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Feasibility Study of Affordable Earth Masonry Housing in the U.S. Gulf Coast Region

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ABSTRACT

Compressed and stabilized earth block (CSEB) structural systems represent a sustainable low-cost alternative to other construction systems that are common in industrialized countries. The wide availability of suitable soils makes these structural systems attractive for building affordable housing worldwide. Currently, CSEB construction in the USA is mainly used in dry and arid regions and has rarely been used in humid climates. In this work, a structural, architectural, and economic feasibility study for CSEB structural systems in the US Gulf Coast is presented. The structural feasibility study presented in this paper included the identification of locally available soils for CSEB fabrication; experimental investigation of mechanical properties of CSEB and mortar as function of their composition; durability study for a CSEB wall with and without protective plastering; and calculation of the wind resistance for a representative CSEB house. The architectural feasibility study investigated the use of CSEB systems in vernacular housing typologies of Southern Louisiana. Finally, the economic feasibility study compared the cost of a reference house built using CSEBs and other more common construction materials. The results obtained in this research suggest that CSEB systems have the potential to provide a modern, cost-effective, sustainable, hurricane-resistant housing construction system as an alternative to more common constructions systems in the US Gulf Coast region.

Keywords: Earth block construction; Feasibility study; Affordable housing; Hurricane-resistant housing.

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Introduction

A significant portion of the world's population currently lives in earth-based dwellings (Avrami et al. 2008). Earth construction provides several advantages over other traditional construction methods (e.g., reinforced concrete, fired masonry, and wood construction). In particular, earth construction is: (1) affordable and locally appropriate, since inexpensive and locally available soils are used as the primary structural materials (Morton et al. 2005; Minke 2012); (2) energy and humidity efficient, due to its relatively high volumetric heat capacity and excellent ability to passively maintain a healthy indoor relative humidity (Torgal and Jalali 2011; Minke 2012); and (3) environmentally friendly, with an embodied energy that can be over 80% lower than that of concrete masonry units and fired clay bricks (Morton et al. 2005; Torgal and Jalali 2011).

Earth construction is also one of the most ancient and sustainable approaches for building construction, dating back over 9000 years ago (Minke 2012), and with examples found all over the world (Gandreau and Delboy 2012). Different earth construction techniques were developed over the centuries, the most prominent of which are cob construction, rammed earth construction, and earth block or adobe construction (Weismann and Bryce 2006; Torgal and Jalali 2011). These traditionally-built earth structures (i.e., non-engineered constructions) are not capable of resisting extreme loads from natural hazards such as earthquakes and strong winds, due to the inherent brittleness of the material (Klingner 2006; Blondet et al. 2008; Korkmaz et al. 2010; Gomes et al. 2011; Sayın et al. 2013); therefore, they are inadequate for mainstream modern construction. However, in the last few decades, significant research has been devoted to develop engineered earth blocks as a more affordable and ecologically friendly alternative to other masonry elements, e.g., fired bricks and concrete blocks (Enteiche and Augusta 1964; Webb 1988; Gooding 1994; Houben and Guillaud 1994). Consequently, engineered earth block construction has emerged as a viable modern construction technique due to its eco-efficiency and extreme affordability (Deboucha and Hashim 2011; Torgal and Jalali 2011). In particular, earth block construction is a promising technique because: (1) its individual components (i.e., earth block and mortar) can be engineered to improve their strength and durability (Houben and Guillaud 1994; Rigassi 1995; Kerali 2001), and (2) the construction technique has many commonalities with ordinary masonry (Rigassi 1995), for which extensive experience and a vast engineering literature are available. Modern earth blocks can be categorized into three different broad categories: (1) compressed earth blocks (CEBs), which are produced by compressing an appropriate soil mix with the help of a hydraulic or a manual press (Delgado and Guerrero 2007; Torgal and Jalali 2011; Brown et al. 2014); (2) stabilized earth blocks (SEBs), which are made from a soil mix that is stabilized using a chemical binder such as Portland cement or lime (Guettala et al. 2002); and (3) compressed and stabilized earth blocks (CSEBs), which are fabricated by mechanically compressing a stabilized soil mix (Kerali 2001; Riza et al. 2011). CSEBs use both mechanisms of CEBs and SEBs to form strong and durable earth blocks, which are more suitable than other earth blocks to satisfy modern construction requirements.

Currently, earth construction in the USA is mainly used in dry and arid regions, e.g., New Mexico, Colorado, Arizona, California, and West Texas (Windstorm 2011). New Mexico has also incorporated the use of earth blocks for non-hurricane prone areas into the state's building code (NMAC 2009). However, CSEB construction has rarely been used in the US Gulf Coast (Hall et al. 2012) because of the poor resistance to degradation generally experienced by earth construction in a humid and rainy climate (Kerali 2001), and the widespread perception of earth construction as a substandard choice for resistance to extreme wind loads. By contrast, recent research based on structural analysis results and controlled laboratory experiments has demonstrated that earth masonry can safely withstand extreme wind loads (Matta et al. 2015) and windborne debris impacts (Geiger 2011, Cuéllar-Azcárate and Matta 2016) due to hurricanes or tornadoes.

The goal of this study is to investigate the feasibility of CSEB systems as a hurricane-resistant, affordable, and durable housing typology that can be reliably used even in the US Gulf Coast's humid climate. This study includes the investigation of structural, architectural, and economic feasibility of a typical earth block house compared with one of a similar size built with common construction techniques. A preliminary investigation of the use of a soil-cement plaster protection for CSEB walls is also presented as part of the structural feasibility study.

Motivation and Significance

A significant portion of the US population (including a significant number of underrepresented and underprivileged groups) live in rural and remote areas, particularly in Louisiana. In these rural areas, affordable housing is key to reducing homelessness, creating jobs, and fostering economic development. According to data published by the US Department of Housing and Urban Development in 2010, 386,000 low-income households in Louisiana are in need of affordable housing (LHFA. 2010). The National Association of Home Builders (Emrath 2014) estimates that, for each newly built house, three full-time equivalent new jobs are created, particularly in the construction and manufacturing industry, and $111,000 in government revenue (including income taxes, government social insurance, permit and license fees, and sales taxes) is generated ($74,400 in federal taxes and $36,600 in state and local taxes). This estimate does not include the indirect economic impact of the new house, e.g., due to the relocation and future earnings of the building owners, which is generated over a prolonged period of time. The critical demand for low-cost housing in the US Gulf Coast is exacerbated by recurring tropical storm, flooding events, subsidence, and water level rising, as recently documented by Davenport and Robertson (2016), in which thousands of residents across southern Louisiana were displaced by the land loss induced by coastal erosion and climate change effects.

In our current period of rising global temperatures, unpredictable events have and will continue to displace thousands of residents in the coastal region of Louisiana. This historic unseating of entire communities necessitates a reconsideration of standard housing solutions. Constructed primarily of materials accessible from the building site, CSEB design and building techniques offer an economical and sustainable approach to the current increase in demand for affordable weather resistant housing. The research presented in this paper proposes the novel use of CSEBs in a hot wet environment and provides the preliminary engineering basis needed to offer affordable, resilient, and sustainable housing for the many individuals in need in the US Gulf Coast region.

Structural Feasibility Study

The structural feasibility of CSEB housing in the US Gulf Coast depends on the mechanical properties of CSEB elements (i.e., blocks and mortar) and CSEB systems (e.g., walls and pillars). These properties need to satisfy several minimum standard requirements to ensure sufficient resistance of the construction to extreme winds as those associated with hurricanes. In addition, the CSEB walls need to achieve a sufficient durability when exposed to the humid weather typical of this region of the US. The CSEB mechanical properties depend mainly on the properties and composition of the available soil, the fabrication process, and the amount of stabilizer used in the soil mix. This section presents: (1) the identification of appropriate soil in the East Baton Rouge area, (2) the description of the CSEB fabrication process adopted in this study, (3) the investigation of the mechanical properties of CSEBs as a function of the amount of cement used as stabilizer, (4) the investigation of the mechanical properties of soil-based mortar as a function of cement and sand content, (5) a durability study of an actual CSEB wall subject to the humid weather in Baton

Rouge, and (6) the estimation of the resistance of the main wind-force resisting system for a hypothetical house built using locally produced CSEBs. It is noted here that Portland cement was used as the stabilizer material and as an ingredient of the weather protection plaster. This preliminary selection was made based on the wide availability of this material and on existing literature, which suggests that cement is highly efficient in increasing the mechanical strength and durability of CSEBs (Kerali 2001; Guettala et al. 2006). However, other more sustainable solutions could also be considered in future studies, e.g., using lime as stabilizer (Hall et al. 2012), or modiying foundations, roofing, and building geometry to minimize the weather effects in rainy environments (Guillaud et al. 1995), and/or investigate other rendering solutions to protect the building envelopes (e.g., earthen plasters stabilized with lime, acrylic emulsions, polymers, asphalt emulsions, agave juice, see (Taylor 1988, 1990).

Soil Identification

Production of high-quality CSEBs requires soils with specific compositions, i.e., the appropriate proportions of sand, silt, and clay contents. Existing literature provides recommended soil composition ranges for fabrication of CEBs (Gooding 1994; Rigassi 1995; Delgado and Guerrero 2007; Torgal and Jalali 2011). These soil compositions can be obtained through a particle size analysis and can be classified using the Unified Soil Classification System (USCS) (ASTM 2010a). **Fig. 1(a)** shows the United State Department of Agriculture (USDA 1999) soil texture triangle, which provides a graphical representation of the composition of a soil. In this figure, the thick blue line identifies the optimal soil compositions for fabricating CEBs, the thick magenta dashed line identifies sub-optimal soil compositions that can still be used for CEBs, and the region outside the above lines represents soil compositions that are generally considered inappropriate for CEB fabrication, according to the existing literature. Additional criteria have been suggested in terms of Atterberg limits ASTM D4318-10 (ASTM 2010b), e.g., with optimal liquid limits (LL) ranging from 25 to 50, and optimal plasticity indexes (PI) ranging from 2.5 to 29 (Delgado and Guerrero 2007; Torgal and Jalali 2011). It is noted here that only scarce information is available in the literature for optimal soil compositions and Atterberg limits for fabrication of CSEBs. However, it is reasonable to expect that a wider range of soil compositions and values of Atterberg limits can be considered acceptable when compared to those for CEB fabrication, since the soil can be partially ameliorated by using appropriate stabilizers.

Soil samples were taken from five different locations (A, B, C, D and E) in Baton Rouge from the layer between 1 and 2 m below the surface, as shown in **Fig. 1(b)**). Simple preliminary in-situ tests (i.e., "cigar" and jar tests) were used to verify if these soils were appropriate for CSEB fabrication based on suggestions provided in the literature (Rigassi 1995). The average "cigar" lengths were in the range between 12-15 cm (see **Fig. 2(a)**), which is considered an acceptable range for CEB fabrication (Rigassi 1995). In the jar test, only one layer of soil particle was observed for all soils, as shown in **Fig. 2(b)**, which indicates that these soils contain almost exclusively fine particles (i.e., silt and clay).

After performing in-situ tests, the granulometry and Atterberg limits of the soil samples were obtained by performing standard laboratory tests. The results of the particle size analysis, performed according to ASTM D6913-04 (ASTM 2009) and ASTM D7928-16 (ASTM 2016b), are presented in **Fig. 3** and were used to classify the different soils on the USDA soil texture triangle presented in **Fig. 1(a)**. The Atterberg limits were measured according to ASTM D4318-10 (ASTM 2010b). The LL were 35.5%, 30%, 28%, 27.5%, and 26.5% for soil A, B,C, D, and E respectively; whereas the PI were 12.5%, 8.0%, 11.5%, and 12% for soil A, B,C, D, and E respectively. The results of the laboratory test indicate that the used soils: (1) have LL and PI values within the optimal ranges, and (2) lay within the sub-optimal composition region (soil B and C) or immediately outside this region as identified on the USDA soil texture triangle (see Fig. 1). The soils used in this study are representative of the soil available in the East Baton Rouge area.

Fabrication Process of CSEBs

The fabrication process of CSEBs, and in particular the compaction process, can significantly affect the CSEB mechanical and physical properties (Lunt 1980; Gooding 1994). CSEBs can be fabricated using: (1) quasi-static compaction, through a slowly applied pressure in single-side compaction, double-side compaction, or extrusion (Gooding 1994; Maillard and Aubert 2014); or (2) dynamic compaction, through impact or vibration (Groth 1984). Quasi-static compaction is most commonly applied by using manually-operated or hydraulic compression machines. A single-stroke manual one-side compaction machine made of steel was fabricated purposely for this study and is shown in **Fig. 4**.

The CSEB fabrication was performed by: (1) extracting, drying, and pulverizing of the soil; (2) sieving the pulverized soil to remove any organic and course particle; (3) weighing the soil, cement, and water to obtain the desired amounts; (4) mixing soil and cement thoroughly with the help of a power-driven mixer for at least 10 min; (5) adding the water to the soil-cement blend in multiple steps while mixing it; and (6) compressing the wet soil-cement blend by using the compaction machine to form blocks. The production time between material mixing and fabrication of all blocks was maintained below 45 minutes for all batches, in order to avoid excessive curing of the cement. Each batch consisted of five to eight blocks. After fabrication, the blocks were cured for 28 days by wet-and-dry curing (Rigassi 1995), i.e., the blocks were wrapped in a plastic sheet inside the laboratory for the first 14 days to maintain a high humidity environment, and avoid rapid evaporation and formation of shrinkage cracks, then they were left to dry for 14 additional days without being directly exposed to sun and wind.

Mechanical Properties of CSEBs

This study investigated the effects of different amounts of cement used as a stabilizer on the compressive and flexural strength of earth blocks made with soil from East Baton Rouge, LA. Compressed earth blocks of dimension 290 x 145 x 75 mm^3 were fabricated with soil A and different percentages in weight (wt%) of type II Portland cement (PC), namely 0 wt% (CEB), 3 wt% (CSEB03), 6 wt% (CSEB06), 9 wt% (CSEB09), and 12 wt% (CSEB12). Five equally-built specimens for each cement content of CSEBs were tested using an MTS universal testing machine with a 50 kN load cell capacity to determine the block's average dry compressive strength, f_{bd} , wet compressive strength, f_{bw}, and modulus of rupture (MOR). The specimens were loaded in displacement-control mode at the rate of 2 mm/min.

First, a three-point bending flexure test was performed on the full-size blocks (NMAC 2009). The displacement was applied at the middle of the block with a 20 mm distance between edge and support, giving a 250 mm clear span, as shown in **Fig. 5(a)**. **Fig. 6** plots the applied load-midspan deflection curves for all tested specimens. The results of the flexure test in terms of sample means, minimum/maximum values, and coefficients of variation for MOR and modulus of elasticity (MOE) are reported in **Table 1**. The flexure test resulted in the formation of a well-defined large crack in the middle of the earth blocks. The two halves of each tested specimen, produced by the fracture of the block in the flexure test, were trimmed using masonry cutting tools to produce two specimens of dimension 100 x 100 x 75 mm^3 to be used in a direct compression test (Walker 1996). For each cement content, five half-block specimens (one from each original earth block) were tested for dry compression tests, whereas the remaining five specimens were immersed in water for 24 hours before being tested for wet compressive strength. Neoprene pads were placed between the steel plates and test specimens during each compression test.

Fig. 7(a) and **(b)** plot the stress-strain curves for all tested specimens corresponding to the dry and wet compression tests, respectively. The results of the dry and wet compression tests in terms of sample means, minimum/maximum values, and coefficients of variation for compressive strength and MOE are reported in **Table 1**, which also reports the estimate of the characteristic uniaxial dry and wet compressive strengths, f_{bkd} and f_{bkw} respectively, accounting for shape and aspect ratio corrections (Middleton and Schneider 1992). The failure mode observed during wet and dry compression tests corresponded to the development of a hour-glass shape following the spalling of the vertical sides of the tested specimen, as shown in **Fig. 5(b)**. This failure mode is similar to that commonly observed in compression tests of typical concrete cubic specimens.

The average MOR of CSEBs is 18% to 136% higher than the average MOR of CEB by increasing the cement content from 3 wt% to 12 wt%. The average dry compressive strength of CSEBs is 36% to 219% higher than the average dry compressive strength of CEB by increasing the cement content from 3 wt% to 12 wt%. For the wet compressive strength, CEBs shows a strength equal to zero, since the blocks dissolved after 24 hours of water submersion. The average wet compressive strength of CSEBs increases by 29%, 111%, and 188% for the CSEB06, CSEB09, and CSEB12, respectively, when compared to the strength of the CSEB03. The wet compressive strength is significantly lower than the dry compressive strength for equal amounts of cement content. In particular, the average wet compressive strength of CSEB03, CSEB06, CSEB09, and CSEB12 are 55%, 52%, 47%, and 44% lower when compared to the corresponding dry compressive strength. This reduction in the compressive strength can be attributed to the development of pore water pressures and a decrease in soil cohesion. As expected, for all three sets of tests performed, the strength of CSEBs increases with increasing cement content. In addition, it is observed that the MOE measured in all tests also follows the same trend as the corresponding strength, i.e., it increases with increasing cement content.

These experimental results were compared to the minimum requirements suggested in current design codes and existing literature. In particular, the New Mexico Administrative Code (NMAC 2009) recommends a minimum average dry compressive strength of 2.07 MPa (300 psi), a minimum sample dry compression strength of 1.72 MPa (250 psi), and minimum average MOR of 0.35 MPa (50 psi) for compressed earth blocks. In addition, in humid environments, CSEBs should also have a minimum average wet compressive strength of 1.5 MPa (Lunt 1980; Houben and Guillaud 1994) or a minimum unconfined characteristic wet compressive strength of 1.0 MPa (Walker and Stace 1997). From the results obtained in this study, it is observed that CSEB09 and CSEB12 satisfy these strength requirements.

Mechanical Properties of Soil-Based Mortar

The mechanical properties of cement-soil mortars produced with the same soil used for CSEBs were investigated to identify mortars that are compatible with the earth blocks for the construction of CSEB structures. It is noteworthy that the New Mexico Administrative Code allows the use of both soil-cement mortar and conventional mortars for CSEB walls (NMAC 2009); however, Venkatarama Reddy and Gupta (2005; 2006) suggested that soil-cement mortars can provide better bond strength, higher initial stiffness, and lower cost than conventional cement-based mortar.

In particular, the effects on the compressive strength of soil-based mortar were investigated for: (1) different amounts of cement used as a stabilizer (soil-cement mortar), and (2) different amount of sand used to ameliorate the soil for a fixed 15 wt% cement content (soil-sand-cement mortar). Mortar cubes with a side dimension equal to 50 mm were fabricated by adding: (1)

different amounts of Type II PC (varying between 3 wt% and 30 wt%, with increment intervals of 3 wt%) to soil A; and (2) different amounts of sand (varying between 10 wt% and 50 wt%, with increment intervals of 10 wt%) to a mix of soil A and 15 wt% cement. The samples were tested after being cured for 28 days (using the same curing procedure used for the CSEBs) to obtain the average dry compressive strength of the mortar, f_m (ASTM. 2016). The results of the compression tests in terms of sample means and coefficients of variation for the dry compressive strength and MOE as functions of the cement and sand contents are reported in **Table 2** together with the estimates of the unconfined characteristic compressive strength of the mortar, f_{mk} (SNZ 1998).

The results indicate that the soil-cement mortar compressive strength increases with increasing cement content. However, a significantly larger cement content is required to achieve a compressive strength that is comparable to that of the CSEBs. In particular, a soil-cement mortar with at least 24 wt% and 30 wt% cement content should be used with CSEB09 and CSEB12 blocks, respectively. This result is most likely due to the high clay content (35-40 wt%) in the soil, which is significantly higher than the amount recommended for soil-cement mortar in CSEB masonry, i.e., up to 10-20 wt% of clay (Walker 1999; Venkatarama Reddy and Gupta 2005, 2006).

As expected, the addition of sand increases the mortar compressive strength for a given amount of cement. It is observed that soil-sand-cement mortars with 15 wt% cement and 30 or 40 wt% sand have a similar compressive strength to that of CSEB09 and CSEB12 blocks, respectively. Thus, these soil-sand-cement mortars can be used in conjunction with CSEB09 and CSEB12.

Durability Investigation of CSEB Wall

The performance of a plaster protection for a CSEB masonry wall exposed to the humid weather in Baton Rouge was investigated. A single-wythe 1220 x 920 mm^2 (4 x 3 ft^2) wall was constructed with CSEBs of dimensions 290 x 150 x 75 mm^3 on June 6, 2015, outside Atkinson Hall, at the

LSU School of Architecture in Baton Rouge, LA. Soils B and C were mixed together in equal parts into soil BC to produce CSEBs with 6 wt% type II PC. The particle size distribution of the reconstituted soil BC is reported in **Fig. 3**. Five of these earth blocks were tested after 28 days curing to determine their flexural and dry compressive strength, which are reported in **Table 3** in terms of sample means and coefficients of variation. These specimens are identified as $CSEB^{I}$ hereinafter to indicate that they were tested before the construction of the wall.

The wall was divided into two parts: a protected side (side P) and an unprotected side (side U). The plaster protection of side P comprised two layers: a 12-mm-thick layer of soil-cement stucco made with soil BC and 6 wt% PC covered by a thin layer of cement paste paint, as shown in **Fig. 8**. The wall was left exposed to outdoor weather conditions for six months and was visually inspected twice a week to observe and document the condition of the wall. After one-month of the exposure, the initiation of erosion was observed on the surface of the CSEBs on the unprotected side of the wall. This erosion progressed with time on the unprotected side, as shown in **Fig. 8(b)**. After three months, the CSEBs at the top corner of the unprotected side of the wall lost their bond with the wall due to degradation of the blocks and the mortar in the top two courses, as shown in **Fig. 8(c)**. **Fig. 8(d)** shows the wall on December 10, 2015, before it was carefully dismantled. Two blocks at the top corner of the unprotected side were slightly dislodged, and one of them was cracked in the middle. By contrast, the protected side of the wall did not show any sign of distress after six months of weather exposure. The blocks from both the protected ($CSEB^{P}$) and unprotected ($CSEB^{U}$) side were recovered and carefully moved to the structural laboratory. Among the recovered blocks that were undamaged under visual inspection, five specimens from each side of the wall were subjected to flexure and compression testing using the same procedure previously described. The results of these experimental tests are reported in **Table 3** in terms of sample means and coefficients of variation for the flexural and dry compressive strengths and the corresponding MOE.

The average MOR and dry compressive strength of the $CSEB^P$ are 72% and 19% higher than those of the $CSEB^U$, respectively, which demonstrates the effectiveness of the double layer plaster in protecting the wall from deterioration due to weather action. In addition, the average MOR and dry compressive strength of the $CSEB^P$ are 11% and 23% higher than those of the $CSEB^I$. This phenomenon may be due to the progress of cement hydration under the high humidity conditions experienced by the wall. It is also observed that the average compressive strength of the $CSEB^U$ is slightly higher than that of the $CSEB^I$, whereas the average MOR is significantly lower. This phenomenon may be due to the counteracting effects of cement hydration (which tends to increase the block strength and seems to be dominant for compressive strength) and superficial erosion (which tends to produce imperfections and cracks and seems to be dominant for flexural strength).

The results of this durability investigation confirm that humid weather produces very demanding conditions for CSEBs and that an exterior coating is needed to mitigate erosion and degradation induced by severe weather conditions. The proposed dual layer plaster consisting of a soil-cement stucco with a coat of cement paste was effective in protecting a CSEB wall from the humid climate that is typical of the US Gulf Coast. However, further investigation is needed to determine an optimal, cost-effective option for protection of CSEB structures.

Hurricane Wind Resistance of CSEB Systems

The hurricane wind resistance of CSEB systems built using local soil was investigated by using the parametric strength demand curves developed by Matta et al. (2015) to identify the minimum acceptable wall thickness for the main wind-force resisting system of one-story single-family dwellings made of CSEB masonry and located in exposure zone C (ASCE 2013). These parametric curves for CSEB structures with flat roofs are shown in **Fig. 9**. The horizontal axis represents the basic wind speed (defined as the 3-s gust speed at 10 m above ground in exposure zone C), the vertical axis indicates the compressive strength of earth block masonry, and the different curves with markers identify the masonry strength required at any given wind speed for CSEB systems with walls of different thickness. The horizontal dashed lines labeled as M09 and M12 identify the characteristic masonry strength for earth block masonry built with: (1) CSEB09 blocks and soil-sand-cement mortar with 15 wt% cement and 30 wt% sand, and (2) CSEB12 blocks soil-sand-cement mortar with 15 wt% cement and 40 wt% sand, respectively. The characteristic compressive strength of the masonry walls was determined as f_c = 1.64 MPa for M09 and f_c = 2.14 MPa for M12, respectively, by using the following equation recommended in Eurocode 6 (CEDN 2005)

$$f_c = 0.55 f_{bd}^{0.7} f_m^{0.3} \tag{1}$$

where f_c denotes the characteristic compressive strength of the masonry. This equation was preferred to other expressions available in the literature and in other design codes (Francis et al. 1971; Khoo and Hendry 1973; Hendry 1990; MSJC 2011) because it applies to the strength ranges considered in this study and it is the most conservative relations among those available in the literature (Zucchini and Lourenço 2007). The vertical solid lines identify the design wind speeds (ASCE 2013) for some of the major cities in Louisiana, i.e., Shreveport, Lafayette, Baton Rouge, New Orleans, and Houma.

The results reported in **Fig. 9** indicate that: (1) in Shreveport and Lafayette, a wall thickness t = 254 mm is sufficient for both M09 and M12; (2) in Baton Rouge, a wall thickness t = 305 mm and 254 mm are needed for M09 and M12, respectively; and (3) in New Orleans and Houma, the minimum wall thickness for M09 and M12 increases to t = 356 mm and 305 mm respectively. Considering the dimension of the blocks, an earth block wall with t = 254 mm can be built using a single-wythe configuration (Guillaud et al. 1995; Auroville Earth Institute 2017), whereas larger wall thicknesses would require a double-wythe configuration. It is noted here that the required wall thickness could be further reduced, e.g., by using steel reinforcement (Matta et al. 2015), or a different set of optimized block sizes could be used (Guillaud et al. 1995; Rigassi 1995; Auroville Earth Institute 2017).

Architectural Feasibility Study

In response to the need for affordable and climate responsive housing in coastal Louisiana, single-family prototype designs were developed using CSEBs as the primary construction element. In appreciation of the rich cultural heritage and environmental context of the Gulf Coast, the proposed prototype housing designs embrace many qualities inherent to local vernacular architecture, which includes Creole and Acadian influences and presents a heritage of building types composed of common elements that evolved from living in a hot wet climate (Edwards 2004). Fundamental aspects, incorporated into the housing designs, include deep porches, high ceilings, and floor to ceiling openings, raised ground floors, and program specific room volumes, which all help to facilitate air movement by means of passive cross ventilation.

Two significant housing types, i.e., the shotgun and the dogtrot (Edwards 2004), were considered in the design of two single-family prototypes. Each prototype was based on a single-family program of around 1000 square feet on one level with an interior volume of 10 to 12 feet in height. They are composed of a main living area, kitchen, bathroom, two bedrooms, and outdoor porches. Beyond these equivalent features, unique characteristics of the housing designs were developed based on specific contextual qualities. The shotgun prototype, based on customs of the Creole who migrated from Haiti, represents an urban house and has a long thin linear arrangement of rooms for efficient cross ventilation and minimal frontage following the organization of dense inner-city land allotment (see **Fig. 10**). A covered exterior porch faces the street and is open on the sides to promote social interaction with adjacent neighbors. The dogtrot prototype, based on customs of the Acadian who stemmed from Nova Scotia, represents a rural house and has an organization based on a central porch (which provides ventilation for adjacent rooms), flanked by public living spaces on one side and private on the other (see **Fig. 11**). The mass of the dogtrot house has a recessed, inward facing porch that functions as an entry way and a private social space in less dense rural communities.

The proposed designs were developed around an architectural logic based on the 10”x6”x3” (25.4 cm x 15.2 cm x 7.6 cm) module of the CSEB. On top of the foundation, a 2’-6”-high (76.2 cm) stem wall (made of a triple layer of earth blocks) supports an elevated floor to promote improved air circulation and ventilation. For the shotgun prototype, the load bearing exterior wall continues vertically from the stem wall and is reinforced by a series of transverse walls that function as buttress bracing for lateral loads, with a maximum span between transverse walls of 30’ (9.14 m). The exterior wall is finished with the proposed dual layer plaster to provide weather protection. Doors and windows openings are supported by wood box frames. All components, details, and connections were kept intentionally simple to help achieve the goal of affordable materials and labor that are readily available. An exploded axonometric illustration of the different assemblies for the shotgun prototype house is presented in **Fig. 12**. Roof, foundations, and their connections with the walls were dimensioned to resist the wind lateral and uplift forces, which were calculated based on the envelope procedure for enclosed simple diaphragm low-rise buildings given in ASCE 7-10 (ASCE 2013). The roof joists are connected to the walls through steel hurricane ties.

It is concluded that CSEB systems can be adapted to design and build simple houses based on local vernacular architecture. Thus, CSEB houses can have the same appearance of houses built using other more traditional construction techniques, which could promote their acceptance from the local population.

Economic Feasibility Study

An economic feasibility study was performed to determine if CSEB structures could represent a sustainable approach for affordable, safe, and weather resistant housing in the US Gulf Coast region. Based on the mechanical properties identified in the structural feasibility study, the shotgun prototype with 1000 ft^2 area was considered as reference single-family dwelling. The cost to build this house was compared to the costs of equivalent houses built using light-frame wood construction, fired brick masonry, and concrete block masonry. For the sake of comparison, components other than the walls (e.g., foundation, roof, and floor systems) were assumed to be equal and, thus, have the same costs for all houses compared here. It is noted here that this assumption is only an approximation and that further study is needed to investigate if and how much the cost of these other components is affected by the usage of different wall systems. However, this investigation is outside the scope of this paper.

Two construction options were considered for the CSEB walls, namely: (1) CSEB walls built using mortar layers of typical thickness to provide the bond between blocks (Guillaud et al. 1995), referred to as mortared CSEB wall hereinafter (**Fig. 13**); and (2) CSEB walls built with interlocking CSEBs (ICSEBs) with thin layers of mortar slurry and grouted vertical steel reinforcement (Wheeler 2005), referred to as mortarless ICSEB wall (**Fig. 13**). In the mortarless ICSEB wall option, the reinforcement consisted of #4 steel reinforcing bars at 406.4 mm center-to-center spacing and was used to speed up the construction process. The detailed cost estimates for all components of these two CSEB wall options are reported in **Table 4.** The total number of blocks needed for construction was estimated at 9680 for the mortared CSEB wall and 10938 for the mortarless ICSEB wall. All costs were determined using the average national costs of material and labor and applying the appropriate city cost index for Baton Rouge, LA (RSMeans 2015). The labor cost for the CSEB walls includes block fabrication, construction, stucco installation (only on exterior walls), and masonry painting. The number of man-hours hour required for building a unit area of mortared CSEB wall was assumed equal to those required to build ordinary fired clay masonry walls when using skilled labor (RSMeans 2015). A 50% reduction of labor hours was considered for building mortarless ICSEB wall walls when compared to the labor needed for mortared CSEB wall (Dwell Earth 2016). In addition, it was assumed that semi-skilled workers could build mortarless ICSEB wall walls under the supervision of a skilled mason (Dwell Earth 2016). These two assumptions were based on existing literature on drystack mortarless masonry (Harris et al. 1992, Hines 1993) and on information obtained by conducting a survey among active US earth block builders (De Jong B., Dwell Earth, personal communication).

The costs of light-frame wood, fired brick, and concrete block walls for the same reference prototype house were also determined by considering national average costs adjusted by the city cost index for Baton Rouge, LA (RSMeans 2014, 2015), as shown in **Table 5**. In addition to the costs of materials and labor, the overhead for general contractors and the costs associated with other components of the house (i.e., concrete footing, light-frame wooden floor, light-frame wooden roof, interior ceiling, doors and windows, kitchen, bathroom, and electric system) were estimated and reported in **Table 5**. Finally, **Table 5** reports the relative costs of the wall systems and entire houses built using the different materials and considering the mortarless ICSEB wall system as reference.

It is observed that, among the solutions considered in this study, the mortarless ICSEB wall system is the least expensive option with a wall cost ratio (wcr) equal to 1.00, followed by the light-frame wood (wcr = 1.053), concrete block (wcr = 1.208), mortared CSEB (wcr = 1.489), and fired brick (wcr = 1.723) wall systems. The cost of the mortarless ICSEB system is very similar to that of a light-frame wood wall system, which is the most commonly used construction technique for housing construction in the region (van de Lindt and Dao 2009). On the contrary, the cost of the mortared CSEB wall system is significantly higher than that of wooden frame walls. This result makes the mortared CSEB wall system economically unfeasible, unless the owners of the house can also be its builders. It is noteworthy that this circumstance is quite common in rural settings and in developing countries, where this type of construction is often adopted by low-income families that can provide the labor (Houben and Guillaud 1994; Norton 1997).

Conclusion

This paper presented the results of a feasibility study for compressed and stabilized earth block (CSEB) construction in the US Gulf Coast, which included structural, architectural, and economic components. Based on the results of the structural component of this feasibility study, the following conclusions are drawn: (1) the soil available in the East Baton Rouge area is suitable for fabricating CSEBs; (2) the CSEBs fabricated with at least 9% in weight (wt%) of cement content satisfy the minimum strength requirements for building single-story dwellings; (3) soil-sand-cement mortars with 15 wt% cement and at least 30 wt% sand can be used in conjunction with CSEBs; (4) exterior CSEB walls need a protection from the weather conditions in a humid climate, and a dual layer plaster consisting of a soil-cement stucco with a coat of cement paste seems to provide a sufficient protection; and (5) hurricane-resistant earthen dwellings can be built using single- or double-wythe earth block masonry walls. The architectural feasibility investigation indicates that CSEB systems can be adapted to design based on local vernacular architecture, which could promote their acceptance from the local population. Finally, the economic feasibility study suggests that mortarless ICSEB wall can be built at a lower cost than other traditional wall systems, i.e. (in order of increasing average cost), light-frame wood, concrete block, and fired clay brick wall systems; whereas mortared CSEB wall system is less expensive than only fired clay brick walls, due to the high labor required for their construction.

The feasibility study presented in this paper shows that earthen dwellings built using mortarless ICSEB wall systems can be an attractive choice for low-cost hurricane-resistant housing in the US Gulf Coast region. However, further detailed investigations are required to understand the performance of earthen dwellings and to provide guidance in the design and code development for this type of structures. In particular, both experimental and numerical investigations are needed to determine the structural resistance and reliability of CSEB systems against extreme loads due to natural hazards (e.g., high winds and earthquakes), the appropriate dimensioning and performance of different type of reinforcements, the effects of different stabilizers and fabrication procedures on the performance of CSEBs and CSEB masonry, as well as the proper configurations of architectural and structural details (e.g., taller foundation walls to separate the wall from the wet soil, alternative wall coating and/or rendering surfaces, shading/shielding elements, specific roofing and grading details, connections between walls and foundation and/or between walls and roof, details of window and door openings).

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Table 1. Mechanical properties of CSEBs for different cement content.

Test	Cement content (%)	Strength*				MOE				f_{bk} ** (MPa)
		Min. (MPa)	Max. (MPa)	Avg. (MPa)	COV (%)	Min. (MPa)	Max. (MPa)	Avg. (MPa)	COV (%)	
Flexure	0	0.29	0.36	0.33	9.50	56.40	82.86	67.00	17.10	-
	3	0.34	0.44	0.39	11.40	71.18	97.63	86.26	12.36	-
	6	0.50	0.58	0.53	6.38	109.90	130.29	118.84	6.38	-
	9	0.63	0.71	0.66	4.87	131.33	180.78	154.47	12.49	-
	12	0.75	0.82	0.78	4.17	170.49	241.86	194.90	14.39	-
Dry Compression	0	1.15	1.33	1.22	6.38	19.42	25.93	23.28	11.40	0.74
	3	1.51	1.86	1.66	8.74	29.90	50.20	38.53	20.49	0.96
	6	1.83	2.16	2.01	6.13	36.95	51.33	44.82	11.47	1.23
	9	2.70	3.27	2.97	7.19	59.05	62.27	60.45	2.34	1.78
	12	3.73	4.24	3.89	5.47	62.28	88.96	74.20	13.41	2.42
Wet Compression	0	-	-	-	-	-	-	-	-	-
	3	0.72	0.81	0.75	4.91	17.26	25.48	22.07	14.53	0.47
	6	0.88	1.11	0.97	9.91	22.17	27.76	24.33	8.97	0.54
	9	1.51	1.68	1.58	4.32	37.03	54.05	44.63	15.46	1.01
	12	1.98	2.33	2.16	5.84	48.00	58.19	52.21	7.26	1.34

* Strength = MOR for flexure test, f_{bd} for dry compression test, and f_{bw} for wet compression test.

** f_{bk} = f_{bkd} for dry compression test, and f_{bkw} for wet compression test.

Table 2. Dry compressive strength and MOE of mortar cubes.

Cement content (%)	Sand content (%)	f_m		MOE		f_{mk} (MPa)
		Avg. (MPa)	COV (%)	Avg. (MPa)	COV (%)	
3	0	0.38	7.47	5.44	17.55	0.23
6	0	0.55	17.89	11.44	27.50	0.25
9	0	0.94	2.19	18.24	45.98	0.63
12	0	1.33	7.28	27.06	15.26	0.79
15	0	1.74	4.89	34.32	14.52	1.10
18	0	1.94	9.43	39.94	18.58	1.10
21	0	2.38	9.06	44.88	24.12	1.36
24	0	2.88	6.87	51.78	24.70	1.74
27	0	3.40	4.10	57.50	23.18	2.18
30	0	3.89	8.39	61.18	13.38	2.26
15	20	2.22	2.17	53.76	30.78	1.49
15	30	3.01	6.92	68.54	10.79	1.81
15	40	3.91	9.21	77.84	15.47	2.23
15	50	4.41	10.83	86.02	20.48	2.41

Table 3. Mechanical properties of CBEBs before construction and after demolition of the wall.

Tested specimens	Flexure test				Compression test			
	MOR		MOE		f_{bd}		MOE	
	Avg. (MPa)	COV (%)	Avg. (MPa)	COV (%)	Avg. (MPa)	COV (%)	Avg. (MPa)	COV (%)
$CSEB^{I}$	0.57	11.28	164.32	22.00	1.38	6.40	31.22	16.98
$CSEB^{P}$	0.64	22.68	279.51	17.11	1.79	5.55	55.61	20.21
$CSEB^{U}$	0.37	21.82	143.33	31.60	1.50	13.80	44.78	26.82

Table 4. Detailed cost estimates of CSEB walls for reference prototype house.

Components	Items	Mortarless ICSEB Wall			Mortared CSEB Wall		
		Quantity	Unit	Cost ($)	Quantity	Unit	Cost ($)
Blocks	Soil	133.3	Ton	-	132.6	Ton	-
	Cement	40,055	lbs.	3,676	39,851	lbs.	3,651
	Labor	584	Hours	4,234	528	Hours	3,828
	Machine	73	Hours	2,555	66	Hours	2,310
Reinforcement	Material	1,610	lbs.	483	-	lbs.	-
	Labor	29	Hour	580	-	Hour	-
Mortar & grout	Soil	10.6	Ton	-	10.6	Ton	-
	Cement	7,806	lbs.	720	7,806	lbs.	720
	Sand	10.6	Ton	531	10.6	Ton	530
Masonry Work	Stem walls	113	Hours	2,250	225	Hours	5,721
	Long walls	288	Hours	5,766	577	Hours	14,755
	Short walls	92	Hours	1,830	183	Hours	4,683
Rendering	Soil	2.7	Ton	-	2.7	Ton	-
	Cement	2,938	lbs.	271	2,938	lbs.	271
	Sand	2.7	Ton	133	2.7	Ton	133
	Masonry paint	5,964	ft2	1,372	5,964	ft2	1,372
	Plastering	87	Hours	2,185	87	Hours	2,185
	Painting	48	Hours	1,193	48	Hours	1,193
	Total cost			**27,779**			**41,352**

Table 5. Cost comparison of different wall systems for reference prototype house.

Items	Mortarless ICSEB	Mortared CSEB	Light-frame Wood	Bricks	Concrete Blocks
Material	7,186	6,676	15,638	19,533	12,844
Labor	20,593	34,674	13,068	27,625	20,255
Overheads	11,112	16,540	12,264	19,840	13,882
Total wall cost	38,891	57,890	40,970	66,997	46,981
Total cost of assemblies	65,110	65,110	65,110	65,110	65,110
Total cost of house	104,001	123,000	106,080	132,107	112,091
Wall cost ratio (wcr)	1.000	1.489	1.053	1.723	1.208
House cost ratio (hcr)	1.000	1.183	1.020	1.270	1.078

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