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Applying Operational Modal Analysis to rammed earth buildings for Seismic assessment: an exploratory study

Guillaume Candoni[1], Michel Vanwolleghem[1], Youness Azzouz[1], Stéphane Hans[1], Antonin Fabbri[1]

[1] LTDS, UMR 5513 CNRS, ENTPE, University of Lyon, 2 rue Maurice Audin, 69100 Vaulx-en-Velin, France
E-mail address:
Guillaume.candoni@entpe.fr
Michel.vanwolleghem@entpe.fr
Youness.azzouz@entpe.fr
Stéphane.hans@entpe.fr
Antonin.fabbri@entpe.fr

ABSTRACT

The practice of operational modal analysis (OMA) on civil structures and infrastructures has grown significantly in recent decades. Several methods have been developed and widely used on large concrete infrastructures such as buildings, bridges, dams and historic monuments. However, very few studies have been carried out on raw earth housing, despite the fact that a third of the world's housing is made up of raw earth buildings. Recent earthquakes in Morocco, Turkey and Nepal have demonstrated the importance of understanding the dynamic behaviour of these structures in order to assess their seismic vulnerability.

This study explores the use of operational modal analysis to assess the dynamic characteristics of rammed earth buildings. The objects of study are rammed earth buildings in the Rhône-Alpes region of France. Frequency domain decomposition (FDD) and stochastic subspace identification (SSI) methods are then used to determine the structure's eigenmodes. The modal frequencies identified are used to establish an initial estimate of the frequency ranges for rammed earth structures and to identify the physical parameters of rammed earth in real building. Besides, the initial damping of these structures is estimated, providing essential information for a better assessment of their seismic performance. The aim is to provide an initial overview of the vibratory behaviour of rammed earth buildings.

The development of the use of operational modal analysis will help to overcome the lack of standards for the earthquake-resistant design of raw earth structures.

Keywords: Operational modal analysis, rammed earth structures, dynamic behaviour, natural frequency, damping ratio

1. INTRODUCTION

Over the last few decades, operational modal analysis (OMA) has become an essential method for monitoring and studying the dynamic behaviour of civil engineering structures [1]. Unlike traditional experimental modal analysis (EMA) method, which require controlled excitation, OMA relies solely on the natural responses of structures subjected to ambient excitations. This makes it particularly suitable for civil engineering structures, where it is often difficult, if not impossible, to artificially generate measurable excitation. Hence essential modal parameters are obtained, such as natural frequencies, deformation modes and damping, without altering the integrity of the structures under study. This non-invasive approach is a valuable tool for assessing the vibratory behaviour of structures in real-life conditions, and contributes to their monitoring and maintenance.

Numerous applications have demonstrated the effectiveness of OMA on large engineering structures and reinforced concrete buildings, particularly bridges [2-4] and high-rise buildings [5-7]. However, its use is still very limited for raw earth structures, particularly those built using the rammed earth method [8], which represent a third of the world's housing. Moreover, the recent earthquakes in Morocco (2023), Turkey (2023) and Nepal (2015) demonstrated the importance of understanding the dynamic behaviour of these structures in order to assess their seismic vulnerability. These buildings often do not benefit from specific design and assessment standards, unlike concrete or steel structures. In addition, the characterisation of their dynamic behaviour remains largely unknown due to the lack of studies and experimental data.

The aim of this study is to explore the application of OMA for the dynamic analysis of rammed earth buildings. The main objective is to identify the modal parameters of small rammed earth buildings (two storeys maximum) in order to improve understanding of their seismic vulnerability. Therefore, two OMA methods are explored using an open-access code [9]: Stochastic Subspace Identification (SSI) and Frequency- Spatial Domain Decomposition (FSDD).

2. IN SITU MEASUREMENTS

2.1. Description of the measured rammed earth building

The study concerns the assessment of dynamic parameters by modal analysis of unstabilised[1] rammed earth structures. 4 different rammed earth buildings are studied. They are located in Montchal, a city in the Rhône-Alpes region of France and they all contain a stone masonry basement of varying heights. The environment for the measurements is very quiet, with little traffic and no construction sites or factories.

In this paper, we focus on one of the 4 structures, which is called the old vicarage (Fig.1). It was built in the 19th century and has a stone base of 60cm high for the ground floor, and 2 upper floors of 170m^2 made in wood. The building has the particularity of displaying 3 dividing walls on the ground floor and only 2 on the 2 upper floors.

[1] Unstabilised rammed earth : rammed earth without any hydraulic binder such as cement or lime.

Figure 1. Overview of the old rammed earth vicarage.

2.2. Operational modal analysis method

The PyOMA2 processing code recently developed by Dag Pasquale Pasca et al [9] is used to analyse the measurements. This code allows the use of the main existing modal analysis methods such as Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD), Frequency-Spatial Domain Decomposition (FSDD), Stochastic Subspace Identification -Data driven- (SSIdat), Stochastic Subspace Identification -Covariance driven- (SSIcov) and Polynomial Least Squares Complex Frequency-domain (pLSCF). In this paper, only 2 modal analysis methods have been chosen: a frequency-domain method and a time-domain method. The frequency-domain method used is FSDD [10 and 11], which is the 3rd generation of the FDD method developed by Brincker et al [12 and 13]. The time-domain method used is SSIdat [14 and 15].

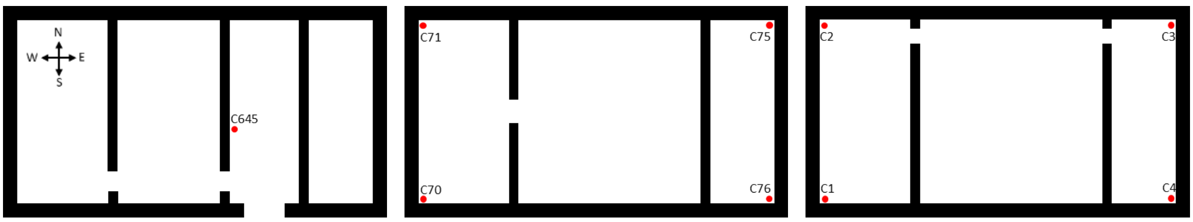
2.3. Sensors for measurements

2.3.1. Properties of Sensors

Nine Trominos® sensors, which are accelerometers and triaxial velocimeters were used. Two types of velocity measurement were possible, one in classical mode and one in highly sensitive mode. The sensors can be calibrated against each other thanks to an integrated GPS antenna, and they have a memory card that avoids cables. This equipment therefore provides 27 measures of output.

2.3.2. Sensor positioning

The measurements were performed under ambient noise without any other solicited vibration. 1 sensor was positioned on the ground floor (sensors C645) then four sensors per floor (sensors C70, C71, C75 and C76 for the first floor and sensors C1, C2, C3 and C4 for the second floor). The sensors on the ground floor are positioned in the centre of the structure, each on one side of the central partition wall, and the sensors on the upper floors are positioned in the corners of the structure. Figure 2 shows the configuration of the sensor in the old vicarage per floor. The advantage of this positioning is that it is easy to identify the torsion modes [1].



a. b. c.

Figure 2. Diagram of sensors positioning: (a) ground floor, (b) first floor, (c) second floor.

2.3.3. Recording parameters

The sensors were initially calibrated by internal GPS. However, a shift of 1 or 2 seconds in time recording is sometimes visible. Therefore, another time calibration was carried out by applying a shock at the start of the recording. The sampling frequency for the measurements was of 256Hz. Once the sensors were placed, the recording proceeds for around 1 hour. The recording of velocity in highly sensitive mode was chosen because of the low level of vibration in the measurement environment.

3. ANALYSIS OF DYNAMIC BEHAVIOUR

3.1. Registration processing

To illustrate registration processing, the sensor C70 was chosen as example in the following figures. In OMA, the first step consists in selecting a good temporal recording, that avoids as much as possible the noise peaks present in the total recording (Fig.3).

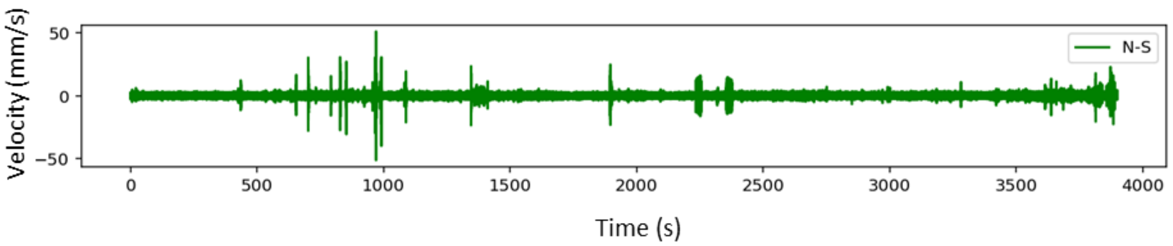


Figure 3. Total recording from sensor C70.

The signal must have a minimum length to be used in OMA. To use the FDD method, Carlo Rainieri and Giovanni Fabbrocino recommended a recording time of approximately 2000 times the period corresponding to the lowest modal frequency [1]. For a 2-stage structure, Bao Q-B et al. [8] found a period of around 0.2s, leading to-a recording time of at least 400 seconds. This is in line with the recording time required for SSI method. Indeed, Chauhan indicated a recording duration of at least 100 to 500 times the first period [16]. However, if the minimum partition of 100 segments recommended by Carlo Rainieri and Giovanni Fabbrocino [1] is respected, the duration of each segment is of 4 seconds. The frequency resolution is then of 0.25Hz. In this, we choose a signal length of 1000 seconds, between 2500s and 3500s of the original signal, to achieve the best compromise between frequency resolution and temporal signal quality (Fig.4).

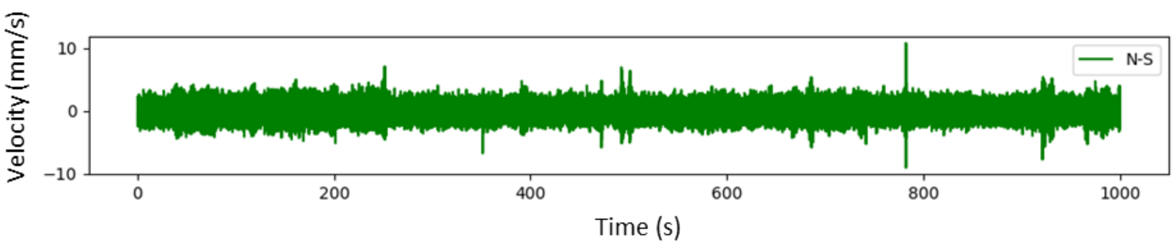


Figure 4. Selected signal from sensor C70.

The quality of the measurements is also verified by calculating the probability density function of each signal (Fig.5). The usual assumption of a Gaussian distribution of the measurements is respected.

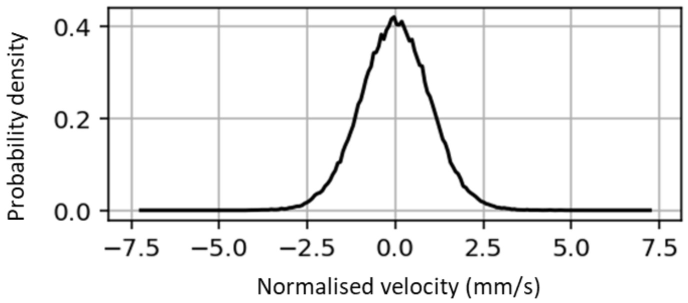


Figure 5. Probability density function of the signal from sensor C70.

As recommended in [1], the signal is detrend and a bandpass filter from 0.1Hz to 100Hz of order 8 is applied in order to cut the high and low frequencies which are not of interest in the study. Finally, the signal is decimated by a factor of two, leading to a sampling frequency of 128Hz.

3.2. Identification of modal parameters

The FSDD is used for 100 10-second segments. The frequency resolution is then of 0.1 Hz. The correlogram method is used to calculate the spectral density. For the SSIdat, we choose a maximum order and a number of block lines in the Hankel matrix of 50 and 128 respectively. These values respect the inequalities (1) and (2) [17 - 19]:

$$\frac{fs}{fo} \leq i \tag{1}$$

Where i is the number of block row in the Hankel matrix (128), fs the sampling frequency (128Hz) and fo the lowest natural frequency (4Hz).

$$n \leq i * l \tag{2}$$

Where l is the number of signals (27) and n the maximum order (50).

We select the modes on the singular value plot for the FSDD and on the stability diagram for the SSIdat. As we are interested in the lowest frequencies in this study, we work in a range of 1Hz to 20Hz to simplify visualisation on the plots (Fig.6 and Fig.7).

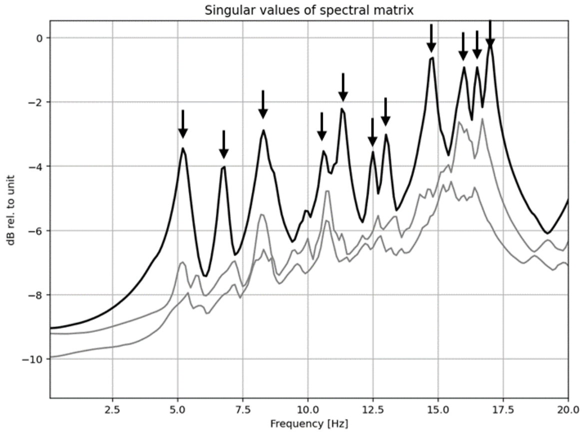


Figure 6. FSDD method: Plot of the first 3 singular values.

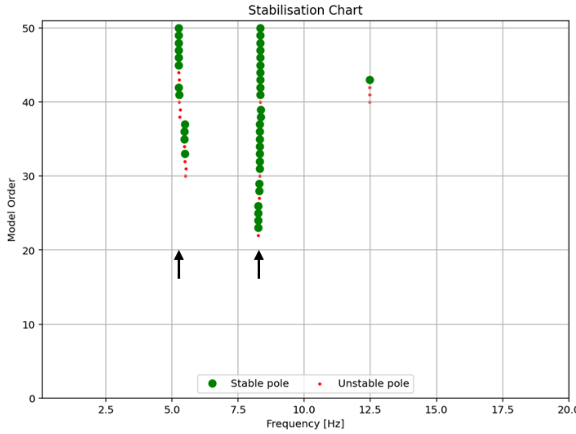


Figure 7. SSIdat method: Stability diagram.

3.3. Modeling and analysis of dynamic parameters

The old vicarage has been modelled using COMSOL® software (Fig 8). the floors and framework have been is modelled with a wood, the masonry stone base has been modelled using concrete characteristics. The roof tiles are added to the roof as a mass of 70kg/m². The aim is to recover the physical properties of rammed earth (Young's modulus and Poisson's ratio) by calibrating with two natural frequencies. For this study, rammed earth was considered to be an isotropic material with a homogeneous modulus.

4. RESULTS

4.1. Modal parameters

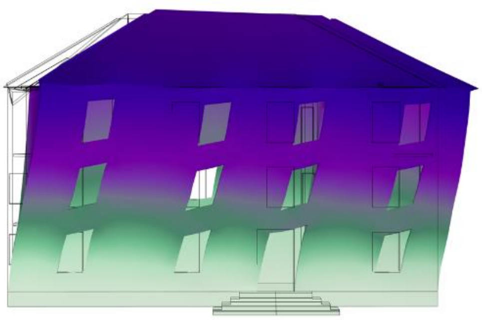
The frequencies and damping found with the methods FSDD and SSIdat are summarized in table 1:

Table 1. Frequency and damping ratio.

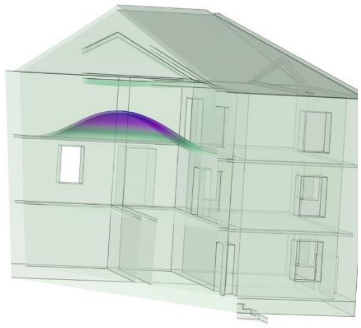
Mode number	1	2	3	4	5	6	7	8	9	10	11
FSDD frequency (Hz)	5.2	6.7	8.2	10.5	11.2	12.5	13.0	14.7	16.0	16.3	17.0
FSDD damping ratio (%)	1.7	0.0	-0.4	-0.2	0.4	-0.4	-0.3	0.9	-0.3	-0.3	0.8
SSIdat frequency (Hz)	5.3	/	8.3	/	/	/	/	/	/	/	/
SSIdat damping ratio (%)	1.3	/	0.8	/	/	/	/	/	/	/	/

The first natural frequency around 5.3Hz correlates with the literature [8]. Nevertheless, the uncertainty on frequencies detected are higher using FSDD method than SSIdat method. Moreover, many of the frequencies detected with FSDD method are associated with negative damping. These damping values are not relevant with those obtained in the case of natural frequency. Therefore, only values of frequencies common to both methods are retained for modelling. The frequency of 5.3Hz corresponds to a bending mode in E-W direction and the frequency of 8.3Hz corresponds to a torsion mode. The modal assurance criteria (MAC) for these frequencies between the two methods is higher than 0.9, confirming that they correspond to the same modes.

The numerical simulation with the FEM code COMSOL shows that floors and workframes of the building generate multiple modes (Fig.8). Maybe, these local modes are detected by the FSDD method - but not by the SSIdat method.



(a)



(b)

Figure 8. Examples of numerical simulation, realised with the FEM code COMSOL, for: (a) bending mode (5.3Hz) and (b) wooden floor (10.3Hz).

4.2. Identification of Rammed Earth

The aim is to find the properties of the material by correlating them with the natural frequencies of the building. The identification is made through numerical simulation, realised with the FEM code COMSOL, with Young's moduli and Poisson's ratios ranging from 0.3GPa to 0.7GPa and from 0.1 to 0.5 respectively. These ranges of values are chosen because they correspond to what is generally mentioned for rammed earth walls [20]. The results obtained for both bending and torsion modes are reported in the figure 9 for a density of 1900kg/m^3 [21].

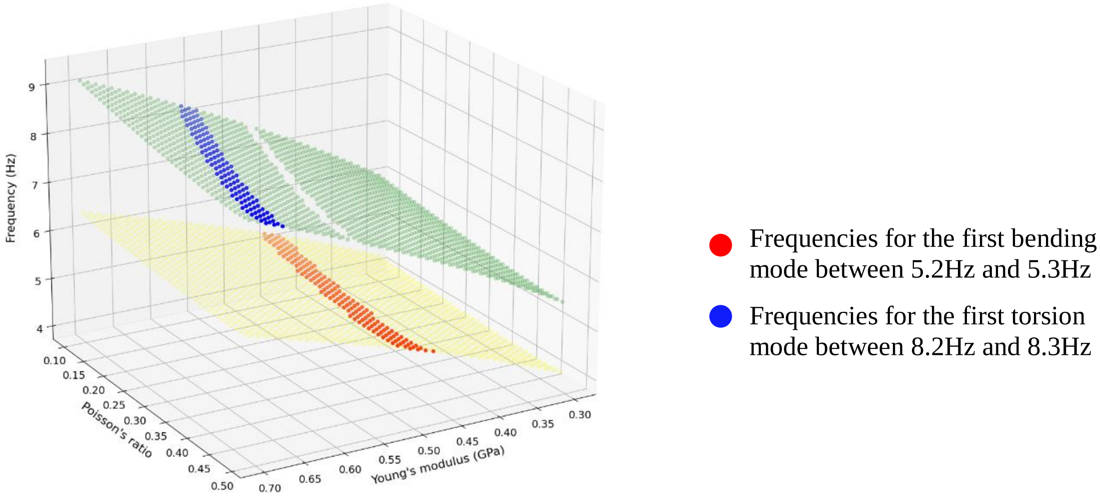


Figure 9. Graph representing the frequencies of the first bending (yellow) and torsion (green) modes as a function of the Young's modulus and Poisson's ratio.

For a Young's modulus between 0.45 GPa and 0.5 GPa, the torsion mode is not clearly identified, which is why no frequency is displayed on the graph. As these frequencies are lower than 8Hz, their absence does not affect the identification of rammed earth pramaeters.

Identification using the first bending mode gives a Young's modulus between 0.40 and 0.50 GPa and a Poisson's ratio between 0.1 and 0.45. If we consider a Poisson's ratio around 0.2 for dry rammed earth [8], we obtain a Young's modulus around 0.47 Gpa which correlates with the Young's modulus found by Bui, QB. Et al. [21]. However, no parameter provides both the first bending mode and the first torsion mode. Perhaps simplifications in the modelling overly affect identification

5. CONCLUSION AND PROSPECTS

Two operational modal analysis methods are applied in this paper to obtain the dynamic parameters of rammed earth buildings. A first natural frequency around 5.3Hz and a damping ratio between 1% and 2% are obtained for the rammed earth building. Only the first bending and torsion frequencies are clearly identified. Identification of the other frequencies and damping ratio is more difficult and is probably disturbed by the presence of local modes. The first bending mode makes it possible to recover the dry rammed earth Young's modulus by fixing the Poisson's ratio. However, no Young's modulus/Poisson's ratio combination provides both the first bending mode and the first torsion mode. Future work will investigate the influence of wooden floors and frameworks on the modal parameters and will improve the identification of rammed earth parameters.

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