

3D NUMERICAL SIMULATIONS OF THE SAN MARINO THIRD TOWER (MONTALE) BASED ON 3D MAPPING

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Abstract. *San Marino historic centre 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 preserving historical buildings and fundamental in order to sustain tourism, a relevant source for the local incomes. In this regard, the historical center was object of an extended project jointly organized by University of San Marino, University of Siena and the Center of Interdisciplinary Science for Art, Architecture and Archaeology California (CISA 3) at University of California, San Diego. In particular, the three middle-age towers of San Marino can be considered a landmark for the Republic and the world. In this framework, the paper aims at calibrating a 3D numerical finite element (FE) of the third tower, called Montale. This study can be seen as a proposal to assess seismic behaviour of historical towers, as well as an easy-to-use model for engineers and consultants all over the world. The presented outcomes will represent an important basis for risk reduction actions by the San Marino authorities.*

1 INTRODUCTION

Cultural heritage is an important asset to the civil, social, cultural and economic life of a country. Its preservation has been improved by adopting various technologies that achieve more effectively the objectives of protection, conservation and valorization of historical and artistic artefacts. The object of this paper is Montale, the third tower among the ones in San Marino and one of its masterpiece (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 and fundamental in order to sustain tourism, a relevant source for the local incomes.

In this regard, the historical center was object of two extended projects jointly organized by University of San Marino, University of Siena and the Center of Interdisciplinary Science for Art, Architecture and Archaeology California (CISA 3) at University of California, San Diego. The first step consisted of the application of ambient vibration technique to the three middle-age towers located in San Marino in order to identifying fundamental (elastic) resonance frequencies, key parameters for assessing seismic behavior of historical buildings. Two campaigns have been carried out on October 2015 and October 2016. The second step was aimed at applying the most credited technologies to register a tridimensional mapping of the historical center. On July 10-17 2016 the mapping campaign was carried out with 3D laser scanners, one cave camera and one drone. The results have been post-processed during the following months at University of California, San Diego. These previous activities gave the possibility to collect many information regarding the dimensions, materials, structural and dynamic characteristics that were fundamental in order to perform a Finite Element Model (FEM) in order to represent the dynamic behavior (the 'response') of the tower under possible seismic motions.

2 CASE STUDY

This paper aims at reproducing the seismic response of Montale tower. It dates back to the end of the XIII century and it is the smallest among the towers. Because of its 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.

The tower is 17.68 m tall. The plan section consists of an irregular pentagon with the five sides of different length (see Figure 1). The structure is divided by two floors. The first is made with stones at a high of about 5 m from the ground. The second is built with wood. Since it was impossible to reach the ground floor, it was decided to consider the first floor thickness around 50 cm. The upper slab is a stone arc floor. The arc thickness goes from more than 1 m in the side until about 30 cm for a little stretch in the middle. The roof is made of wood with shingle blocked with some rocks. In correspondence with the highest part of the tower, there are two important medieval components: the shrinkage and the battlements all around the building.

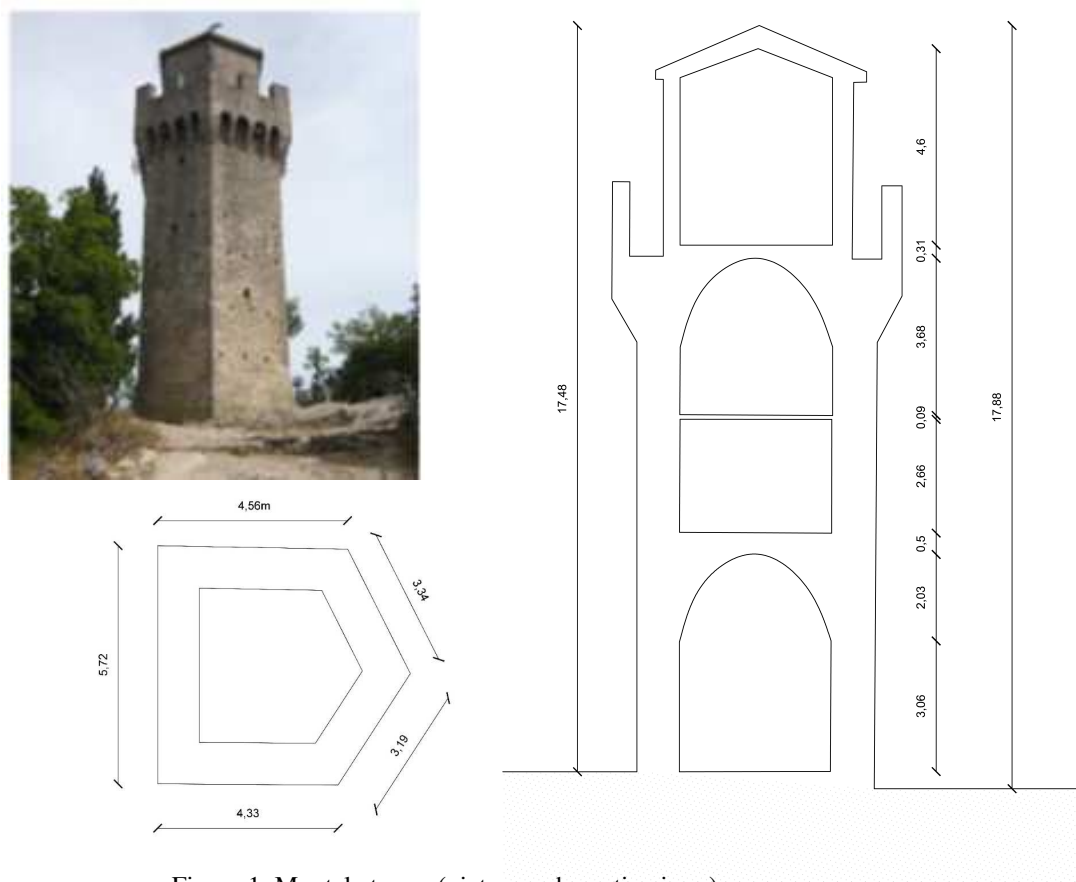


Figure 1. Montale tower (picture, schematic views)

3 3D MAPPING

Computer technology has been transferred to artistic and cultural heritage protection and diagnosis [1] and [2]. In this regard, a project joined between University of San Marino and the Center of Interdisciplinary Science for Art, Architecture and Archaeology California (CISA 3) at University of California, San Diego (UCSD) was carried with the aim of realizing a 3D mapping of the historical center, in particular its principal monuments. The project was sponsored by UNESCO national commission in San Marino, the Environmental and the University and Research Ministers of the Republic of San Marino.. The aim was the assessment of the actual state of the tower in order to study possible restoration procedures. 3D laser scanner technology was chosen in order to have the complete survey of the building with 2D data (floor plants and section) and 3D data (point cloud of the tower) in the faster and easier way. A difficulty of the project was the total absence of data and reliable plans of many of the historical buildings of the Republic of San Marino and particularly the third tower.

The team from UCSD came to San Marino between July 10th to July 17th, 2016. The instruments consisted essentially in the Faro focus, one drone and one cave camera. In order to have a day-by-day preview of the work, at the end of each day, the team sent the acquired files at the computer of California Institute for Telecommunications and Information Technology to post-process the data.

3.1 Instrumentations

The laser scanner (3D Faro Focus [3] and [4]) is one of the best instrument for this kind of project and it offers many advantages. It is a non-invasive method to collect data, suitable in cases of detection of historic buildings. The large amount of data obtained in a very short time allows to analyse the current state of the monument. Efficiency is another advantage of such technology, compared to a traditional method of relief. In particular, historical monuments are often characterized by irregular geometries and many imperfections. In this regard, a conventional-way survey would have required more time and human resources. The efficiency consists of high scanning speed and high precision. In particular, Focus3D generates (with millimetre precision) a virtual copy of reality to the speed of 976.000 measurement points per second. After the elaboration of this kind of data it is possible to obtain dense point clouds that can be transformed in geometric elements such as floor plants and section. Faro focus is made of a tripod, with three extensible legs, a screw in the centre of the base to secure the instrument, a toric compass through which you can put the instrument perfectly horizontal. Figure 2 shows the structure of the instrument that essentially consists of a parallelepiped-shaped body with a central rotating mirror that directs the laser beams against the surfaces to be recorded. Faro Focus 3D has a recording range up to a maximum of 305° along the vertical axis and 360° along the horizontal axis.

A complete survey of the tower involved some parts which were difficult to be accessed, like the below part of the roof or some part near the cliff of the mount Titano. For these elements, capturing the data with the Faro Focus 3D was almost impossible. Therefore, one drone (Figure 3(a)) was used for this project. It is a professional drone, named DJI phantom 3 [5] quadcopter with a high resolution camera on the bottom. The camera can register a 4K movie at 30 frame for second and 12-megapixel photo. A 3-axis gimbal was used to stabilize the camera, by the numerous vibrations of the drone. With this data was possible to complete the high external part of the third tower. The use of the drone was essential in order to capture the profile of the entire mount Titano and the city centre of San Marino. It was fundamental to connect the three towers in the 3D point cloud as well.

One cave camera (Figure 3(b)) was used as well. This instrument is composed by a tripod with two cameras fixed at the top of it. Cave camera is able to rotate in the vertical and horizontal axis and take pictures with the two cameras every step for all the 360° for a total of 96 picture for camera. The results consist of two (one per each camera) different single pictures of resolution 32884×16442 pixel and 614 MB of size representing the left and right eyes. The software Agisoft PhotoScan was applied to align the pictures and create a unique one.

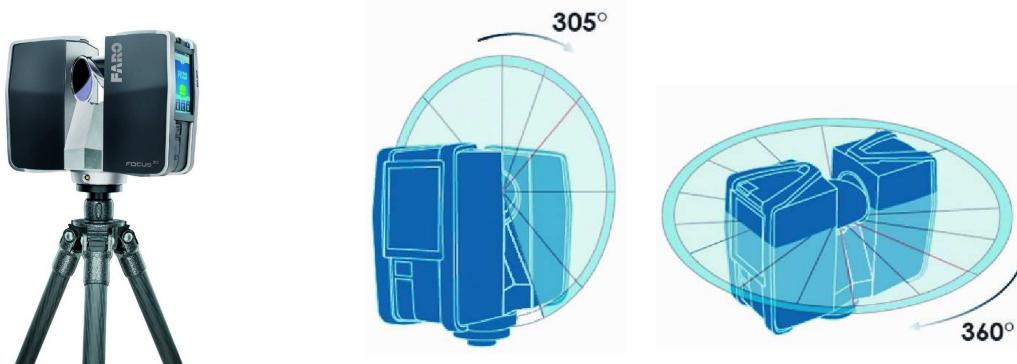


Figure 2. The laser scanner (3D Faro Focus) applied in the study



Figure 3. Drone (a) and Cave Camera (b) applied in the study

3.2 Post processing

The data were elaborated with Agisoft PhotoScan, a stand-alone software solution for automatic generation of dense point clouds, textured polygonal models, georeferenced true orthomosaics from still images. Agisoft is capable of processing of thousands of high-speed photos and providing at the same time high accurate results (up to 3 cm for aerial and up to 1 mm for close-range photography). After the important operation of alignment of the photos, dense point cloud models can be generated by PhotoScan. Based on the estimated camera positions, the software calculates depth information for each camera to be combined into a single dense point cloud. The photos of input added in the software were 2460. The first step was to align photos and the results is showed in Figure 4(a). Then, it was necessary to reconstruct every shots taken with the drones, to build the dense cloud and to delineate the area around the tower. Figure 4(b) shows the results of this process. The final model was built with triangular meshes that connect the points.

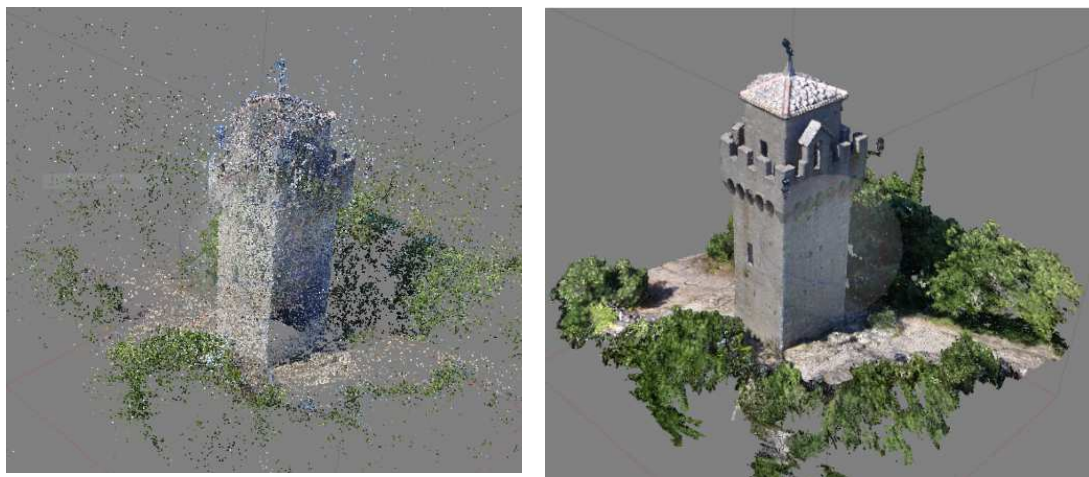


Figure 4 (a): point cloud (first step), (b): final point cloud

4 SSR IDENTIFICATION

A preliminary study of identification of the principal dynamic properties of the tower was provided in the frame of a research agreement between University of San Marino and University of Siena [1] and [2]. Resonance frequencies of the tower (in the small strain domain) have been estimated by applying the Standard Spectral Ratios (SSR) approach aiming at evaluating seismic response of old buildings based on ambient vibration monitoring (e.g., [6]). The technique consists in measuring (by velocimetric sensors) average spectral amplitudes of vibrations at any floor or level of the structure induced by ambient ground shaking. These are compared with those obtained (asynchronously) in the free field near the building to be evaluated. Spectral ratios are then computed to identify main natural frequencies of the structure coupled with the soil. In particular, in the presence of a relatively rigid soil (as in the case of San Marino), the contribution of soil-structure interaction can be assumed negligible: in this situation, resonance periods deduced in this way 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. More details in [1] and [2]. Figure 5 and Table 1 show the results in terms of SSR for the 4 levels of the tower (L0-L4) in the North South (N-S) component and in the East West (E-W) component.

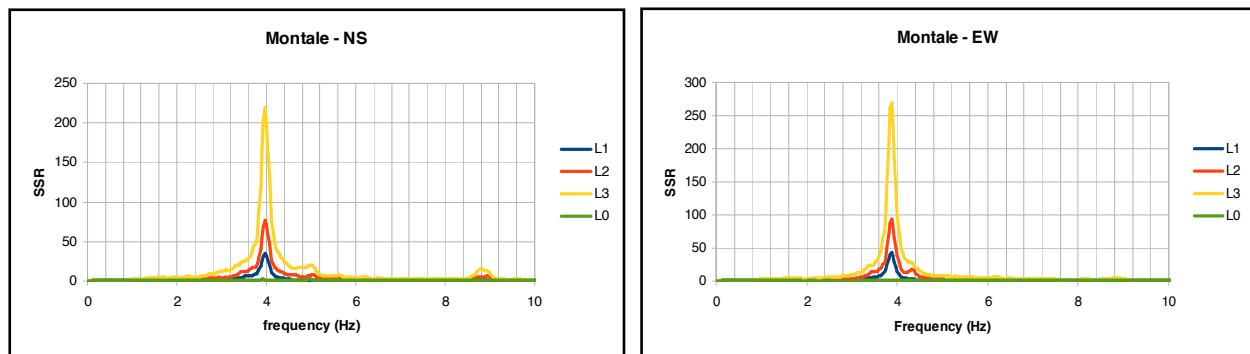


Figure 5 Outcomes of the SSR measurements: (a): N-S component, (b): E-W component

Frequency	N-S	E-W
1 st	4.02	3.85
2 nd	6.19	6.18
3 rd	8.93	8.93
4 th	9.62	9.86
5 th	15.20	14.96

Table 1: Results from the SSR identification

5 FEM MODEL

The finite element model (FEM) of the tower was performed with the software Sap 2000. The model has been calibrated by comparing the resulted fundamental frequencies and shape modes with those from the ambient vibration technique survey. The geometric characteristics have been taken by the database from the 3D mapping. In particular, some simplifications of the geometry were necessary. For example, the intermediate wood slab has been neglected in

the model because it was considered irrelevant in determining the behavior of the tower. The upper arc thickness was considered homogenous and 75 cm thick. The roof was modelled with a 25 cm thickness wood slab. The shrinkage and the battlements were neglected in the model. For this reason, the total mass of the tower was decreased of 300kN, in order to consider the area lost on the wall due to the battlements. In order to take into account the weight, the density of the floor which is at the same level of the battlement has been decreased. Finally, the effects of soil structure interaction have been neglected and the tower was assumed fixed at the ground. This simplification is realistic, since the building is directly founded on a hard rock.

In order to calibrate the model, four models have been performed in terms of overall size and distribution of the finite elements. Since the aim of the study is the reproduction of the frequencies, the fundamental period of the tower was selected as the main parameter to compare the convergence. The performed meshes (Figure 5) have increasing number of joints and elements (Table 2).

Figure 6 shows the first six frequencies of the tower for the four different mesh in the following images. The results show that increasing the number of finite elements, the tower becomes less rigid. There is a good convergence between the four meshes. The most precise mesh is Mesh_04, but computational time was high, that it was decided to use the mesh_03.

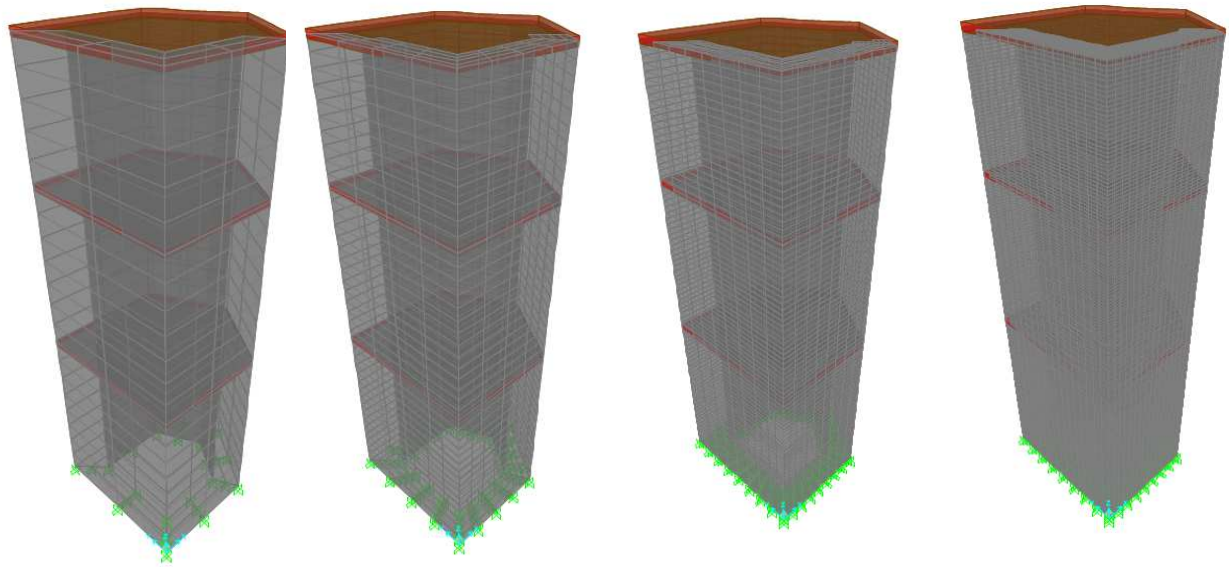


Figure 5: Meshes adopted in the study

Frequency	joints	3D elements
Mesh_01	630	400
Mesh_02	4100	3200
Mesh_03	29160	25600
Mesh_04	218960	204800

Table 2: Meshes adopted in the study

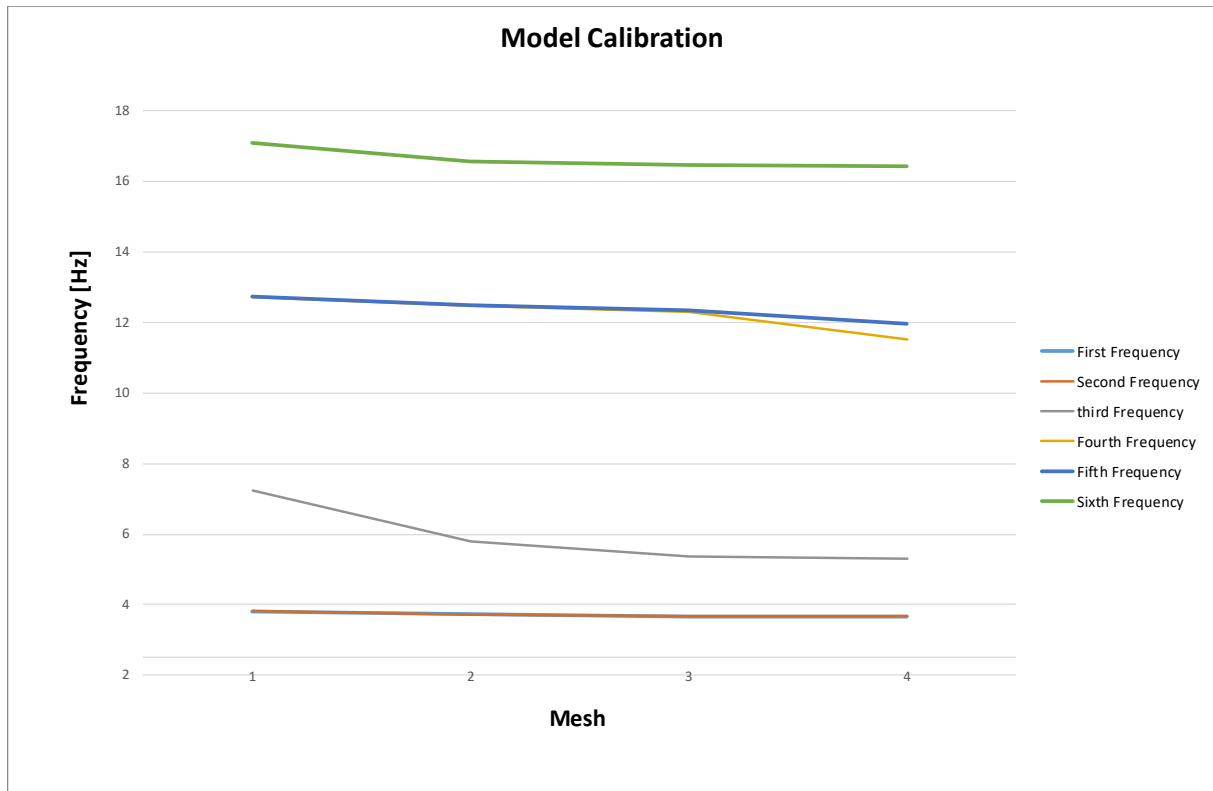


Figure 6: Convergence study

Frequency	Mesh_01	Mesh_02	Mesh_03	Mesh_04
1 st	3.805490068	3.719211041	3.662752134	3.669343392
2 nd	3.823920667	3.734800987	3.688762513	3.685809059
3 rd	7.217976694	5.772516122	5.37781980	5.298982183
4 th	12.69843017	12.45309568	12.29501209	11.50587126
5 th	12.73537497	12.48305270	12.34966401	11.57131375
6 th	17.07189782	16.57264044	16.44002199	15.52045169

Table 3: First six frequency for the 4 meshes adopted in the study

6 NUMERICAL MODEL

In order to set up the material parameters, a literature review on several case studies applied to similar structures with the same historical ages was carried out [7], [8] and [9]. In particular, [8] studied the implementation of a finite element model of Chiesa Collegiata, located in Collegiata, Italy. The applied material model was ortotropic material In order to assess the influence of the material parameters, a parametric studies have been performed, by varying several parameters, such as the density, Young modulus and Poisson coefficient. The final characteristics are shown in Table 4 (where 1, 2 and 3 means the directions of the material).

Figure 7 show three shape modes for final mesh adopted in the study. In order to validate the FEM model, these results were compared with the SSR identification shown in paragraph 5. In particular, the first FE model frequency was compared with the NS component of the first modal form, while the second from Sap2000, with the EW component. The superior

modes are compared with both components because the frequency founded with the FEM are combined in both directions. Table 5 shows the results in terms of frequencies. The first and second frequency (translational motions) are close. The mistake in correspondence with the third frequency (the torsional ones) is bigger. The superior frequencies are not so close, but the structure is rigid and the participation masses do not have big influence in the dynamic behavior, since the participation masses on the first frequencies reach the 75% for both NS direction and EW direction, as shown in Table 5.

Density (kN/m ³)	Poisson Coefficient	Coefficient of thermal exp. (°C ⁻¹)	Modulus of Elasticity (GPa)		Shear Modulus (GPa)
15.5	0.15	9.90 ⁻⁰⁶	E ₁	3.50	G ₁₂ 1.30
			E ₂	8.05	G ₁₃ 0.28
			E ₃	9.05	G ₂₃ 0.28

Table 4: Ortotropic material: characteristics

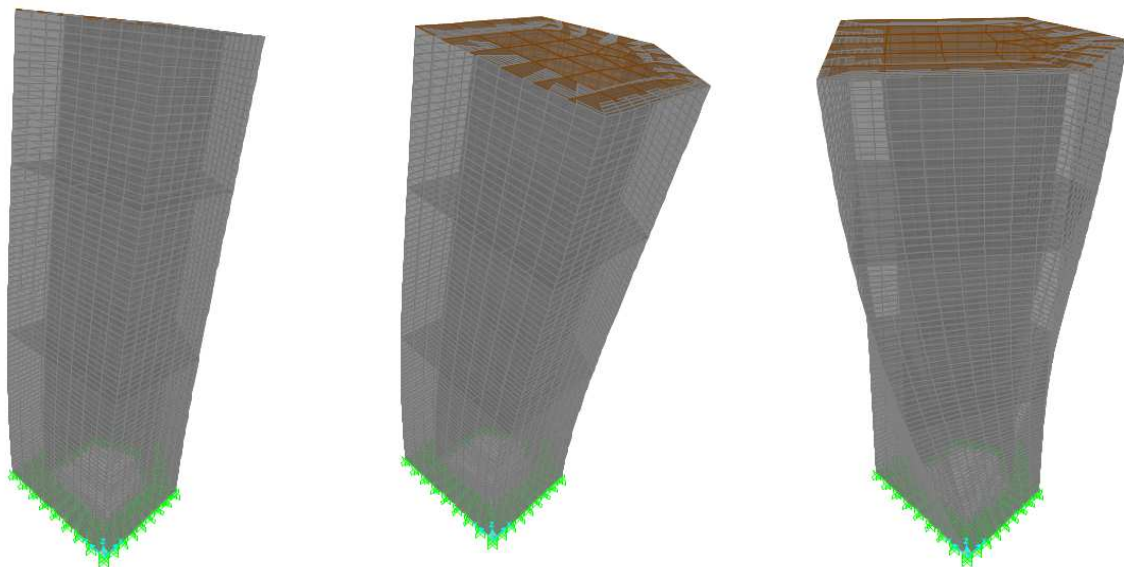


Figure 7: final model performed in the study: first three shape modes

Freq	SAP2000	SSR(N/S)	Mx	Error (%)	SSR(E/W)	My	Error (%)
1 st	3.67	4.02	0.752	-8.70	-	0.017	
2 nd	3.67	-	0.017	-	3.85	0.753	-4.68
3 rd	5.38	6.19	0.000	-13.10	6.18	0.000	-12.95
4 th	12.30	8.93	0.121	+37.74	8.93	0.000	+37.74
5 th	12.35	9.62	0.005	+28.38	9.86	0.120	+25.25
6 th	16.44	15.20	0.000	+8.16	14.96	0.000	+10.04

Table 5: Comparison FEM – SSR frequencies

7 CONCLUSIONS

The study presented here is part of a bigger project organized by University of San Marino, University of Siena and the Center of Interdisciplinary Science for Art, Architecture and Archaeology California (CISA 3) at University of California, San Diego. This paper aims at as-

sessing the state of Montale, the third tower in San Marino historical city center. A FEM has been built and performed on the basis of an ambient vibration survey (step 1) and a 3D mapping (step 2). The tower has been performed with SAP2000. The material characteristics have been deduced by a literature review and a parametric study. The frequencies resulted by the numerical simulations have been compared with those resulted by the survey. The presented study can be considered a first attempt to assess seismic behaviors of San Marino historic buildings. The procedure will be extended to other monuments in the historic site. The emerged results can be interesting for San Marino government in order to promote historic heritage conservation actions.

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REFERENCES

- [1] G. Peruzzi, D. Forcellini, K. Venturini, D. Albarello, *Ambient vibrations applied to San Marino historical building survey*. Proceedings of the XIV World Conference on Earthquake Engineering, Santiago, Chile, 9-13 January, 2017, Paper N° 985.
- [2] G. Peruzzi, D. Forcellini, K. Venturini and D. Albarello, *Seismic Characterization of Historical Buildings in San Marino Republic from Ambient Vibration Monitoring*. International Journal of New Technology and Research, vol. 2, Issue 7, 95-102 ISSN: 2454-4116, 2016.
- [3] <http://www.faro.com/en-us/products/3d-surveying/faro-focus3d/overview>
- [4] FARO® Laser Scanner Focus3D Manual October 2011
- [5] <http://www.dji.com/phantom-3-pro>
- [6] Lunedei, E., Peruzzi, G. and Albarello, D. (2015). *Ambient vibrations in seismic studying the UNESCO cultural heritage site of San Gimignano (Italy)*. Proceedings of the International Conference Georisks in the Mediterranean and their mitigation, Valletta, Malta, 20–21 July 2015, 243-247, ISBN: 978-88-98161-20-1
- [7] A. Gregori, H. Salem, T. Harak, K. Fassieh, A. Khalil *collapse analysis of Santo Stefano tower using applied element method* Proceedings of 16th World Conference on Earthquake Engineering, 16WCEE 2017, Santiago Chile, January 9th to 13th 2017, Paper N° 2394
- [8] C. Gentile, A. Saisi and A. Cabboi *Structural Identification of a Masonry Tower Based on Operational Modal Analysis*, International Journal of Architectural Heritage: Conservation, analysis and Restoration, 9:2, 98–110, DOI: 10.1080/15583058.2014.951792, 2015
- [9] C. Gentile, A. Saisi, *Ambient vibration testing of historic masonry towers for structural identification and damage assessment*, Construction and Building materials 21 (2007) 1311-1321, 2006