16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 0985

Registration Code: S-E1461431646

AMBIENT VIBRATIONS APPLIED TO SAN MARINO HISTORICAL BUILDING SURVEY

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Abstract

The San Marino Historic Centre was included in the UNESCO world heritage list in 2008. The site is located in a region characterized by medium level of seismic hazard. Therefore, mitigating earthquake damages is an important goal for conservation of historical buildings. From an economic point of view, this issue is fundamental in order to sustain tourism, which is a relevant source of local economy. In particular, effective retrofitting interventions require a reliable assessment of seismic vulnerability of unique historic buildings. Seismic retrofitting is a particularly complex task for old structures. A first step in this direction is the evaluation of dynamic response to seismic loads at least in the domain of small strain levels corresponding to the beginning of damage. Several recent studies demonstrate, this task can be achieved in an efficient way by using suitable single station asynchronous ambient vibration measurements. This technique has been applied to three medieval towers and the Palazzo Pubblico located in San Marino and allowed identifying fundamental (elastic) resonance frequency, a key parameter for assessing seismic behavior of historical buildings.

Keywords: San Marino, UNESCO, Ambient Vibrations, Standard spectral ratio, Fundamental frequencies

1. Introduction

Cultural heritage is an important asset to the civil, social, cultural, and economic life of a country. As a consequence, significant attention should be given to its preservation by adopting various technologies that achieve more effectively the objectives of protection, conservation and valorization of historical and artistic artefacts. More specifically, computer technology often used to organize cultural tourism and physical technologies has been transferred to the artistic and cultural heritage industry for diagnostic studies. In recent years, there have been numerous partnership between universities, research institutes, and enterprises for implementing new technologies and methods of intervention in this area. In particular:

– computer technologies have been utilized to catalogue, archive, analyze, diagnose, virtual art exhibitions, construct 3D models of historical places, cultural heritage databases and much more;
– satellite technologies to survey archaeological sites;
– chemical technologies applied to the conservation and restoration of artworks;
– laser technologies mapping for cultural heritage sites [1].

Among these innovative technological tools, there are those devoted to seismic protection. Historical buildings were built before the introduction of seismic design rules. Moreover, they were often built with antiquated concepts, and thus many contain vulnerable structural elements such as tall and slender masonry towers, large span vaults, and timber floors [2]. To define an effective seismic risk reduction strategy of a building, the authority needs to define action priorities on the basis of risk assessment. These estimations require the determination of seismic hazard, of building vulnerability, and the evaluation of their value in order to prioritize retrofitting interventions.

The aim of this paper is to apply a non-invasive technique to evaluate seismic response of old buildings based on ambient vibration monitoring (e.g., [3]). In particular, Standard Spectral Ratio (SSR) technique (e.g., [4]) was applied to the main historical buildings of the Republic of San Marino in order to evaluate their seismic response in the small strain domain.

San Marino Historic Centre dates back to the foundation of the Republic as a city-state in the 13th century. In 2008 the historical centre was included in the UNESCO World Heritage list. The criterion, which gave this important award, is that “San Marino and Mount Titano are an exceptional testimony of the establishment of a representative democracy based on civic autonomy and self-governance, with a unique, uninterrupted continuity as the capital of an independent republic since the 13th century. San Marino is an exceptional testimony to a living cultural tradition that has persisted over the last seven hundred years” [5]. The city centre includes walls, gates, and bastions, as well as the 19th century neo-classical basilica, 14th and 16th century convents, the Palazzo Pubblico, as well as three fortification towers. Guaita, Cesta, and Montale Towers are the three “pinnacles” of Mount Titano, which represent defensive bulwarks of liberty, which is so important to San Marino citizens [6].

The San Marino area is characterized by a medium level seismic risk, by the Italian code [7]. Therefore, results of the present study will be valuable for the local government to promote historic heritage conservation. The paper is organized as follows: section 2 is focused on SSR technique, section 3 presents the case study, section 4 analyses the results discussed in relationship with the Italian codes suggestions in section 5. Finally, Section 6 reports the conclusions.

2. SSR Technique

Structural identification of dynamic behavior of buildings requires expensive and invasive measurements. Alternatively, direct measurements of a building seismic response to small earthquakes (‘weak motion’) may provide important information concerning the behavior of the structure (e.g., to retrieve the fundamental resonance period of the structure) in the small strain domain, which represents the earlier phases of damage. Since such events are not frequent enough, the same information can be deduced from the monitoring of ambient vibrations. These are commonly referred to as “micro tremors”, “seismic noise” or “microseisms”). They are commonly present in unconsolidated sediments or soils due to natural (wind, oceans, etc.) or human (traffic, industrial activities, etc…) causes.

Recent studies [8] showed that such methodologies can be applied to assess Soil Structure Interaction (SSI) effects and dynamic characteristics of buildings as well. In particular, as shown in [9], SSI effects should be considered in correspondence with ordinary buildings and thus with historical buildings.

Many applications to historical buildings have been described in the current literature (e.g., [10-14]). In particular, the Standard Spectral Ratios (SSR) technique is a survey strategy allowing the exploitation of this kind of load to experimentally assess some important characteristics of the building response to ground shaking. In this regard, main resonance periods of the structure can be retrieved and they are of great importance for anti-seismic retrofitting design assessments (for details, see [15]).

Basic ideas and assumptions behind the SSR technique can be summarized as follows. In general, measuring displacements of a structure induced by ground shaking at any floor or level may lead to the modal characteristics of the structure coupled with the soil. In the presence of a relatively rigid soil (as in the case of San Marino), the contribution of soil-structure interaction can be assumed weak. Moreover, modal parameters of the structure coupled with the soil are expected to be close to those of the same structure on a rigid base (at least for the first modes). In principle, this allows for the derivation of the intrinsic properties of the structure from the measurement of displacements. In these conditions, the motion at the base of the structure can be assumed as nearly identical to those of incident ground motion. Additionally ‘the structure motion observed at the non-Galilean frame of reference attached to the base define the rigid-basis Transfer Function of the building. Consequently, the intrinsic behavior of the structure can be deduced by suppressing the rigid body motion that is induced by the base motion [14]. For any building in the linear domain, the motion $u_i(h,t)$ as a function of the time t in the i-th direction at any floor at the height h from the ground can be written as:

$$u_i(h,t) = \int_{-\infty}^{+\infty} G_i(h,\tau) s_i(\tau - t) d\tau \tag{1}$$

where an independent motion response function G_i is assumed in each direction and s_i is the input ground motion in the same i-th direction. In the frequency domain, equation (1) becomes

$$\tilde{u}_i(h,\nu) = \tilde{G}_i(h,\nu)\tilde{s}_i(\nu) \tag{2}$$

where the symbol ~ indicates the Fourier Transform of the relevant variable and ν indicates frequency. When the frequency of concern corresponds to the vibrational modes of the structure, the Fourier transform of the response function is provided by the spectral ratios

$$\tilde{G}_i(h,\nu) = \frac{\tilde{u}_i(h,\nu)}{\tilde{s}_i(\nu)} \tag{3}$$

If, as discussed above, one assumes that

$$\tilde{u}_i(0,\nu) \cong \tilde{s}_i(\nu) \tag{4}$$

it is possible to obtain:

$$\tilde{G}_i(h,\nu) = \frac{\tilde{u}_i(h,\nu)}{\tilde{s}_i(\nu)} \cong \frac{\tilde{u}_i(h,\nu)}{\tilde{u}_i(0,\nu)} = SSR(h,\nu) \tag{5}$$

This position implies that the ratio between the spectral amplitudes of displacements measured at the height (h) and the ground level or in the free field (the Standard Spectral Ratio) allows estimating the response of the structure (at least in the range of approximations here considered). In particular, maxima of the SSR function should correspond to the resonance frequencies of the structure under study. Furthermore, in the case that at a given resonance frequency a single vibrational mode dominates, the maxima of the SSR function could be directly interpreted in terms of a resonance frequency (or period) associated to a specific mode. Moreover, if one assumes that the input ground motion is a stationary stochastic process, time ergodicity can be assumed. This implies that average spectral amplitudes measured during any j-th time interval Δt_j (long enough to capture average properties of the underlying stochastic process) should be independent from the specific time windows considered. This allows measuring the SSR in equation (5) by separately measuring numerator and denominator by asynchronous measurements. Of course, this kind of procedure will not allow the identification of modal shapes relative to building oscillations.

3. Case Study

The ambient vibration survey by following the SSR approach was performed on the following buildings (Fig. 1), described in detail in the next section:
– Guaita Tower (First tower),
– Cesta Tower (Second tower),
– Montale Tower (Third tower),
– Palazzo Pubblico.

Velocimetric measurements have been taken at all accessible floors of the buildings and in correspondence with the ground, outside the buildings. In particular, three components portable seismographs called Tromino™, by Micromed S.p.a. have been used. The devices were oriented with principle axes parallel with the buildings facades. Therefore, North-South (N-S) and East-West (EW) components in the following sections have to be considered conventional. The Up – Down (UD) component corresponds to the vertical.

Measurements were made over 30 minutes durations and with a sampling rate of 128 cps. Recordings were processed as follows:

• the series have been divided into time windows of 32 sec;

• time series relative to the ground motion components (NS, EW, UD) in each time window have been de-trended and the residuals tapered with a cosine window (5% of total duration);

• Fourier spectrum has been computed for each window and component; no zero padding was required;

• the spectra have been smoothed with a triangular moving window having a width corresponding to 1% of the central frequency;

Finally, the average spectral amplitudes for each of the 3 components (N-S, EW and UD) have been calculated as the average of the spectral amplitudes computed for each time window.

The measurement at ground floor was considered the reference value with which every floor's SSR spectrum has been related. In particular, the reference site was chosen to be the farthest possible from the structure and near buildings, in order to reproduce free field conditions. This approximation appears less reliable for the first two towers, since they are situated on the crest of the east slope of Mount Titano and surrounded by other buildings. The third tower is isolated and free field conditions were much easier to be realistically represented. In order to consider vibrational variability of ground vibrational field, the reference measurement was done twice, at the beginning and at the end of the campaign. Therefore, the SSR ratio values have been related with the two reference measures and compared. Finally, two devices have been applied. In the following, the measurements are named Sx and Rx, in order to considered the two type of devices.

The fundamental frequencies of the relevant building were assumed to correspond to the maxima SSR values. In all SSR curves, at least one maximum value was clearly determined with a high amplitude and defined frequency localization. In order to evaluate the robustness of the estimate, SSR curves obtained at each floor of the same building have been compared: in all the cases, a good correspondence of respective SSR maxima was observed. As expected, these maxima show a monotonic increase in the amplitude when the height of the floor increases. For the first tower, several SSR peak values were observed as a possible indication of several modes excitation. The small differences in the frequency location of the corresponding SSR peaks observed at each floor were considered to estimate the possible uncertainty affecting the detected resonance frequency. In any case, the minimum uncertainty range was assumed to be larger than 0.02 Hz, i.e., the frequency resolution of the Fourier Transform in the considered cases.

Fig. 1 – Building locations inside San Marino Historical center

3.1 Guaita Tower

The First tower is built directly on bedrock with no foundation, and it has a pentagonal base. It dates back to the 10th century and it has been reinforced many times in the past. It was rebuilt in the second half of the 15 th century, and in the 16 th century, it was covered with a sloping roof. It is called the "Guaita", and within its solid walls, is protected by double walls (the external wall with merlons and truncated towers at the corners). Some parts of the tower were used as prisons until October, 1970 [6].

The measurements were made during two different days, in order to verify the coherence of some resulted output. In particular, outside measurements were named S1, R1, R5 and obtained the first day and R15 the second day. Fig. 2 shows where these measurements were located. Inside measurements were taken in correspondence with the windows at various floors.

Fig. 2 – Guaita Tower and location of the measurements performed outside and inside the building. The green line indicates the direction of the walls assumed as reference (NS component). With the grey circle are indicated the measurements performed with an instrument, with the red one the measurements performed with the other one.

3.2 Cesta Tower

Cesta Tower stands on the highest pinnacle of Mount Titano, 756 meters high. It was built at the end of the XI century and also with the characteristic pentagonal floor plan. The Second Tower housed the Fortification Guards Division as well as some prison cells. Around the end of the XVI century, when the tower was no longer of strategic importance, it fell into disuse. In 1930, as a result of the construction of the Rimini – San Marino railroad, it was decided to restore the medieval monuments in order to stimulate tourism. Today, Cesta tower houses the Museum of Archaic Arms, back to various periods from the Middle Ages to the end of 1800 [6].

The measurements have been done in two different days. The outside measurements were named S5, R6, R9. Fig.3 shows where these measurements have been sited. The inside measurements (floor 1, 2 and 3) were taken in correspondence with the windows in the NE part of the building (R11, R12, R13 and R14) and in the opposite side of the tower (S8, S10, S11 and S12), in order to consider the effect of the surrounding structures (Fig. 4).

Fig. 3 – Cesta Tower and location of the measurements performed outside the building. The green line indicates the direction of the walls assumed as reference (NS component).

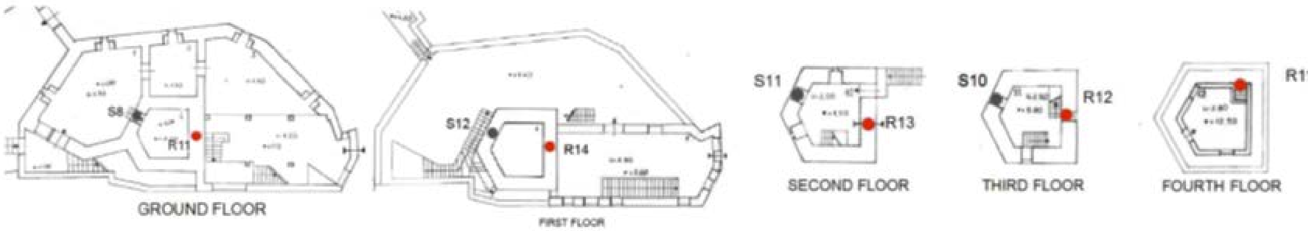

Fig. 4 – Locations of the measurements performed inside the building of Cesta Tower, (see the grey circles) are the measurements performed with an instrument, while the red circles indicate measurements performed with the other instrument.

3.3 Montale Tower

Montale Tower dates back to the end of the XIII century. It is the smallest tower, and because of it optimal position for a look-out post, it played a strategic role for defensive purposes. The fortress, with its pentagonal floor plan, has been restored on numerous occasions during the course of the centuries. The last restoration took place in 1935. Inside, there is a prison 8 meters deep, called "the bottom of the tower". Montale is surrounded by very large rocks arranged to form a primitive wall structure [6]. This is the only isolated tower, and it's not accessible. For this reason, only outside measurements have been taken (S6, S7, R7, Fig. 5). One measurement was taken in correspondence with the foundation along the NE edge (named R8 in Fig. 5).

Fig. 5 – Montale Tower and location of the measurements performed outside the building. The green line indicates the direction of the walls assumed as reference (established NS component).

3.4 Palazzo Pubblico

Palazzo Pubblico is San Marino's town hall and official Government Building. Official State ceremonies are hosted at the Palazzo Pubblico. In addition it is the seat of the Republic main institutions, including the Captains Regent, the Grand and General Council, the Council of XII, and the Congress of State. The main section of the building is topped by battlements over a series of corbels. The overlying clock tower also features a similar arrangement of battlements and corbels. Located on the site of an ancient building called the Domus Magna Comunis, the current building was designed by the architect Francesco Azzurri and was built between 1884 and 1894. After a hundred years of existence, a complex restoration project was undertaken. The renovation was completed by the architect Gae Aulenti on 30 September 1996.

The building is partially embedded into bedrock. Twelve measurements were needed. Three external (Fig. 5, named S1, R1 and S6): 2 in correspondence with Liberty Square, at the same level of the ground floor. The third measurement was done in the external courtyard in the correspondence with the -1 floor. The inside measurements were taken in correspondence with the various floors (Fig. 6).

Fig. 5 – Palazzo Pubblico and location of the measurements performed outside the building. The green line indicates the direction of the walls assumed as reference (established NS component).

Fig. 6 – Palazzo Pubblico (sections) and location of the measurements performed inside the building.

4. Results

The results of the SSR methodology for the three towers and Palazzo Pubblico are reported below.

4.1 Guaita Tower

Fig. 7 shows the SSR response (for three components NS, EW and UD) for Guaita Tower. A fundamental frequency (f1) of approximately 4.5 Hz is evident for all components. There are other two peaks in correspondence with higher frequencies. f_2 frequency is around 5.70 Hz, EW component has the same value as $f_{1.}$ The other peak f_3 is around 7.9 Hz, but with inferior values (see Table 1).

For this structure, the presence of the second peak induced the authors to investigate the nature of the surrounding structures around the tower, in particular the bell-tower. In this regard, a measurement was done in correspondence with its top level. The results show a peak around 5 Hz in NS direction and 5.5 Hz in EW component. These values are close to those obtained for the tower. Therefore, it is possible to assess that the second peak is due to the interaction between the tower and the bell-tower and other structures that surround the tower itself.

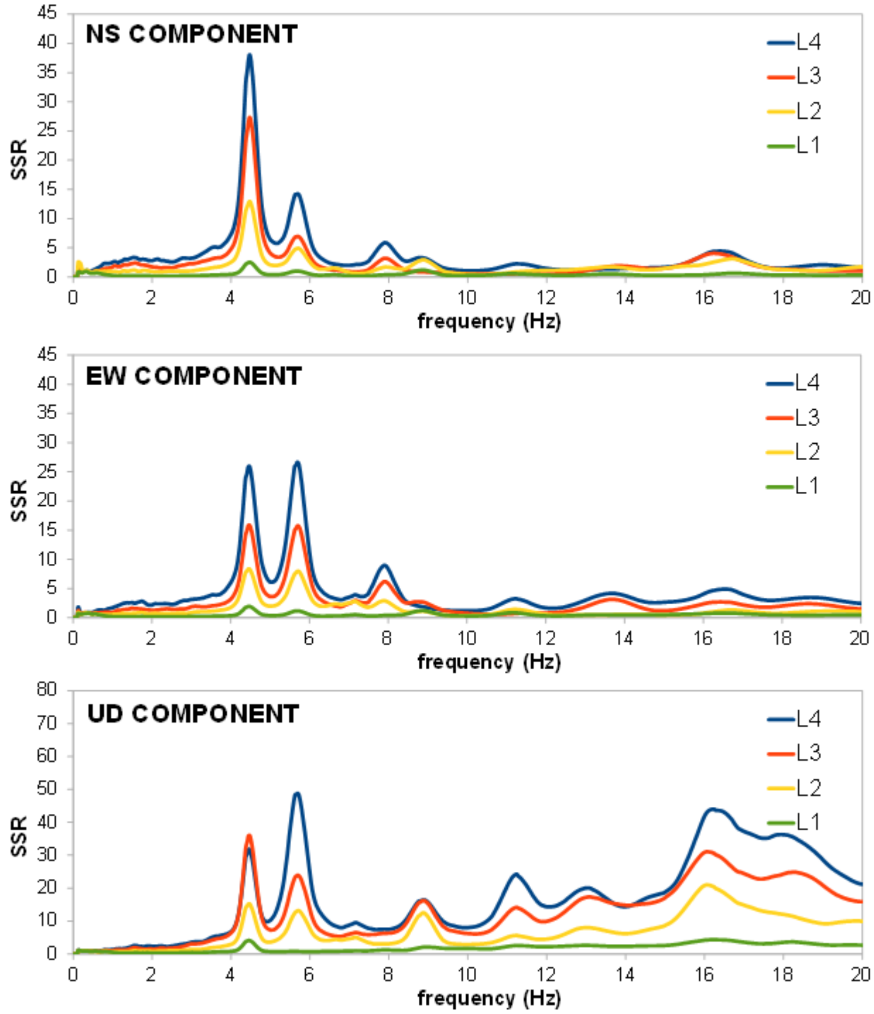

Fig. 7 – SSR curves (R15 as reference measurements), Guaita Tower, NS, EW, UD components.

4.2 Cesta Tower

Fig. 8 shows the SSR response (for three components NS, EW and UD) for Cesta Tower. A fundamental frequency (f1) around 5 Hz can be seen for every component (see Table 1). There is another peak in correspondence with 9 Hz. The peak values (for every floor except the top) are bigger than those resulted for Guaita Tower. Upper floors (L5 and L4) SSR values are much bigger than those obtained in the L3 floor for both NS and EW components.

In order to take into consideration the interaction between the tower and the surrounding structures, two measurements were done inside the tower. The first measurement was taken in correspondence with the windows in the North East part of the building (R11, R12, R13 and R14), and the second one was taken in the opposite side of the tower (S8, S10, S11 and S12). For more details, refer to Fig. 4. In this regard, comparing the SSR in the horizontal components, no big differences resulted. In particular, for every floor the S measurements are bigger than R, mainly in NS component. In EW, SSR response is much closer.

This is due to the fact that the surrounding structures are concentrated mainly in NS component. Moreover, amplifications at the lower floor are two times those registered on the second floor. It seems that the effect of the surrounding structures decreases with the tower floor level. Again, this effect results only for the NS component.

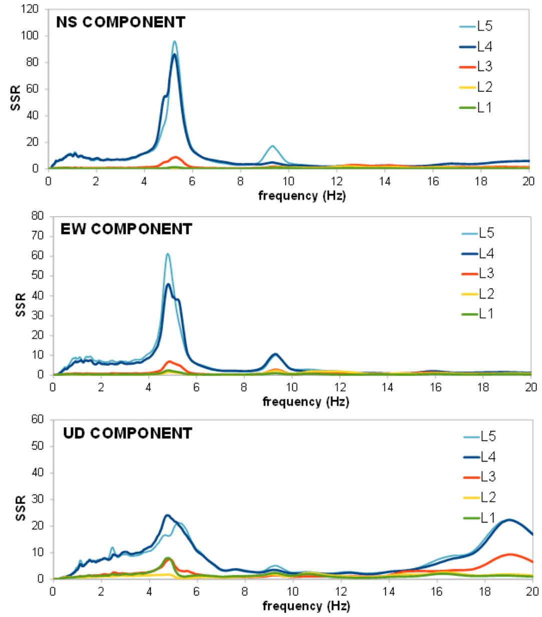

Fig. 8 – SSR curves (R9 as reference measurements), Cesta Tower, NS, EW, UD components.

4.3 Montale Tower

Fig. 9 shows the SSR response (for three components NS, EW and UD) for Montale Tower. A fundamental frequency (f1) around 4 Hz (see Table 1) can be seen for every component. In correspondence with the UD component, the resulted amplification is particularly big and not emerged in the other two towers. This can be done to the different sensitivity to the site quote. In particular, since it was not possible to enter the tower, the relative quote between the two measurements was only around 1 m. This fact particularly affected the NS and EW components, which are more quote-sensitive than the UD component.

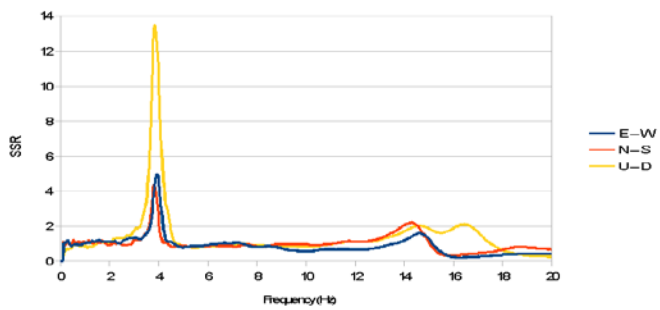

Fig. 9 – SSR curves (R7 as reference measurements), Montale Tower, NS, EW, UD components. Confidence intervals relative to each value have been computed as the maximum between 0.02 Hz (the spectral resolution relative to the Fourier Transform) and standard deviation of the set of estimates provided at the different floors

Table 1 – SSR values and relative uncertainties (Towers)

	Guaita				**Cesta**			**Montale**
components	**f_1 (Hz)**	**f_2 (Hz)**	**f_3 (Hz)**		**f_1 (Hz)**	**f_2 (Hz)**		**f_1 (Hz)**
NS	4.5±0.2	5.7±0.3	7.9±0.4		5.2±0.2	9.4±0.5		3.8 ±0.2
EW	4.5±0.2	5.7±0.3	7.9±0.4		4.8±0.2	9.3±0.5		4.0±0.2
UD	4.4±0.2	5.7±0.3	7.9±0.4		4.8±0.2	9.2±0.5		3.8±0.2

4.4 Palazzo Pubblico

Fig. 10 shows the SSR response (for three components NS, EW and UD) for Palazzo Pubblico. The building has a different behavior in the NS and EW components. In particular, in the NS component, the building is embedded in the ground at the Liberty Square level (total height 17.20 m). Instead, in the EW component the building is embedded at the deeper level and the total height is 27.70 m.

This structural complexity affects the dynamic characteristics of the building. In particular, two frequencies (f2 and f3) can be seen for every components (see Table 2). In correspondence with the EW component, other amplifications result: f_1 around 3.5 Hz and a higher frequency (f4) around 9.5 Hz. In the NS component, f_1 and f_4 did not result. Finally, in correspondence with the UD component, the three peaks (f_1, f_2 and f_3) appeared, even if the higher ones are smaller.

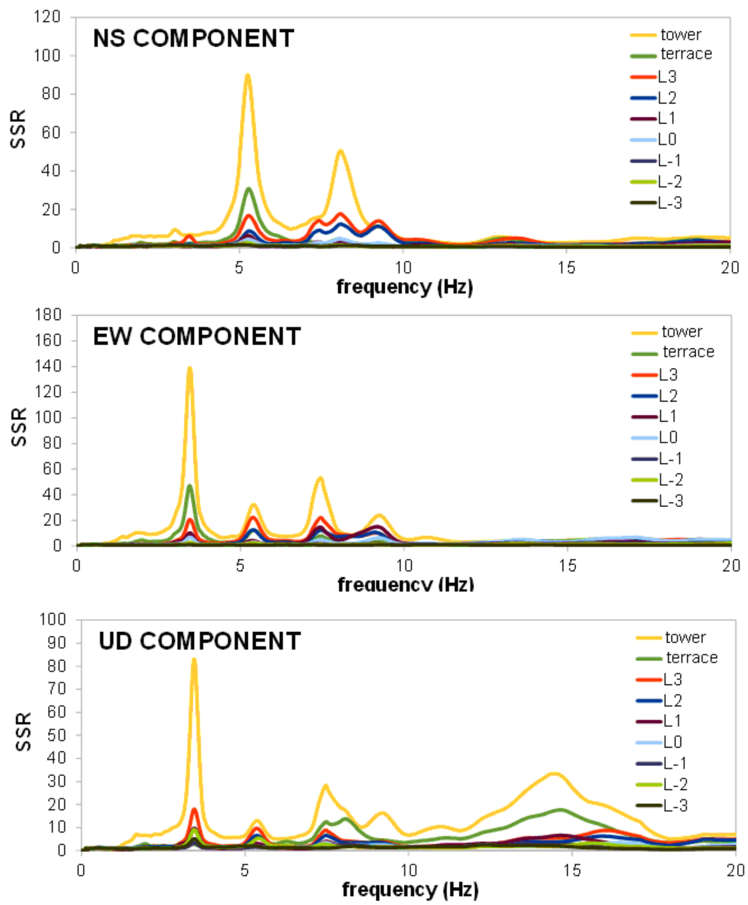

Fig. 10 – SSR curves (S6 as reference measurements), Palazzo Pubblico, NS, EW, UD components.

Table 2 – SSR values and relative uncertainties (Palazzo Pubblico)

components	**f_1 (Hz)**	**f_2 (Hz)**	**f_3 (Hz)**	**f_4 (Hz)**
NS	-	5.3±0.3	7.9±0.4	-
EW	3.5±0.2	5.4±0.3	7.5±0.4	9.2±0.5
UD	3.5±0.2	5.4±0.3	7.5±0.4	-

5. Discussion

In recent years, empirical and numerical relationships have been proposed in order to estimate the fundamental period of existing buildings (especially RC buildings) starting from their height and structural type. The mathematical functional ($T=\alpha H^{\beta}$) of this formulation was theoretically derived using the Rayleigh's method. This expression, or slight variations of it, has been subsequently adopted by many codes all over the world, such as the European seismic design regulation, [16]. In Fig. 11, red points represent the results of the presented study. These results have been compared with formulation ($T=0.05H^{0.75}$, [16]) in blue lines, assumed for the structures herein considered. The two curves are distant each other, since the study focuses on historical buildings that are more heterogeneous than those considered in the codes. In addition, the number of the case studies presented here is not sufficient to support any statistical considerations. Anyway, the green line is a proposed estimation of the obtained results, and $\alpha = 0.025$ was shown to be the best fitting value.

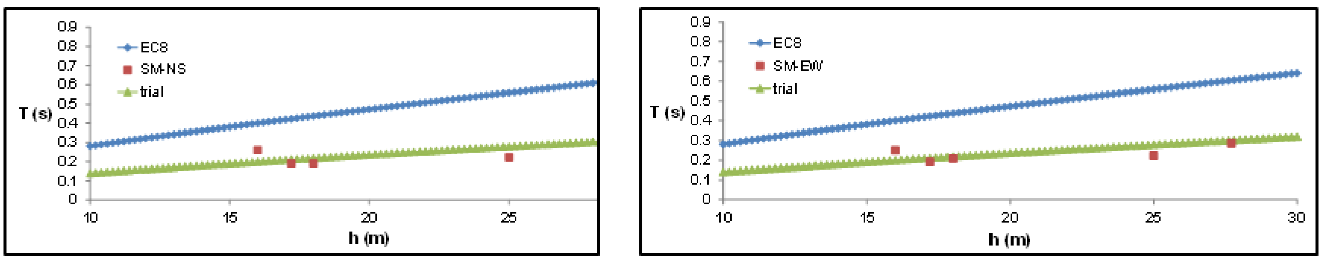

Fig. 11 – Estimation of fundamental curves EW and NS components.

6. Conclusions

The presented study was aimed at assessing the vibrational behaviors of historic buildings with SSR technique. The campaign estimated the fundamental frequencies of the main buildings in San Marino historical city center. The first and the second tower measurements showed the influence of the surrounding structures in the evaluation of vibrational characteristics of the buildings. It was also possible to assess the potentialities of SSR technology in the case of the third tower, which was not accessible and for Palazzo Pubblico because of its structural complexity.

The paper shows a comparison between the obtained fundamental periods and the one suggested by [16], proposing a curve that can fit the results properly. In this regard, the presented study can be considered a first attempt to assess seismic behaviors of historic buildings with an easy-to-use procedure for engineers all over the world.

The emerged results can be interesting for San Marino and other historical towns in order to promote heritage conservation measures. Further developments are due to proceed with more detailed identifications.

7. Acknowledgements

The presented study could be possible thanks to Segreteria di Stato Istruzione e Cultura, Segreteria di Stato per il Territorio, l'Ambiente, l'Agricoltura e i Rapporti con l'AASP, Istituti Culturali and Commissione Nazionale Unesco of the Repubblic of San Marino. The authors want to acknowledge also Dr. Jack Grippi and Dr. Nancy Morris for their help in reviewing the paper.

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