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Seismic Characterization of Historical Buildings in San Marino Republic From Ambient Vibration Monitoring

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***Abstract-* San Marino Historic Centre town was included in UNESCO world heritage list in 2008. The site is located in a region characterized by medium seismic hazard levels. Therefore, preventing 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, a relevant source for the local incomes. However, effective retrofitting interventions require a reliable assessment of seismic vulnerability of single historic buildings, that is a quite complex task when old non-engineered structures are of concern. 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. As 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 the three middle-age towers located in San Marino and allowed identifying fundamental (elastic) resonance frequency, a key parameter for assessing seismic behaviour of historical buildings.**

***Index terms-* Ambient Vibrations, fundamental frequencies, San Marino, standard spectral ratio, UNESCO.**

I. Introduction

The cultural heritage is an important asset for civil, social, cultural and economic life of a country. As a consequence, significant attention has been given to its preservation by adopting various technologies in order to achieve more effectively the objectives of protection, conservation and valorization of historical and artistic goods.

More specifically, computer technology is now often used to organize cultural tourism and physical technologies have been transferred to the artistic and cultural heritage industry for diagnostic studies. In recent years, there have been numerous projects of partnership between universities, enterprises for experimenting new technologies and methods of intervention in this area. In particular:

- computer technologies to catalogue, archive, analyze, diagnose, for virtual art exhibitions,
- 3D reconstructions of historical places, cultural heritage databases and much more;
- satellite technologies to survey and control archaeological sites;
- chemical technologies applied to the conservation and restoration of artworks;
- laser technologies for the preservation of cultural heritage [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 tall stone masonry, large span vaults as well as timber floors that are particularly vulnerable to earthquakes [2]. To define an effective seismic risk reduction strategy of a building, the authority needs to define action priorities on the basis of reliable risk estimates. These estimates require assessments of seismic hazard at the site, the vulnerability of buildings to expected earthquakes and any 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]) has been considered on purpose has been applied to three 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 a neo-classical basilica of the 19th century, 14th and 16th century convents, the Palazzo Pubblico of the 19th century, as well as the three fortification towers. Guaita, Cesta and Montale Tower are the three "pinnacles", symbol of Mount Titano, defensive bulwarks of the liberty, so important to the San Marino citizens [6].

The area where San Marino is located is characterized by a medium level seismic hazard, by the Italian code [7]. Thus, outcomes of the present study will be useful also for the local government to promote historic heritage conservation. The paper is organized as follows: Section 1 is focused on SSR technique, Section 2 presents

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the case study of San Marino, Sections 3 analyses the results and Section 4 reports the conclusions.

II. SSR TECHNIQUE

Structural identification of dynamic behavior of buildings requires expensive and invasive measurements. In alternative, direct measurements of the seismic response of buildings to small earthquakes ('weak motion') may provide important information at least as concerns the behavior of the buildings (e.g., to retrieve the fundamental resonance period of the structure) in the small strain domain, that 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 (sometimes called "micro tremors" or 'seismic noise' or 'microseisms'). They are generally present in the soil due to natural (wind, oceans, etc.) or human (traffic, industrial activities, etc…) causes. Such sources can be similarly effective (even if with small amplitude) as the small natural earthquakes for dynamic identification of historical buildings.

Recent studies [8] showed that such methodology can be applied in order to assess soil-structure interaction 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]). The Standard Spectral Ratios (SSR) technique is a possible survey strategy allowing the exploitation of this kind of load to define experimentally some important characteristics of the building response to ground shaking. In particular, main resonance periods of the structure can be retrieved and they are of great importance for anti-seismic retrofitting design assessments (e.g. [15]).

Basic ideas and assumptions behind the SSR technique can be found in [14] and summarized as follows. In general, measuring displacements of a structure induced by ground shaking at any floor or level h 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 as 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 to derive the intrinsic properties of the structure from measured displacements. In these conditions, the motion at the bases of the structure can be assumed as nearly identical to those of incident ground motion and 'the structure motion observed at the non-galilean frame 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 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:

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

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

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

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

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

If, as discussed above, one assumes that

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

it is possible to obtain:

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

This position implies that 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 mode identification by defining the shape of the building oscillations.

III. CASE STUDY

The ambient vibration survey by following the SSR approach described above has been performed on the following buildings (Fig. 1):

- Guaita Tower (First tower),

- Cesta Tower (Second tower),
- Montale Tower (Third tower).

Fig. 1. Tower locations inside the historical centre of San Marino

Velocimetric measurements have been taken at every accessible floor of the buildings and in correspondence with the ground, outside the buildings. In particular, three component portable seismographs called Tromino™, by *Micromed S.p.a.* have been used. The devices have been oriented in order to have their principle axes parallel with the buildings facades. Therefore, directions North-South (N-S) and East-West (E-W) in the following, have to be considered conventional. The Up – Down (U-D) direction, of course corresponds to the vertical.

Measurements had duration of 30 minutes and with a sampling reference of 128 cps. Recordings have been processed as follows:

- the series have been divided into time windows of 32 sec;
- in every window eventual linear derivation *(de-trend)* has been tapered with a cosine window (5 of total duration);
- Fourier transfer functions have been applied to every series and relative spectral component have been smoothed with a triangular window with 1% of the central frequency amplitude;
- for every component (N-S, E-W, U-D) the spectrum has been calculated as a mean of every windows.

The window duration (32 s) has been chosen in order to have a number of data that follows power of 2: $128 \cdot 32 = 4096 = 2^{12}$. Therefore, Fast Fourier Transfer (FFT) was possible to be completed without the introduction of zero values. As a consequence, frequency values were divided with a regular frequency corresponding to the minimum value possible to be registered (Nyquist frequency): 1/32 = 0.03125 Hz. Finally, the spectra for the 3 directions (N-S, E-W and U-D) have been calculated. The measurement at ground floor was considered the reference value with that every floor SSR spectrum has been related with. 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 was particularly difficult for the first two towers, since they are sited on the crest of the east slope of Mount Titano and surrounded by other buildings. 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 these two type of devices.

The tower fundamental frequency have been defined as the which where the maximum SSR values were registered. In every building, at least one maximum value was clearly determined with a high amplitude and defined localization. The amplitude was clearly increasing with the height of the building. For the first Tower other peak values were registered with the same clearness as the peak values. The use of different sets of SSR curves for the same structure was used in order to assess possible uncertainties of the registered frequencies. In particular, for each registered frequency, the range of maximum vibration has been calculated and symmetrically enlarged at 0.016 Hz. This value was chosen because it corresponds to the half of the frequency resolution. Therefore the fundamental value has been taken as the mean value of such range. In the following, the three structures, considered in the study, are described.

A. Guaita Tower

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

The measurements have been done in 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. Fig. 2 shows where these measurements have been sited. The inside measurements were taken in correspondence with the windows at various floors. (Fig. 3).

Fig. 2. Guaita tower (a) and location of the measurements performed outside the building (b). The green line indicates the direction of the walls assumed as reference (N-S direction)

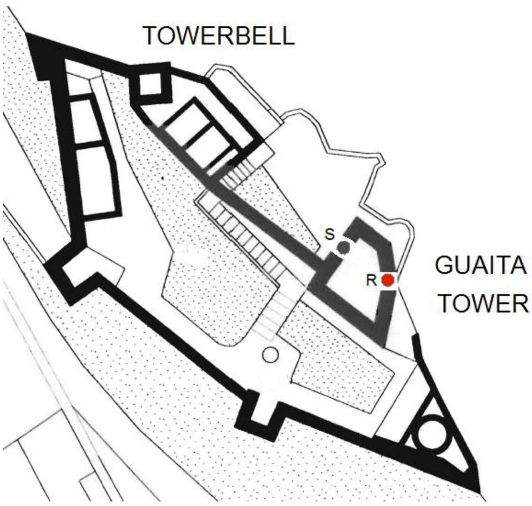

Fig. 3. Location of the measurements performed inside the building of Guaita tower, with the grey circle are indicated the measurements performed with an instrument, with the red one the measurements performed with another one

B. 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: the first and the second are obtained the first day, while the last the second. Fig. 4 shows where these measurements have been sited. The inside measurements (floor 1, 2 and 3) were taken in correspondence with the windows in the N-E 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. 5, 6 and 7).

Fig. 4. Cesta Tower (a) and location of the measurements performed outside the building (b). The green line indicates the direction of the walls assumed as reference (N-S direction)

Fig. 5. Location of the measurements performed inside the building of "Torre Cesta" (at the ground floor), with the grey circle are indicated the measurements performed with an instrument, with the red one the measurements performed with another one

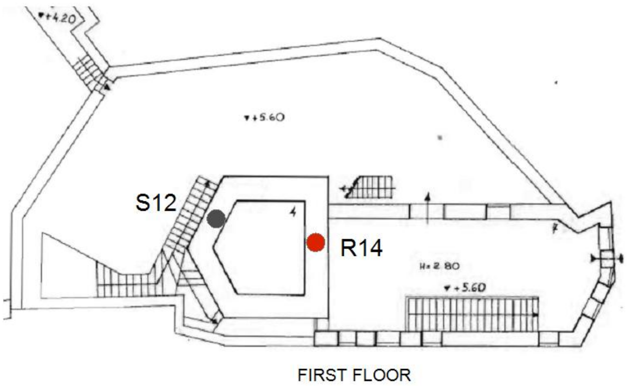

Fig. 6. Location of the measurements performed inside the building of "Torre Cesta" (at the first floor), with the grey circle are indicated the measurements performed with an instrument, with the red one the measurements performed with another one

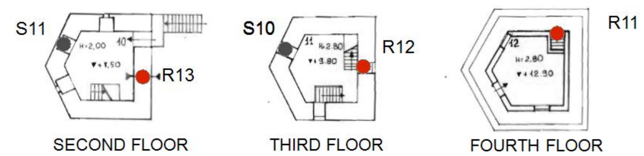

Fig. 7. Location of the measurements performed inside the building of "Torre Cesta" (at the second, third, and fourth), with the grey circle are indicated the measurements performed with an instrument, with the red one the measurements performed with another one

C. Montale Tower

Montale Tower dates back to the end of the XIII century. This is the smallest of the towers but because of the best position for a look-out post, this tower played a strategic role as its 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 and ancient rocks arranged to form a primitive wall structure [6]. This is the only isolated tower and not accessible. For this reason, only external measurements have been taken (S6, S7, R7, Fig. 8). One measurement has been taken in correspondence with the foundation at N-E edge (named R8 in Fig. 8).

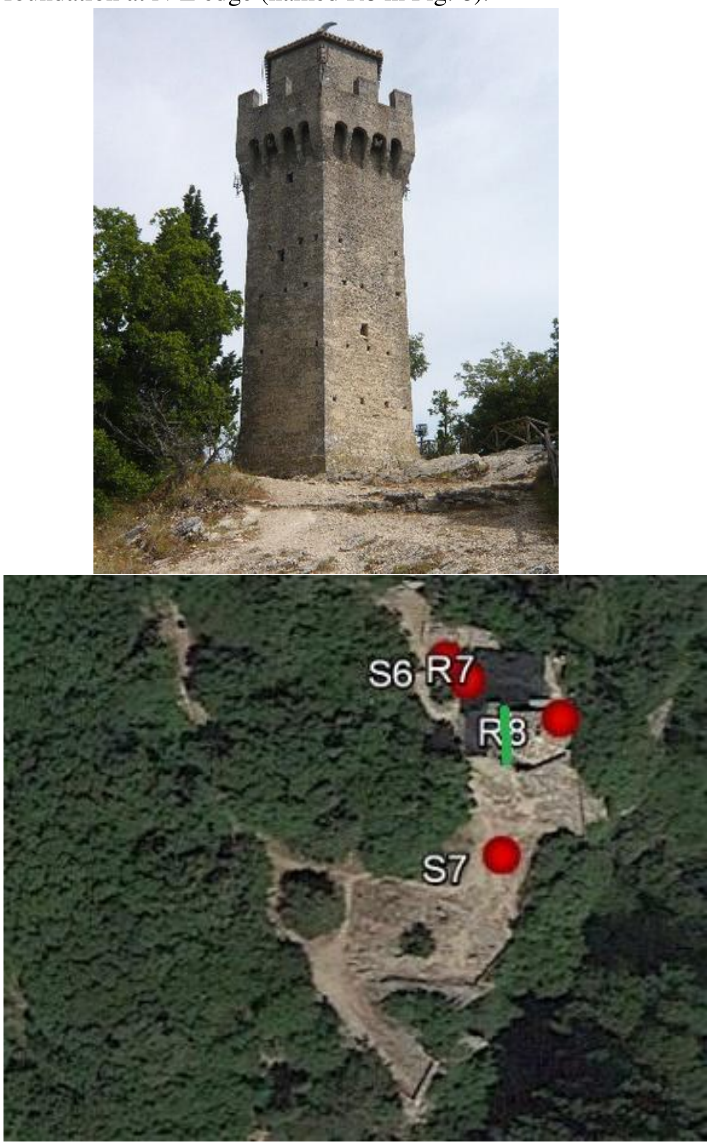

Fig. 8. Montale tower and location of the measurements performed outside the building. The green line indicates the direction of the walls assumed as reference (established NS direction)

IV. RESULTS

In this paragraph results in terms of SSR are reported for the three towers.

A. Guaita tower

Fig. 9-11 show the SSR response (for three components N-S, E-W and U-D) for Guaita tower. It can be seen a fundamental frequency (f_1) around 4.5 Hz (for more details see Table I) for every components. There are other two peaks in correspondence with bigger frequencies. F_2 frequency is around 5.7 Hz and in E-W direction has the same value as f_1. The other peak f3 is around 7.9 Hz, but with inferior values.

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 towerbell (Fig. 3). In this regard, a measurement was done in correspondence with the top of it. The results shown a peak around 5 Hz in N-S direction and 5.5 HZ in E-W direction. 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 towerbell and other structures that surround the tower itself.

Table I. SSR values and relative uncertainties

components	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)
N-S	4.5 ± 0.2	5.7 ± 0.3	7.9 ± 0.4
E-W	4.5 ± 0.2	5.7 ± 0.3	7.9 ± 0.4
U-D	4.4 ± 0.2	5.7 ± 0.3	7.9 ± 0.4

Fig. 9. SSR curves (R15 as reference measurements), Guaita tower, N-S direction

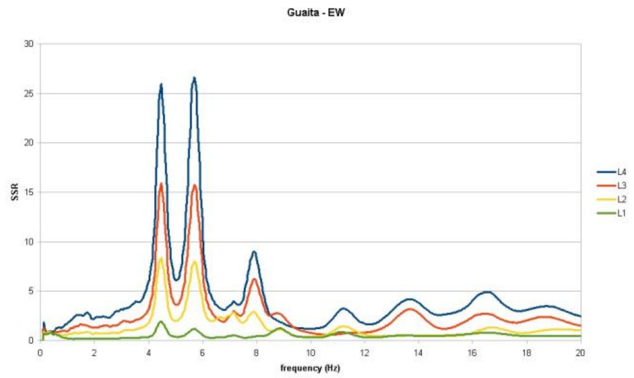

Fig. 10. SSR curves (R15 as reference measurements), Guaita tower, E-W direction

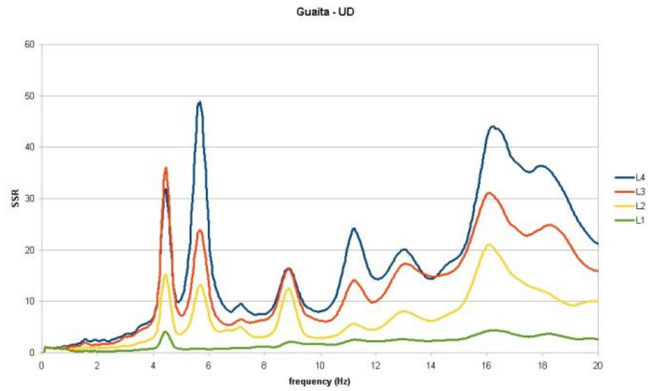

Fig. 11. SSR curves (R15 as reference measurements), Guaita tower, U-D direction

B. Cesta Tower

Fig. 12-14 show the SSR response (for three components N-S, E-W and U-D) for Cesta Tower. It can be seen a fundamental frequency (f_1) around 5 Hz (for more details see Table II) for every components. 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 in correspondence with L3 floor for both N-S and E-W directions.

In order to take into consideration the interaction between the tower and the surrounding structures, two inside measurements have been done. The first, in correspondence with the windows in the N-E part of the building (R11, R12, R13 and R14). The second in the opposite side of the tower (S8, S10, S11 and S12), for more details, see Fig. 5-7. In this regard, comparing the SSR in the horizontal components, no big differences resulted. In particular, for every floor the S measurements are bigger that R, mainly in N-S direction. In E-W SSR response are much closer. This is due to the fact that the surrounding structures are concentrated mainly in N-S direction. Moreover, amplifications at the lower floor are quite double that those registered at second floor. It seems that the effect of the surrounding structures decreases with the height of the tower. Again, this effect results only for the N-S component.

Table II. SSR values and relative uncertainties

components	f_1 (Hz)	f_2 (Hz)
NS	5.2 ± 0.2	9.4 ± 0.5
EW	4.8 ± 0.2	9.3 ± 0.5
Z	4.8 ± 0.2	9.2 ± 0.5

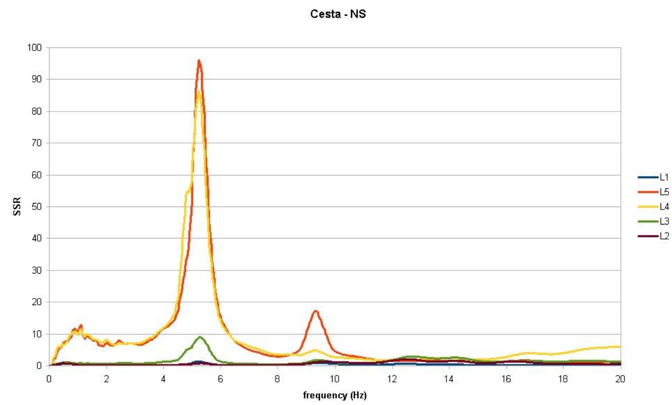

Fig. 12. SSR curves (R9 as reference measurements), Cesta tower, N-S direction

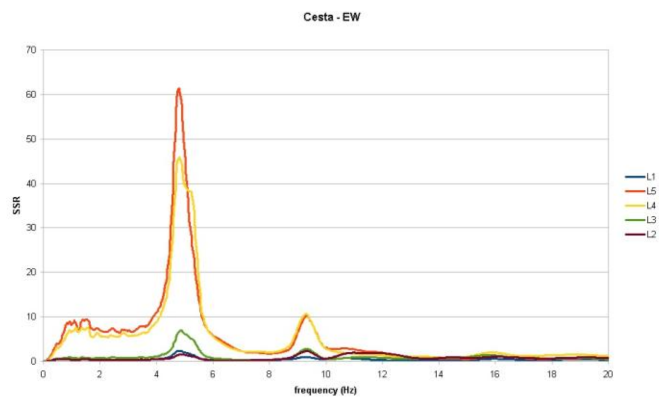

Fig. 13. SSR curves (R9 as reference measurements), Cesta tower, E-W direction

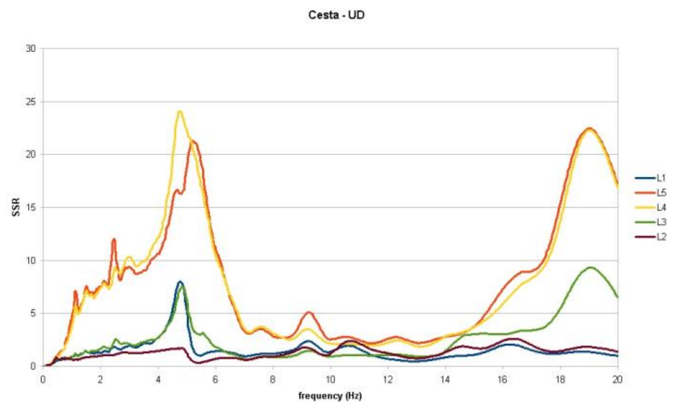

Fig. 14. SSR curves (R9 as reference measurements), Cesta tower, U-D direction

C. Montale Tower

Fig. 15 shows the SSR response (for three components N-S, E-W and U-D) for Montale Tower. A fundamental frequency (f_1) around 4 Hz (for more details see Table III) can be seen for every components. In correspondence with the U-D direction, 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 N-S and E-W components, that are more quote-sensitive than the U-D direction.

Table III. SSR values and relative uncertainties

Components	f_1 (Hz)
NS	3.8 ± 0.2
EW	4.0 ± 0.2
Z	3.8 ± 0.2

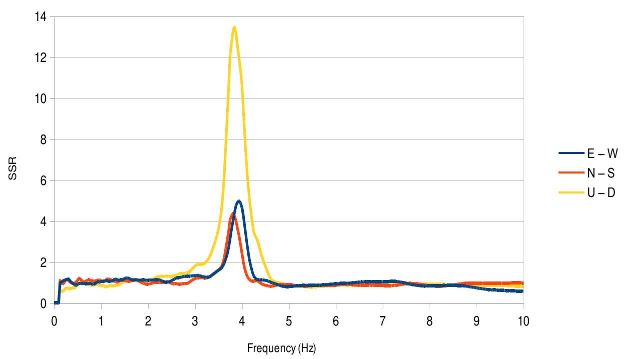

Fig. 15. SSR curves (R7 as reference measurements), Montale tower, N-S direction

V. CONCLUSIONS

The presented study was aimed at assessing the vibrational behaviours of historic buildings with SSR technique. The campaign estimated the fundamental frequencies of the towers in San Marino historical city center. The frequencies resulted 4 Hz, 4.5 Hz and around 5 Hz for Montale, Guaita and Cesta towers respectively. The first and the second tower measurements showed the effects of the surrounding structures in the evaluation of vibrational characteristics of the buildings. It was also possible to assess the potentialities of SSR technology, also in the case of the third tower, which was not accessible.

The peaks in correspondence with higher values are presumably due to the superior shape modes. However, the level of such methodology does not allow assessing details of such behavior. For this reason, the presented study can be considered a first attempt to assess seismic behaviours of historic building with a easy-to-use procedure for engineers all over the world. In this regard, the emerged results can be interesting for San Marino Government in order to promote historic heritage conservation actions. Further applications are due to proceed with more detailed identifications.

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