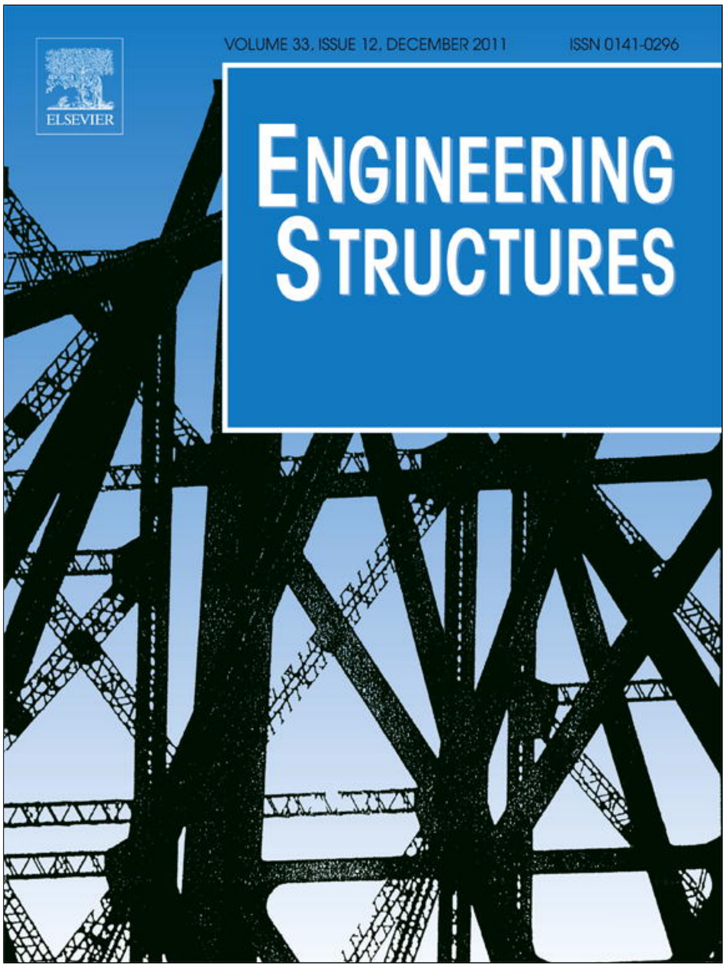
ELSEVIER
VOLUME 33, ISSUE 12, DECEMBER 2011
ISSN 0141-0296
ENGINEERING STRUCTURES

Engineering Structures 33 (2011) 3690–3695

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

First exploratory study on dynamic characteristics of rammed earth buildings

Q.-B. Bui [a,b], S. Hans [a], J.-C. Morel [a,*], A.-P. Do [a]

[a] Université de Lyon; Ecole Nationale des Travaux Publics de l'Etat, CNRS, FRE 3237, Département Génie Civil et Bâtiment, rue Maurice Audin, 69120 Vaulx-en-Velin, France
[b] FiliaTerre, LOQUIS Eco-construction, 3 Place Alexandre Médecin, 06100 Nice, France

ARTICLE INFO

Article history:
Received 8 April 2011
Received in revised form
28 July 2011
Accepted 1 August 2011
Available online 3 September 2011

Keywords:
Sustainable development
Rammed earth
Natural frequency
Damping ratio

ABSTRACT

Rammed earth construction is attracting a renewed interest throughout the world thanks to its "green" characteristics in the context of sustainable development. Several studies have been carried out to investigate this material and evaluate its durability along with its mechanical, thermal and earthquake capacities. This paper presents a study on the parameters needed for the seismic design of rammed earth buildings in accordance with current earthquake standards. First, the dynamic parameters of buildings such as natural frequencies and damping ratios – which were necessary to determine the equivalent static seismic force – were identified using in-situ dynamic measurements. Then, these experimental values were compared with the values calculated by empirical formulas suggested in Eurocode 8 to demonstrate that these formulas were applicable for the cases of rammed earth structures. Then, modeling was done to find a simple suitable model for rammed earth structures. Laboratory experiments were developed to measure the Poisson's ratio which was necessary for the models. The results provided by the shear-beam model were close to that of in-situ experiments, which showed a shearing behavior of rammed earth structures. Elements which influenced the dynamic behavior of this structural type were also discussed. Understanding the dynamic characteristics of rammed earth structures will help engineers in their design of new rammed earth buildings but also in earthquake analyses of existing rammed earth buildings.

1. Introduction

Rammed earth construction is a vernacular technique which is attracting renewed interest throughout the world today. A rammed earth wall is manufactured by compacting a clayey soil (earth) into a formwork. The earth composition varies greatly but contains no organic component and enough clay which acts as a binder between the grains, a mixture of silt, sand, gravels and stones with a diameter of a few centimeters. Compaction is performed using a water content considered as optimum i.e. providing the highest dry density for a fixed compaction energy. This process is called the dry method because the water content is around 10%, while a paste (in case of mortar or adobes) should have a water content of about 25%. Rammed earth is composed of several layers of earth. The earth is poured in layers about 15 cm thick into a formwork (wooden or metal). It is rammed with a rammer (manual or pneumatic). After compaction, the thickness of each layer is about 10 cm. The procedure is repeated until the desired height of the wall is obtained.

Traditionally, the material used to manufacture rammed earth walls is the natural earth on the site. Today, in many cases, cement or lime (hydraulic lime or calcic lime) may be added to improve the water sensitivity and the strength of traditional rammed earth. This new rammed earth is called "stabilized rammed earth".

Detailed presentation of rammed earth material can be found in [1]. Rammed earth is well known as an environmentally friendly material because it has a very low embodied energy thanks to the use of local material (soil on site or near the site).

Owing to the "green" characteristics of rammed earth construction in the current context of sustainable development, several studies have been carried out recently to analyze its characteristics: durability and sensitivity to water [2,3], thermal properties [4,5], living comfort [6] and mechanical characteristics in compression [7–10].

With this world-wide revival of rammed earth building, the earthquake resistance of rammed earth structures has to be studied. However, for now, there are only a small number of scientific studies on the seismic capacity of rammed earth buildings. Among them, Minke [11], Hamilton et al. [12] and Cheah et al. [13] studied the efficiency of reinforcements using vertical ties in the rammed earth, stabilized rammed earth and flax-fiber reinforced earth walls respectively. The proposed solutions in Minke's research were empirical, the research of Hamilton et al. and Cheah et al. was restricted to the case of static forces cyclically applied to small walls in laboratory. Gomes et al. [14] conducted a theoretical study by finite element method without comparison with

* Corresponding author. Tel.: +33 4 72 04 70 67; fax: +33 4 72 04 71 56.
E-mail address: Jean-Claude.MOREL@entpe.fr (J.-C. Morel).

0141-0296/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2011.08.004

experimental results. As far as we know, there is no research today on the experimental dynamic behavior of rammed earth structures.

Due to this lack of scientific research, in most countries around the world (including France) today, there are no specific standards to calculate the earthquake resistance of rammed earth structures. This creates difficulties for designers in the seismic design of rammed earth structures because rammed earth strength is approximately 20 times lower than concrete or baked brick, not homogeneous at the scale of 10 cm (bed height), with an elasto–plastic behavior [7,8]. The aim of this study is to introduce methods to assess the dynamic parameters of rammed earth structures which could be used for seismic design. The material studied in this paper is unstabilized rammed earth but the presented methods are also applicable in the case of stabilized rammed earth.

2. Meeting actual earthquake design codes

Current seismic standards have mainly been established for conventional building materials. The compatibility of their applications in the case of rammed earth buildings has not been verified. However, in the present context, a favorable calculation note in accordance with seismic standards is required to obtain a construction permit in several countries. Therefore, a study of the compatibility of the seismic standards in the case of rammed earth buildings is necessary.

According to current seismic standards (e.g. Eurocode 8), the seismic action on a building can be considered equal to an equivalent static force applied to the base of the structure. This force is considered an inertial force which depends on the building fundamental period T_1 and the damping ratio μ of the material constituting the structure. There are still other parameters that influence the seismic force applied to the building such as the characteristics of the soil of the foundation; the seismic zone where the building is situated; the class of soil; the topography. However, in this first exploratory study on the seismic characteristics of rammed earth buildings, these items will not be discussed. This study is restrained to the two parameters T_1 and μ.

3. In-situ dynamic measurements

3.1. Basic principle of in-situ dynamic measurements

Civil engineering structures are always affected by several excitations which are due to micro-earthquakes, vehicles, wind, sea waves for example. These excitations are the background noise and are considered to be a *white-noise*, having all frequencies [15]. By using the relationships between the response of the structure and the excitation, the dynamic characteristics of the structure can be identified.

In-situ dynamic measurements are directly performed on real structures. Accelerometers or velocimeters are used as sensors to measure respectively the accelerations and the velocities of the structure.

3.2. FDD technique

Rammed earth structures often possess local modes (see Gomes et al. [14] for example). So if the classical technique of the data processing (Fast Fourier Transform) is applied, the main vibration modes will not be clearly identified. That is why in this paper, a recent technique – Frequency Domain Decomposition (FDD) – is used for data processing. The FDD is known as one of the most user friendly and powerful techniques for operational modal analysis of structures in the recent years. The principle of this technique can be found in [16] or [17].

Any displacement vector $\mathbf{v}$ (static or dynamic) for this structure can be developed by superposing suitable amplitudes of the normal modes: $\mathbf{v}(t) = \Phi_1\, q_1(t) + \Phi_2\, q_2(t) + \cdots + \Phi_N q_N(t) = \mathbf{\Phi q}(t)$.

In time domain, the covariance matrix of the responses: $\mathbf{R}_{vv}(\tau) = E\{\mathbf{v}(t+\tau)\mathbf{v}(t)^T\}$

$$\Rightarrow \mathbf{R}_{vv}(\tau) = E\{\mathbf{\Phi q}(t+\tau)\mathbf{q}(t)^H\mathbf{\Phi}^H\} = \mathbf{\Phi C}_{qq}(\tau)\mathbf{\Phi}^H$$

^{H} is the Hermitian transposed operator. The equivalent relation in the frequency domain is obtained by using the Fourier transform: $\mathbf{S}_{vv}(\omega) = \mathbf{\Phi S}_{qq}(\tau)\mathbf{\Phi}^H$.

If the modal coordinates $(q_1, q_2, \ldots)$ are uncorrelated, then the power spectral density (PSD) matrix $\mathbf{S_{qq}}(\boldsymbol{\omega})$ is diagonal [15]. And if the mode shapes are orthogonal, then the above equation is a singular value decomposition (SVD) of the spectral response matrix.

Therefore, FDD is based on taking the SVD of the spectral density matrix: $\mathbf{S}_{vv}(\omega) = \mathbf{U}(\omega)[\mathbf{s}_i]\mathbf{\Phi}(\omega)^H$.

The matrix $\mathbf{U}(\omega)$ is a matrix of singular vectors and the matrix [**si**] is a diagonal matrix of singular values. As it appears from this explanation, plotting the singular values of the spectral density matrix will provide an overlaid plot of the auto spectral densities of the modal coordinates. Note that here the singular matrix $\mathbf{U}(\omega)$ is a function of frequency because of the sorting process that is taking place as a part of the SVD algorithm.

3.3. Presentation of measured structures

Four rammed earth structures located in the Rhone–Alpine region (France) were investigated (Fig. 1). They will be called respectively Lavort, Perigneux, St Jean de Bournay and Sermentizon, according to the names of the towns where they are located. All these structures have walls made of rammed earth 50 cm thick, which is the common thickness of rammed earth walls in France. Their main structures consist of weight-bearing rammed earth walls and timber floors.

The Lavort chateau was built in the 18th century and has two levels. Its plans are presented in Fig. 2 and the floor surface is around 550 m^2. The Perigneux house was built ten years ago, its floor surface is approximately 75 m^2. The St Jean de Bournay house was built about 100 years ago. The Sermentizon house consists of a single level and was built in 2008. The infill between the rammed earth walls is made of wood.

Due to limited space of this paper, among four measured structures we will only present detailed analysis of the Lavort chateau which can totally illustrate what is met during the data processing from in-situ measurements: translational modes, torsion modes, vibrations out measured axis.

3.4. Disposition of measurements

3.4.1. Sensors

The used sensors are Tromino triaxial velocimeters. Each sensor can simultaneously measure the three main orthogonal components (two in the horizontal direction and one in the vertical direction) of the vibration's velocity of the structure. Each velocimeter has an internal memory card which dismisses the use of cables to connect computers during measurements.

3.4.2. Configurations of measurements

Measurements were performed over unsolicited noise. In each house, several measurement configurations were implemented. Fig. 3 presents examples of the configurations on the Lavort chateau. The "deformed configuration" was used to detect the axial deformation (translations) of the structure. In this configuration, the sensors were placed on the vertical axis passing through

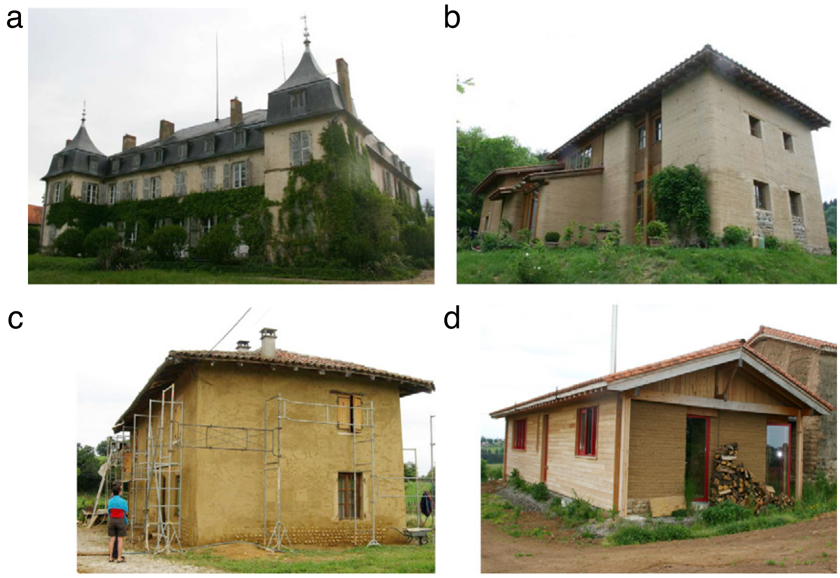

Fig. 1. Overview of the studied structures: (a) Lavort, (b) Perigneux, (c) St Jean de Bournay, (d) Sermentizon.

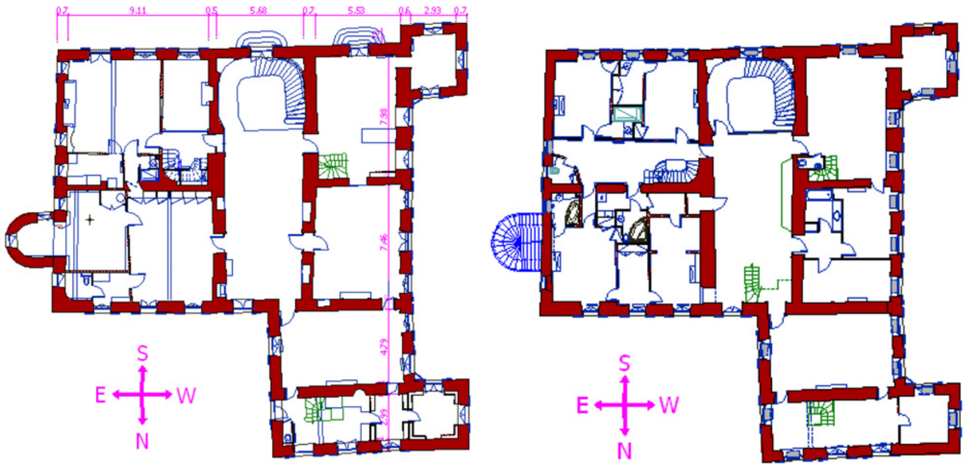

Fig. 2. Plan of the first (left) and second (right) levels of the Lavort chateau.

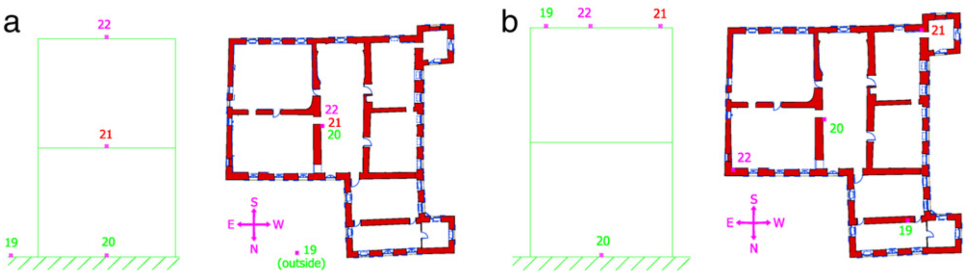

Fig. 3. Examples of the measurements on the Lavort chateau: (a) deformed configuration; (b) torsion configuration.

the geometric center of the building (Fig. 3(a)). In this figure, sensor 19 was placed outside to measure the soil vibration. The "torsion configuration" (Fig. 3(b)) was used to detect the torsional movements of the structure.

4. Analyses of the dynamic behavior of the measured structures — case of Lavort chateau

In this study, the main investigation is the first natural frequencies (in the main directions of the structures), i.e. frequencies of higher modes were not studied in detail. First, because in the case of common buildings, the first natural frequencies (in main directions) are the most important and prevail over other frequencies. Then, in the case of low-rise buildings, identification of higher modes is often difficult.

Fig. 4 shows the example of the singular values obtained in a "deformed" configuration, on the Lavort chateau. On this figure, the first three peaks that are at 4.1, 4.7 and 5.3 Hz respectively are the most interesting. The modal shape of the structure at 4.1 and 4.7 Hz are presented in Fig. 5, and the modal shape at 5.3 Hz

Table 1
Comparison of first natural periods obtained on site and calculated according to the empirical formula in Eurocode 8 [18]. X_0 and Y_0 correspond to the two main vibration axes of each building.

Structures	Height h (m)	$f_{1\ (\mathrm{site})\ X_0}$ (Hz)	$f_{1\ (\mathrm{site})\ Y_0}$ (Hz)	$f_{1\ (\mathrm{EC8})}$ (Hz)	$f_{1\ (\mathrm{EC8})} / f_{1\ (\mathrm{site})\ X_0}$	$f_{1\ (\mathrm{EC8})}/f_{1\ (\mathrm{site}) Y_0}$
Lavort	7.2	4.1 ± 0.1	4.7 ± 0.1	4.7	1.14	1.00
Perigneux	5.4	5.8 ± 0.1	6.9 ± 0.1	5.8	1.00	0.84
St Jean de Bournay	5.2	6.7 ± 0.2	6.7 ± 0.2	6.0	0.89	0.89
Sermentizon	2.9	10.1 ± 0.2	12.1 ± 0.2	9.2	0.91	0.76

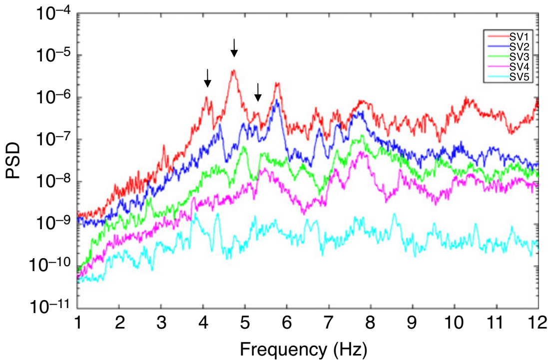

Fig. 4. Power spectral density singular values obtained from a "deformed" configuration, on the Lavort chateau.

is presented in Fig. 6. In Fig. 4, the peak at 5.3 Hz is not clear because this torsion mode is not well detected in a "deformed" configuration. In Fig. 5, the lines on the horizontal plane are the projections of the modal shape on this plane, thus enabling a more accurate observation of the vibration directions in each mode.

The first natural frequency of the structure can be identified at 4.1 Hz. The shape of this mode (Fig. 5(a)) corresponds to a translational vibration in the direction which makes an angle of about 10° from the EW direction. The vibration shape at 4.7 Hz (Fig. 5(b)) also corresponds to a translational vibration which makes an angle of about 10° from the NS direction. The reason for these vibrations is that the building is not symmetrical, neither the EW nor the NS direction is the main direction of the structure.

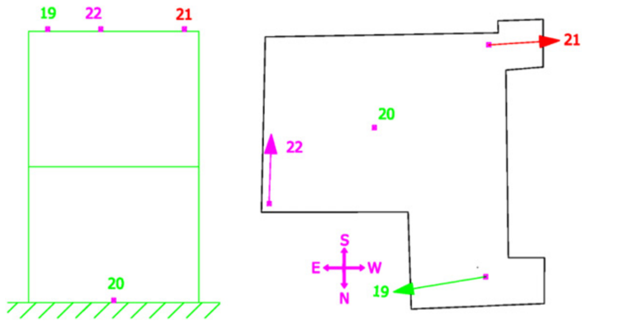

Fig. 6. In this torsion configuration (left): sensors 19, 21, 22 at roof level; sensor 20 on the ground floor. Right: vibration is a torsion mode at 5.3 Hz.

For 5.3 Hz, with information from torsion configuration (Fig. 6), this frequency can be identified as a torsion mode.

5. Dominant frequencies

A synthesis of the first natural frequencies of the investigated structures in each main vibration direction is presented in the third and fourth columns of Table 1.

5.1. Comparison with the formulas in the seismic design standards

For low-rise buildings, standards provide simple empirical formulas to quickly determine the first natural period. These formulas are based on structures made with conventional materials

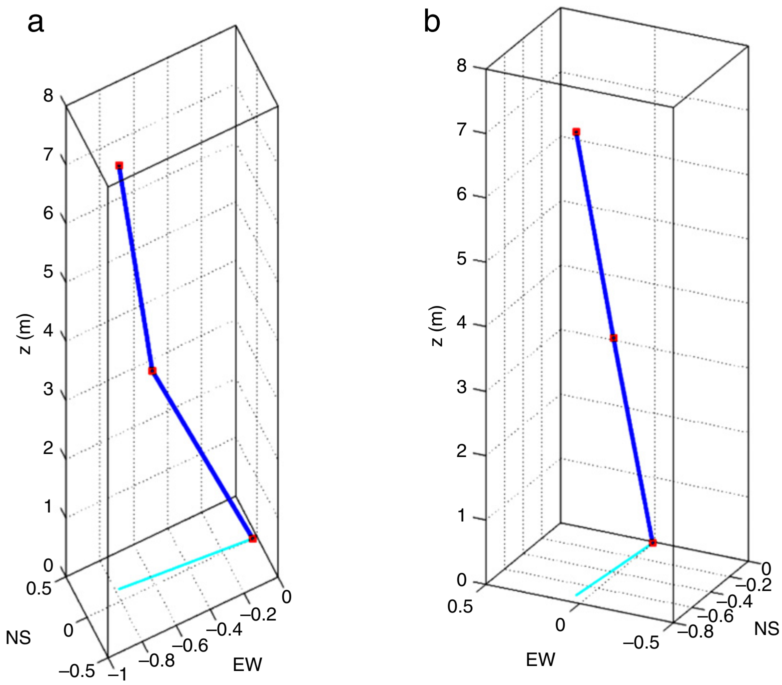

Fig. 5. First vibration modes of the Lavort chateau: (a) at 4.1 Hz; (b) at 4.7 Hz.

(steel, concrete, brick) and will be checked to see whether these formulas are applicable to rammed earth structures or not.

One of the most commonly used formulas is (Eurocode 8):

$$T_1 = C_t \cdot {h_n}^{3/4} \quad (1)$$

where h_n is the building height calculated from natural ground and C_t is the coefficient which depends on the structural type:

- $C_t = 0.0853$ for buildings of steel frame.
- $C_t = 0.0731$ for buildings of reinforced concrete frame.
- $C_t = 0.0488$ for other building types.

The value $C_t = 0.0488$ was used for the rammed earth structures in our case. The comparison of the first natural periods measured on site and calculated by the empirical formula is presented in Table 1. The comparison shows that the empirical formula in the standards gives similar results to those obtained on site. So this formula seems applicable to the rammed earth houses. Explanations will be discussed in the following section.

5.2. Modeling of the structures

The purpose of this section is to provide simple tools to analyze dynamic behavior of rammed earth buildings. The choice of using simple models is privileged to be able to apply them in practice. Two simple and commonly used models will be tried, namely discrete-shear-beam (or "concentrated masses") and continuous-shear-beam.

In the modeling, the following hypotheses were used. First, the structure is embedded at the foundation level. So the corresponding boundary conditions are: no horizontal displacement, no rotation of the structure at this level.

Second, in the case of ambient vibration measurements, the material is still working in very small strains. Therefore, rammed earth material was assumed to be elastic and isotropic in this domain. This assumption was justified in the previous studies [7,8].

The *concentrated-masses* model is commonly used in earthquake engineering. It is a discrete analogue of the pure shear-beam. In this model, stiffness of the floors are assumed to be infinitely high in its plane (non-deformable floors) and the story masses are concentrated at the floor levels. A preliminary study has been made, showing that this model was not compatible for rammed earth structures. The reasons are linked to the assumptions of the concentration of the masses on the floor levels and the non deformability of the latter. Indeed, in the case of rammed earth structures, the walls are thick and heavy whereas the timber floors are light and flexible. This is why the assumptions for the conventional buildings are not compatible with these buildings.

The *shear-beam* model is the model of a classical continuous beam which has shear behavior. The boundary condition is: the shear force at roof level is zero, giving the formula of natural frequencies:

$$f_1 = \frac{1}{4h}\sqrt{\frac{G}{\rho}} \quad (2)$$

where h is the beam height; ρ is the volumic mass; G is the shear modulus. For an elastic and isotropic material: $G = \frac{E}{2(1+\nu)}$ with E: Young's modulus and ν: Poisson's ratio.

From the above formulas, the following parameters are necessary for the calculations of Eigen frequencies of the model: Young's modulus, Poisson's ratio and volumic mass.

- Young's modulus: previous studies, which carried out dynamic measurements on the rammed earth walls alone, showed that the modulus of unstabilized rammed earth can vary from 100 MPa (old walls in the study of Bui et al. [19]) to 500 MPa (new walls in the study of Bui et al. [7]).

Table 2
Lavort's first natural frequencies, on site and calculated from the shear-beam model.

	$f_{1\text{model}}/f_{1\,(\text{site})}\ X_0$	$f_{1\text{ model}}/f_{1\,(\text{site})}\ Y_0$
$E = 500$ MPa	2.70	2.36
$E = 100$ MPa	1.21	1.06

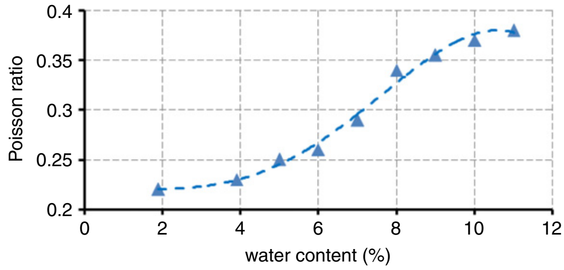

Fig. 7. Variation of Poisson's ratio compared with water content of the Sermentizon material.

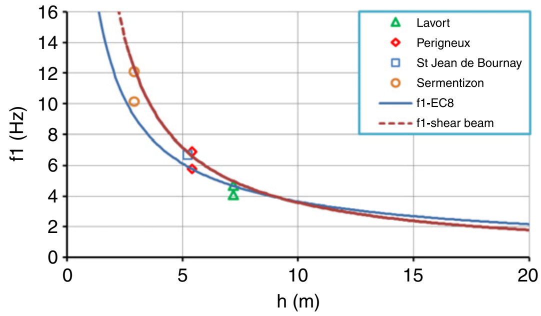

Fig. 8. First frequencies by the shear-beam model ($G = 41$ MPa, $\gamma = 2000$ kg/m^3); by EC8; and by *in-situ* measurements.

- Volumic mass: in general, volumic mass of rammed earth is about 2000 kg/m^3 [7], so this value was used for the modeling.
- Poisson's ratio: laboratory tests were carried out to measure the Poisson's ratio of rammed earth. Fig. 7 presents the variation of the Poisson's ratio according to the water content of samples of 16 cm of diameter, 30 cm height, which were manufactured with the soil used in Sermentizon building. The results show that Poisson's ratio can vary from 0.22 up to 0.4, which depends on the water content of the material. For the modeling, a value of 0.22 for the Poisson's ratio was used which corresponds to the cases of almost dry rammed earth ($w = 2\%$).

The value of the Young's modulus used in the models was $E = 100$ and 500 MPa and compared to the site measurements in Table 2. Following the results given in Table 2, value calculated with Young's modulus of 100 MPa is the most accurate in the range of 100–500 MPa.

The matching of the shear-beam model to the other structures is checked in Fig. 8 where the first frequencies of the shear-beam model are plotted according to the height of the structures, with a Young's modulus of 100 MPa (shear modulus of 41 MPa). This point shows that rammed earth structures have shear behavior. Another remark is that starting from the 5 m of height of the structures, the frequencies obtained with the shear-beam model and the formula of Eurocode 8 are very close.

The model fits with a Young's modulus of 100 MPa which is the smallest bound of the modulus found in the literature (from 100 to 500 MPa). In the case of Sermentizon building, the Young's modulus of the rammed earth walls alone (without connections, wooden frames etc.) was measured on site and is equal to 500 MPa. In the case of the whole building, the rammed earth walls were linked to timber frames that decreased the global stiffness of the whole building.

Table 3
Measured damping ratio of rammed earth structures.

	Lavort	Perigneux	St Jean de Bournay	Sermentizon
Damping ratio	0.032 ± 0.002	0.024 ± 0.002	0.036 ± 0.002	0.04 ± 0.002

6. Damping ratio

The damping ratio of the rammed earth structures was determined by using the "Half-Power Band Width Method" [15]. The damping ratios measured for the structures of this study are between 2.5% and 4% (Table 3). There are several reasons for the differences between the damping ratios of investigated structures. The first reason is that the earth is different for each house, giving different rammed earth. The second element is the water content of the rammed earth walls at the measurement time which can also change the behavior of rammed earth structure. Another element is that the connections with other elements (windows, wooden frames) can also change the global damping of the rammed earth structures.

7. Conclusions and prospects

This paper is the first experimental study on the dynamic behavior of in-situ rammed earth structures. Due to the complexity of this structural type that often presents local modes, the recent FDD technique was used to identify the dynamic characteristics of the studied structures.

From in-situ dynamic measurements, a damping ratio of 3%–4% for unstabilized rammed earth structures was measured. The results of the first natural frequencies of rammed earth structures obtained from in-situ measurements and those obtained from the empiric formula of Eurocode 8 were similar. This means that the formula of Eurocode 8 is applicable to rammed earth structures.

The models with concentrated mass which were usually used for the conventional buildings are not suitable for the case of rammed earth buildings. The reason is that the rammed earth walls are thick and heavy whereas the timber floors are light and flexible.

Laboratory experiments were carried out to measure the Poisson's ratio of rammed earth. This last parameter can vary from 0.2 for dry material up to 0.4 for a water content of 10%. This study showed that the dynamic behavior of the rammed earth structures was close to a shear-beam with a shear modulus G of about 40 MPa. With the assumption that the material of the beam is isotropic, this shear modulus corresponded to a Young's modulus of about 100 MPa. With these values, the shear-beam model gave results close to those of Eurocode 8.

The experimental results in this study contribute to the comprehension on the dynamic behavior of *in-situ* rammed earth structures which can be used as a reference in other studies both in research and in engineering practice. The modeling results of this study can be used to assess the seismic vulnerability of existing rammed earth structures and also to design new rammed earth structures, for example calculations of the maximum displacement at the head of the building; calculations of the drifts between the floors.

Acknowledgments

The authors wish to acknowledge Nicolas Meunier and the building owners for their help in the in-situ measurements. Jennifer Randall and Pierre-Antoine Chabriac are thanked very much for the revision of the English of this paper.

References

[1] Walker P, Keable R, Martin J, Maniatidis V. Rammed earth-design and construction guidlines. BRE Bookshop; 2005. p. 146.

[2] Bui QB, Morel JC, Reddy BVV, Ghayad W. Durability of rammed earth walls exposed for 20 years of natural weathering. Build Environ 2009;44:912–9.

[3] Hall M, Djerbib Y. Rammed earth sample production: context, recommendations and consistency. Constr Build Mater 2004;18:281–6.

[4] Taylor P, Fuller RJ, Luther MB. Energy use and thermal comfort in a rammed earth office building. Energy Build 2008;40:793–800.

[5] Taylor P, Luther MB. Evaluating rammed earth walls: a case study. Solar Energy 2004;76:79–84.

[6] Paul WL, Taylor PA. A comparison of occupant comfort and satisfaction between a green building and a conventional building. Build Environ 2008; 43:1858–70.

[7] Bui QB, Morel JC, Hans S, Meunier N. Compression behaviour of nonindustrial materials in civil engineering by three scale experiments: the case of rammed earth. Mater Struct 2009;42:1101–16.

[8] Bui QB, Morel JC. Assessing the anisotropy of rammed earth. Constr Build Mater 2009;23:3005–11.

[9] Maniatidis V, Walker P. Structural capacity of rammed earth in compression. J Mater Civil Eng 2008;20(3):230–8.

[10] Hall M, Djerbib Y. Moisture ingress in rammed earth: part 1-the effect of soil particle-size distribution on the rate of capillary suction. Constr Build Mater 2004;18:269–80.

[11] Minke G. 2001. Construction manual for earthquake-resistant houses built of earth. GATE-BASIN Building Advisory Service and Information Network. p. 51.

[12] Hamilton HR, McBride J, Grill J. Cyclic testing of rammed earth walls containing post-tensioned reinforcement. Earthq Spectra 2006;22(4):937–59.

[13] Cheah JS, Morgan TKKB, Ingham JM. Cyclic testing of a full-size stabilized, flax-fibre reinforced earth Uku wall system with openings. In: The 14th world conference on earthquake engineering. 2007.

[14] Gomes MI, Lopes M, Brito J. Seismic resistance of earth construction in Portugal. Eng Struct 2011;33(3):932–41.

[15] Clough RW, Penzien J. Dynamics of structures. Berkeley: Computers & Structures Inc; 1995. p. 746.

[16] Brincker R, Zhang L, Andersen P. Modal identification of output-only systems using frequency domain decomposition. Smart Mater Struct 2001;10:441–5.

[17] Andersen P, Brincker R, Goursat M, Mevel L. Automated modal parameter estimation for operational modal analysis of large systems. In: Proc 2nd IOMAC. 2007.

[18] EN 1998-1:2004. Eurocode 8: Design of structures for earthquake resistance. European Commitee for Standardization. 1998.

[19] Bui QB, Hans S, Morel JC. The compressive strength and pseudo elastic modulus of rammed earth. In: International symposium on earthen sructures. 2007, p. 217–23.