Identification of building rotational modes using an ambient vibration technique

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ABSTRACT

Heavy structural damage on buildings subjected to seismic motion is frequently due to torsional effects. These effects have been extensively studied in the last years and incorporated in seismic codes. The standard approach for the experimental evaluation of such effects involves the installation of a multi-channel accelerometric system on buildings, either for continuous monitoring of earthquakes or to record forced vibrations. This time- and resource-consuming approach is usually applied to single buildings, but cannot be used in large scale studies in order to validate building code provisions or in quick estimations of building dynamic properties during vulnerability evaluations. In this paper we propose a simpler experimental set-up based on ambient vibration recordings, which is widely used for the identification of translational modes. To validate the methodology we compare our results with a full empirical and numerical experiment performed on a two-story steel frame. A single high-resolution seismometer proves to be able to identify at least the first two torsional frequencies, while with more instruments it is possible to identify also the mode shapes.

Keywords: Structural Monitoring – Dynamic Identification – Rotational Modes – Ambient Vibration

1. INTRODUCTION

Heavy structural damage on buildings subjected to seismic motion is frequently due to torsional effects. In fact, due to torsional response, an uneven distribution of lateral loads can result, which can increase damage at key points in a structure, particularly when subjected to strong earthquakes. Torsional effects can be caused by:

- irregular configuration in plan and/or in elevation;
- irregular distribution of masses and stiffnesses in plan and/or in elevation.

The configuration of a structure can significantly affect its behaviour under seismic actions. Past earthquakes have frequently shown that buildings having an irregular configuration suffer higher damage than the regular ones.

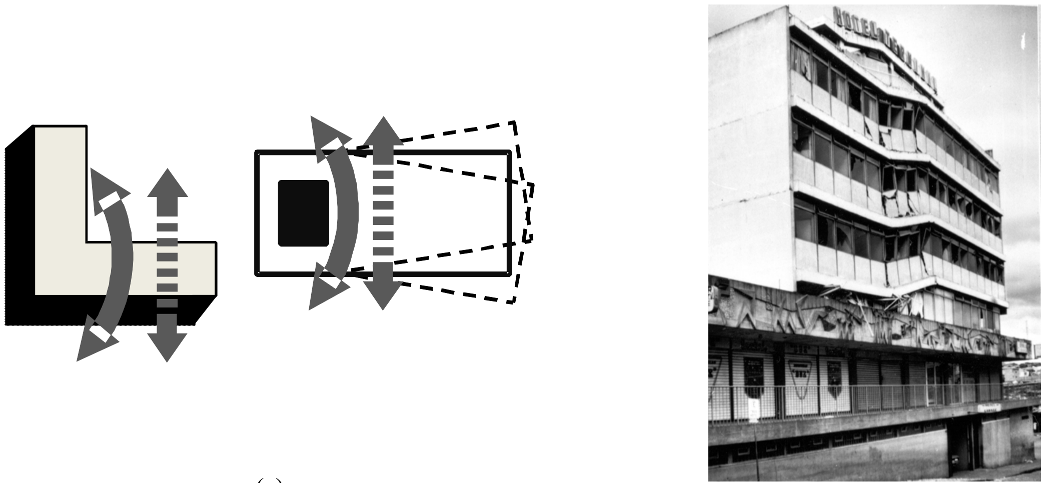
The evaluation of torsional effects is an important topic in modern seismic engineering, both for new (e.g. CEN, 2003; UBC, 2000) and existing buildings having poor seismic design (e.g. NZEES, 2006; CEN, 2004; OPCM, 2003).

Among the basic principles governing the conceptual design of new buildings, some are relevant to building configuration and regularity, such as uniformity, symmetry, torsional resistance and stiffness. Specifically, uniformity in plan is achieved through an even distribution of the structural members, so that a short and direct transmission of the inertia forces created in the distributed masses of the building is allowed. Further, besides lateral resistance and stiffness, building structures should possess adequate torsional resistance and stiffness in order to limit the development of torsional motions which tend to stress the different structural members in a non-uniform way.

Criteria for regularity in plan and in elevation are provided in Eurocode 8 (CEN, 2003), so that building structures can be categorized into being regular or non-regular. As regards plan regularity, an important condition is minimizing the distance between the center of mass, where horizontal seismic floor forces may be assumed to be concentrated, and the center of stiffness. This result can be achieved if lateral stiffness and mass distribution of the building structure are approximately symmetrical in plan with respect to two orthogonal axes. As regards elevation regularity, both the lateral stiffness and the mass of the individual story shall remain constant or reduce gradually, without abrupt changes, from the base to the top. The distinction between regular and non-regular buildings has major implications on the design process, specifically concerning the choice of the structural model (planar or spatial), the method of analysis to be adopted, and the value of the behaviour factor (i.e. the factor used for design purposes to reduce the forces obtained from a linear analysis in order to account for the non-linear response of a structure) which shall be decreased for buildings non-regular in elevation.

In NZEES (2006), plan and vertical irregularities are considered among the critical structural

weaknesses in the assessment of performance of existing buildings. While modern standards discourage design of irregular buildings, existing buildings designed without seismic criteria, may have severe plan and elevation irregularities. As already said, such irregularities can give rise to higher than normal ductility demands on some structural members. Post-earthquake field inspections show many cases of structural damage, up to partial or total collapse, that can be attributed to torsional effects, particularly in building structures with L and U-shaped plans or having a very stiff off-center core (see Fig. 1 a and b).
A remarkable example of such a behaviour is provided by the damage distribution detected after the Mexico City earthquake, where torsional effects were recognized as one of the main factors causing building failure (Rosenblueth and Meli, 1986).



(a) (b)

Figure 1. a) Torsional effects created by irregular shape of building plan (L configuration) and by irregular distribution of plan stiffness (Bertero, 1985); b) Torsional failure of the second story of the Hotel Terminal, Guatemala City, during the 1976 Earthquake (courtesy of USGS Photo Library).

Torsional effects have been extensively studied in the last years. Many analytical and experimental works (e.g. Stathopoulos and Anagnostopoulos, 2005) have been carried out in order to tackle this question. In particular, in the last years, laboratory experiments have been carried out by using shaking-table or pseudo-dynamic tests to better understand the seismic behaviour of structures subjected to torsional effects as well as to improve the efficiency of structural models and codes provisions.
The standard seismological contribution to this topic is the continuous monitoring of structures with permanent accelerometric arrays and the subsequent analysis of the recorded earthquakes. In the meantime, our group carried out both experimental (Ditommaso *et al.*, 2010a and 2010b; Dolce *et al.*, 2008; Mucciarelli and Gallipoli, 2007; Ponzo *et al.*, 2010a and 2010b) and numerical studies (Masi and Vona, 2008) to evaluate the translational dynamic behaviour of the existing buildings in a simplified and cheaper way. This approach could be beneficial for large-scale seismic vulnerability studies, because of the current developments of new methods for seismic risk estimation based on the dynamic properties of existing buildings.
Of course, this goal cannot be attained with continuous earthquake monitoring of building. Modern technologies allow to perform in a short time (10-15 minutes) an assessment of the translational dynamic properties of a single building with ambient noise, so to study a large number of constructions with a limited effort.
We propose in this paper, a fast experimental set-up aimed at identifying also the structural torsional effects. The main aim of this work is to investigate the dynamic properties of a 2/3 scaled 3D frame in the Structural Laboratory of the University of Basilicata using a low level of excitation (ambient noise) and an simple instrumentation. In this work, the microtremor measurements on the steel frame are compared with the experimental results obtained by a classic dynamic identification technique using accelerometers and forced vibrations. The proposed methodology has some advantages, among

them the simplicity of instrumentation set-up, and the reduced amount of data and, therefore, of time and money resources required.

2. EXPERIMENTAL TECHNIQUES

In order to identify the dynamic characteristics of the structures, different techniques can be used depending on types and location of the structures, requested range of motion amplitude and available economic resource. In seismic areas, the structures can be instrumented to record their response to a seismic input. This requires earthquake occurrence to gather data, thus in the past 50 years (since Sparks, 1935) alternative techniques were proposed to evaluate the dynamic behaviour of buildings. With regard to excitation source, the main difference concerns the location of structures under test. In a laboratory, the motion is controlled by means of shaking tables or hydraulic jacks. These methods cannot be applied on an existing building in the field, where three different kinds of excitation are used: shocks or impact action (transient), harmonic forcing induced by shaker (sinusoidal), ambient vibrations (random). These techniques have been used for decades, since the pioneering works of Blume (1935) with vibrodynes, and of Crawford and Ward (1964) with ambient (wind) excitation. Shock tests are performed by impacting the upper part of the building in the two main directions by means of a backhoe. This method is used if the building has to be demolished, as it could cause heavy damage on the structure. Otherwise, tests can be realized by means of a mass impacting on the ground nearby the building. In both methods the excitation is a short impulsive action with a peak acceleration ground about 10-2g. A mechanical shaker (vibrodyne) can be used to induce a frequency-varying, constant-amplitude sinusoidal horizontal acceleration to identify the dynamic behaviour of the building using a resonance approach. The peak ground acceleration obtained with this technique is about 10-4 – 10-3g. A less common approach is the pull and release test, that can be applied either to base isolated buildings (Mucciarelli *et al.*, 2003) or also to buildings to be demolished (Gallipoli *et al.*, 2006).
Ambient noise technique is often disregarded as the less accurate method (the peak acceleration ground is about 10-5g), even though it shows the lower costs and greater simplicity. This is probably due to the same reason that adversely affected noise techniques for the study of soil properties: the widespread use of accelerometers instead of high resolution seismometers (Mucciarelli, 1998). Recent works have demonstrated the reliability of ambient vibration. Yuen *et al.* (2002) proved that the stationarity hypothesis is not needed, and that transient-rich noise can provide building identification with a single output measurement without knowing the input motion. Gallipoli *et al.* (2004) showed that with ambient noise it is possible to detect the presence of soil-structure interaction and also to detect structural damage by determining the frequency shift of the buildings. Hans *et al.* (2005) demonstrated how the estimated fundamental frequency is substantially invariant when using impacts, forced vibration or ambient noise.
Ambient vibration is the most promising solution when large sets of building are examined for vulnerability studies considering the possible presence of soil-building resonance (Navarro *et al.*, 2004; Mucciarelli and Gallipoli, 2007).

3. DESCRIPTION OF THE EXPERIMENTAL MODEL

The test structure, known as Mock-up Frame (Dolce *et al.*, 2008; Gattulli *et al.*, 2009; Ponzo *et al.*, 2007), is a two-storey 3D steel frame (Figure 2). This model is a part of an extensive program of dynamic experimental tests, named JetPacs (Joint Experimental Testing on Passive and semi Active Control Systems), carried out at the Structural Laboratory of the University of Basilicata, developed within the DPC – RELUIS 2005-08 Project, Research Line 7. The frame, with one bay in each horizontal direction, is a 2/3 scaled model of a full-scale frame. The plan frame dimensions are 3.00 m × 4.00 m, and the inter-story height is 2.00 m. Floors are made of a 100 mm thick steel-concrete slab connected to the main beams in the longer direction. The floors can be considered as rigid in their own plane. The beams have the same section (IPE 180) in both directions and at two stories, as well as the four columns that have constant cross section (HEB 140) at both stories. Fe360 grade steel has been used for the structural members, having Young modulus E=206000 N/mm2 and yield strength fy=235 N/mm^2. All structural members have been designed considering dead and live loads for civil residential buildings. Moreover, because the 3D frame has been mainly designed to test the effectiveness of seismic control techniques based on different energy dissipating bracing systems, at both stories two stiff V-inverted steel braces have been mounted, on top of them the energy dissipating devices will be placed during the seismic tests. Finally, the test structure has been bolted on steel beams (HE220B section) used to connect it to the hydraulic jack for forced vibrations. The experimental tests have been carried out with additional lumped masses located at each story. These masses are 8 concrete blocks (4 on each story) of equal weight (about 3450 N), representing both dead and live loads considered in seismic design.

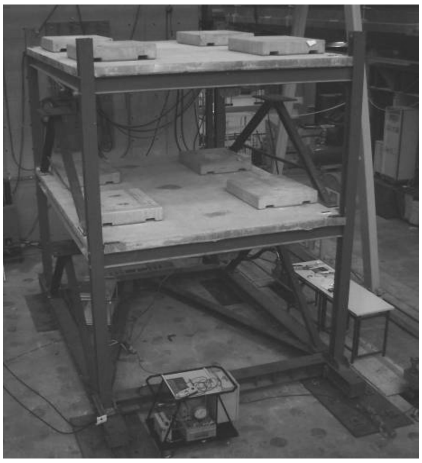
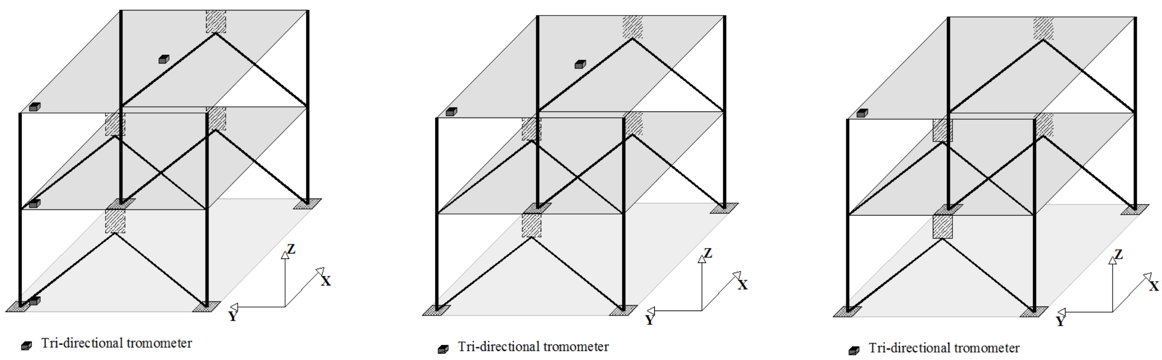


Figure 2. The two-story, 3D steel frame with additional masses in places, ready for the tests. Note the four inverted-V-shape supports for the damping system, not yet mounted.

4. RESULTS OF TESTS

To validate the methodology proposed in this work, we have compared our results with those obtained by a standard method based on an accelerometer apparatus. The dynamic identification (Ponzo *et al.*, 2007) was carried out using 15 acquisition channels to adequately capture the structural response due to forced vibrations.



(a) (b) (c)

Figure 3. The three different set-up of the instrumentation used in the experiment: (a) with four tromometers; (b) with two instruments; (c) the stand-alone configuration.

In order to identify the dynamic characteristics of the 3D frame, we have carried out a measurement campaign using a digital tri-directional tromometer (Tromino, Micromed) that is a tri-directional geophone attached to a 24 bit A/D converter whose dynamic is devoted to measure the lowermost part of the amplitude range. Compared with standard accelerometers used for building monitoring, this kind of instrumentation could easily saturate if used for recording earthquakes, but has better performances when used to record ambient noise. We sampled 10 minutes of ambient noise at 256 Hz (this allows us to resolve the second decimal digit in frequency analysis). In the first experimental set-up, four instruments were synchronized using a built-in GPS receiver. In such a way, the records have been processed with an unique reference time. One digital tri-directional tromometer has been placed in the corner of each floor from the bottom to the top along the same vertical (Fig. 3a), and another tromometer has been placed in the center of last story.

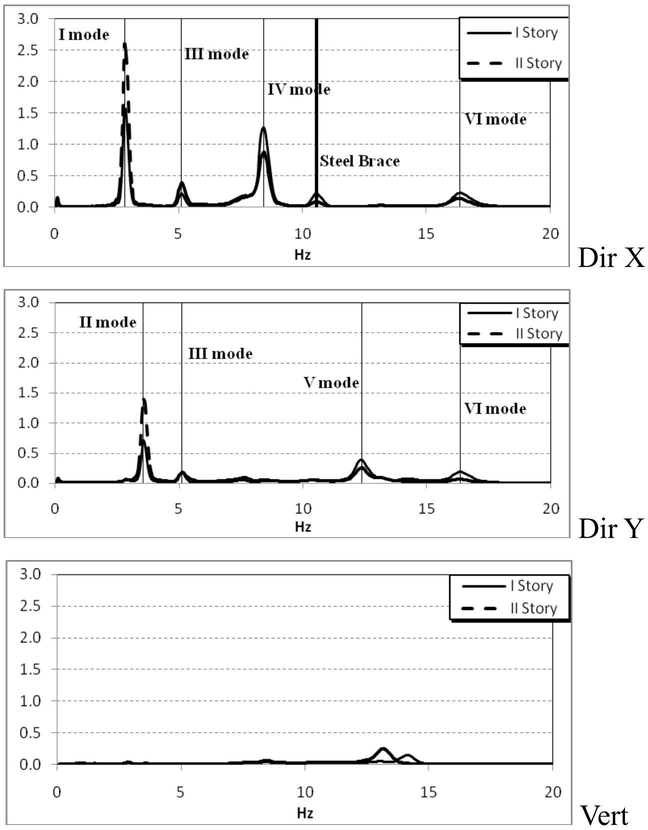


Figure 4. Frequency identification for the steel frame using the instrument configuration of fig. 3-top. Each FTT is normalized to the corresponding component at the base level.

With this first experimental set-up both the natural frequencies and the modal shapes of the first six modes have been identified. The results are synthesized in Fig. 4, where the continuous and dotted line are relevant to the FFT of recordings at middle and top level of the frame respectively, normalized to the corresponding component at the base. The frequency of the first mode (f_1=2.84 Hz) is characterized by translation in Y direction while the frequency of the second mode (f_2=3.56 Hz) is characterized by translation in X direction. The third mode is a torsional one characterized by a frequency f_3 equal to 5.12 Hz.

Table 1. Comparison between the frequencies obtained using ambient noise recorded by tromometers and those from the accelerometric monitoring of forced vibrations.

	I Mode	**II Mode**	**III Mode**	**IV Mode**	**V Mode**	**VI Mode**
	Trasl. Dir Y	**Trasl. Dir X**	**Rot. Z**	**Trasl. Dir Y**	**Trasl. Dir X**	**Rot. Z**
	f (Hz)	**f (Hz)**	**f (Hz)**	**f (Hz)**	**f (Hz)**	**f (Hz)**
Tromometer	2.83	3.56	5.12	8.43	12.38	16.34
Accelerometers	2.83	3.61	5.08	8.40	12.41	16.22

The three higher modes repeat the same sequence (Y, X, R) of the fundamental ones. Moreover, a frequency attributed to the inverted-V steel brace is identifiable. In order to confirm this identification, we have carried out a measurement directly on V-inverted steel braces that returned an out-of-plane frequency equal to 10.53 Hertz. Mode shapes have been estimated in time domain. Once the mode frequencies are known, we filtered the time histories with a pass-band filter, with 1 Hz band amplitude centered around each frequency. Overlapping all the time histories recorded at different levels, the mode shape is estimated normalizing each curve at a given instant. The timing for the normalization can be selected according different criteria, e.g. maximum value at the last level, local maximum, etc. In this study the maximum value at the last level has been used. The results obtained using ambient noise and tromometers are in good agreement with those obtained by the accelerometer monitoring of forced vibrations; the differences between natural frequencies are negligible (Table 1) and the modal shapes are practically coincident (see Figure 5).

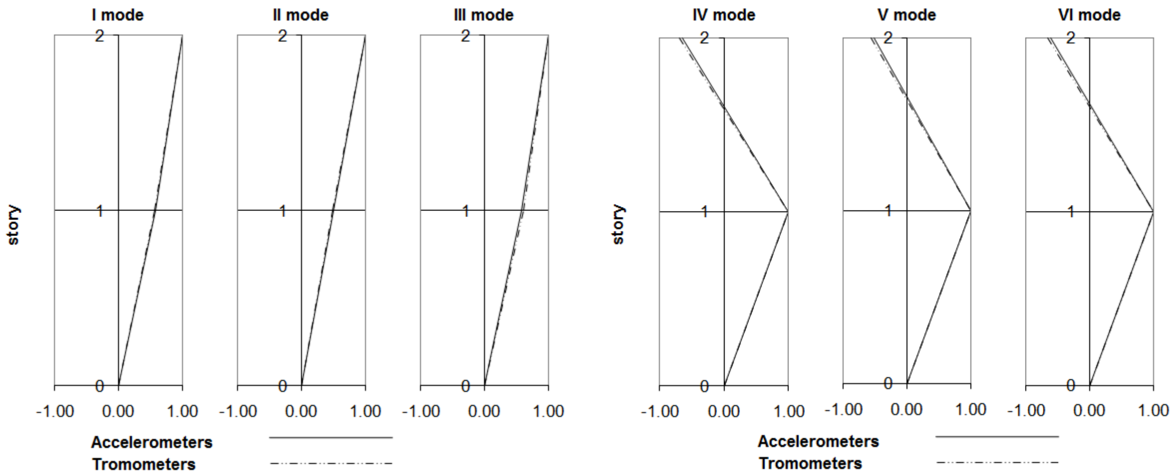


Figure 5. Comparison between the mode shapes obtained using ambient noise recorded by tromometers and those from the accelerometric monitoring of forced vibrations.

This result encouraged us to try different procedures to perform the ambient noise measurements with simpler instrumental set-up. The procedure based on a tromometer at each floor is very accurate but time-consuming when applied on existing buildings. One instrument could be left at the base while another one is moving across upper floors, but for a building of N floors this would require at least N x 10 min. Moreover, a good knowledge of the first six frequency (including the two rotational ones) would be more than enough for several practical applications, even without complete knowledge of the mode shapes. Thus, we have investigated different procedures based on two or one tromometer located at the last floor, and we have verified how these methods are able to predict at least the frequency of the torsional fundamental mode. In a first step, we have located one tromometer in the corner and in the center of the upper story (Fig. 3b). We then have performed a ratio between the FFT of the 10 minutes time histories, using the central instrument as a reference (hereinafter Corner to Center Ratio, CoCeR).

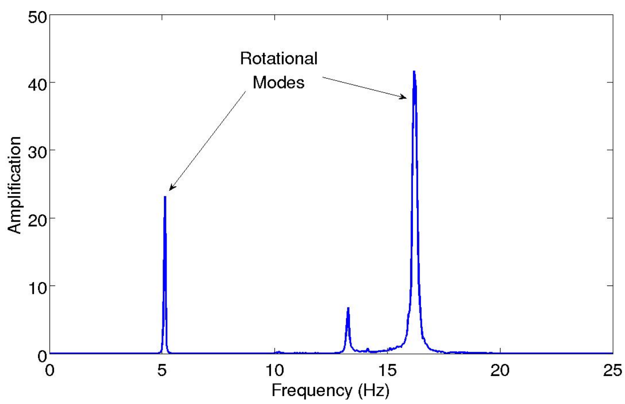


Figure 6. Corner to Center Ratio (CoCeR) for one horizontal component at the last floor.

Figure 6 shows the CoCeR for one of the two components (the other returns obviously the same frequencies). The results obtained agree with those of Tab. 1, with the first and the second rotational frequency slightly above 5 and 16 Hz, respectively. It is interesting to note that another peak appears at about 13 Hz, corresponding to the frequency of the vertical component (see Fig. 4), that can be interpreted as the frequency of a rocking mode.

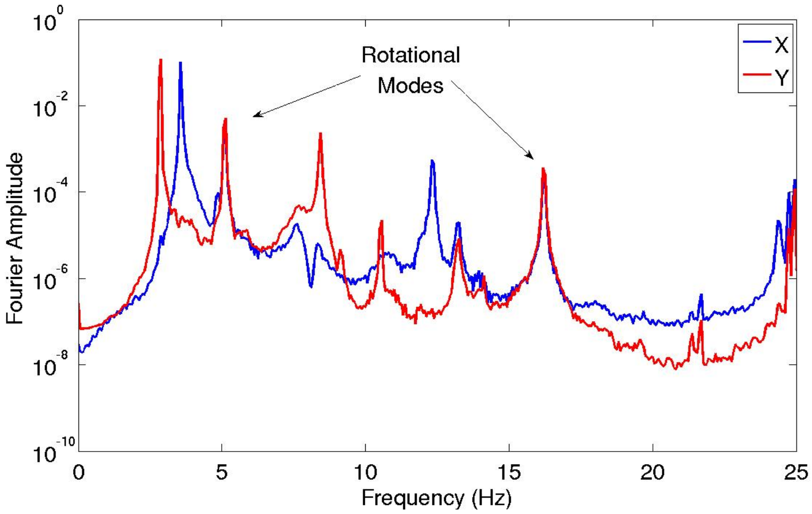


Figure 7. FFT of the horizontal components; ambient noise, 10 minute recording at the top level.

Finally, we have verified the methodology capability to identify the frequency of the first six vibration modes using just one tromometer placed in the corner of the upper story. Figure 7 shows the results. The six frequencies identified with the first set-up are clearly visible. The two fundamental translational frequencies are the easiest to be identified. The second translational modes are clearly visible, even if of course it is not possible to demonstrate that their amplitude is larger at mid-height. The rotational modes are unmistakable, since their amplitude is equal on both components.

5. CONCLUSIONS

The identification of torsional modes is very important in the seismic vulnerability assessment of existing buildings. In the practice it would be desirable to perform quick but reliable empirical estimate of building dynamic characteristics, in order to study large sets of building structures. We compared the results of a laboratory experiment based on forced vibrations of a 3D steel frame with three different set-ups recording ambient noise. With the most complete system it is possible to retrieve mode shapes that are practically identical to those ones obtained by forced vibrations. With two instruments located at the top floor, using CoCeR it is possible to separate global rotational modes from rocking modes. Even with the stand-alone configuration it is possible to retrieve the six first modes of the structure in the horizontal plane, including the first two rotational modes.

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