A Robust Approach for Numerical Modelling of a Historical Masonry Tower using Sensors

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Abstract— **Conservation of historical structures is a pivotal role for every nation and nowadays several studies have been performed in order to assess the vulnerability of the structures subjected to different types of risks. Numerical modeling of historical structures is challenging because destructive tests are not allowed on these structures and some of them are so complex in architecture. In this paper combination of two types of sensors has been discussed for finite element modeling of a stone masonry tower. Firstly, 3D laser scanners are utilized as a fast and precise tool for 3D representation of the structure and the 3D drawing is converted to numerical modeling. Afterward, operational modal analysis is performed using accelerometers for deriving dynamic characteristics and of the structure and updating the finite element model.**

Keywords—Finite element modeling; Historical masonry tower; 3D laser scanner; Accelerometer; Operational modal analysis

I. Introduction

Comprehensive knowledge about the geometry of the structure, material properties, and boundary conditions are required to have a robust numerical model of historical structures in a non-invasive way [1]. Afterward in order to assess the vulnerability of the structure different types of risks and their effects on the structure should be investigated and applied to the numerical model [2, 3].

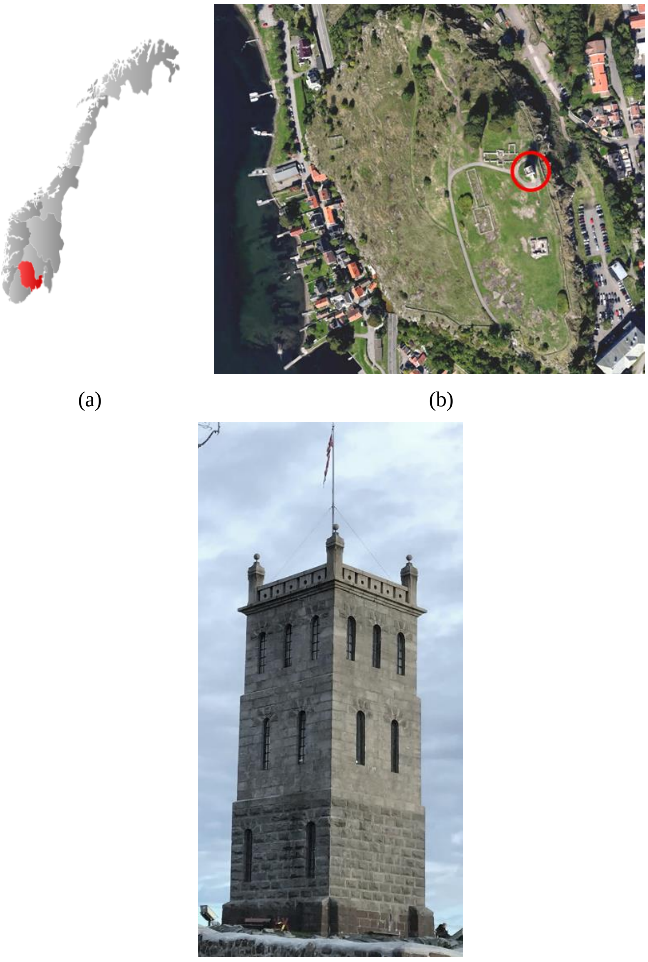
In recent years contemporary digital methods help structural engineers for geometric documentation of structures. 3-dimensional (3D) laser scanner is one of remote sensing technique for providing reliable, realistic, and accurate 3D models can be easily exploited even by non-experts in new technologies and can be converted to 3D finite element models (FEM) for structural analysis [4-8].

After providing a reliable 3D FEM from the raw data of the laser scanners, operational modal analysis (OMA) of the structure by accelerometer sensors is a tool to constrain and calibrate the FEMs [9-11]. FEM tuning of historical structures has been done by dynamic identification of historical structures including masonry towers as a non-destructive procedure [12-15]. Optimization algorithms have been employed for accurate calibration of the masonry towers in a way that the tower was divided to different parts and material properties if each part was updated based on the results from ambient vibration testing [16].

Boundary conditions including soil structure interaction (SSI) is another aspect in numerical modeling of historical towers [1]. One option is to neglect SSI, but the basement level structural elements must be modeled. This procedure will be employed in different studies [17-19].

In this paper FEM of a historical stone masonry tower in Tønsberg, Norway has been developed. The Slottsfjell tower is located on a rocky hill which dates from 1888 with architectural characteristics of middle age towers (See Fig.1).

A 3D laser scanner has been employed as a 3D representation and documentation tool. Accelerometer sensors have been installed for OMA of the tower in order to derive the dynamic characteristics of the tower. Afterward, the 3D geometry converted to FEM. In the FEM of the tower, SSI effect has been neglected and the updating process of the material properties of the structure is performed from the results from the OMA.



(a) (b)

(c)

Fig. 1.a) the place of Tønsberg in Norway and b) the place of The Slottsfjell tower on top the hill c) Slottsfjell tower, a stone masonry tower in Tønsberg

II. NUMERICAL MODELING

A Topcon 2000 3D laser scanner for deriving the dense point clouds of the structure. Totally 20 scans have been performed inside and outside of the tower and the data is imported into Autodesk Recap to combine the raw point clouds of the shots into one complete model. The combined point clouds are then imported to Autodesk Revit for 3D modeling of the tower as it is illustrated in Fig.2.

After developing an accurate 3D model of the tower as it is shown in Fig.3, the drawing file is imported to DIANA FEA software package. In this software, the 3D geometry of the tower is converted to FEM as it is shown in Fig.4 by considering homogenized method which is a robust and prevalent method for numerical modeling of the masonry structures [20].

Orthotropic material will result in a better dynamic characteristic of a masonry tower therefore an orthotropic material has been considered for the stone masonry [21]. For this purpose, shear modulus has been considered .33 times of Elasticity modulus (E).

Fig. 2. Point clouds derived from the 3D laser scanner and position of the scanners

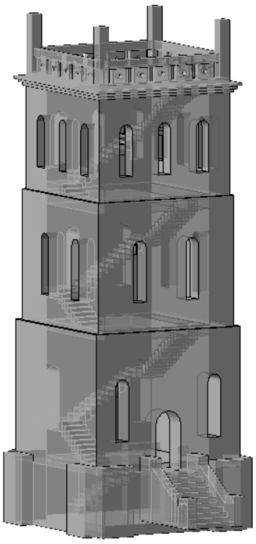
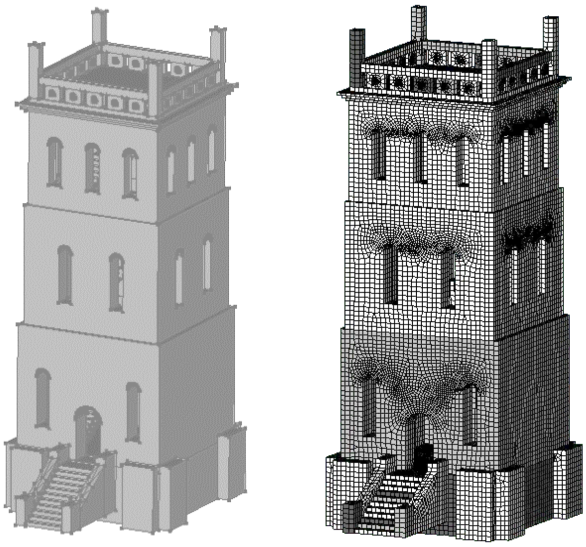


Fig. 3. 3D documentation of the tower in Revit software



(a) (b)

Fig. 4. a) FEM of the case study converted from 3D drawing b) FEM of the tower with meshing

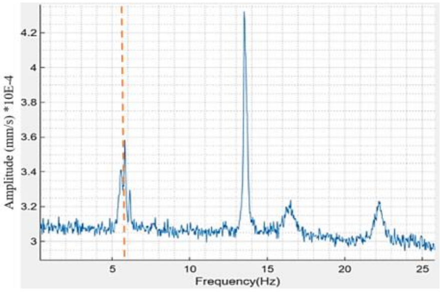
Restrained boundary conditions have been considered for the bottom of the tower in all directions. The tower has a basement floor, and, in the model, the soil loads are neglected [12, 13, 21].

III. DYNAMIC IDENTIFICATION

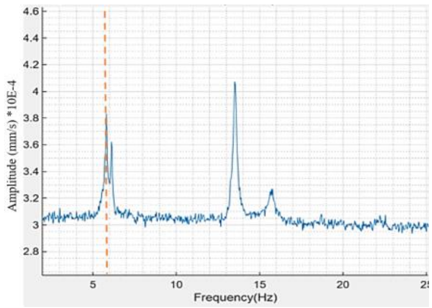
OMA has been done in order to derive the dynamic characteristics of the tower including the natural frequencies. For OMA, 3-Axis MEMS digital Unquake accelerometers with the maximum sensitivity of 8 g have been installed in the second and the third floors with the heights of 7.9 m and 13.3 m respectively. Fig.5 shows the test setup of the accelerometer.

Ambient vibration testing has been performed for three days and Fast Fourier Transform (FFT) has been utilized for each sensor in order to investigate the natural frequency of the structure [22]. As it is illustrated in Fig.6 the first dominant natural frequency of the tower in each direction for two sensors is 5.7 Hz.

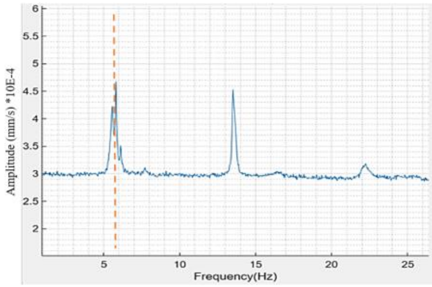
Fig. 5. Data logger and the accelerometer of the test setup



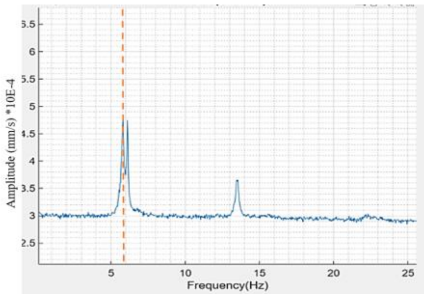
(a)



(b)



(c)



(d)

Fig. 6. FFT of the raw data from a) X direction of the second floor b) Y direction of the second floor c) X direction of the third floor d) Y direction of the third floor

IV. FEM UPDATING

After providing natural frequencies of the tower from OMA the FEM will be updated. A Sensitivity analysis has been done to investigate the exact material properties of the tower including modulus of elasticity and shear. The final material properties of the FEM can be seen in Table I.

The calibrated material properties of the tower are more rigid than the initial try which was derived from the previous studies on stone masonry prisms [23]. Several interventions have been performed until now on the tower which can be the result of this difference.

TABLE I. FINAL MATERIAL PROPERTIES AFTER FEM UPDATING

Property	**Material**
	Masonry
E-modulus	7.25 GPa
Poisson’s ratio	0.2
Shear modulus	2.4 MPa
Density	2000 kg/m^3

Now the FEM is ready for further analysis. Nonlinear behavior of the masonry can be applied on the model based on the literature and codes [23]. Afterwards static or dynamic nonlinear analysis can be done to investigate the vulnerability of the tower subjected to different types of risks i.e. earthquake, extreme wind etc.

V. CONCLUSION

3D scanners for providing a reliable and fast 3D model of the structures which can be easily converted to FEM and accelerometer sensors as a tool for calibrating the FEM are two sides of a coin for the robust approach which is presented in this paper. FFT is a fast and reliable method for deriving the exact dynamic characteristics of the structures including natural frequencies. Converting 3D geometries that can be derived from 3D laser scanners to FEM is possible in some FEM software packages including DIANA FEA which can accelerate the modeling procedure. Therefore, a reliable FEM is developed for numerical modeling of the case study utilizing 3D laser scanners and accelerometers which can be used for further numerical analysis to assess the vulnerability of the structure subjected to different types of risks. Although different OMA techniques will be required to be done to investigate the mode shapes of the tower, derive the frequency of each mode, and update the FEM.

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