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Dominique Daudon, Yannick Sieffert, Osvaldo Albarracin, Lucas Garino Alibardi, Gustavo Navarta. Adobe Construction Modeling by Discrete Element Method: First Methodological Steps. *Procedia Economics and Finance*, 2014, 4th International Conference on Building Resilience, 8-11 September 2014, Salford Quays, United Kingdom, 18, pp.247-254. 10.1016/s2212-5671(14)00937-x . hal-02004091

HAL Id: hal-02004091

<https://hal.science/hal-02004091>

Submitted on 1 Feb 2019

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4th International Conference on Building Resilience, 8-11 September 2014,
Salford Quays, United Kingdom

Adobe construction modeling by discrete element method: first methodological steps

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Abstract

Adobe constructions are used worldwide but especially in regions where transportation of constructing manufactured materials or wood are costly like in Andean or oriental Himalayan mountains. These regions are often very seismic and this type of housing is very vulnerable. However, this vernacular architecture may be the right one on the way to more sustainability, as revisited now, thermal, acoustical property, and environmental impact reveals his qualities. But it suffers of less mechanical resistance especially to earthquake and do not have any codification of building rules in the majority of the countries. In order to fill this gap, numerical modeling is necessary. Lot of studies has been done in order to characterize the behavior both experimentally and numerically and some modeling is current in finite elements method. A few studies are made with the discrete elements method even if it should be really usefully as each brick could be considered as a particle and the cement joint may be modeled by the simple contact laws largely provided in this type of code. The paper presents experimental and DEM studies at a real scale and at a small scale in order to valid the ability of DEM for modeling adobe housing.

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Selection and/or peer-reviewed under responsibility of the Centre for Disaster Resilience, School of the Built Environment, University of Salford.

Keywords: adobe housing, Argentina, experiment, modeling, seismic scenarios

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1. Introduction

1.1. Adobe construction

The adobe bricks have been used for about eleven millennia. Adobe bricks are a sun-dried earth bricks, and are one of the most used vernacular earth construction process such as rammed earth, and quincha-baharaque walls. In Europe, the onset of adobe architecture in the western basin Mediterranean has revealed the complexity of the origins that can be attributed to a "phenomenon" that develops at the beginning of the Iron Age (Chazelles 1995). It is the testimony of the architecture of many centuries.

In European countries also, some vernacular architecture are using earth construction and the south of France near Toulouse is one of the French region who still have some old farm in adobe or mixt adobe cooked earth brick (fig 1).

In some South America's cities, there are churches of the 17eme in Adobe still in run but the premises where relieved in 900 BC (Zegarra 2000). In these countries, the adobe constructions are an old construction process (Cirvini 2011) devoted now to quite poorest places as types of construction are often linked, such as South America and Himalaya, with difficulties to build in some part of the world: in high mountain and less forested parts, highest seismicity zones and generally arid regions.

As it is not cooked and stabilized the adobe bricks are fragile and also susceptible to be largely damaged by climatic events. To prevent degradation they need to be highly maintained and generally covered by earth, cement, and painted.

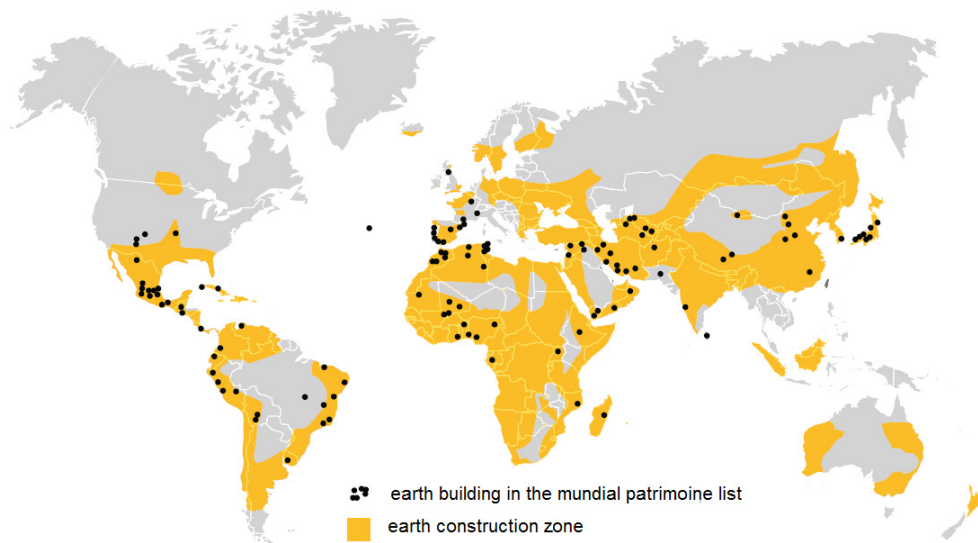


Fig. 1: earth construction in the world with patrimoines UNESCO (adapted from Gandreau & al 2010)

1.2. Characterization studies

Nowadays, the use of adobe is declining because of the abundance of manufactured building material (Parra-Saldivar, Batty, 2006). Some recommendation guides for adobe construction exists see Morales et al. (1993), Minke (2001), HIAEE (2004) et ASTM (2010) and in Peru a building code is used (Waffer 2010) because this material and auto-building technic are really common and escape to the actual marketing and building lobbies. In 2010, ASTM provides the first recommendations guide that may be offers more legal future to adobe constructions. In some country such as Argentina, this type of construction is prohibited due to the seismic vulnerability. Two major earthquakes suck this country in 1861 in Mendoza and in 1945 in San Juan's. Nevertheless adobe constructions still

remain largely used by the rural populations for tradition and/or financial reasons, and lot of vestiges exists in the Cuyo region (Cirvini 2011).

1.3. Seismic behavior of adobe masonry

As said before, the regions where adobes are the most dwelling coincide with high seismic regions. Large earth cities have been destroyed in the past and in the recent time: Bam's citadel in southeastern Iran was the largest adobe city built before his destruction by a seismic event in 2003. The fortified town on the Silk Road was built in the first century BC. Listed as UNESCO heritage; it was always inhabited until the 2003 earthquake which devastated the city. The mud brick adobes therefore appear to be an efficient material that can withstand for centuries except in case of an earthquake. This weakness is due to the fact that the constructions are not reinforced. Earth constructions; at the level of material, have low strengtheners resistance, even compacted, except if cement or fiber (generally vegetal) is added in the paste (Alvarez-Ramirez 2012). In the Himalayan range, in order to increase the seismic behavior people insert wood in constructions, creating some isolators and separating between wall panels which leads to limited the total deformation of panels.

In South America, the seismic resistance of adobe constructions have been studied largely in Colombia, Chili, Argentina, but overall in Peru by pioneer M. Blondet's research team. For example, the last earthquake of 2010 in Chile has destroyed more than 140000 houses with a majority constructed in adobe without anti-seismic reinforcement. (Fundación Terram, 2010). The problems of adobe constructions are caused mainly by the weight of the structure, the low resistance and its behavior breaking (Blondet, 2003). The contemporain studies were essentially focused on construction amelioration designs in avoiding currents construction errors: height of the house, too large panels without chain, room disposition, house position in the relief and also good fabrication of the adobe himself with right proportion of each component (Minke 1993, Jimenez 2007, Morales 1993, et cetera. Large studies have been done by the university catolica pontifica de Peru for years in order to understand the seismic behavior and structural approaches to strengthen : wall's corners with plastic network, metallic on, adding cane bars near the top to circle, and to repair the dwelling after the event when possible(Cristafulli 2008). In fact, all countries would tend to replace the dried brick by the cooked one, more rigid, and more reliable if correctly used, and the most new constructions when financially is met is to build housing and building in "mamposteria encadenada" that is to say, to constructs reinforce concrete column and beams around mamposterias panels)

1.4. Resilience and sustainability of adobe construction

With sustainability approaches and re-using development in Civil engineering (Siefert 2014), adobe construction is a way to rediscover. A lot of recent books and articles on this subject are actually easily to find (Schroder 2010, Morton 2010 Seth 2012, Sanchez 2008) Note that the pioneer work is the architect Minke (2000, 2001, 2006) who also have travelled in Himalayan and Andean countries in order to increase and promote the local construction technic to resist to seism event.

Almost all land mineral clay could be used in constructions (Houben, 2006). At all stages of its use, it requires very little gray energy. Available locally, the land requires no transportation, no processing or expensive cooking energy. Maintenance and repairs are easy. End of life, the frame is destroyed and the earth can be re-used or returned to the soil. Its ecological footprint close to zero represent a huge advantage over the warmer climate and the need to reduce energy consumption, as demonstrated by Shukla (2009) in the study of a new construction in India.

Waffer 2010 demonstrated in his studies that adobe has significant advantages over materials industrial. It has the ability to regulate the air humidity, the stored heat, save energy consumption, produce virtually no pollution, to be 100% reusable, and preserve the wood and other materials while absorbing organic pollutants in the indoor air of homes.

In a scenario where natural resources are limited, the adobe constructions could be a very interesting material, not only in developing countries but also in countries Cold America and Europe (Chel and Tiwari, 2009). Indeed, earth is cheap, environmentally sustainable and especially abundant (Binici et al., 2005). The issue for the future is then to try to study this type of material and building in the modern context, and needs of security, aesthetic, and take experience of the previous constructions cultures. For example, thermal properties are quite good as for a density of

1600 kg/m³ (2500 kg/m³ for reinforced concrete), it gives a thermal conductivity of 0.81 (W/m.K) better than concrete (1.81 (W/m.K)) and a specific warm de 650 (J/Kg.K) in comparison with 850 (J/Kg.K) for concrete.

1.5. Numerical modeling of masonry construction

Numerical modelling of masonry structure is well done in finite elements, using some homogenization technic as MEF with largely numbers of interface elements are generally a challenge in geometry description, parameters evaluation and in time calculation (Illampas 2011). In fact, the numerical method to use depends on the aims of the calculation, and homogenization techniques are needed in the FEM when a global behavior is required for the study, especially in the elastic domain (Colas 2009). But when some more local process is or when it is not possible to study globally like in arches architecture, or in some antic architecture like column, the FEM method may be not pertinent. Cundall (1971) proposes a discrete element methods code for some study of geotechnical material (rock slopes with joints). As fractured rock massif modelling is not so far from masonry modelling, pioneers applications are devotes to Lourenco (1996) and Lemos (1997) as the method could describe the behavior of every collection of solids interacting together. A lot of different vernacular and more contemporizing construction have been studied by this way, for example the Pont du Gard (Chetouane 2004, Kiyono 2006), behavior of classical masonry in cooked earth brick (Bui 2012) and stone masonry (Mohebkah 2012). When done after a disaster, and aiming to re-analysis the FEM calculation of the behavior of a structure consisted in general in first static loading and naturel vibration mode calculation (ref Peruvian church), in order to understand the collapse scheme. Some experimental studies are also modelled in order to get the parameter needed in the code, and proceed then to various exploratory studies. The common are the simple compression, shear and tension of the jointed structure and of a brick itself. Then more complex tests are modelled as cyclic ones and real seismic one on vibrating table in real or reduced scales.

In fact both numerical method finite element and discrete element fail in the representation of the real structures behaviors as parameters properties and overall its variability may need a specific approach that may be sometime rapid (Daudon 2012), but with strong hypothesis on the variability of the parameters (Baroth 2012).

As a resume, the capacity of the vernacular adobe construction to be one of the sustainable materials of the future is not to demonstrate more. Facing disaster situation, it is generally a fragile material as special care as not be done in many points: material, but also anarchic disposition. In fact disaster situation is the key possibility of reconstructing with the attention needed to pursuit the vernacular architecture that is generally in the zone and better it in order to gain is sustainability, reliability and increase resilience. As only few building codification and resistance verification exist in the world for this construction, the way to design this type of auto construction is always open. In order to explore the possibility, the authors have performed reduced scale, and real scale tests aimed to characterize mechanicals parameters for furthers exploratory studies over the seismic loading of Caceute (Argentine 1977) of a real tested structure.

2. Numerical Modeling with 3DEC DEM

Discrete elements modeling rose in the 1970 with first application to soil and rock materials. This type of calculation codes consider the structure or matter as a collection of particles in interaction one from each other over the 2nd principle of dynamical equations. It was first developed in 2 dimension with circular particle due to contact properties to manage. Large amount of different particles codes exist now in 3D accepting various shapes of particles and various problems.

In the case of masonry structures, this type of code is well adapted as the bricks are considered as a particle, and the joint may be assumed by the contact behavior laws chosen. The contact law is the key parameter when the particles are considered as rigid solid.

The law may be very simple as elastic one for example, needing only 2 parameters assumed to be the rigidity in normal contact and in tangential contact. More complex one's may integrate some contact laws cut in shear or tension, with or without frictions, as plastic ones with the needed parameters to fulfill.

In the case of adobe structures modeling, the particle may be rigid and the damage will concentrate only on the joints or elastic-plastic in order to consider the possible damage of the brick itself.

The chosen code to verify the DEM ability to model such construction is Itasca’s one 3DEC (Itasca 2011). In the context of future professional work and teaching modelling, the code gives the tutorial support needed and allows a lot of other possibility such as thermal behavior, rebar’s inclusion, and seismic calculation. Lot of literature exist on the discrete element method (Cundall 1971, Donze 2009)

2.1. Ability of the DEM code to reproduce the behavior

In the discrete element model of a adobe or brick construction some mechanical parameters are needed. The brick one’s are: density, rigidity normal and tangential, and if needed by the behavior choice: elastic brick or rigid one young and Poisson modulus. The numerical values of the parameters may be defined according to experiments and literature if not know (table 1)

And the joint may be as for the bricks, rigidity normal and tangential, and if needed by the behavior choice: elastic brick or rigid one young and Poisson modulus, and friction coefficient.

A simple shear test of an earth joint between two commercial adobe bricks of dimension 24cm*12.5cm*7.5cm was modelled in order to reproduce the experimental shear resistance obtained of 172 daN that is approximately 0.57 MPa, in current range values for this type of material (de Almeida 2012, Mile 1980).



Fig 2: a) experimental vertical stress/strain curve b) Shear test by 45° compression of the adobe assembly . c) End of the test

The load displacement curve is represented in figure 2a, that lead to a wall shear strength value of approximately 0.9 MPa, not too far from the single brick one. The shear test was reproduced using the parameters in the table 1

The figure 3 presents both the experimental and the numerical wall. It shows that the displacement are in the same range even if not exactly same due to choice of the numerical collapse time. Moreover, the numerical vertical loading curve gives a similar value of the collapse vertical force that has been applied to the wall sample (7.8kN for the experimental one and 8kN for the numerical one).

Table 1: Mechanical parameter of the simulation

Mechanical properties	range
Density of Adobe	1800 kg/m ³
Bulk modulus	64 MPa
Shear Modulus	48 MPa
Joint Normal Rigidity	220 GigaN
Joint Tangential Rigidity	32 GigaN
Joint Shear Rupture	5.6 MPa
Joint Tension Rupture	0.49 MPa
Joint Dilation Angle	0
Joint Friction angle	25°

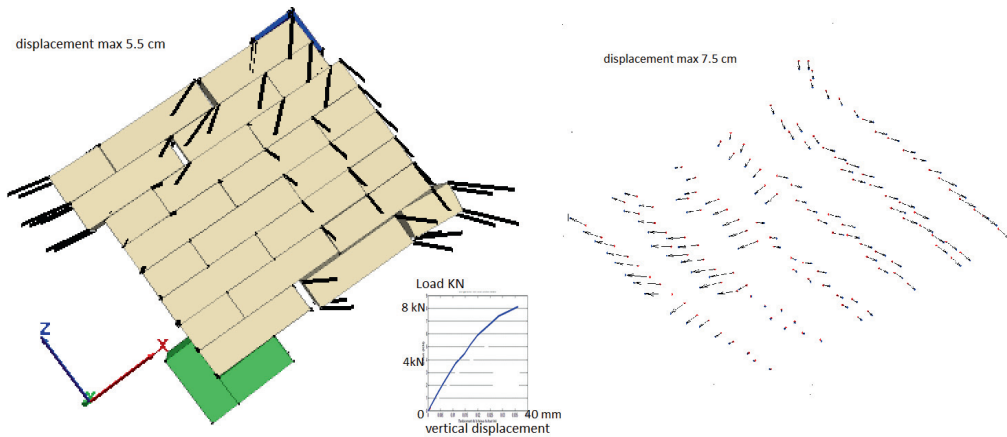


Fig.3: numerical wall displacements by 3DEC with measured one afterimage analysis by TRACER (Combe & Richefeu 2013) and force/displacement numerical curve at the collapse.

2.3. Vibrating table test modeling

Dynamic tests of a 1:2 scale model built with adobes were made(Fig 4a). For this test the shaking table of Earthquake Research Institute of the National University of San Juan, Argentina, was used.

This table is essentially a metal platform of 2.90m by 2.10m of side, connected to the foundation by two vertical planes bi-articulated .The capacity table is 10t and can reach for this mass an horizontal acceleration of 0.50 g .

The horizontal acceleration is achieved by a double acting hydraulic actuator that includes a system of closed loop control .The model has a height of 1.45m by 2.00m of side, and has two side openings.

The dynamic test is divided into two stages. First, the period of vibration of the structure is located. Then ,for this period, dynamic tests were performed using sine waves with gradual increases acceleration .

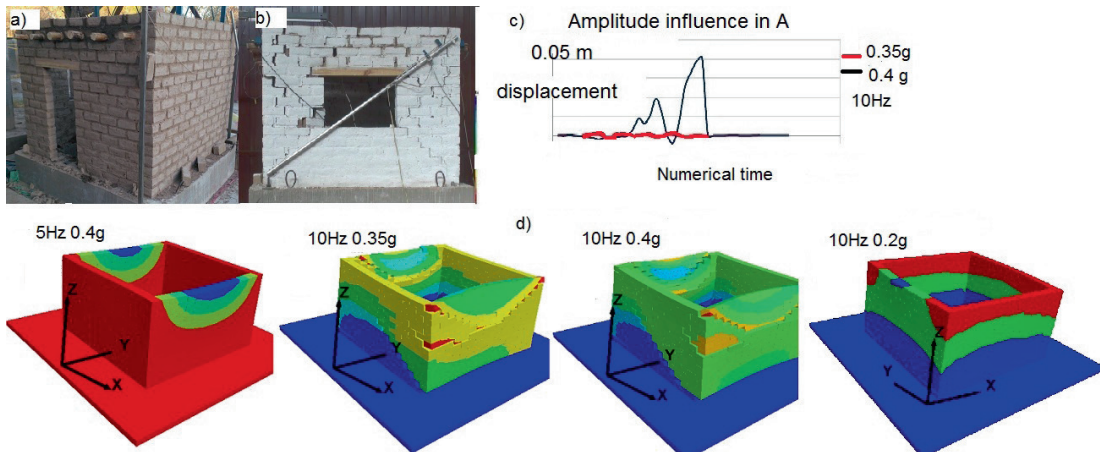


Fig.4 : a) the Adobe House, b) final state of a the end of the 3 serial tests c) Amplitude influence on joints displacements from the numerical simulation d) Displacement scheme at the same step, for the numerical simulation tests. from left to right the maximum amplitude of displacement of the brick is 7.6 cm(5Hz-0.4g) ;11,3 cm(10Hz-0.35g) ; 15cm(10Hz-0.4g) 6cm (10hz-0.2g);

Figure 4b shows the final state of the model after the application of a dynamic movement with a horizontal acceleration of 0.40g and a frequency of 5Hz. The entire experimental tests were tried in the numerical model but without the opening windows and doors in a first intention (fig 4d). The influence of the frequency is well

demonstrated by the comparison of the 2 first left schemes. The amplitude influence is easy to see on the 2 right ones. The down curves show influences of amplitude acceleration for (frequency 10Hz) on the top point of the out of plane wall (Fig 4c).

Other numerical simulations of small scale experimental tests (not presented here) were done in order to validate the ability of reproducing natural frequency of the construction in the aim of proposing a calibration methodology of the numerical parameters. In fact, some nondestructive characterization technic of building health are using a natural frequency characterization by ambient noise and the challenge of characterizing the mechanical characteristic of some modelling parameters may be done by this way in elastic behavior (Montella 2013, Migliaccio 2013).

Rather few results are presented here, and it has to be completed and exploited with more rigorous developments in order to compare with measurements of the preliminary numerical tests, but the possibilities are interesting in order to do large influence parameters campaigns in the future, when complete calibrations of the numerical parameters is done.

3.Conclusion

The aim of this paper is to present some modelling that may be used in the future for earth construction modelling. As this vernacular type of construction largely used from centuries, may be one of the future, regarding to the great advantage it presents in the sustainability way of re-using, low impact Carbone, and raw materials avoiding such as large amount of sand as in the concrete construction. In fact, as the building codes for adobe construction exist only in few countries, it may be a challenge to enlarge that those code to European country in order to define new design construction codes that would allow this type of sustainable constructions. In the case of the present study, other simulations have been done but not presented as the characterization of the existing construction may be done by natural frequency measuring. In fact, the development for the future is in term of mechanical parameters characterization by numerical optimization on the discrete element simulations. Moreover, it will be possible to have adequate procedure in order to describe a building code as it exist for concrete structure and enchainned masonry ones.

Acknowledgements

The author would like to acknowledges : all the students of Licence 3 MMK, Master 1 GCI, Master 2 SIM, and the two Italians Erasmus students of San Frederico (Napoli) that have participated, for there help and enthusiasm in developing the numerical tools; The VOR federation for supporting financially the Erasmus students, and the new collaboration with IDIA San Juan university Argentina, and the Rhone Alpes region for providing the founding for the 3DEC version in innovative teaching at the Grenoble University.

This paper from 3SR laboratory is part of the Labex Tech21.

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