Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 145 (2016) 1185 – 1192

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

Seismic assessment of rammed earth walls using pushover tests

R. Nabouch[a], Q.B. Bui[a,]*, O. Plé[a], P. Perrotin[a], C. Poinard[a], T. Goldin[a], J.P. Plassiard[a]

[a] *University Savoie Mont Blanc, LOCIE – CNRS UMR5271, 73000 Chambery, France*

Abstract

Rammed earth (RE) construction is attracting renewed interest throughout the world thanks to its sustainable characteristics: a very low embodied energy, an advantageous living comfort due to a substantial thermal inertia, good natural moisture buffering, and an attractive appearance. This is why several studies have been carried out recently to investigate RE. However, there have not yet been sufficient studies on the seismic performance of RE buildings.
This paper presents an experimental study on the static nonlinear pushover method and its application on the seismic performance of RE structures. Several walls with two height/length ratios were built and tested to obtain the nonlinear "shear force–displacement" curves. By transposing to the "acceleration-displacement" system and by using the standard spectra presented in Eurocode 8, the performance points could be determined which enabled to assess the seismic performance of the studied walls in different conditions (seismicity zones and soil types).

Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: rammed earth, seismic performance, sustainable buildings, pushover tests

1. Introduction

One of the most common materials used in the past is rammed earth (RE). With other forms of local earthen construction, RE has a long and continuous history throughout many regions of the world. It is estimated that more than half of the world population live in earth constructions [1]. The use of earth in construction reduces the

* Corresponding author. Tel.: +33 479 759 470; fax: +33 479 758 144.
E-mail address: quoc-bao.bui@univ-smb.fr

Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.153

embodied energy and assumes an environmental advantage through a building life cycle: from construction, operation, maintenance, renovation, and demolition. Due to its low embodied energy, RE constructions had become competitive when compared to conventional materials [2].

Fig. 1. A RE house built by N. Meunier in France.

RE walls are made by compacting earth between vertical formworks (wooden or metal forms). The earth is compacted into layers of approximately 15 cm by using a manual or pneumatic rammer. Today the manual rammer is usually replaced by a more powerful pneumatic rammer that increases the rapidity of manufacturing and the material density. Fig.1 displays a recent RE house built in France.

In the context of sustainable development and preserving the heritage of rammed earth buildings, RE is the object of several scientific investigations. Several studies have recently been carried out to investigate this material on several aspects: durability [3], mechanical [4]-[6], thermal [7], dynamic characteristics [8, 9]. However, the seismic performance of RE structures has not yet been studied in detail. This paper presents an investigation assessing the seismic performance of RE walls by using the pushover tests. RE walls with two different ratios (height/length) were studied.

2. Pushover method

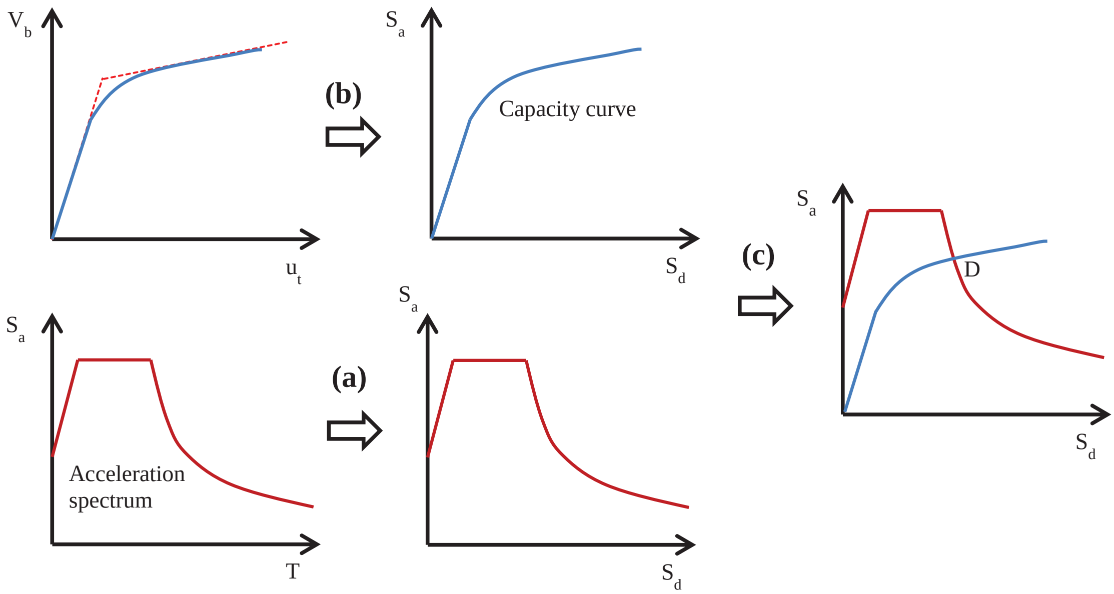

Fig. 2. Pushover analysis processing.

Pushover is a nonlinear static method which is from the displacement-based approach and currently used to assess the seismic performance of the structures [10]. The processing is summarized in the Fig. 2. First, the standard acceleration spectrum S_a is transformed in acceleration-displacement (S_a-S_d) format (Fig.2a), where S_d is the response spectrum in displacement:

$$S_d = \frac{T^2}{4\pi^2} S_a \tag{1}$$

The capacity curve - presented by the relationship between the shear force V and roof displacement d - is also established in (S_a-S_d) format where the shear force V is converted to the maximum acceleration S_a, and the displacement on top of the wall is converted to spectral displacement S_d (Fig.2b).

The intersection point D between the capacity curve and the demand spectrum (Fig.2c) is called the performance point. From the performance point, the seismic demand and the damage states of the structure can be assessed.

3. Experiments

3.1. Specimen manufacturing

RE walls were constructed in the laboratory by the laboratory's staffs who had already had a training (2 days) with a RE professional. Two types of wall were manufactured. Two walls had 1.5 m height × 1.5 m width × 0.25m thickness representing a wall of 3m-height and 0.5m thickness - the current case for RE buildings in France. Two other walls had the same width and thickness but had 1.0 m height, to study the influence of the height/width ratio on the in-plane seismic performance of RE walls. The used earth was provided by a professional RE builder. The water was added to the earth to obtain the optimum manufacturing water content (approximately 12% by weight). The mixture was then poured in a steel formwork and compacted in layers by using a pneumatic rammer. The wall was built on a 0.25 m × 0.25 m × 1.8 m concrete beam. After the wall construction, another 0.25m × 0.25m × 1.8m concrete beam was placed on top of the wall. This beam enables to apply a horizontal load on the wall top during the pushover test. Before putting the concrete beam, a thin lime mortar layer was added on the top surface of the wall to increase the bonding between the wall and the beam, Fig. 3b.

For each wall, a prismatic specimen (0.25m × 0.25m × 0.5 m height) was also manufactured for the uniaxial compression test. The dimensions of these specimens were chosen to reproduce compaction energy applied on the walls. The representativeness of the specimens was discussed in Bui et al. [4]. The walls and the specimens were unmolded after the construction and let to cure at the laboratory ambient conditions (20 ˚C and 60% RH) for two months. This is the time necessary to obtain quasi-dry specimens [4]. The moisture contents of all walls and specimens at the test moment were about 3 %.

3.2. Experimental devices

The experimental device consists of a steel loading frame where the beams and columns have HEB400 cross section. The bottom concrete beam was fixed to the steel frame by four steel brackets that can be mechanically adjusted to have a correct embedment, Fig. 3a. Another steel jack (SJ on Fig. 3a) was used as support to prevent the beam sliding when applying the top horizontal displacement. The bottom concrete beam was also maintained by vertical tie rods to avoid the beam rocking.

Displacement sensors M1 (vertical) and M2 (horizontal) were used to check if there is any movement of the bottom concrete beam during the test (Fig. 3a).The displacements measured by the horizontal sensor M3 are used to verify the accuracy of the results obtained from the DIC (digital image correlation) .

For a pushover test, first, vertical loads were applied on the top of the wall to simulate the vertical loads in a building (dead and live loads). Two electrical actuators VE1 and VE2 were used to apply these vertical loads. These loads were applied at a rate of 1 kN/s until 60 kN in each actuator. These vertical loads were maintained constant during the horizontal pushover. They represent a normal stress of 0.3 MPa which is the current case of RE walls in a

2 stories house. These loads were distributed on the top concrete beam through a system that includes a UPN 300 steel profile and cylindrical rolls placed at the top surface of the upper concrete beam (Fig. 3b).

a b

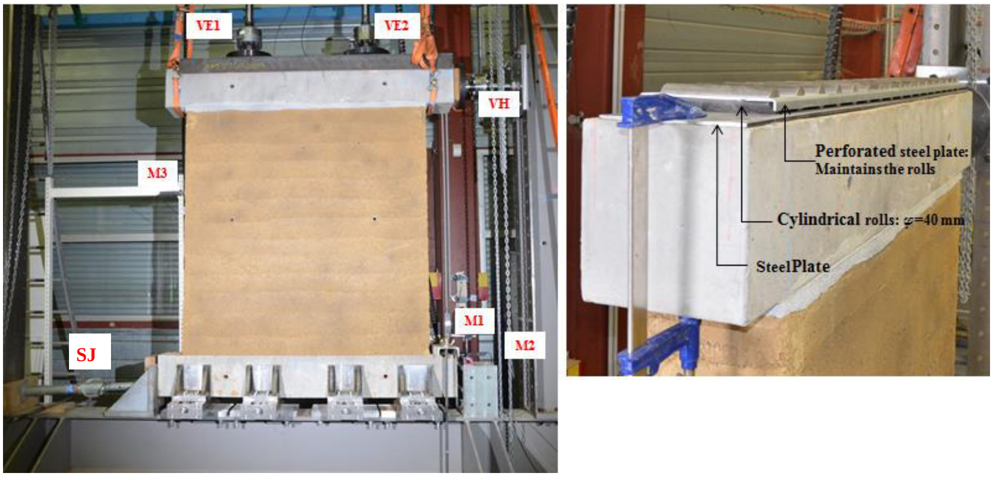

Fig. 3. (a) Test setup on a RE wall (1.5 m ×1.5 m × 0.25 m), (b) System placed on top of the beam.

Then, the horizontal pushover was carried out by a hydraulic actuator (VH) with displacement control, Fig. 3a. The loading rate was 1 mm/min up to failure. The horizontal load simulates a horizontal seismic action in the plan of the wall.

Uniaxial compression tests were also performed on the prismatic specimens which gave a mean compressive strength of 0.97 MPa. This compressive strength is closed to the results presented in the previous studies where specimens were manufactured by RE professionals [4] - [6].

The DIC was performed by using a professional camera with a resolution of 16 Mpixels. The DIC data processing was performed with the 7D software which was developed by Vacher et al. [11]. The displacement fields were determined by comparing the images after and before the loading (reference image). The DIC enabled to determine the displacements and the cracking development during the test.

3.3. Results

Fig. 4 shows the horizontal force in function of the horizontal displacement on top of the four walls. These displacements were obtained from the DIC which was more accurate than the displacement given by the horizontal actuator (influenced by the stiffness of the steel loading frame).

The curves in Fig.4 indicate the similar stiffness for the tested walls at the beginning of the horizontal loading (before 10 kN). It was also observed during the test that none of the tested walls had a brittle behaviour; after the test, the walls still support the concrete beam and could be transported by elevator without collapse

Walls 2 and 3 which have the same height (1.5m) exhibit similar behaviours: a maximal horizontal load about 40 kN and a ductile behaviour. Walls 1 and 4 having the same height (1.0m) but presented different behaviours. Wall 1 had a maximal horizontal load close to that of walls 2 and 3 but no ductile behaviour was observed. Wall 4 had a maximal horizontal load clearly more important than the other walls. A better behaviour of wall 4 comparing to walls 2 and 3 could be expected due to its lower height (less important flexural moment at the bottom section). However the net difference between wall 4 and wall 1 was relatively surprising. It could be suggested that the manufacturing of wall 1 was less well controlled than the other walls, since it was the first wall constructed and the laboratory's staff had less experiences.

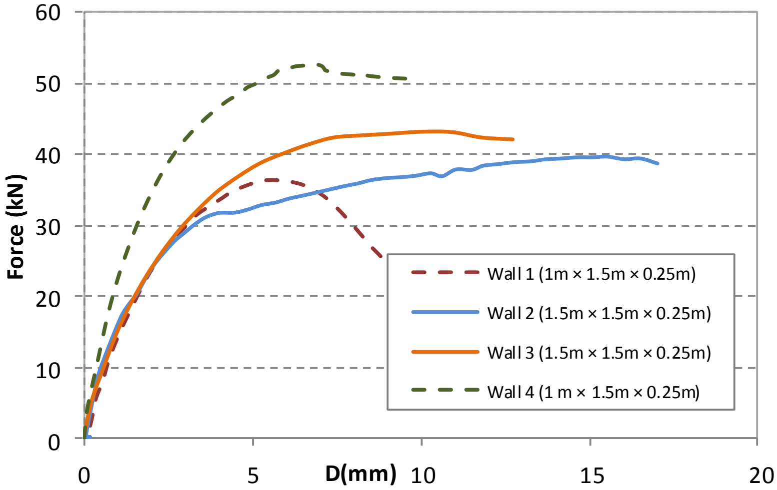

Fig. 4. The variation of the horizontal force on top of the wall in function of the top horizontal displacement.

Fig.5 illustrates the crack propagation of wall 2. For the tested walls, quasi-diagonal cracks were generally observed. A horizontal crack, at the left-lower part of the wall, was also observed at an interface between two earthen layers. This horizontal crack appeared when the horizontal reached about 85% of the maximal load. The interfaces between earthen layers are usually considered as “weak points” for the RE walls, but the presented result shows that there is an acceptable cohesion between the earthen layers.

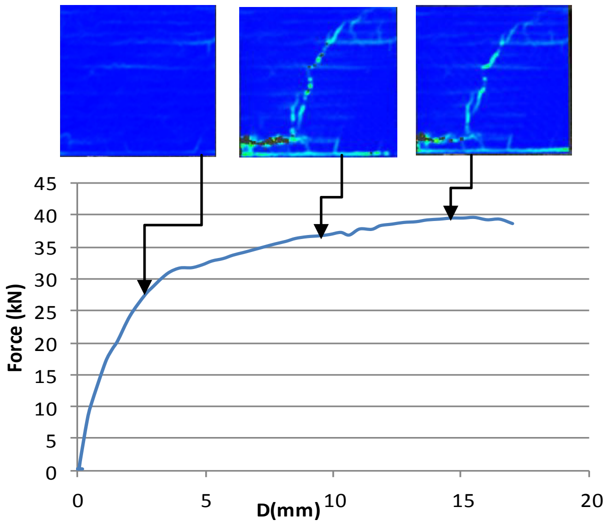

Fig. 5. Evolution of cracking for the wall 2 in function of the horizontal displacement.

Rocking of the walls at their base was noted for the tested walls but more clear for walls 2 and 3. These local uplifts were developed during the test, due to the more important tensile stresses of these walls which had a more important slenderness ratio.

4. Seismic assessment

Two approaches are usually used to assess the seismic performance of a structure: the classical force-based approach and the more recent displacement-based approach [12]. The second approach is well-known more adapted for the earthquake design, that was why in this study, the displacement-based approach was used to assess the seismic performance of the studied walls.

First the demand spectrum has been built for the buildings of class II (current buildings), and for two types of foundation soil: type A and B. Following Eurocode 8 [10], the A-type soil corresponds to a rock or very stiff soil (shear waves velocity v_s > 800 m/s) and the B-type soil corresponds to a good soil (shear wave velocity v_s = 360–800 m/s).

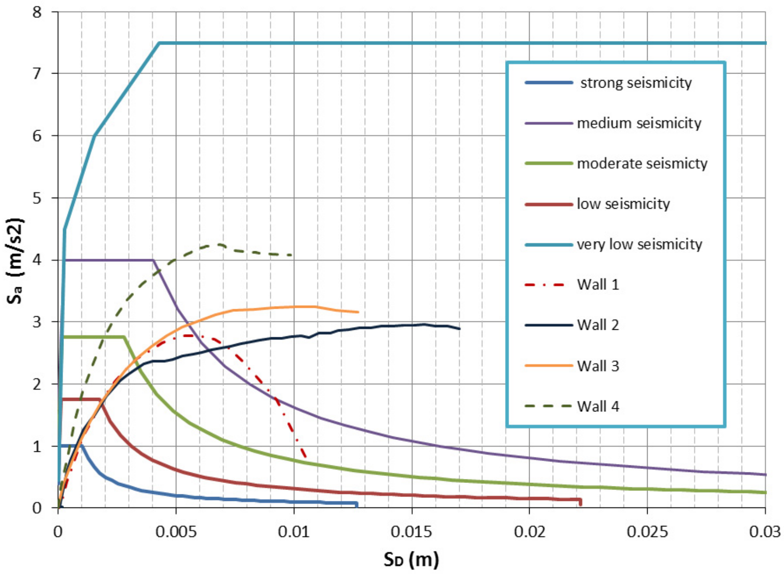

Fig.6. Capacity spectrum method for different zones of seismicity, case of soil A.

Fig. 6 presents the results for the type-A soil. The performance points for each wall on each seismicity zone can be determined (intersection points) which give the corresponding target displacements (S_d of the performance point). Then, the inter-story drift ratios of each wall can be calculated:

Inter-story drift = the target displacement / height of the wall (2)

To assess the damage state from the drifts, the limits proposed by Calvi et al. [13] for masonry structures were used (Fig. 7) because until now, no limit state (LS) has yet been proposed for RE walls.

- LS1: no damage
- LS2 (Minor structural damage and/or moderate non-structural damage): structure can be utilized after the earthquake, without any need for significant strengthening and repair to structural elements. The suggested drift limit is 0.1 %.
- LS3 (Significant structural damage and extensive non-structural damage): the building cannot be used after the earthquake without significant repair. The suggested drift limit is 0.3 %.
- LS4 (Collapse): repairing the building is neither possible nor economically reasonable. The structure will have to be demolished after the earthquake. Beyond this LS, global collapse with danger for human life has to be expected. The suggested drift limit is 0.5 %.

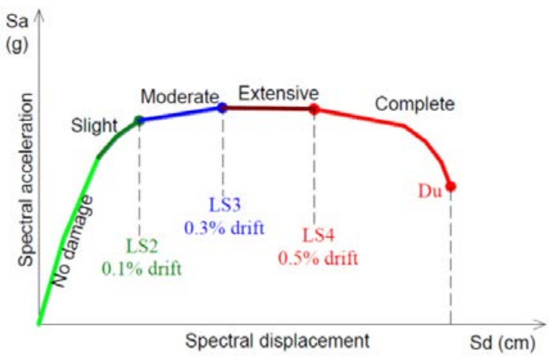

Fig. 7. Damage limit states following the drifts.

According to the above descriptions, LS3 can be considered as the limit for RE buildings. The LS of the studied walls for the type-A soil are summarized in Tab. 1. Following the used criteria, the studied walls can have a satisfactory performance on the seismicity zones from “very low” to “medium”. The results for type-B soil are presented in Tab. 2, where the studied walls have an acceptable performance on the seismicity zones from “very low” to “moderate”, except wall 1 which is acceptable only for “very low” and “moderate”, due to its non-ductile behavior as mentioned earlier.

Table 1. Inter-story drifts calculated for soil A.

Seismicity zone	Wall 1		Wall 2		Wall 3		Wall 4	
	Drift (%)	Damage state	Drift (%)	Damage state	Drift (%)	Damage state	Drift (%)	Damage state
Very low	0.033	Slight	0.031	Slight	0.033	Slight	0.015	Slight
Low	0.056	Slight	0.059	Slight	0.059	Slight	0.035	Slight
Moderate	0.11	Moderate	0.136	Moderate	0.136	Moderate	0.064	Slight
Medium	0.19	Moderate	0.21	Moderate	0.21	Moderate	0.14	Moderate
Strong	∞	**Complete**	∞	**Complete**	∞	**Complete**	∞	**Complete**

Table 2. Inter-story drifts calculated for soil B.

Seismicity zone	Wall 1		Wall 2		Wall 3		Wall 4	
	Drift (%)	Damage state	Drift (%)	Damage state	Drift (%)	Damage state	Drift (%)	Damage state
Very low	0.045	Slight	0.045	Slight	0.045	Slight	0.023	Slight
Low	0.11	Moderate	0.13	Moderate	0.11	Moderate	0.049	Slight
Moderate	∞	**Complete**	0.26	Moderate	0.23	Moderate	0.12	Moderate
Medium	∞	**Complete**	0.51	**Complete**	0.5	**Extensive**	0.41	**Extensive**
Strong	∞	**Complete**	∞	**Complete**	∞	**Complete**	∞	**Complete**

5. Conclusion and outlook

This study investigates the in-plane seismic performance capacity of RE walls. Four walls with two different heights were constructed in laboratory and submitted to pushover tests. The capacity curves were established for the studied walls and the damage states were determined for different seismicity zones and soil types. Following the damage limits currently used for masonry structures, the studied RE walls can have a satisfactory performance on the seismicity zones from “very low” to “medium” with the type-A soil. However for type-B soil, the acceptable results were only found for seismicity zones from “very low” to “moderate” (except wall 1). Other soil types (C and D) were not studied but the performance would be less good than for the type-B soil. The different results obtained for walls 1 and 4 (with the same height) showed that the manufacturing process could have an important influence on the seismic performance of RE walls.

It is important to mention that the walls presented in this paper were tested under a vertical load of 120 kN (corresponding to the dead and live loads of the floor and roof), which is was an important load to support for a RE walls. This means the obtained results correspond to an unfavorable case in practice. For the case where these dead and live loads are less important (one story RE house; ground floor in RE and second floor in wood), the obtained seismic performance will be better.

The study used 0.5-scale RE walls for the pushover tests. A numerical model was performed with an advance FE code to simulate the experimental results on RE specimens [14]. Once the numerical model is validated by the pushover results presented in this paper, it can be used to investigate the seismic performance of the real scale RE walls. The scale effects will be then assessed.

Acknowledgment

The authors wish to thank the French National Research Agency (ANR) for the funding of the PRIMATERRE project (ANR-12-Villes et Bâtiments Durables).

References

[1] H. Guillaud, E. Avrami, M. Hardy, Terra Literature review:an overview of research in earthen architecture conservation, Los Angeles, The Getty Conservation Institute, 2008.

[2] J.C. Morel, A. Mesbah, M. Oggero, P.Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Building and Environment. 36 (2001) 1119-26.

[3] Q.B. Bui, J.C. Morel, B.V.V. Reddy, W. Ghayad, Durability of rammed earth walls exposed for 20 years to natural weathering, Building and Environment. 44 (2009) 912-919.

[4] Q.B. Bui, J.C. Morel, S. Hans, N. Meunier, Compression behaviour of nonindustrial materials in civil engineering by three scale experiments: the case of rammed earth, Materials and Structures, 42 (2009) 1101-1116.

[5] T.T. Bui, Q.B. Bui, A. Limam, S. Maximilien, Failure of rammed earth walls: from observations to quantifications, Construction and Building Materials. 51 (2014) 295-302.

[6] V. Maniatidis, P. Walker, Structural capacity of rammed earth in compression, Journal of Materials in Civil Engineering. 20 (2008) 230-38.

[7] P. Taylor, R.J. Fuller, M.B. Luther, Energy use and thermal comfort in a rammed earth office building, Energy and buildings, 40 (2008) 793-800.

[8] Q.B. Bui, S. Hans, J.C. Morel, A.P. Do, First exploratory study on dynamic characteristics of rammed earth buildings, Engineering Structures, 33 (2011) 3690–3695.

[9] M.I. Gomes, M. Lopes, J. De Brito, Seismic resistance of earth construction in Portugal, Engineering Structures, 33 (2011) 932-41.

[10] EN 1998-1:2004, Eurocode 8: Design of structures for earthquake resistance, European Committee for Standardization, 1998.

[11] P. Vacher, S. Dumoulin, F. Morestin, S. Mguil-Touchal, Bidimensional strain measurement using digital images, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 213 (1999) 811-17.

[12] A.K. Chopra, R.K. Goel, A modal pushover analysis procedure for estimating seismic demands for buildings, Earthquake Engineering & Structural Dynamics, 31 (2002) 561-582.

[13] G.M. Calvi, A displacement-based approach for vulnerability evaluation of classes of buildings. Journal of Earthquake Engineering, 3 (1999) 411-38.

[14] R. Nabouch, Q.B. Bui, P. Perrotin, O. Plé, J.P. Plassiard, Numerical modeling of rammed earth constructions: analysis and recommendations, 1st International Conference on Bio-based Building Materials, Clermont Ferrand (France), RILEM, June 21-24 2015, paper 57.