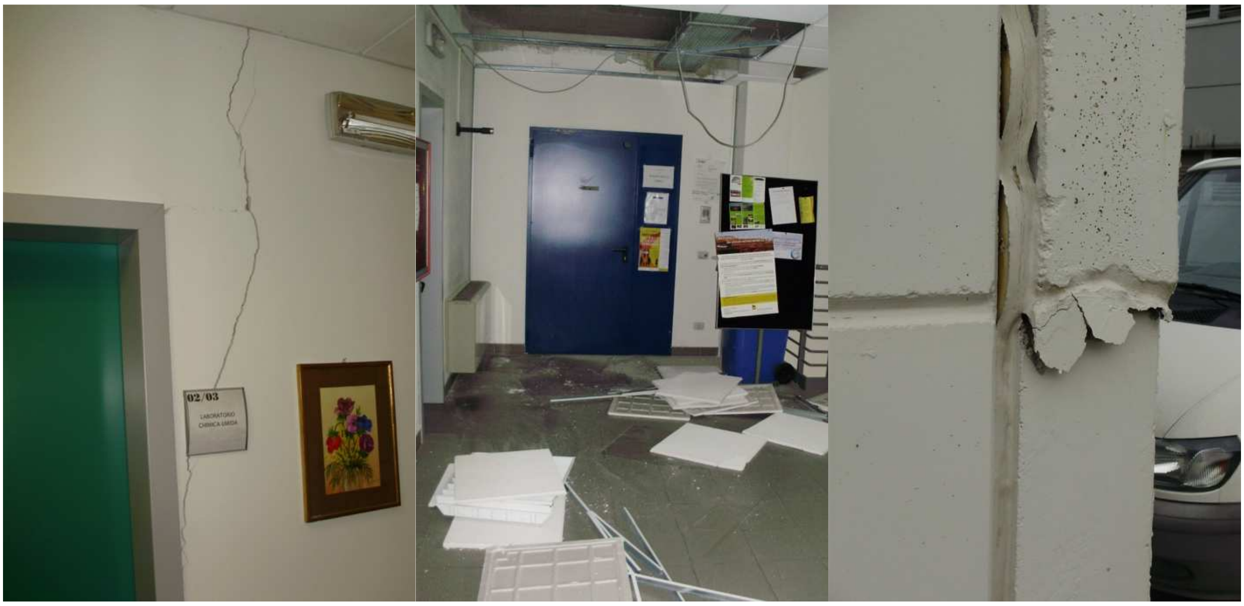
(a)





(b) (c)

Figure 2 – (a) View on the scientific pole, red circle shows the investigated building; (b) floor layout and (c) side view of the investigated building.



(a) (b) (c)

Figure 3 – Damage occurred on the SDT side of the investigated building. (a) curtain wall of the chemistry laboratory at the ground floor; (b) SDT side entrance at the second floor; (c) detail of one of the external wall.

3. INSTRUMENTS AND METHODS

Horizontal-to-Vertical Noise Spectral Ratio (HVNSR, Mucciarelli, 1998; Chavez-Garcia and Cardenas-Soto, 2002; Gallipoli et al., 2004; Mucciarelli et al., 2011) and Standard Spectral Ratio (SSR) analyses with different kind of instruments were performed during time (since April 13, 2012) to evaluate the state of health of the monitored building of the University of Ferrara, as reported in Table 1.

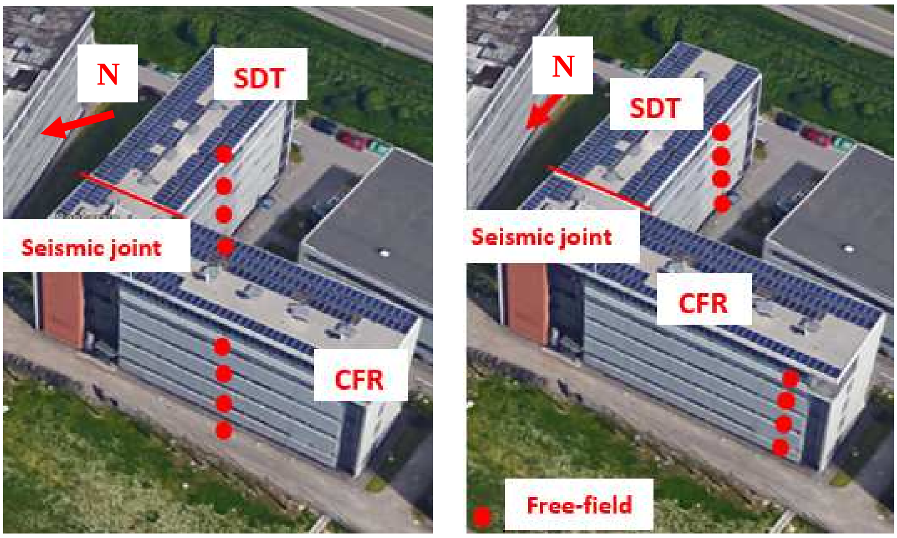
Table 1 – Sensors used for the monitoring with their period of acquisition, kind of data acquired and methods used for the analysis.

Sensor	Acquisition Date	Kind of data	Type of analysis
In house built seismograph (NI electronics)	13/04/2012 and28/05/2012	Ambient noise	HVNSR
Tromino (Moho)	09/02/2016 and11/10/2016	Ambient noise	HVNSR and SSR

In particular, the instruments used for ambient vibration tests were of two kinds (see Table 1):

- In house built (Department of Physics and Earth Sciences, University of Ferrara) single station seismograph based on National Instruments©-DAQ-PXI-6120 40 dB gain, 18 bit A/D converter connected to a PC, used for the acquisition of the first two seismic ambient noise data-sets (before and after the May 20, 2012, Ml 5.9 earthquake). The data logger was connected to a 3C L22 Mark Products seismometer with a natural frequency of 2 Hz.The GUI was coded in Labview©. Microtremors were acquired for 40 minutes at 1000 Hz acquisition frequency, then decimated to 125 Hz before processing.
- 3 tromographs (Tromino, Moho) equipped with three velocimetric channels for seismic ambient microtremor recordings (up to ± 1.5 mm/s), and working in the frequency range of 0.1–1024 Hz on all channels with analog/digital conversion of > 24 bit equivalent at 128

Hz.These instruments were used for the acquisition of the third seismic ambient noise data-set (after the damage repair), with acquisition length of 20 minutes at 128 Hz acquisition frequency.



(a) (b)

Figure 4 – View on the building, SDT and CFR sides, seismic joint position, position and direction of measurements for ambient vibration tests at each floor before and after the May 20 earthquake (a), and after the damage repair(b).

Figure 4 shows the position and the orientation of the instruments used for the ambient vibration tests.The HVNSRs have been estimated by dividing the signal into 5% overlapping windows of 20 s; each window was de-trended, tapered, padded, Fast Fourier Transformed and smoothed with triangular windows with a width equal to 5% of the central frequency. The Euclidean average was used to combine E-W and N-S components in the single horizontal (H) spectrum. Average vertical component spectra were obtained from the same procedure. For each HVNSR curve the relative ±2 confidence interval is given. Some authors suggest that transient can affect estimatesof fundamental frequency of soils, but in our previous experience a simple variation of amplitude never caused this problem, according to Parolai and Galiana-Merino (2006), Mucciarelli (2007) and Parolai et al. (2008).

Microtremor HVNSR technique has been demonstrated to be effective in the assessment of the fundamental frequency response of the ground, in checking soil-structure interaction effects and to detect building fundamental modes (Gallipoli et al., 2004). In this approach, the vertical component of ambient vibrations is assumed as reference under the hypothesis that it is weekly affected by building dynamical properties. Under this assumption, if the structural frequency of the building is distinct enough from the soil’s natural frequency, interpretation can be safely performed. This indeed was the case of our data-sets, where the natural frequencies of the soil were clearly identified at 0.75 Hz (Figure 5), while the structural frequency of the building was found to be higher (2-3 Hz).

4. RESULTS

In this paragraph, the results of the analysis will be presented. The first part deals with the measures taken in the free field for foundation soil characterization. Afterwards, results of ambient vibration tests on the building before and after the earthquake, and after the damage repairare exposed.

4.1 HVNSR on free-field

A test was performed on the free-field close to the building with the aim of estimating the soil resonance frequency. The results of free-field survey highlighted two peaks at low frequencies (0.75 Hz and 0.3 Hz) (Figure 5a), whose stratigraphic nature is confirmed by the geology of the area. The HVNSR applied to the records acquired in the basement of the building shows an identical curve.

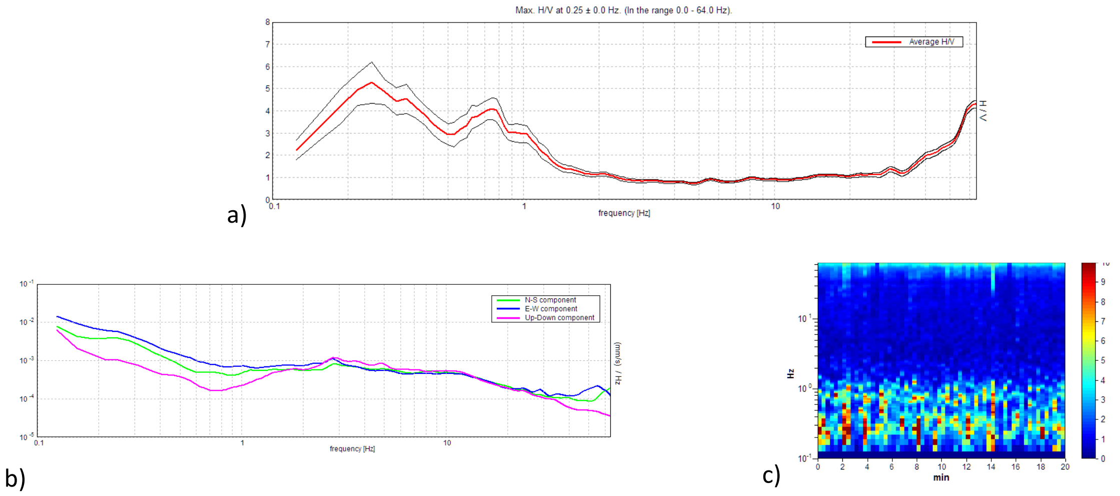


Figure 5 – a) HVNSR curve, acquired on free-field conditions; b) three components Fourier spectra; c) Spectral stability (Time Frequency Analysis).

4.2 HVNSR analysis on the building

The HVNSR average functions acquired inside the building (Figure 6) show a significant and permanent drop of the SDT main frequency due to the damage. The frequency before the Mw 5.8 earthquake of October 20, 2016 is 2.9 Hz, after the earthquake it decreases at 2.2 Hz, and nearly recovering its position (approximately 2.7 Hz) after the damage repair intervention. In a similar way, the peak amplitude, which increased after the earthquake, shows a significant reduction after the damage repairintervention. Changes in frequency and amplitude are both related to the variation of structural stiffness, since the mass had, instead, not changed. Considering the HVNSR functions for each component (longitudinal and transversal direction), it is noted that the decrease is evident only for the transversal HVNSR function (Figure 6 and Figure 7), in fact the cracks are mainly on the shorter site of the building. The drop is about of 24%, according to the value estimated by Vidal et al. (2013). On the contrary, the CFR block has the main frequency at about 3 Hz and it remains unchanged after the earthquake and after the damage repairintervention (Figure 6).

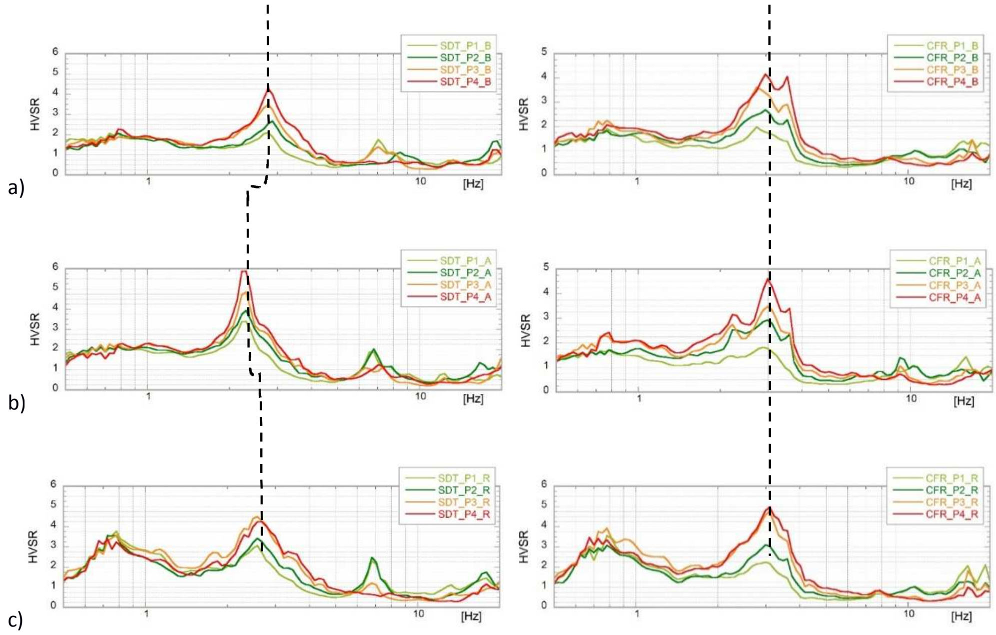


Figure 6 – HVNSR spectra acquired on STD side (left) and CFR side (right): a) before the earthquake; b) after the earthquake; c) after the damage repair.

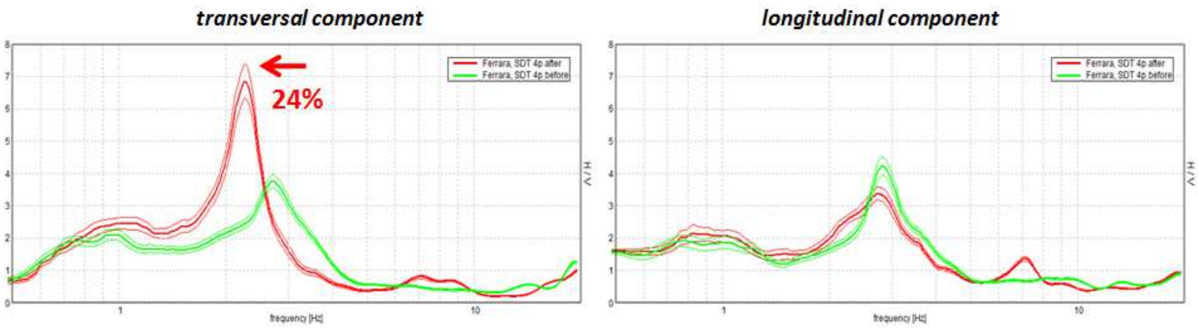


Figure 7 – HVNSRs acquired on STD side for the transversal component (left) and for the longitudinal component (right), before the earthquake (green line) and after the earthquake (red line).

5. CONCLUSIONS AND DISCUSSIONS

In this work, the main frequency of a L-shaped, 5 floors building of the University of Ferrara (Emilia Romagna Region, northern Italy) was estimated before and after the strong motion due to the May 20, 2012, Emilia earthquake, and after the damage repair intervention concluded in October 2012. The HVNSR analysis were applied to seismic ambient noise acquired by several sensors installed at each floor of the SDT and CFR sides during time to monitor its state of health.

First of all, the HVNSRsestimated before the May 20 Ml 5.9 earthquake both on the free-field close to the building and on the building, ensured that the structural frequency of the building is distinct enough from the soil's natural frequency. Subsequently, the HVNSRs estimated on the building before and after the May 20 Ml 5.9 earthquake presented a permanent frequency drop from 2.9 Hz to 2.2 Hz only on the building side (SDT) and only in the transversal direction which suffered slight damages due to earthquake. The damage repair intervention was able to restore the natural frequency (2.7 Hz) nearly up to its original value.The obtained results suggest as:

- seismic ambient noiseHVSRanalyses are sensitive to damages that could not be simply spotted by sight, thus such an approach can be considered as a very efficient and cost-effective diagnostic method;
- the building monitoring, even with low-cost instruments, allows understanding if and how the frequency of a building changes due to an earthquake: if the frequency does not change permanentlyit is possible to excluding damage. Low-cost permanent monitoring systems can therefore be considered a valuable prevention and monitoring tool for judging the state of health of the building, provided that a pre-damage building elastic behavior is known.

6. ACKNOWLEDGMENTS

This study was funded by the project CLARA (CLoud plAtform and smart underground imaging for natural Risk Assessment), MIUR Program - Smart Cities and Communities and Social Innovation (identification code SCN_00451).

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