Experimental measurement of fundamental periods of damaged R.C. buildings

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SUMMARY:
The more recent earthquake engineering research has highlighted the mismatch between experimental and theoretical period-height relationships not only for undamaged buildings but also for damaged ones. For the first time in Italy, after the 2009 L'Aquila earthquake, we have estimated the fundamental periods of 48 RC buildings after a strong seismic sequence. Performing ambient vibration measurements we investigated the fundamental translational frequencies of 48 buildings with different built typology, structural characteristics, age and heights affected by different damage levels (four out of the 5 damage levels defined by EMS 98). The distribution of fundamental period versus buildings height and damage level has been evaluated. The fundamental period of RC damaged buildings, for low damage level, is close to undamaged buildings ones. When damage levels gets higher, the fundamental periods show as expected a general increase, but reaching values lower than those provided some recent codes.

Keywords: L'Aquila earthquake, EMS damage, fundamental period, ambient vibration

1. INTRODUCTION

The effects of seismic actions on building structures are well know in terms of damage. Less attention was paid to the influence of earthquake on buildings dynamic characteristics, due to the limited number of monitored structures. On the other hand, in recent years many researchers have focused their studies on numerical and experimental investigation about the undamaged buildings dynamic characteristics with special regard to the fundamental period of vibration. In particular, our research group focused on empirical estimation of the dynamic properties of large sets of existing RC building in Europe (Gallipoli et al. 2010, Gallipoli et al. 2009), obtaining results confirmed also by other researchers (Oliveira and Navarro, 2010). These studies highlighted the strong difference between experimental values and period-height empirical expressions provided by design codes (e.g. ATC 1978, BSSC 2003, CEN 2003, NZSEE 2006). These relationship have been defined with regards to new structures with anti-seismic design, but are also increasingly adopted in the assessment of the capacity of existing RC buildings. Then, the real behaviour of existing RC buildings (in particular the period elongation, due to degradation of structures) during and after strong ground shaking is an issue of great interest and has been investigated in few cases (e.g. Mucciarelli at al. 2004, Masi and Vona 2009, Mucciarelli et al. 2010). This is the background knowledge that prompted us to perform experimental in-situ measurements on RC building that suffered damage after the April 6th, 2009 L'Aquila earthquake.

2. DESCRIPTION OF BUILDING CHARACTERISTICS AND DAMAGE

We carried out measurements on about 50 RC buildings. The investigated structures have been randomly selected in L'Aquila town and nearby villages to cover a wide span of characteristics such as design, construction age and height and, in particular, all damage levels as defined in the European

Macroseimic Scale (EMS 98, (Grünthal, 1998). The age of construction is ranging from 1950 to 2000. With regard to design, is to be remembered that L'Aquila was classified as seismic after the 1903 Avezzano earthquake. Thus, all RC buildings studied were designed taking into account the Italian Code enforced at time of construction. Even if no more design details were available, we noted that the damage assessed during post earthquake investigation showed that the behaviour of anti-seismic RC buildings in L'Aquila town is not very different by that of RC buildings designed to resist to vertical loads only.
The 48 RC buildings were selected to have heights range from 11 to 27m. Then it is possible to study the relationship between fundamental period and buildings height in a range comparable to the one used for undamaged Italian buildings in Gallipoli et al. 2009. The RC buildings studied exhibit different damage level so that we can estimate the influence of strong ground motion on fundamental period and compare these results with those obtained with regard to undamaged buildings. The damage levels are ranging between Ld = 1 (no structural damage) and Ld = 4 (heavy structural damage) as defined in EMS 98.
The main characteristics of the studied buildings are summarized in table 1. We considered also some particular cases: two buildings with completely bare frames (number 32 and 33 in table 1), two buildings without stiff stair-structure (number 28 and 29 in table 1), and one building with just one story with completely bare frames (number 37 in table 1).

Table 1 Main characteristics of surveyed RC buildings

	Building age	**Height [m]**	**Damage Level**	**Fundamental Period**		**Building age**	**Height [m]**	**Damage Level**	**Fundamental Period**
1	1992-2000	21.7	1	0.58	**25**	1962-1971	17.6	2	0.70
2	1982-1991	17.6	1	0.23	**26**	1972-1981	20.7	2	0.44
3	1972-1981	14.5	1	0.22	**27**	1946-1961	17.6	2	0.42
4	1982-1991	14.5	1	0.21	**28**	1946-1961	17.6	2	0.39
5	1982-1991	14.5	1	0.27	**29**	1946-1961	14.5	2	0.27
6	1982-1991	14.5	1	0.27	**30**	1946-1961	11.4	2	0.25
7	1982-1991	14.5	1	0.25	**31**	1946-1961	11.4	2	0.34
8	1982-1991	11.7	1	0.20	**32**	1946-1961	14.5	2	0.26
9	1982-1991	20.7	2	0.57	**33**	1946-1961	20.7	2	0.57
10	1982-1991	20.7	2	0.60	**34**	1972-1981	14.5	2	0.34
11	1982-1991	14.5	2	0.47	**35**	1972-1981	14.5	2	0.39
12	1972-1981	18.6	2	0.48	**36**	1982-1991	18.6	3	0.55
13	1972-1981	17.6	2	0.33	**37**	1982-1991	18.6	3	0.61
14	1972-1981	17.6	2	0.33	**38**	1972-1981	18.6	3	0.53
15	1972-1981	20.7	2	0.33	**39**	1972-1981	17.6	3	0.54
16	1982-1991	11.4	2	0.33	**40**	1972-1981	14.5	3	0.50
17	1962-1971	11.4	2	0.31	**41**	1982-1991	11.4	3	0.31
18	1972-1981	14.5	2	0.39	**42**	1972-1981	26.9	3	0.50
19	1972-1981	26.9	2	0.50	**43**	1992-2000	11.4	3	0.38
20	1972-1981	23.8	2	0.76	**44**	1946-1961	12.8	3	0.34
21	1972-1981	23.8	2	0.81	**45**	1982-1991	18.6	4	0.63
22	1962-1971	17.6	2	0.40	**46**	1982-1991	11.4	4	0.41
23	1962-1971	17.6	2	0.21	**47**	1982-1991	11.4	4	0.38
24	1962-1971	14.5	2	0.55	**48**	1982-1991	11.4	4	0.38

3. STRUCTURAL DYNAMIC CHARACTERIZATION

In order to characterize the building behaviour it is possible to use several kind of instrumentation and several techniques (Ditommaso et al 2010a, Ditommaso et al 2010b). In this work the frequencies were estimated using ambient noise measured by a portable tri-directional tromometer (Tromino - Micromed). When it was possible we performed several measurements within each building at different points but, in many cases, in order to identify the fundamental frequency for a single

structure, we take just one measurement at the highest accessible floor.
The instrument position, both in plan and in elevation, was conditioned by the accessibility and damage state of the building. For this reason in some cases we have carried out just a single measurement in the staircase: in all of these cases, the position was central and symmetric if compared with the entire building. Measurements were performed using a time-window length equal to 6-10 minutes and using a sample frequency equal to 256 Hz. All records were first corrected using baseline correction, trend removals, and a band-pass filter in the frequency range 0.1-30 Hz; the spectra were evaluated dividing the seismic noise into 10 seconds moving windows with 50% overlap and then averaging over the whole duration.
To estimate the buildings frequencies we used the Horizontal to Vertical Spectral Ratio (HVSR) technique. Gallipoli et al. (2009 and 2010) and Ditommaso et al. (2009) have compared several techniques for structural dynamic identification using ambient noise and the result was that in these cases HVSR is a very useful tool for characterize the fundamental frequency and related modal shape. In this work, in order to better identify if the main mode of each building was purely translational or rotational the Fourier spectra, HVSR technique and rotational HVSR were used. The latter one allows to evaluate the building frequencies and the related directions in the horizontal plane. Positioning the NS instrument direction along the longitudinal building direction, and using it as a conventional 0 degree marker, it is easy to understand the building behavior, evaluate the fundamental frequency and to do some consideration about the presence of rotational modes. Figure 1 shows as an example, the results obtained for a building located in L'Aquila (Pastorelli street, building A – number 44 in table 1) using the analysis of rotational HVSR compared with the Fourier spectra evaluated along the orthogonal directions (Fig. 2)
It is possible to estimate the building fundamental frequency with a very good reliability: the fundamental frequency (2.3 Hz) appears along the transversal direction (WE), rotated of 90° respect to the NS direction. Then a second mode is clearly visible along the longitudinal direction at 2.7 Hz. A third, roto-traslational mode is visible at 3.7 Hz while higher modes appear above 8 Hz.

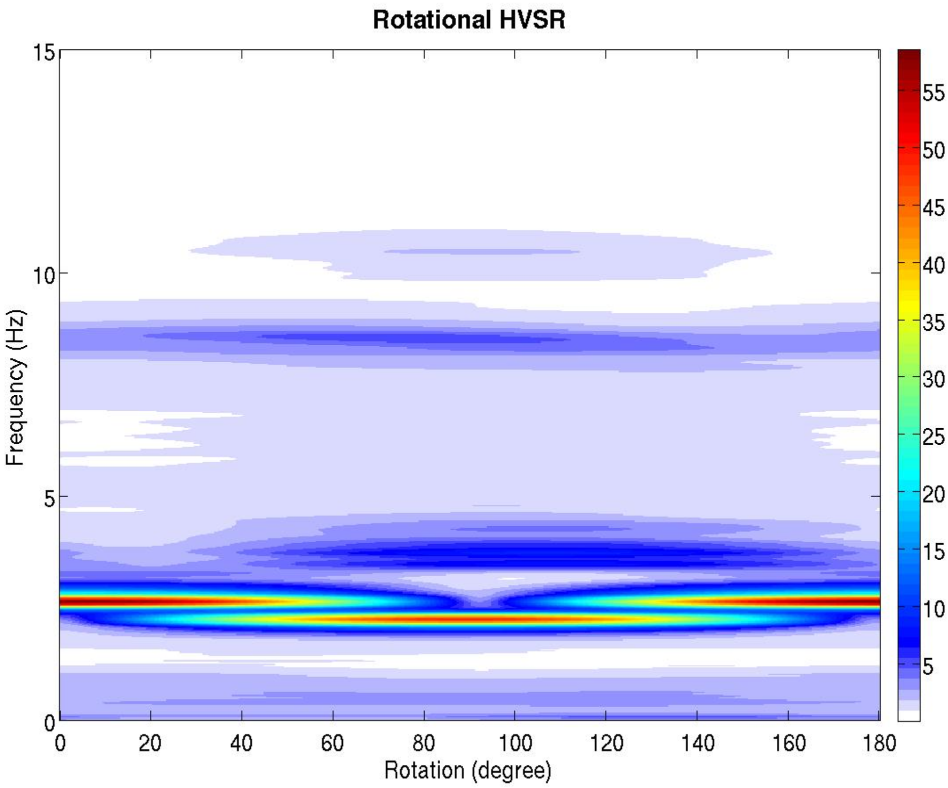

Figure 1. Example of rotational HVSR analysis for building n° 44

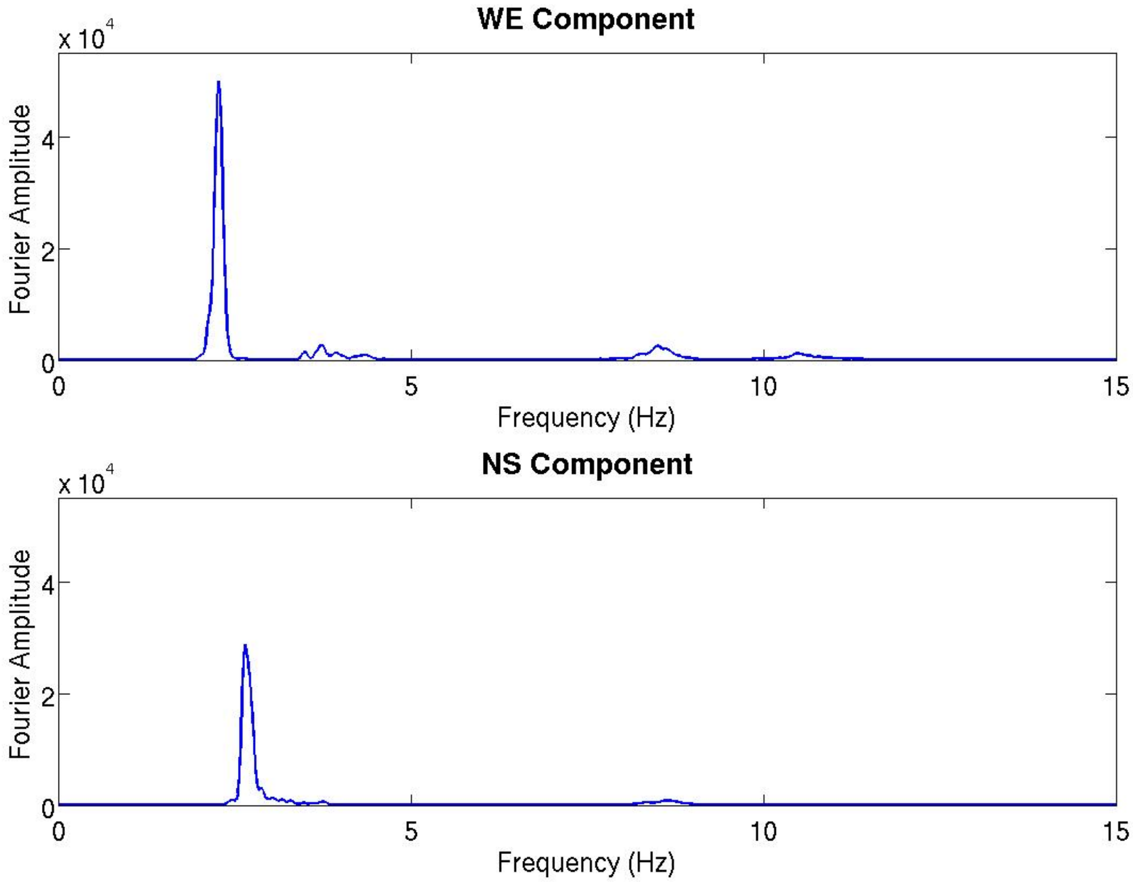

Figure 2. Example of rotational HVSR analysis for building n° 44

4. RESULTS

The buildings frequencies have been estimated using the Horizontal to Vertical Spectral Ratio (HVSR) technique as above describe. Figure 4 shows the comparison between our results and those obtained for undamaged RC European buildings (Gallipoli et al., 2010). We also compare them with the equation provided by the Eurocode EC8.

It is interesting to note that the theoretical equation (EC8) returns an over-estimation of building periods also considering the highest damage level (DL = 4). Supposing that the buildings in L'Aquila before the damage would lay along the lower line, the frequency decrease due to damage never exceeds 50%, in agreement with the observation provided for the only Italian building whose dynamic behaviour was observed during a damaging earthquake occurred in Molise, October 2002 (Mucciarelli et al, 2004) and as reported in Masi and Vona, 2009.

On the contrary, the special cases (bare frames, no internal staircase) show a better agreement between the theoretical equation (EC8) and experimental results. It is also to be noted that the higher damage levels (DL = 3, DL = 4) are often localized only within one or two storey, in some cases only on few elements. These observations confirm that seismic codes do not consider the contribution of the infills or staircases and hypothesise a diffuse damage on the frame instead of the concentrated one observed on existing structures.

The further development of the study will involve in situ measurements on a larger number of undamaged buildings to be used as reference, and then a detailed modelling aimed to explain the difference between observed and expected frequencies.

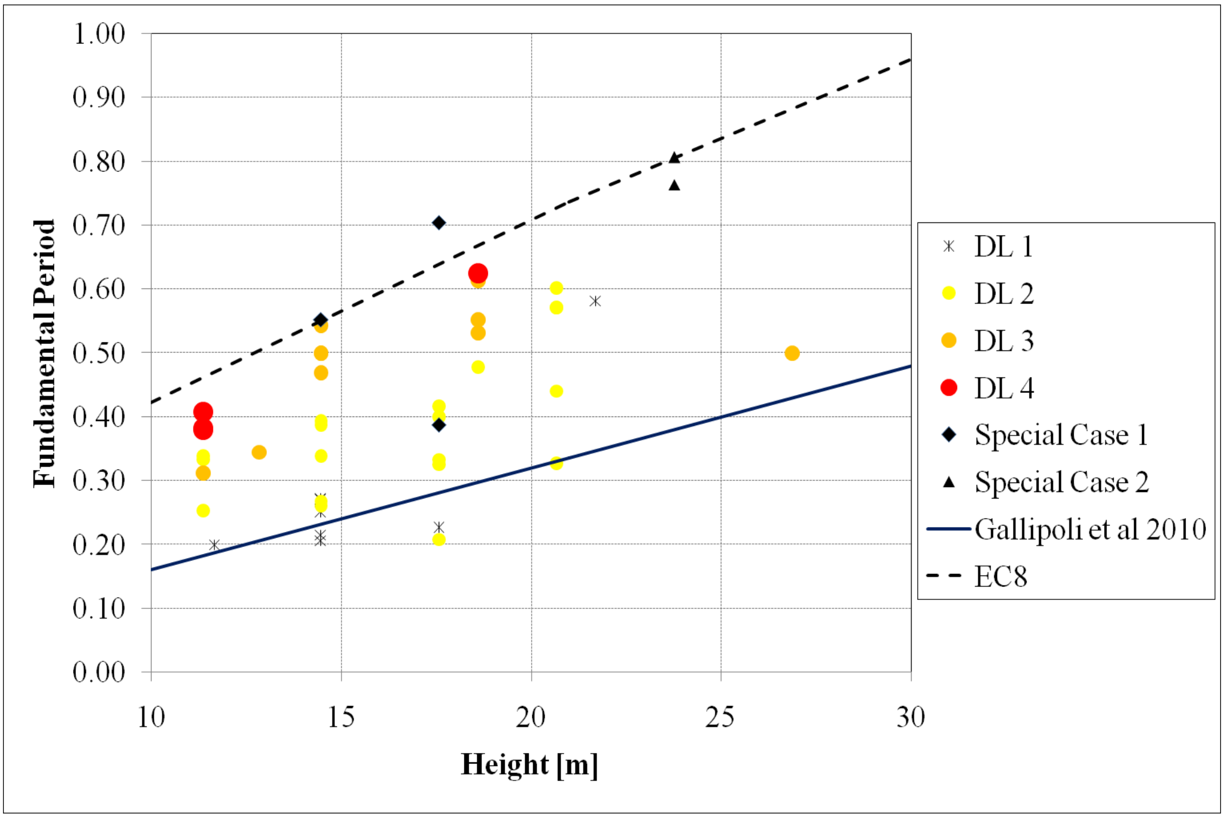

Figure 3. Correlation among building height, fundamental period, and damage level

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