Mechanical characterization of dry-stack interlocking compressed earth masonry

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ABSTRACT: Earth has been a traditional building material to construct houses in Africa. One of the most common techniques is the use of sun dried or kiln fired adobe bricks with mud mortar. Although this technique is low-cost, the bricks vary largely in shape, strength and durability. This leads to weak houses which suffer considerable damage during floods and seismic events. A solution is the use of dry-stack masonry with stabilized interlocking compressed earth blocks (ICEB). These blocks are manufactured by compacting cement stabilized earth in a manual or hydraulic press into a mould and then air dried. The resulting blocks present uniform shapes and higher values of strength and durability. This work presents the work made in the context of the HiLoTec project. It focuses on the experimental campaign of the project to characterize the strength of ICEBs and the behaviour of dry-stack masonry.

Keywords: *Social houses, compressed earth blocks, dry-stack, interlocking, testing*

NOTATION

A	cross section area of specimen;	f_p	confining stress;
α_k	internal friction angle;	f_{v0}	initial shear strength;
B	specimen width;	H	specimen height;
D	diameter of the specimen;	L	length of the specimen;
F	maximum load;	l	span between supports;
f_{it}	indirect tensile strength;		

1   INTRODUCTION

Since social responsibilities in developing countries have been increasing in importance in recent decades, housing policies are now a major concern. Most developing countries face a problem of providing suitable houses for their citizens, addressing increasing demands on comfort and health, but also urbanization and growing population. As the population of the globe grows, the need for housings is also increasing. The United Nations estimates that the world's population will increase to nearly 9 billion by the year 2050, with its main growth in Africa, but also to the Middle East and parts of the American Pacific coastline (see growth maps in [1]). It is interesting that these regions are also the regions in which earthen architecture is common. Developing countries of these regions are

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already facing the enormous difficulty to provide their population with affordable solutions of social housing for today and for future, and this trend is expected to last for several decades.

Taking into account the growing demand for housing, it seems impossible, both technically and economically, to meet this demand only with industrialized building materials, such as concrete or steel, and with modern construction techniques. The demand for housing also needs to be addressed by using local materials and by encouraging self-construction. For example, earth as a construction material can be found in most regions and is an efficient solution for the building demand [2]. Earth will continue to be the primary building material for communities in developing countries, where modern materials are simply too costly. However, in recent years earth has also been enjoying renewed interest by the academic and technical community, due to the sustainability aspects.

Therefore, the future of the construction industry will require changes at many levels. One is the ability of constructors to adapt to new challenges and simultaneously contributing to the solving of social and environmental problems. In the coming decades we will see a change in attitude in the industry, with a strong tendency to adopt natural and recycled materials, as well as bet on green technology and social innovation oriented to emerging countries.

This paper presents the work carried out during the Project HiLoTec – Development of a Sustainable Self-Construction System for Developing Countries, supported by Mota-Engil S.A. and Fundação Manuel António da Mota, and focuses mainly on the engineering aspects of this project. The study focused on the use of interlocking compressed earth blocks (ICEB) for use in dry-stack masonry in regions with moderate seismicity. Compressed earth blocks (CEB) are blocks which are made from cement or lime stabilised earth, which are pressed in mould in a manual or hydraulic machine and then air dried until they are cured (see Figure 1). In this way no firing in kilns is needed.

| (a) | (b) | (c) |

Figure 1. ICEB production: (a) pouring stabilized earth into the machine; (b) compressing the block; (c) finished ICEB.

1.1. The HiLoTec project

Through a cooperative action between the construction company Mota-Engil Engineering and the University of Minho in Portugal, a construction technology based on the use of compressed earth blocks (CEB) has been studied as part of a social concept for innovative small houses, favouring the adoption of local and natural materials and with the main premise of being dedicated to self-construction.

This collaborative work carries the name of the project: HiLoTec. The name itself appeals to various aspects of this work; "Lo" (i.e. low) for the use of cheap and environmental friendly materials with a low amount of manufactured items and "Hi" (i.e. high) as an improvement of the quality of existing houses and development of a sustainable "Tec"hnology for the construction industry. The proposed construction technology combines both natural and traditional building materials with more advanced

construction techniques. Sustainability and low cost housing were the main objectives for the HiLoTec project.

The architectural challenges and the strength and durability of stabilized earth were deeply studied and they can be seen in [3][4][5].

1.2. Building with CEB

Disasters are a consequence of inadequate management of risk and housing solutions must be compatible with the local hazards. The two most severe natural hazards for earth constructions are earthquakes and floods. Earthquakes create horizontal and vertical ground accelerations that induce inertial forces on the whole structure, while floods affect, at least, the foundations and the base of walls and weaken the material. Damage produced by earthquakes in adobe houses is recurrent. Damage is not only linked to the weakness of the material, but also to poor construction techniques and details. Simple additions such as ring beams and vertical reinforcement (timber, steel or cane rods) can improve the strength of a building in order to avoid excessive damage and killing people [6]. The use of CEB with interlocking, in conjunction with adequate construction details such as strong foundations, wall reinforcement, ring beams and overhanging roofs, has the potential of offering new possibilities for affordable, safe and quality housing in regions of moderate.

The subject of seismic vulnerability of earthen construction is still being studied by various authors, since no definite and cheap solution has been proposed and implemented in practice in a wide scale. Although significant research has been undertaken to optimize the properties of (stabilized) earth for construction ([7][8][9], amongst others), little research has been done to investigate the performance of integral building systems using this technology [10]. This is specially the case of elements built with dry-stack ICEB, with or without reinforcement. Several earth construction codes of seismic countries, such as the New Zealand standard NZS4297 [11] or the Peruvian E-080 [12] code, do not mention the use of ICEB. These codes focus on the maximum slenderness of walls and seem to be based on a conservative empirical criterion rather than on experimental or analytical results. To the authors' knowledge, except for the tests performed by [13] regarding out of plane behaviour and [10] regarding in-plane behaviour, no extensive test campaigns have been carried out on dry-stack ICEB masonry specimens to characterize their seismic behaviour.

As a contribution to this subject, this work focuses on the study of dry-stack ICEB. The aim is to characterize the mechanical properties of the system for its use in developing countries with moderate seismicity. For this purpose, a joint venture with the major Portuguese contractor was made, selecting Malawi as the reference country for application of the technique and soil samples of different ordinary sites in Malawi have been used for testing and material selection. The present paper presents a broad summary of the works carried out regarding the engineering aspects of houses constructed with dry-stack CEB.

2 MATERIAL TESTING

The material testing which was carried out can be divided into three phases according to the size of the samples and the characteristics to be studied: (i) small cylinder samples; (ii) units; and (iii) small masonry specimens. The results of these tests contribute to the characterization of the material used (soil), the strength of the ICEBs (units) and strength of the masonry walls (under vertical and horizontal loading).

In all compression tests, the compressive stress was obtained by dividing the vertical load by the net area of the cross section of the specimen and the Young's modulus (E) was obtained as the tangent curve between 40% and 70% of the peak stress.

2.1. Small cylinder samples

As a way of characterizing the material properties of the stabilized soil to produce the ICEBs and for quality control reasons, samples of the soil mix were taken. With this soil samples, specimens of an average length of 65 mm and 50 mm diameter (1.3 slender ratio) were made (see Figure 2a). These specimens were compressed with a pressure of 2 MPa, which replicates the effect of the pressing machine to make the blocks.
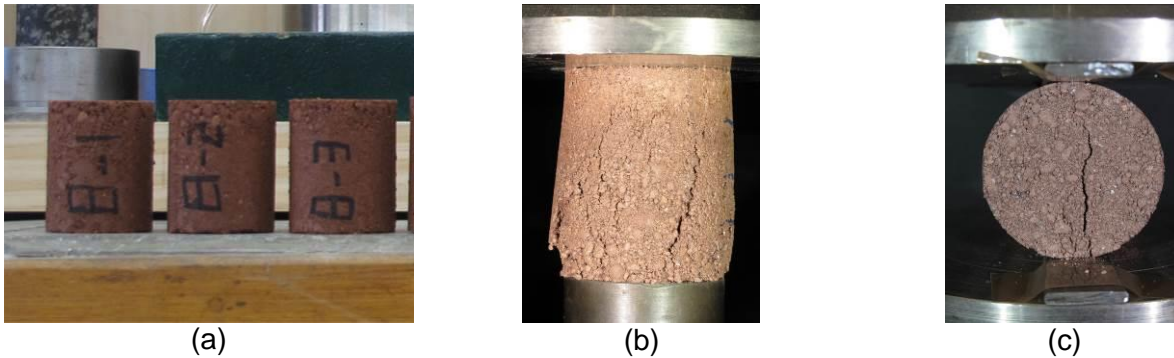

| (a) | (b) | (c) |

Figure 2. Small cylinder tests: (a) small cylinder samples; (b) compression test; (c) indirect tensile test.

These specimens were used to determine the compressive and tensile strength of the material of which the blocks are made. A 50 kN electro-mechanic testing machine with displacement control was used. The compression tests were made under direct compression at 28 days of age to determine the compressive strength of the soil (f_c). The average compression strength of this test was equal to 1.10 MPa with a covariance (CoV) of 34% and the average Young's modulus was equal to 106 MPa with a CoV of 32%. Figure 2b shows a tested specimen.

The tensile strength of the stabilized soil was determined with the indirect tensile test method proposed by the EN13286-42 (2003). This test determines the tensile strength (f_{it}) by applying a vertical force on two parallel faces of a horizontally laid cylinder, see Figure 2.c. The specimen then splits vertically along its length and the tensile strength can be determined indirectly by the following expression:

$$f_{it} = \frac{2F}{\pi LD} \tag{1}$$

where F is the maximum load, L the specimen's length and D the diameter. The average tensile strength which was determined was equal to 0.06 MPa with a CoV of 24%.

2.2. Units

Compressive strength has become a basic and universally accepted characteristic for measuring the quality of masonry units [14]. A common criterion adopted by codes or guidelines of earth construction is to demand compressive strengths higher or equal to 2 MPa ([15][16][17], amongst others).

The standard followed for this test was the [18]. The tests were carried out with a hydraulic press under force control at 7, 14 and 28 days, as [17] suggests. For comparison, both ICEB made of soil from Malawi and from local soil (Portugal) were tested. The average compression strength of this test was equal to 2.34 MPa with a CoV of 24% and the average Young's modulus was equal to 163 MPa with a CoV of 30%.

The three point bending test is used to determine the tensile strength indirectly, being known as flexural strength (f_{bf}). In this test, the block is laid on two simple supports at its ends and a vertical force is applied in the middle of the block. The tests were carried out in accordance to [19], but with modifications inspired on [17], because the European Standards do not fit the dimensions of the ICEB. The vertical load was applied by means of a hydraulic actuator with displacement control. The flexural strength is then calculated by the following expression [17]:

$$f_{bf} = \frac{3lF}{2BH} \qquad (2)$$

where l is the span between supports, B is the width and H is the height. The average flexural strength of this test was equal to 0.21 MPa with aCoV of 19%.

2.3. Tests of masonry specimens

Since the proposed ICEB will be dry-stacked, the expected strength should be governed by the properties of the stabilized soil, by the frictional interface between units, by the contact in the interlocking and by geometrical aspects. Compression tests of stacked bond prisms or masonry wallets are frequently used to determine the compression strength of masonry. Both tests were carried out to characterize the impact of the specimen type on the compressive strength, as the stack bonded test is much easier to carry out in developing countries.

The test on masonry prisms (or stacked bond prisms) has the advantage that the specimens are small and that the test is easy to carry out. The obvious disadvantage of the test is that it does not replicate the bond pattern of the masonry. This test followed the [20] standard. Due to the dimensions of the specimens, the result of this test is also referred to as unconfined compressive strength. Figure 3a shows a tested masonry prism. The average compression strength of this test was equal to 0.87 MPa with a CoV of 24% and the average Young's modulus was equal to 129 MPa with a CoV of 19%.
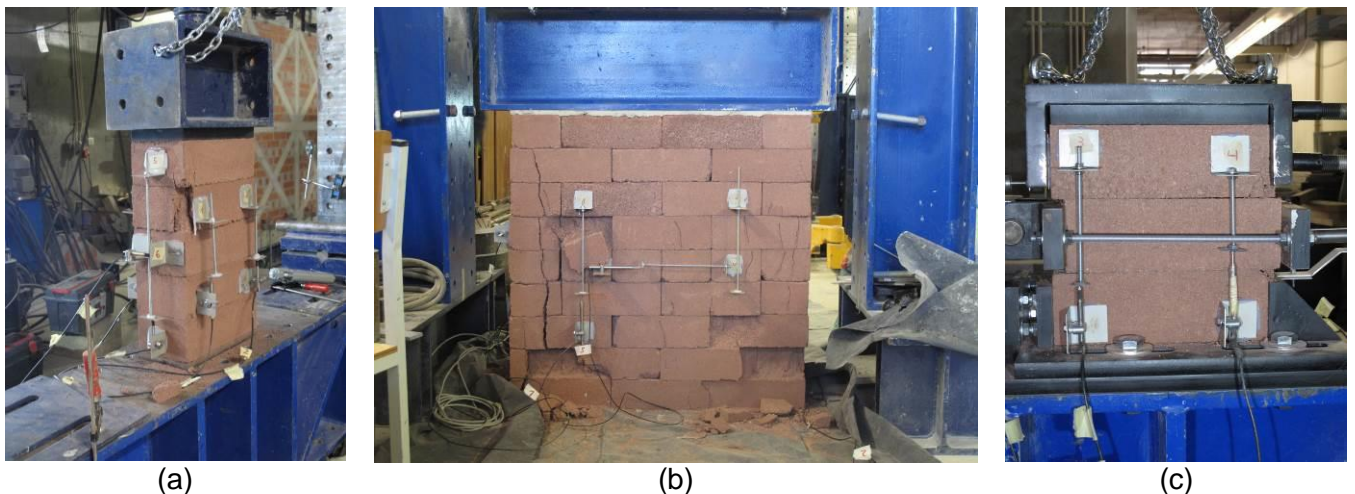

| (a) | (b) | (c) |

Figure 3. Tested masonry specimens: (a) prisms; (b) wallets; (c) triplet shear test

For the test of masonry wallets the [21] standard was adopted. Single and double-leaf wallets were tested. The specimens were 0.84 m in length and 0.84 m in height. This is equivalent to wall specimens of 3 blocks in length and 9 blocks in height. The thickness was 0.14 m for the single leaf walls and 0.28 m for the double leaf walls. After levelling with hard mortar the top of the wallets, a stiff steel beam of more than 0.3 m in height was placed on top of the specimens to uniformly distribute the vertical load of the actuator, see Figure 3b. The average compression strength of the masonry

wallets was equal to 0.53 MPa with a CoV of 12% and the average Young's modulus was equal to 102 MPa with a CoV of 39%. No significant difference between the compression strength of single and double leaf wallets was observed.

Masonry is often treated as an isotropic material, even if it can exhibit a high orthotropic behaviour, depending on factors such as the unit to mortar strength and the bond arrangement. The shear strength of dry-stack masonry with ICEB is governed mainly by the friction between the units, i.e. the dry interface, and the interlocking of the indentation. The Coulomb friction law has long been used as a constitutive model of friction interfaces, in which the shear strength is dependent of the initial shear strength (f_{v0}, also known as cohesion) and the tangent of the internal friction angle ($\tan\alpha$).

The shear behaviour of this dry-stack masonry was determined through the triplet test according to [22] standard, although modifications had to be made to the proposed setup, in a similar fashion to [23]. The vertical force was kept constant and the horizontal force was applied under displacement control. Three tests were made with three different confining loads: 0.02 Mpa, 0.15 Mpa and 0.30 Mpa. The shear strength f_v at a confining stress f_p of an individual sample is obtained by dividing the maximum attained shear force by two times the net cross area.

The results can then be plotted in terms of confining stress f_p versus the attained shear strength f_v. The Coulomb friction plane is then obtained by a linear regression of these results, in which $\tan\alpha$ is the slope of the line and f_{v0} is the shear stress where the line crosses the y axis. Hence, the shear strength f_v can be written as a function of the initial shear strength f_{v0} and the confining stress f_p:

$$f_v = \tan(\alpha_k)f_p + f_{v0}$$

(3)

The results of this test are shown in Figure 4. Using a linear regression, the determined tangent of the internal friction angle $\tan\alpha$ was equal to 0.733 and the initial shear strength f_{v0} was equal to 0.035 MPa.
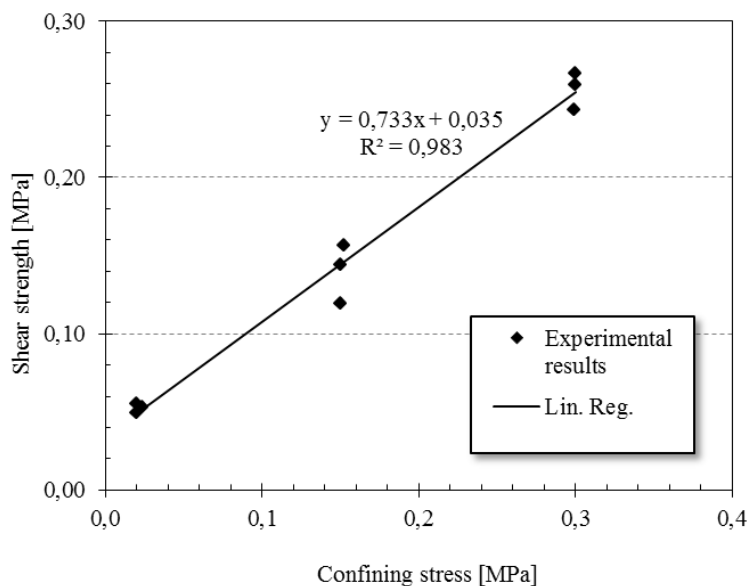

Figure 4. Results of the triplet shear test.

3   SHEAR WALL

The overall behaviour of a large specimen (wall) might be different than that of a small specimens. In larger specimens various phenomena interact. Therefore, failure modes can be the result of interaction between compression, shear and flexural forces. Moreover, geometrical instabilities due to the height and length of a wall may influence the strength and behaviour. To assess the strength of actual unreinforced ICEB dry-stack masonry walls, two large specimens were tested under static cyclic loading in the in-plane direction.

The wall specimens were built in the Structural Lab from University of Minho on tops of a 0.35 m x 0.4 m x 2.85 m reinforced concrete beam. This beam was fixed to the reaction slab of the laboratory. The wall specimens were double leaf walls which had a dimension of 2.1 m in length, 1.9 m in height and 0.28 m of depth. This is equivalent to a double leaf wall of 7.5 blocks in length and 20 blocks of height. After levelling with hard mortar the top of the wall, a 0.35 m x 0.4 m x 2.7 m reinforced concrete beam was glued to the tops of the wall. This beams serves as dead weight and allows distributing the compression coming from three hydraulic jacks, generating a compression state equal to 0.05 MPa (i.e. similar to service conditions). It is also the element which is pushed and pulled in the in-plane direction (Figure 5).

A total of 16 displacement transducers (LVDT) were fixed to the wall. Five LVDTs measured the in-plane displacements of the wall along the height, two LVDTs measured the vertical deformation of the wall on each face and two LVDTs measured the diagonal deformation of each face of the wall. Two LVDTs monitored that no sliding was taking place between the concrete beams and the wall.
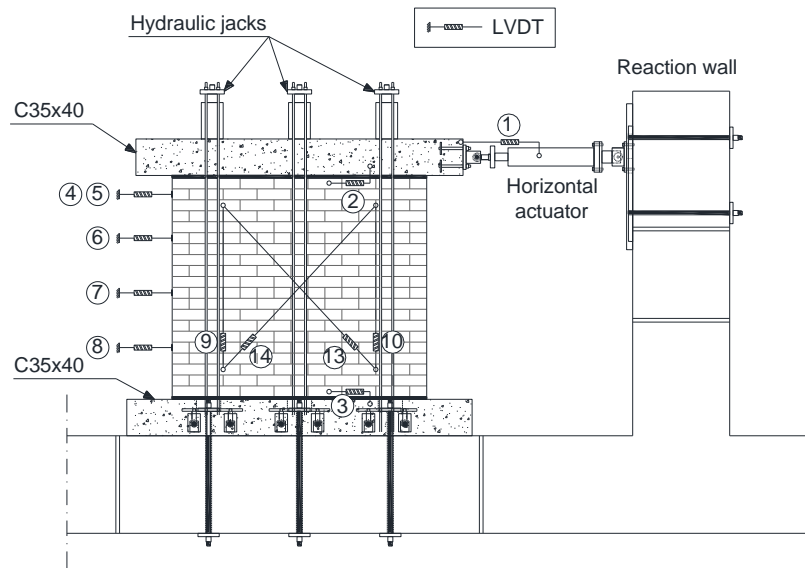

Figure 5.   Setup of the in-plane shear test of a wall.

A total of two walls were tested. The load was displacement controlled at the top of the wall. The cycles were sinusoidal going through ±0.25 mm, ±0.5 mm, ±1 mm, ±2 mm, ±4 mm, ±8 mm, ±12 mm, ±16 mm, ±20 mm and ±25 mm of amplitude. Each sinusoidal was repeated one time.

The first wall reached a maximum lateral force equal to 11.7 kN and the second 10.9 kN. The maximum displacement at the top of the first wall reached 20 mm and the one of the second reached 25 mm. Figure 6 shows the two shear walls after the test.
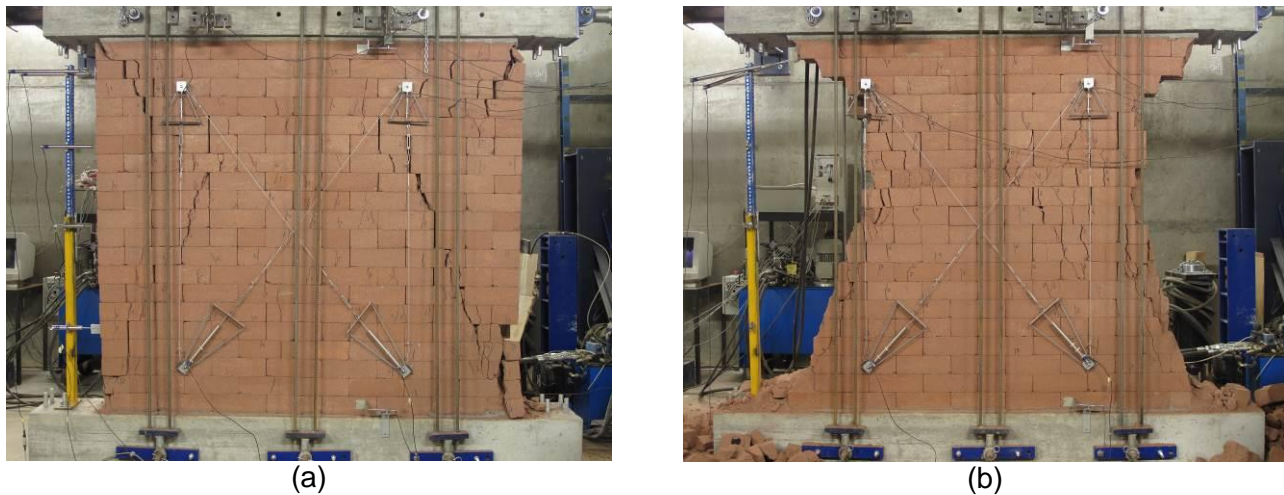
Figure 6.   In-plane shear test of wall: (a) Wall N° 1; (b) Wall N° 2.

4   SHAKING TABLE TEST

To study the behaviour of a real structure under seismic action, a small masonry house was tested on the 3D shaking table of the *National Laboratory of Civil Engineering* (LNEC) of Portugal in Lisbon. This test aims at simulating the behaviour of an ICEB house under seismic action in laboratory conditions, with the intention to relate the seismic action applied at the base of the mock-up with the response of the structure.

The motion used for this test was horizontal translational in both main directions. Before and after every seismic test, a dynamic identification of the structure was made.

4.1.   Description of the Mock-up

A mock-up of a structure is a scaled structure which represents a larger structure and which is usually used as a prototype for testing. A mock-up should represent, even though on a smaller scale, the real structure to be studied. Therefore, a mock-up to represent the rural configuration of the HiLoTec house, described in [3], had to be conceived. The configuration of the rural HiLoTec house has a plan size of 7 m × 7.58 m while the table has a plan size of only 4.6 m × 5.6 m.

The plan of the mock-up is presented in Figure 7a. Two different views of the model can be seen in Figure 7b and Figure 7c. This mock-up was not a scaled structure per se, since the thicknesses of the single and double leaf walls were the same as in the original structure. The advantage of this approach is that no Cauchy similitude adaptations have to be made to the input signal and the post analysis.

High inertial forces in the out-of-plane direction of the walls were expected. In total, 58 piezoelectric accelerometers were attached to the walls, most of them measuring in the out-of-plane direction.

4.1.   Dynamic identification

A dynamic identification consists in a procedure through which the natural frequencies and mode shapes of a structure can be estimated. Therefore, before running a seismic test, it is necessary to perform a dynamic identification.

For the dynamic identification of the mock-up, a pulse excitation procedure of maximum accelerations of 0.05 g was used.
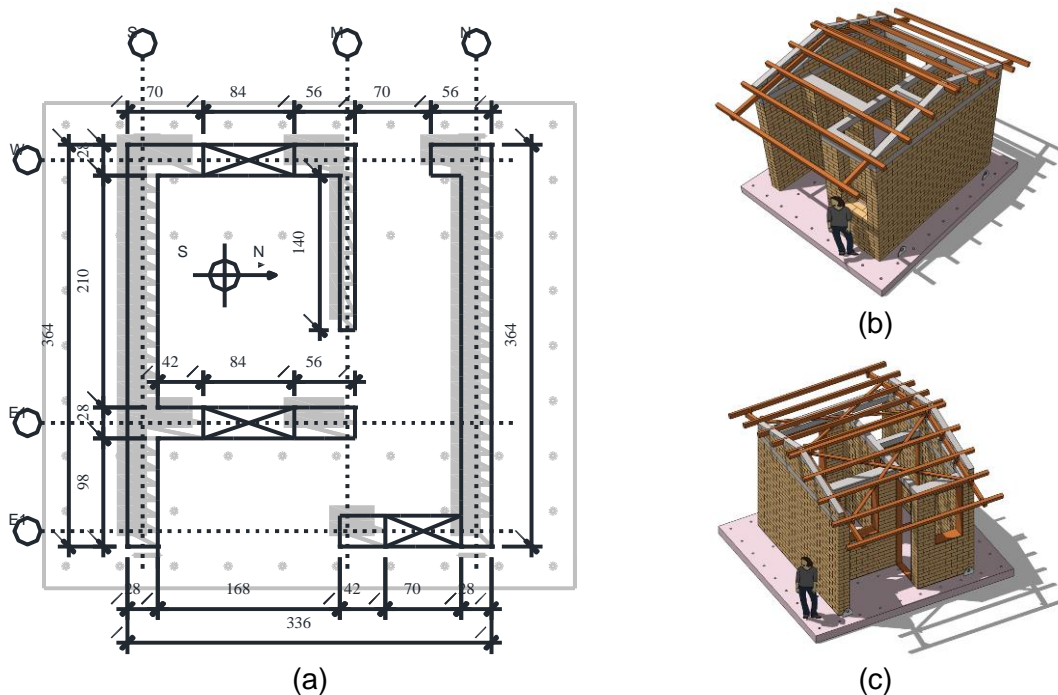
Figure 7. Description of the mock-up: (a) plan configuration; (b) iso view; (c) iso view.

4.2. Seismic test

No accelerograms of Malawi or South Africa could be found to create the input signal of the seismic test. The used synthetic signals were based in related literature and the seismic information available form Malawi [24][25][26]. From an engineering point of view, the most important information gathered indicates that earthquakes in Malawi are near field, with a focal depth of less than 15 km. There are recurrent earthquakes of magnitude lower than 5.5 and very rare larger earthquakes which go up to a magnitude of 6.5. This means that they can cause great damage, but in a small radius. The duration of the earthquakes is normally under 15 s. The peak ground accelerations (PGA) of earthquakes of magnitude lower than 5.5 are of around 2.4 m/s^2 (10 % exceedance in 50 years with a return period of 475 years) and for earthquakes of magnitude up to 6.5 of around 3.2 m/s^2 (10% exceedance in 100 years with a return period of 950 years) [26]. Another important information is found in EC8 [27], which recommends the use of its elastic type 2 spectrum for earthquakes of magnitudes lower than 5.5. Since the natural frequencies of the mock-up fall in the range of the plateau, these type of earthquakes impose a maximum demand on the structure.

Based on the available information, an artificial target signal was generated. This signal had a length of around 10 s and a PGA of approximately 0.3 g, which is the maximum PGA expected for Malawi. Two signals had to be created, since earthquakes have components of motion in two orthogonal directions. The signals reproduced the EC8 [27] type 2 spectrum, but with some noise. Having noise content is important, since the noise accounts for the randomness of the signal, as it happens in a real earthquake.

The procedure for the seismic tests consisted in subsequent scaled signals. The stages started at 10% and went through 20%, 30%, 40%, 50%, 75%, 100%, 125% and 150%. Each stage was repeated at least two times, which is similar to having longer earthquakes than a 10 s earthquake. After each stage, a dynamic identification was performed to detect changes in the mock-up's dynamic properties, which is equivalent of detecting accumulated damage in the mock-up. Besides the dynamic identification, also visual inspections of the mock-up were made after each step of the drives. The test went up to a stage of 175%, at which point the accumulated damage was considerable and a pier of a wall had collapsed. Therefore 175% was the last stage, which is equivalent to 0.53 g.

4.3. Results

No significant cracks or displacement between blocks were observed until stage 100%. Up to that stage almost only cracks in the middle of few blocks, due to flexure with no apparent systematic pattern was observed. After stage 100% more cracks formed with some apparent pattern. It could also visually be observed during the stages of 125% to 175% that the upper part of the structure, ring beam and gables, started to behave as a rigid body which was not moving while the walls beneath the ring beam oscillated freely. This indicates that after stage 100% the connection between the ring beam and walls was partially lost. Despite this, no critical structural damage with risk of collapse was registered until the last drive. During the last stage (175%), the spandrel of the inner east wall failed and rotated in the in-plane direction and the corner of the west-south facade almost broke off, see Figure 8.

| (a) | (b) | (c) |

Figure 8.   Damage survey of mock-up: (a) South wall; (b) damaged spandrel; (c) damaged corner.

The dynamic identification showed that the first translational mode in the N-S and W-E direction had an initial frequency of 2.93 Hz and 3.71 Hz, respectively, and after the last stage of seismic tests they went down to 1.95 Hz and 2.14 Hz, respectively.

5   CONSTRUCTION OF THE MANUAL

The final result of this project was the elaboration of a construction manual. The knowledge gained during this project and the lessons which were learned were condensed into this document, which throughout its six chapters addresses the following topics:

1. Introduction
2. Soil selection
3. Manufacturing blocks

4. Construction and foundations
5. Building walls
6. Construction of the roof

This self-construction manual can be used by rural or urban families with lower incomes in developing countries, which need better houses for living. Therefore, the HiLoTec self-building manual addresses a building system which is economically competitive with current systems and more sustainable from the energy point of view. Figure 9 shows the end result of this manual.
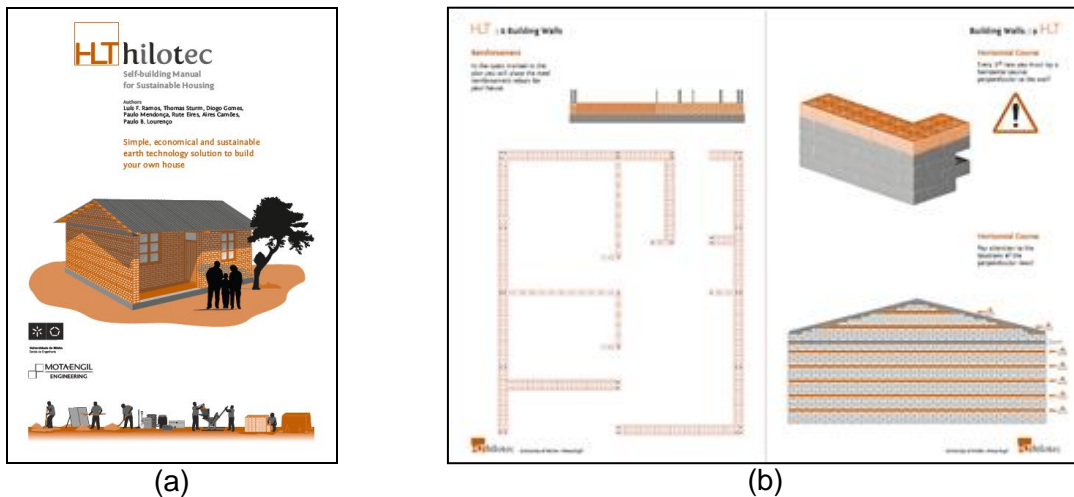
(a)   (b)

Figure 9. HiLoTec construction manual: (a) Cover page; (b) a look inside the manual.

6 CONCLUSIONS

The paper describes the main activities of the project HiLoTec - Development of a Sustainable Self-Construction System for Developing Countries. The project was focused on the use of interlocking compressed earth blocks to use in dry stack masonry one storey houses in regions with moderate seismicity. Malawi country was selected as the case study, where soils were collected and tested mechanically. A new interlocking compressed earth block was developed and mechanical tests to characterize structural properties were carried out, starting from simple blocks to a final shaking table tests. The final result of this project was the elaboration of a graphical self-construction manual.

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