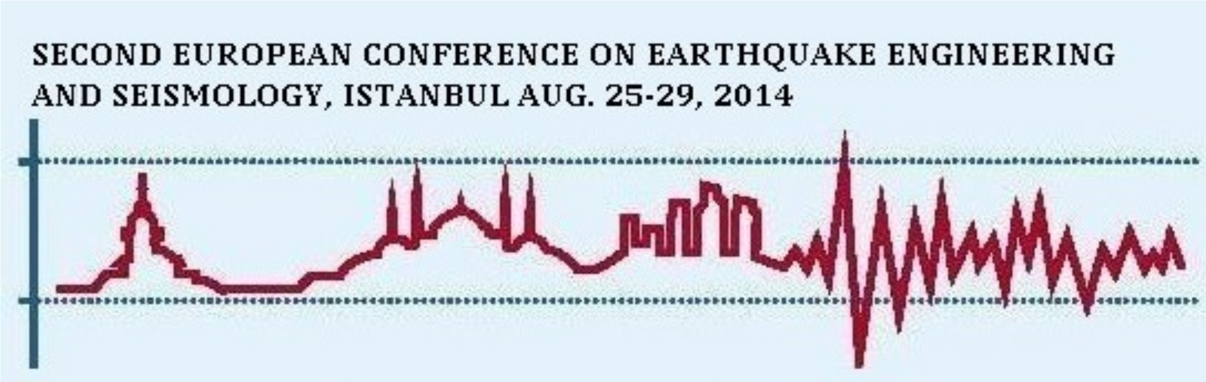

TESTING BUILDINGS USING AMBIENT VIBRATIONS FOR EARTHQUAKE ENGINEERING: A EUROPEAN REVIEW

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ABSTRACT

The objective of this paper is to present an inventory of practices and progress made in recent years on the use of ambient vibrations for Earthquake Engineering. We focus on the expertise acquired in Europe, with links to the activities observed in the rest of the world. For this, a first introduction in the European context will present the state of knowledge and current practices for Earthquake Engineering. The main interest of ambient vibration measurements performed in a structure is to allow the representation of its elastic dynamic response, avoiding any hypothesis as to the quality of its materials, its design or the soil-structure interaction. Three topics will be discussed: (1) the relationship between height and period of buildings, compared to the seismic code relationships, (2) integrating ambient vibrations for seismic vulnerability assessment, and (3) the variation of period and damping according to the state of the building and the level of shaking.

INTRODUCTION

As the years 80' - 90' have seen the numerical methods prevailing on others ways, a renewed interest in experimental methods appeared in recent years. This is particularly due to the considerable improvement of instruments (cheaper and more sensitive) and processing means providing new robust and reliable information to characterize a building/structure (e.g., Clinton and Heaton, 2002). On the other hand, the spread of low-cost sensors, such as those based on MEMS or Lidar technologies, accompanied by rapid developments regarding their performances, suggested growing applications and therefore new information accessible for Earthquake Engineering in the future. Several scientific communities are involved in this activity, from the instrumental development and signal processing, up to data management and communication systems. These applications are also accompanied by effective algorithms developments for identification of elastic properties of structures and infrastructures (e.g., He and Fu, 2001), for detection and localization of structural changes (e.g., Farrar and Worden, 2007) and for the design of monitoring systems and operational warning (Celebi, 2007).

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These last three activities have some interest in earthquake engineering. There is no doubt that the response of a structure under seismic loading reflects the actual response of a structure incorporating the complexity of its design and the boundary conditions (soil-structure interaction). Although ambient vibrations, due to their low level of deformation, provide information only about the elastic response of structures, the recordings of ambient vibrations can be made in large numbers of buildings in a inexpensive way and are useful to characterize the dynamics of complex structures. The use of ambient vibrations for earthquake engineering activities have thus had growth considerably over the last few years for characterization of large area such as a city, or many buildings (or group of buildings) with different design and therefore having different seismic response.

One difficulty that is observed for assessing the seismic vulnerability of a structure is to define its model, even elastic. According to Spence et al. (2003), this difficulty is certainly the main source of epistemic uncertainty of the fragility curves. On the other hand, after a major seismic event, the variation of elastic properties of structures, mainly the deformation modes and the resonance frequencies, provides information for detecting and quantifying post-earthquake damage. This information advantageously contributes to the classification of the damaged buildings immediately after an extreme event. Finally, deployment of permanent or semi-permanent instrumentation coupled to the transmission and recording of data allows the continuous monitoring of some elastic properties. By consequent, this activity then gives us reliable information on the temporal evolution of the response of structures.

In this paper, the ambient noise measures are used to estimate simple empirical relationships like those found for example in seismic codes between the period of vibration and the height of the buildings. These relations will be presented and discussed in the first part, and how the results could update significantly the numerical models. On the other hand, measurements can be introduced for the definition of fragility curves, reducing the epistemic uncertainty related to building model. This activity will be presented in a second part, based on examples and case studies. Finally, the non-destructive testing of structures will be discussed in the last section, with the relevance of measures to assess post-earthquake damage, relying mainly on achievements made after significant earthquakes (Boumerdes, l'Aquila, Lorca etc...).

AMBIENT VIBRATION FOR UPDATING OF PERIOD-HEIGHT RELATIONSHIPS

As a matter of fact, period values can be influenced by many factors. With respect to Reinforced Concrete (RC) buildings the main factors are as follows: 1) building height; 2) structural type (i.e. moment resisting frames MRFs or Structural Walls); 3) regularity in plan and in elevation; 4) infills; 5) RC members' cracking; 6) Earthquake Resistant Design Level (mainly gravity-load design or anti-seismic design); 7) soil-structure interaction; 8) damage state.

Seismic codes (e.g. CEN, 2003) provide simplified period-height expressions whose typical form is $T = C H^{\alpha}$, where C and α are coefficients theoretically or experimentally derived. Generally, they have been calibrated bearing in mind a force-based design (Goel and Chopra, 1997), thus providing lower values when compared to those ones to be used in the framework of a displacement-based design approach (e.g. Chopra and Goel, 2000). Their use is directed to easily achieve estimations of the period of a building in verifying the applicability of simple methods of analysis, e.g. as prescribed in the EC8-1 (CEN, 2003) for the application of the lateral force analysis. With respect to the period-height relationships derived by numerical models, an overview of the different numerical approaches applied to RC building types widely present in the European built environment is reported in Masi and Vona (2010) and in Hatzigeorgiou and Kanapitsas (2013), where the role of some structural characteristics (cracking, masonry infills, elevation irregularities, etc.) on the period-height expressions is carefully studied. Concerning the period-height relationships experimentally derived, many studies demonstrated the good capability of seismic ambient noise as an input signal to estimate the main frequencies of a building, among which the NATO Science for Peace project "Assessment of Seismic Site Amplification and Seismic Building Vulnerability in the FYR of Macedonia, Croatia and Slovenia" (Gallipoli et al., 2009; 2010), as well as other projects (e.g. Michel et al., 2008; 2010b; Navarro and Oliveira, 2005; 2006).

By comparing period-height relationships obtained from the three above described approaches, large differences arise. These discrepancies are found also comparing numerical simulations performed on carefully set up models (see e.g. Crowley and Pinho, 2004; Priestley *et al.*, 2007) with those ones derived from experimental measurements based on ambient vibration analyses (Gallipoli et al., 2009; Masi and Vona 2009).

In Figure 1 some examples of period-height expressions are reported. They are related to numerical analyses on RC structural types representative of buildings without (Bare Frames, BF) or with masonry infills (Infilled Frames, IF), and experimental evaluations of T values through ambient vibration analyses based on measurements carried out using quick survey techniques (Horizontal-to-Vertical Spectral Ratio, Castro et al., 1998; Gallipoli et al., 2004; Di Giulio et al., 2005 and Standard Spectral Ratio, Parolai et al., 2005). Specifically, concerning numerical results the T-H relationships, Goel and Chopra (1997), Masi and Vona (2009) and Crowley and Pinho (2006) are displayed, while for the T-H relationships experimentally estimated the results by Navarro et al. (2007) for 39 Spanish buildings, Guler et al. (2008) for 6 Turkish buildings, Gallipoli et al. (2010) for 244 European buildings, Michel at al. (2010b) for 93 French buildings, Chiauzzi et al. (2012) for 12 Canadian buildings, and Pan et al. (2013) for 116 Singaporean buildings, are displayed. Experimental measurements have been performed on RC MRFs generally gravity-load designed, except for the results by Chiauzzi et al. (Fig. 1 right, yellow line) relevant to 12 Canadian buildings with Earthquake Resistant Design (ERD).

The comparisons confirm the large differences between period values of RC undamaged buildings obtained from numerical analyses and from experimental measurements. Even when elastic values T_e are considered, numerical analyses provide period values from 2 to 5 times larger than the experimental ones, respectively for in-filled (IF) and bare (BF) types. Further, comparing both the numerical and the experimental expressions with the empirical formula currently provided in EC8 (CEN 2003) large differences are found too.

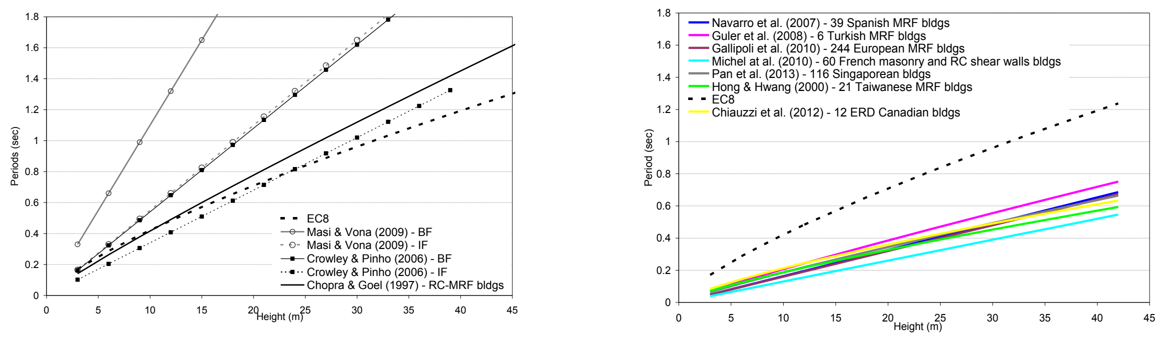

Fig. 1 Left: Comparison between period-height relationships from numerical models of RC MRF buildings without (BF) or with infill walls (IF) with EC8 (CEN, 2003) – Right: Comparison between period-height relationships from experimental estimations on RC MRF buildings with EC8 (CEN, 2003).

The comparison between numerical and experimental results shows very large differences also when numerical simulations were carried out on models where the role of soil-structure interaction was taken into account (Hatzigeorgiou and Kanapitsas, 2013). Figure 2 reports the comparison between the experimental relationships derived measuring the periods on RC MRF buildings located on rock/firm soil (Fig. 2 left, curve and points in blue) and on soft-soil (Fig. 2 right, curve and points in pink) with numerical models considering the effect of infills and soil-building interaction, in one case considering a rigid/rock soil model (Fig. 2 left, black points) and in the other a medium-dense/dense sands (Fig. 2 right, black points).

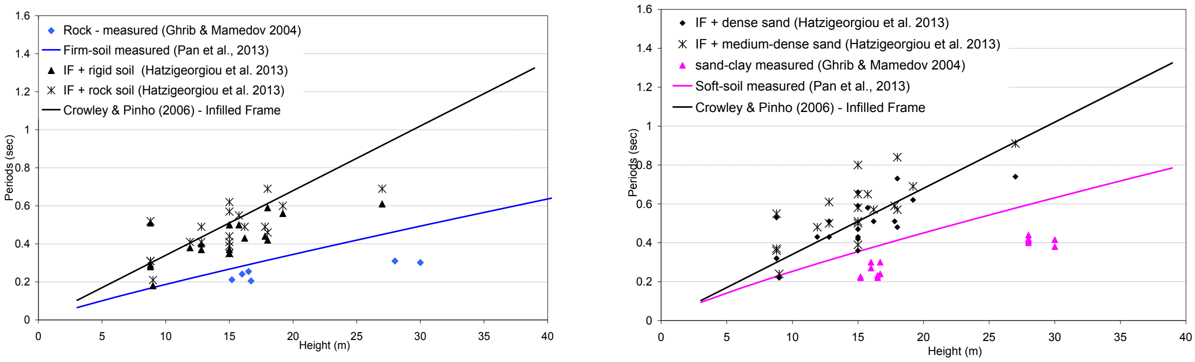

Figure 2. Left: Fundamental periods of RC MRF buildings considering the effect of infills and rigid soil-building interaction: comparison between numerical and experimental values. Right: Fundamental periods of RC MRF buildings considering the effect of infills and soft soil-building interaction: comparison between numerical and experimental values.

The comparisons carried out show that further studies, both numerical and experimental, are needed to better understand the role of the most important structural parameters on the period values of RC buildings in view of explaining the large differences between numerical and experimental values, also taking into account the peculiarities of the built environment in different countries.

AMBIENT VIBRATIONS FOR VULNERABILITY ASSESSMENT

Since nearly 20 years, the earthquake engineering community is developing mechanical-based methods to assess the seismic vulnerability of buildings in order to move away from the traditional empirical methods (Calvi et al., 2006a). However, the seismic assessment of existing buildings is a difficult task due to the difficulty to obtain structural plans and accurate basis parameters (stiffness, displacement capacity), and to estimate the variations of these values due to previous damage, aging, and actual implementation of design. Dynamic numerical models necessarily include simplifications that may bias the final estimation of the vulnerability.

Therefore, using in situ experimental data is necessary to better model the dynamic behavior of existing buildings and therefore their vulnerability. Among experimental methods, ambient vibration tests are particularly informative since it directly provides the vibration modes of the structure. On one hand they can be used to validate the assumptions done in a structural model (Skolnik et al., 2006; Michel et al., 2010c; Caprili et al., 2011; Oliveira et al., 2012; Snoj et al., 2013) or be used directly to compute the structural response under dynamic loading (Michel et al., 2008, 2010c, 2012; Perrault et al., 2013).

Ambient vibration tests are used for several decades in civil engineering to validate and eventually update numerical models. However, the application to earthquake engineering was less developed because non-linear models were too simplistic in the elastic range to reproduce observed data under ambient vibrations. However, modeling is becoming more and more realistic. For instance, neglecting masonry infill of RC frames w/o seismic design leads to a very coarse approximation of the seismic behavior since infill is providing a large stiffness (Caprili et al., 2011). Therefore, earthquake engineers started to compare modeling with AV data in order to limit bias in their assessment of seismic vulnerability. Knowing the limitations of such a comparison due to the modeling uncertainties is however critical to avoid over-fitting the data.

Oropeza et al. (2010) compared their simplified mechanical model with AV results to demonstrate that their assumptions were realistic and later computed fragility curves based on the validated model. Snoj et al. (2013) compared successfully different modeling strategies currently used in earthquake engineering (macro-element method, linear FE modeling) with results of AV tests. Skolnik et al. (2006) propose an updating method for a linear numerical model and validate their modeling against earthquake recordings in the structure. Michel et al. (2010c) compared an AV test with a non-linear model of a structure to validate the modeling assumptions and later assess the non-linear response to strong events (Fig. 3). Caprili et al. (2011) used an optimization algorithm to fit the values of modal frequencies (linear model) by adjusting several elastic moduli and boundary conditions. This approach is however debatable since modeling uncertainties are large and the risk of over-fitting is high. The updated model is then used to assess the seismic behavior of the building with classical earthquake engineering methods. A similar but simpler approach was followed by Oliveira et al. (2012) to model the seismic response of minarets. In this case, the geometry is simpler and therefore modeling uncertainties smaller.

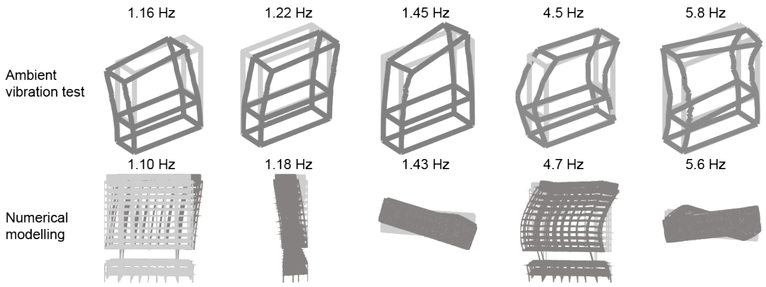

Figure 3. Validation of an advanced non-linear numerical model with AV test results for an existing building in Grenoble (France). Adapted from Michel et al. (2010c).

Since AV tests are providing directly the dynamic behavior of the structure, Michel et al. (2008, 2010c) proposed to avoid trying to model the buildings using physical properties but directly compute their response based on the measured modal parameters (resonance frequencies, modal shapes and damping ratio). Using the classical Duhamel integral, no further assumptions are needed to reproduce the building motion under low earthquake excitation. Michel et al. (2012) went further on this idea and computed the fragility curve corresponding to the slight damage based on this model, a database of input ground motions and inter-story drift limits corresponding to this damage level from the literature (Fig. 4). With one model per building type, they assessed the seismic vulnerability and risk of the city of Grenoble, but only until slight damage. Perrault et al. (2013) slightly modified the previous modeling assumptions and estimated the benefit of using the observed modal parameters in terms of uncertainties in the fragility curves. Finally, Michel et al. (2009) followed the same idea for higher damage grades just accounting for the stiffness degradation in the structure.

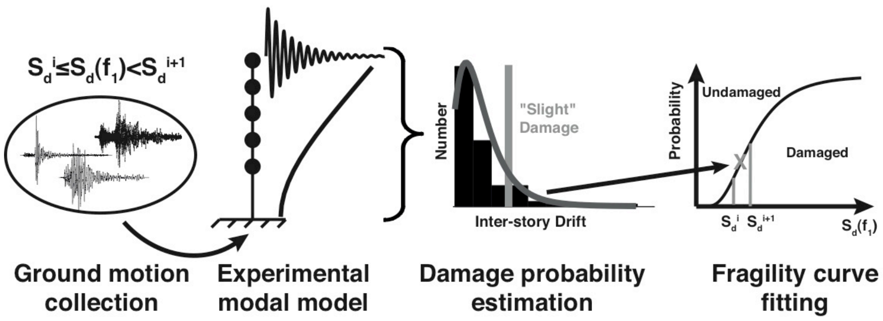

Figure 4. Method of Michel et al. (2012) to derive fragility curves corresponding to slight damage directly from results of AV tests.

As a conclusion, whatever the followed strategy for vulnerability assessment using mechanical methods, AV tests constitute a good linear starting point in order to limit bias in the final results.

AMBIENT VIBRATIONS FOR BUILDING DAMAGE

The damaging process in buildings during earthquakes produces a permanent loss of structural stiffness and then a permanent increase of the fundamental period (e.g., Clinton et al., 2006; Michel and Gueguen, 2010a). Damage detection has been typically carried out by monitoring variations in physical parameters of the structure (Consuegra and Irfanoglu, 2012). Correlating damage level and changes in dynamic characteristics of a structure forms the basis for non-destructive damage evaluation (NDE) techniques (Ditommaso et al. 2010; Picozzi et al. 2010a, b; Ponzo et al. 2010) and they are widely used in structural health monitoring. Small-amplitude vibrations are commonly used to estimate dynamic characteristics of buildings (fundamental period, damping factor and modal shape) assuming a linear behaviour of the building structure. Along this line, ambient noise analysis is a quick, efficient and inexpensive technique, mostly because only a short duration of time series data may be needed to obtain stable results. The use of natural period as a diagnostic parameter has its basis on the assumption that natural frequencies are sensitive indicators of structural integrity (Salawu, 1997) and are directly related to the strength of the building. In contrast to period and mode shapes, damping ratio is not an intrinsic parameter of the building, and is not typically used as an indicator of damage in structures. Damping ratio depends of many factors as structure and soil characteristics as well as soil-structure interaction. Thus its determination is an extremely complex problem because it is influenced not only by the amplitude of motion but also by the time variations of the mentioned factors.

During the past two decades, an abundant scientific literature using shaking table (Calvi et al., 2006b) or post-earthquake observations (e.g. Dunand et al., 2004; Clinton et al., 2006; Calvi et al. 2006b; Snieder et al. 2007; Masi and Vona 2009, 2010; Gallipoli et al. 2010; Régnier et al., 2013 and references therein) deals with this period elongation (stiffness degradation) after damaging earthquakes. Calvi et al. (2006b) reviewed the existing knowledge at that time, concluding that the period elongation attributed to the accumulation of damage can lead to periods of vibration of up to 1.8 to 2.5 times the initial period. These values were observed for shaking table test leading to the collapse of structure, while experimental data on monitored buildings indicate that the onset of structural damage occurs for elongation in the range 1.5-2.0. Hans et al (2005), during a controlled demolition experiment, noticed that the period determined from ambient noise measurements, vibrodine test and impact shock was the same. They concluded on the stability of period of vibration for shaking ranging from 10^{-5} and 10^{-2} g. Gallipoli et al. (2009) measured an 8% temporary decrease of frequency on a building subjected to ambient noise and weak earthquake motion. During 1999 Athens earthquake, elongation of period was observed in RC buildings for ground acceleration equal to 0.05g. This shift to longer period values for higher intensity excitations can be attributed to the formation of microcrackings as well as the activation of various extra friction mechanisms in the structure, recovering the initial period once the shaking ended (Karakostas et al., 2003). Data collected during the L'Aquila, 2009, and Emilia earthquake (respectively by Mucciarelli et al, 2011; and Masi et al, 2013) showed that strong motion in the range 0.01 g to 0.30 g caused temporary period shifts up to 30% when no damage (or increase of it) was observed, while permanent period elongation was associate to damage. Dunand et al. (2004) observed the degradation of frequency for red-orange-green classified buildings after the 21 May, 2003 (M=6.8) Boumerdes earthquake and concluding on the efficiency of the frequency for helping the building state classification. About 50-70% of elongating period for red classified buildings was observed (Fig. 5).

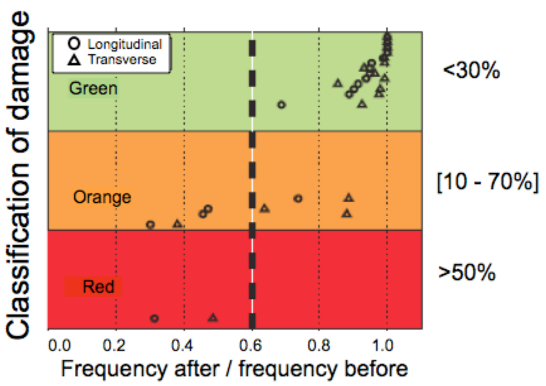

Figure 5. Variation of the fundamental frequency of damaged or undamaged buildings after the 21 may, 2003 (M=6.8) earthquake, according to the red-orange-green damage classification (adapted from Dunand et al., 2004).

In recent years more experimental evidence was gained, following two experimental lines: the first involves monitoring the same building under increasing excitation, the second involves ambient noise measurements on building pre- and post-damage. The variations of fundamental period (T) and damping factor (h) for swaying motion of a large set of existing RC-building structures were analysed after the May 11th, 2011 Lorca earthquake (Navarro et al. 2012; Vidal et al. 2013), and compared to the EMS98 damage scale. Ambient vibration measurements were performed on the top floor pre- and post- Lorca earthquake. The results obtained from measurements performed before earthquake on 59 RC buildings with a number of storeys ranging from 2 to 12 show that the empirical relationship between the natural period of fundamental mode (T) and the number storeys (N) was: $T = (0.054 \pm 0.002)\ N$. This result is similar to those obtained in other European cities by using ambient vibrations (e.g.: Kobayashi et al. 1996; Navarro et al. 2004, 2007; Navarro and Oliveira 2005; Gallipoli et al. 2010; Oliveira and Navarro 2010). After Lorca 2011 earthquake, 34 RC buildings with different damage degree were measured in Lorca town. The Fourier amplitude spectrum shows changes in the natural period of damaged buildings measured before and after Lorca earthquake (Fig. 6). The results show again that the natural period of damaged buildings (T*) increases with the number of storeys (N) and EMS's damage level. The best linear fit ($R^2 = 0.985$, SD = 0.002) between T* and N for Lorca damaged RC buildings (Fig. 6) gives the following relationship: $T^* = (0.075 \pm 0.002)\ N$. This increase in modal period reveals a reduction of stiffness in the damaged structures.

The relative variations of natural periods increase as the damage degree increases, as deduced when comparing the results obtained for the same 23 buildings measured in Lorca before and after the earthquake (Fig. 7). Results show that normalized period variations in both main directions are very similar, showing an average difference of about 9 %, being the longitudinal period relative increment (ΔTL) larger than the transversal one (ΔTT) (Fig. 7).

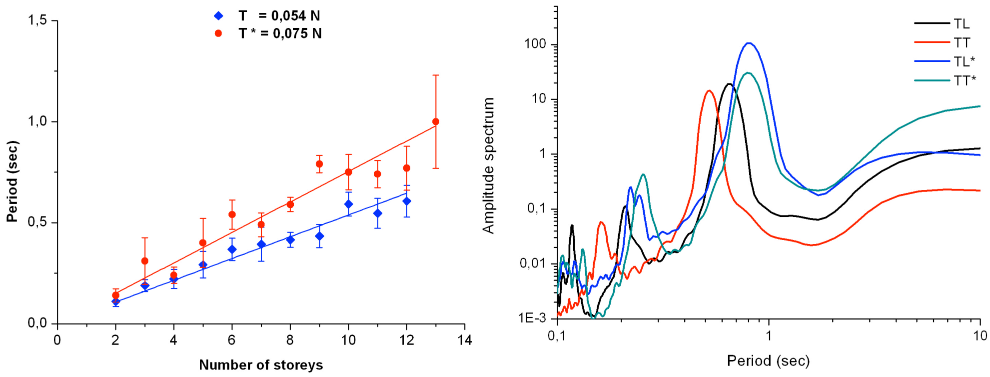

Figure 6. Left: Example of noticeable changes in the natural period of the longitudinal and the transverse directions measured before (TL, TT) and after (TL*, TT*) Lorca earthquake for a building of 10 storeys and damage grade 2. Right: Relationship between the average natural period (T) and the number of storeys (N) for RC buildings obtained from ambient noise analysis. Symbols and fit lines in red and blue colors correspond to buildings measured before [T(N)] and after [T*(N)] the 2011 earthquake, respectively. Vertical bars represent standard deviations.

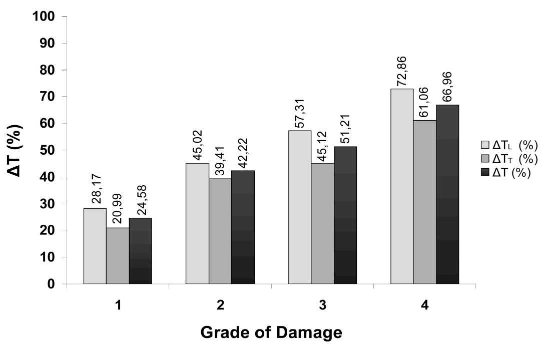

Figure 7. Mean increase (in %) of natural periods (longitudinal TL, transversal TT, and average T) versus degree of damage for 23 buildings measured in Lorca pre- and post-earthquake.

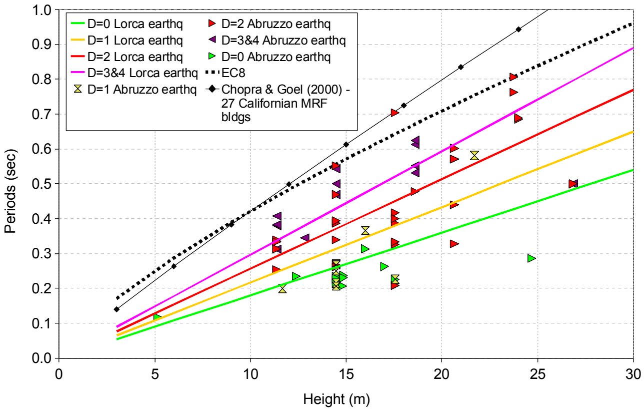

Figure 8. Variation of building period with respect to the height of the building for the Lorca and L'Aquila earthquakes. The black lines correspond to the EC8 and the US empirical relationships.

The relationship between average period of fundamental mode (T) and the number of storeys (N) obtained for horizontal motion before Lorca 2011 earthquake is T = (0.054 ± 0.002) N. The results obtained from 34 RC buildings with different damage degree measured in Lorca town after the 2011 earthquake gives the following period–height expression: T* = (0.075 ± 0.002) N. This period elongation after the quake reveals a relevant stiffness degradation of the structures. The increasing in the fundamental period of damaged buildings with their damage degree is a relevant finding. Trending in the average increase of T values suggests that we can expect more than a 10% of this ΔT in some buildings visually classified as undamaged. This result is in agreement with the loss of natural frequencies of about 10% obtained by Zembatya et al. (2006) in apparent intact state of RC frames before the appearance of visible cracks.

Ditommaso et al. (2013) performed measurements on damaged and undamaged building after l'Aquila earthquake, and compared to the EMS98 damage scale. The synthesis of both earthquakes (Lorca and L'Aquila) is displayed Figure 8. It is possible to note that both groups found period-height relationships with period increasing for the same height when damage is increasing.

Moreover, in order to evaluate directly the damping factor (h) of existing RC building structures pre- and post- Lorca 2011 earthquake, RANDOMDEC technique (Cole, 1968; Mikael et al., 2012) was applied using ambient vibration measurements. The results obtained from the measurements performed pre- earthquake show the average h value is 3.2% with standard deviation 2.6 %. Lorca buildings measured after the quake have an average damping ratio h* of 2.2 % (SD = 1.6 %). Damping factor data and best power estimated fits corresponding to buildings pre- and post-earthquake are graphed in Figure 9. According to previous researches (e.g. Kobayashi et al. 1987; Lagomarsino 1993; Navarro et al. 2002; Dunand et al. 2002; Navarro & Oliveira 2005; Oliveira & Navarro 2010) the empirical relationship between the two variables (h, T) was investigated, considering one typical formulation h T = constant) generally used to tackle this problem. The relationship between the damping factor h and the natural period T for swaying motion was estimated (Fig. 9) as hT = 0.75 ± 0.04 % from data obtained before Lorca 2011 earthquake, and for after that: h*T* = 0.80 ± 0.05 % sec. As expected, both results are similar, because hT value can be considered almost constant for buildings located on soils with same typology, being hT value larger for buildings on soft ground than on hard ground. However, these hT values are different compared with the results obtained in other cities by using ambient vibrations (e.g. Kobayashi et al. 1987, 1996; Navarro et al. 2002; Navarro & Oliveira 2005; Oliveira & Navarro 2010). These differences could be caused by the different structural typologies and different soil conditions in each region.

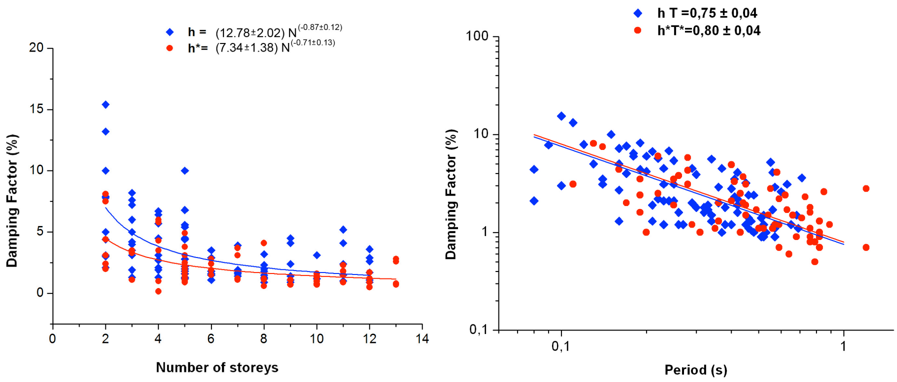

Figure 9. Left: Relationship between the average damping factor (h) and the number of floors (N) for RC buildings of Lorca town obtained from ambient noise measurements. Symbols and fit lines in gray and black correspond to buildings measured before and after the 2011 earthquake, respectively. Right: Relationship between damping factor (h) and natural period (T) for swaying motion of Mula and Lorca RC buildings measured before (in red) and after (in blue) the 2011 earthquake.

In contrast to natural frequency, estimated damping ratio does not shown up a significant variation with earthquake damage degree. Variations of this parameter are quite small and sometimes the same order as the measurement errors. That result points out that damping parameter obtained from ambient vibration measurements is a bad indicator of damage in structures. The product of damping coefficient and the natural period for swaying motion remain near constant when we compare hT values obtained before and after 2011 earthquake. This result suggests the most effective factor dominating hT value could be the soil condition of each site.

CONCLUSIONS

Ambient vibration analysis is proposed as an alternative way to improve the knowledge of existing buildings, providing their dynamic characteristics and their state after earthquakes. This fast and low-cost method is well adapted to large-scale studies for which a large amount of buildings has to be checked. Because building frequencies directly rule the earthquake design and ambient vibrations records are cheap and easily done, frequencies, mode shapes and damping derived from ambient vibrations records could be used as an efficient tool in helping to increase the design quality and then the seismic vulnerability assessment.

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