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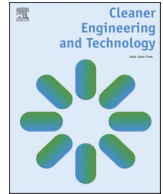
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## Behaviour of masonry lateral loaded walls made with sediment-based bricks from the Usumacinta river (Mexico)

I. Djeran-Maigre<sup>a,\*</sup>, A. Morsel<sup>a,1</sup>, M. Hussain<sup>b</sup>, D. Levacher<sup>b</sup>, A.R. Razakamanantsoa<sup>c</sup>, E. Delfosse<sup>a</sup>

<sup>a</sup> Univ Lyon, INSA Lyon, GEOMAS, EA7495, 69621, Villeurbanne, France

<sup>b</sup> Normandie Université, Unicaen, UMR 6143 CNRS-M2C, 14000, Caen, France

<sup>c</sup> Université Gustave Eiffel, Département GERS-GIE, 44344 Bouguenais, France

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### ABSTRACT

A feasibility study on Usumacinta River sediment-based bricks for resilient housing adapted to both climate change and seismic risks is performed on laterally loaded reduced-scale walls. Mortar formulations with different volume ratios of lime and sand (2/1, 1/2, 1/4, 1/6) are prepared while different types of sediment-based bricks are thoroughly investigated, manufactured and strength characterized. Commercial fired bricks as reference bricks completed the set of bricks tested (FRS: Fired River Sediment-based brick (at 850 °C); LRS: Lime treated River Sediment-based unfired brick (1.5% of lime addition); NRS: Natural fiber Reinforced river Sediment-based unfired brick and FR: commercial Fired Reference brick made without sediment). Walls of different sizes were built with these types of bricks and mortars. Tests under lateral in-plane loads of walls *i.e.* pushover tests, were conducted.

The most significant results are as follows: (1) the addition of lime increases the strength of the mortar; (2) the wall size effect is observed for wall built with reference bricks (FR) and mortar ratio (1/2), where, large walls (LW), intermediate walls (IW) and small walls (SW) exhibiting maximum load of about 1200 N, 440 N and 260 N respectively. Rocking failure mode is the most observed unlike shear and sliding mode which are rarer. (3) maximum load measured during a pushover test performed on walls with sediment-based bricks provides a satisfactory average of 130 N, which exceeds the strength recommended for light buildings; The failure mode is sliding for fired bricks and rocking for unfired bricks. (4) the sediment-based bricks walls give an interesting ductility to pushover test while (2.6–40).

These results show promising perspectives on the possibility of using the Usumacinta River sediment-based bricks in walls for light constructions under seismic loading.

### 1. Introduction

The Usumacinta River in Mexico flows through a vulnerable area, not only in terms of the environment and climate change, but also of seismic risk. In order to promote a sustainable development along the river, while integrating the socio-economic aspects of the inhabitants, the ancestral building materials are analyzed to propose alternative solutions to the current energy-consuming construction materials.

Earthen construction has always accompanied human civilizations. The various remains in the world confirm their durability vs time (Hamard et al., 2016; Morel et al., 2021). Recent studies in Europe have

demonstrated the possibility of estimating the quantities available for earthen construction (Hamard et al., 2018; Verron et al., 2022). Verron et al., (2022) reported that earthen structure is an eco-compatible practice with materials that exist in abundance.

Centuries ago, the Chontal Mayas of the Mexican state of Tabasco used bricks as a building material (Ochoa, 2004) a more elaborate method of earthen structure. Bricks are still widely used in Mexico, with an estimated production of several million bricks per year (CCA Coalition, 2015; Custodio-García et al., 2007). The traditional method of clay brick manufacturing is similar in many parts of the world and has not changed significantly over time. Brick production consists of various

\* Corresponding author.

E-mail address: [irini.djeran-maigre@insa-lyon.fr](mailto:irini.djeran-maigre@insa-lyon.fr) (I. Djeran-Maigre).

<sup>1</sup> currently: ECN, Laboratoire GeM, UMR 6183, 44300 Nantes, France.



Fig. 1. (a) State of Tabasco in Mexico –  
(b) Location of sampling sites on the Usumacinta River.

steps: (1) raw material selection and preparation, (2) mixing, molding and shaping, (3) fresh material drying. The last step of earthen bricks is done outdoors, then the bricks are classified as sun-dried bricks. For fired bricks, in a traditional brick-making kiln, the bricks are fired at temperatures between 850 °C and 1000 °C, to increase their resistance (Dalkılıç and Nabikoğlu, 2017).

Recent studies have examined several innovative approaches that have been developed to achieve more sustainable and energy-efficient brick manufacturing processes (Hussain et al., 2022a). Research work is carried out according to two directions: a material-oriented approach and a process-oriented approach. Verma et al. (2016); Shakir and Mohammed (2013) and Zhang et al. (2016) present a literature review for innovative brick formulations: calcium silicate bricks, clay bricks mixed with various additives of coal fly ash and coal bottom ash, cigarette butts, plastic fibers, straw and polystyrene fabrics, sugar cane bagasse waste, or even bricks entirely made of recyclable waste materials (Hussain et al., 2022b). On the other hand, process-oriented research studies innovative and energy-saving methods such as calcium-silicate-hydrate-based bricks or geopolymer-based bricks (Zhang et al., 2016).

Several feasibility studies have already been performed using dredged sediments for brick manufacturing (Samara et al., 2009; Capuyns et al., 2015; Goure-Doubi et al., 2015; Mesrar et al., 2021; Gillot et al., 2021). Experimental bricks are made either from 100% dredged sediment (Mezencevova et al., 2012) or the sediment mixed with clay (Chiang et al., 2008; Torres et al., 2009; Xu et al., 2014) or cement (Yang et al., 2021). Moreover, all these studies are related to the fired brick manufacturing. Only a few studies have focused on sediment-based compacted earth blocks (Serbah et al., 2018; Brahim et al., 2022; Hussain et al., 2022b). In bricks research investigations, physical and mechanical properties are usually required to compare performance with respect to firing and shaping of bricks. Finally, the main parameters are the compressive strength, thermal and acoustic performance and, to a lesser extent, leaching behaviour (Dalkılıç and Nabikoğlu, 2017).

None of these studies addressed sediment-based behavioral brick

walls that are subjected to seismic stresses from earthquakes at reduced scale. Collapse of building structures is the main cause of the large number of casualties reported after major earthquakes everywhere in the world. Masonry is commonly used as a structural material for building construction in most developing countries. Even this long tradition, past and recent experiences prove that masonry buildings perform poorly during earthquake events. Most of the time, there is a serious risk of complete structural failure of buildings with many lives lost (EERI, 2001; EERI, 2002). Thus, a better understanding of how masonry walls function under lateral loading is essential for assessing the seismic vulnerability of already existing buildings. For future work, a better understanding of wall behaviour will also be useful in the construction of new buildings by establishing new design guidelines for masonry walls (Pandey and Meguro, 2004).

The current study focuses on the use of the Usumacinta River sediments as raw materials for bricks, and production for local construction needs, under a joint research program (VAL-USES, 2017). The in-plane response is studied by performing a pushover test on masonry walls built with sediment-based bricks i.e., sediments come from Usumacinta River (Mexico), is studied. The adopted methodology was as follows:

- i) Formulation of sediment-based bricks: fired and unfired or earth bricks. Unfired bricks are made from a mixture of sediments with lime or natural oil palm flower fibres. Fired bricks contains only sediments, i.e. 100% of sediments.
- ii) Formulation of joint mortars with different ratios of lime and sand (L/S)
- iii) Masonry wall models: different sizes (height, length and width), use of joint mortars and sediment-based bricks in addition to reference or control bricks.
- iv) Pushover tests on wall-models: Comparison of the pushover performance of the different wall-models including reference bricks. The wall behaviour is analyzed in terms of the maximum resisted lateral load and failure mode. Ductility is also investigated regarding the resistance of the walls against earthquakes.

**Table 1**  
Testing methods and standards used for the characterization of the sediments.

Characteristics	Tests	Standards
Grain size distribution Atterberg limits (LL, PL)	Laser particle sizer	NF ISO 13320
	Fall cone test (LL)	NF EN ISO/TS 17892-12 <sup>a</sup>
	Casagrande test (LL)	NF EN ISO/TS 17892-12 <sup>a</sup>
	Rolled thread method (PL)	NF EN ISO/TS 17892-12
Clay presence	Methylene blue (MB) tests	NF P 94-068
	Calcination	NF P 94-047
Organic Matter (OM) CaCO <sub>3</sub>	Calcimeter	NF P 94-048
	Proctor test	NF P 94-093
Optimal water content (w <sub>opt</sub> )		
pH	Multiparameter probe	NF ISO 10390

Note: LL = Liquidity Limit - PL = Plasticity Limit.

<sup>a</sup> Liquidity Limit (LL) is measured using two different methods (fall cone test and Casagrande test). The final value of the liquidity limits is the mean value of the results of the two methods.

The effect of adding lime to the mortar, the effect of brick dimensions on lateral pushover loading, the possible reuse of bricks, the relationship between maximum resisted lateral load and wall weight and/or area are discussed through the data reported.

**2. Materials**

**2.1. Usumacinta river sediments sampling**

The sediments studied come from the Usumacinta River, a 1000-km long river that runs through the state of Tabasco, Mexico (Fig. 1). The sediments have been sampled using common samplers (cone samplers, shovels, buckets) upstream from Tenosique and downstream from Jonuta, two cities in the area. The saturated samples have been stored in airtight barrels and transported to France by boat.

**Table 2**  
Characteristics of the sediments.

Sediments	Clay (%)	Silt (%)	Sand (%)	CaCO <sub>3</sub> (%)	OM (%)	MBV (g/100g)	pH	LL	PL	PI	w <sub>opt</sub> (%)	GTR classification
T5	7.6	63.4	29.0	–	3.6	5.7	8.5	40.9	25.7	15.2	19.9	A2
T6	4.7	41.1	54.2	7.3	3.5	2.5	8.6	55.0	–	55	18.1	A1
J3	5.9	41.3	52.8	7.8	4.5	2.7	7.5	37.7	7.8	29.9	19.3	A2

Note: PI: Plasticity Index, PI = LL – PL.

**Table 3**  
Preparation steps for production of reinforced sediment-based bricks.

Preparation & mixing	Molding & compaction	Drying
FRS: sediment + water	✓	drying in ambient air + firing at 850°
LRS: lime + sediment + water	✓	wrapping and curing
NRS: natural fibre + sediment + water	✓	during in oven at 40°



**2.2. Geotechnical characterization of the sediments**

The geotechnical characterization of the Usumacinta River sediments is summarized in Table 1.

The sediments collected from the Usumacinta River are identified using letters and numbers. The letter designates the city where the sediments come from and the associated number corresponds to the specific location of sampling. T is used for Tenosique and J for Jonuta. According to the GTR, NF P 11 300 standard (1992), T6 is classified as A1: low plastic silts, loess, alluvial silts, low polluted fine sands, low plastic, whereas T5 and J3 are classified as A2: low plastic fine clayey sands, silts, clays and marls (Table 2).

**2.3. Preparation of the Usumacinta river sediment-based bricks**

Three types of 4 × 4x16 cm<sup>3</sup> bricks are prepared: (1) fired bricks (FRS) i.e. traditionally manufactured using Usumacinta sediments, and two types of unfired bricks (2) limed-bricks, stabilized with (LRS), and (3) fiber reinforced sediment-based bricks (NRS), using natural palm oil flower fibres as mechanical reinforcement (Table 3).

**2.3.1. Fired River Sediment bricks (FRS)**

Fired sediment-based bricks are prepared with sediments T5, the most clayey sediments (MBV = 5.7, PL = 25.7), which best suit the firing process without swelling phenomena. The moisture content level is defined as  $w = w_p + (PI/2)$ , with  $w_p = w_{opt}$  giving the highest density. Bricks are compacted into 4 × 4x16 cm<sup>3</sup> prismatic moulds (Hussain et al., 2022b) and dried for four to 12 h in an oven at 40 °C and then fired for 6 h at 850 °C. The shrinkage factor of the bricks, measured after drying and firing, is approximately 0.35%.

**2.3.2. Lime treated river sediment bricks (LRS)**

Sediments T6 are used for the stabilisation of the brick with lime, which is a less energy consuming method than firing.

The amount of lime required to initiate the pozzolanic reaction is measured according to the standard ASTM D6276 (2019) and is equal to 1.5%. The sediments are first mixed with water and stored for 24 h. Then lime is added. The mixture obtained is re-homogenised, put in moulds

**Table 4**  
Fired and unfired bricks unconfined compressive strengths.

Type of brick	Brick nature	Density (kg/m <sup>3</sup> )	UCS (MPa)
Fired Reference brick (FR)	Fired	1880	21.3
Fired River Sediment brick (FRS)	Fired	1731	4.9
Lime treated River Sediment brick (LRS)	Unfired	1674.5	2.0
Natural fiber Reinforced River Sediment brick (NRS)	Unfired	1524	2.8

and compacted in two separate layers at normal Proctor energy (NF P 94-093, 2014). After compaction, bricks are, individually wrapped and cured at room temperature for 28 days.

### 2.3.3. Natural fiber reinforced river sediments bricks (NRS)

Sediments J3, which have the highest plasticity index (PI = 29.9), are the more workable and thus are used to be reinforced using palm oil flower fibres as proposed in Hussain et al. (2022a).

The moisture content level required for compaction of the sediment and fibre mixture is obtained using the normal Proctor test parameters and is around 19.3%. To stabilize the water absorption level of fibres and sediments, the fibres are saturated with water before mixing.

The fibre average length is 9.48 mm with a maximum grid length of 2 cm. The percentage of fibres by weight based on the total weight of sediments is 4%. The mixture (sediments, fibres and water) is moulded and compacted using dynamic loading under normal Proctor energy. (NRS) bricks are then oven-dried at 40 °C for 3–4 days and air-dried at 20 °C, for about 2 weeks.

### 2.4. Implementation of the fired reference bricks (FR)

One wall is built and tested per type of river sediment-based bricks. For comparison purposes between Mexican bricks, produced with sediments, French standard fired bricks are used. These latter have served as reference bricks for the implementation and definition of the test procedure. The fired reference bricks, called (FR), are selected because produced in France and are readily available. Their dimensions (5.5 × 5.5 × 22 cm<sup>3</sup>) moreover give the same ratio of length to width than the Mexican bricks (4 × 4 × 16 cm<sup>3</sup>).

### 2.5. Mechanical characterization of fired and unfired bricks

The Uniaxial Compressive Strength (UCS) is carried out according to standard ASTM-C67 (2018). Table 4 summarizes the compression strength values obtained for each type of brick: fired reference brick (FR), river sediment fired bricks (FRS) and unfired bricks including (LRS) and (NRS) ones. The averaged values given in Table 4 result of the three tests performed according the standard.

According to the standard XP P13-901 (2001), both types of unfired sediment bricks, either stabilized with lime (LRS) or reinforced with fibres (NRS) are suitable for wall construction because their UCS is equal or higher to 2 MPa. The sediment-based bricks have interesting mechanical properties. With only 1.5% of lime content, the treated sediment bricks reach a UCS higher to 1 MPa. For fired sediment-based bricks, a UCS observed of 4.9 MPa is higher than the 4 MPa recommended for light constructions.

### 2.6. Mortar formulation

A mixture of sand, natural hydraulic lime and water is proposed for mortar formulation. Three different lime-to-sand volume ratios (volumelime/volumesand = L/S) are considered. The compressive strength is measured at different curing time periods i.e. 7, 14 and 28 days, respectively, on mortar samples of the same size as the Mexican bricks, i.e., 4 × 4 × 16 cm<sup>3</sup> (Table 5).

**Table 5**  
Mortar samples densities and strengths vs lime/sand ratios.

Ratio L/S	Density (kg/m <sup>3</sup> )			Unconfined Compressive Strength (MPa)		
	7 days	15days	28 days	7 days	15days	28 days
2/1	1550	1530	1520	0.83	1.56	1.81
1/2	1740	1750	1760	0.90	0.90	1.11
1/4	1700	1710	1730	0.49	0.51	0.71
1/6	1670	1690	1740	0.36	0.39	0.59

Note: Values correspond to the average of 3 tests.

It is observed that the higher the quantity of lime in the mortar, the higher the compressive strength (Table 5). According to Pauley and Priestley (1992), the higher the strength of bricks and mortar, the higher the strength of the wall. This conclusion remains true for the different curing period time tested. The selection of the mortar ratio is proposed according to UCS value of the brick. L/S = 1/2 ratio is considered for bricks with UCS equal to 21 MPa of UCS, while 2/1 L/S is used for river sediment-based bricks.

## 3. Experimental procedure

The repeatability of the experimental procedure and the effects of implementation parameters such as: wall dimensions, brick size and mortar strength have been investigated. Series of tests were conducted with reference bricks. The satisfactory approach will then be adopted for the masonry walls made of sediment-based bricks.

### 3.1. Masonry wall construction

The masonry wall foundations are built on a specially designed reinforced concrete beam. This foundation consists of a reinforced concrete beam 200 cm in length and 20 cm in width and height, which is clamped to a 1-m thick slab capable to withstand the maximum expected loads.

The laboratory walls consist in a single row of bricks. Vertical and horizontal wall joints are about 10 mm thick and are fully filled (Fig. 2). The bricks are not soaked in water before use. Once wall is built, a 15-day drying period is considered before testing starts. It should be noticed, that, regarding mortar performances after 15 days, the compressive strength has already reached more than 80% of the strength at 28 days.

### 3.2. Pushover testing procedure

The pushover tests carried out on the experimental walls consist of applying in-plane lateral load at the top of the wall. The load is applied using a servo-hydraulic testing actuator connected to a rigid steel loading beam (Fig. 3). The loading rate is 1 mm/min. Loading and displacements are recorded using sensors placed in the servo-hydraulic actuator.

Two walls are built on each foundation beam. So, when the pushover test is over for the first wall, the foundation beam is turned and the pushover test continues for the second wall in the same conditions as the previous one. The turning phase is carefully done without damaging the walls. When correctly positioned, the foundation beam is anchored again to the 1-m thick slab using six post-tensioned steel bars.

### 3.3. Testing program

Three different sized walls are built with the 5.5 × 5.5 × 22 cm<sup>3</sup> (FR) bricks: (1) a large wall 100 cm wide and 100 cm high (LW), (2) an intermediate 50 cm × 67 cm wall (IW) (width cm x height cm) and (3) a small 50 cm × 50 cm wall (SW). So, the wall scale effect has been investigated.

Some (FR) bricks are cut the same size than river sediment bricks, i.

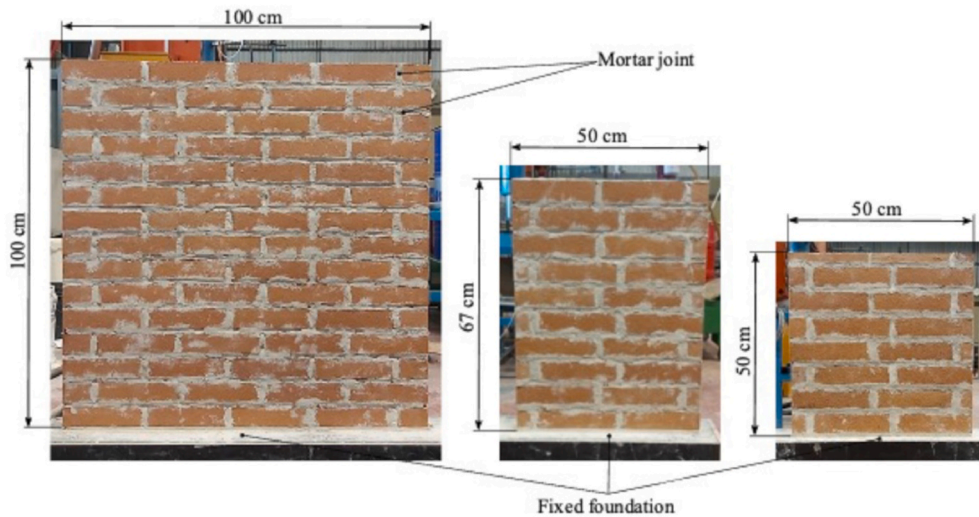


Fig. 2. Dimensions of fired reference (FR) bricks walls.

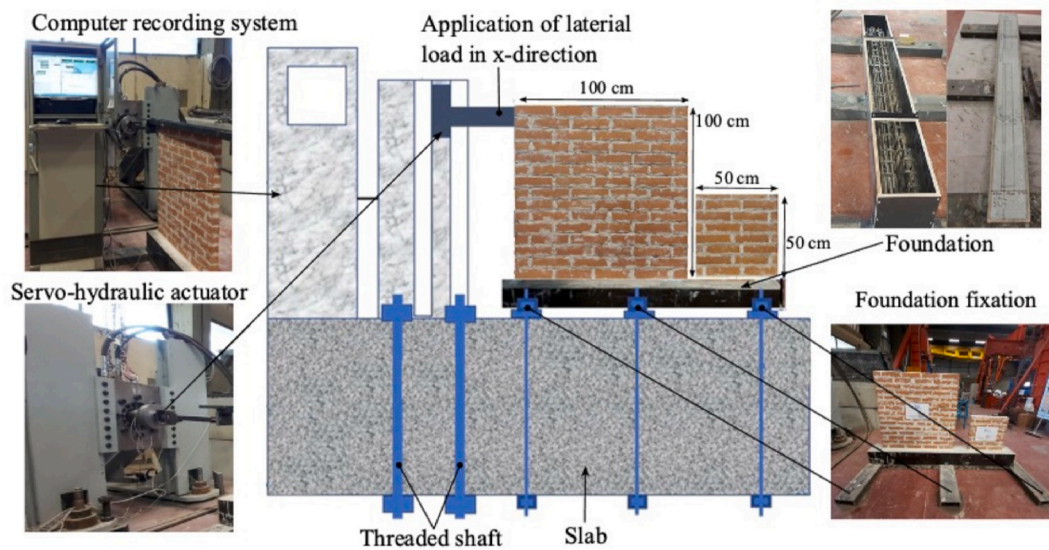


Fig. 3. Scheme of the experimental setup for pushover test on walls.

e.,  $4 \times 4 \times 16 \text{ cm}^3$ . Two intermediate walls (W10 and W12), both jointed with the same mortar *i.e.* L/S ratio constant, are also tested to study brick scale influence.

The possibility of reuse the bricks was studied with bricks recovered after the pushover test performed on the W10 wall. A new wall W12 was built and tested.

**Table 6**  
Wall characteristics prepared to perform the pushover tests.

Wall reference	Brick type	Brick nature	Brick comment	Brick dimensions (cm <sup>3</sup> )	Mortar ratio L/S (-)	Wall size width x height x thickness (cm <sup>3</sup> )	Wall models
W1	FR			5.5 x 5.5 x 22	1/2	100 x 100 x 5.5	LW
W6				5.5 x 5.5 x 22	1/2	50 x 67 x 5.5	IW
W7				5.5 x 5.5 x 22	1/2	50 x 67 x 5.5	IW
W8				5.5 x 5.5 x 22	1/2	100 x 100 x 5.5	LW
W9				5.5 x 5.5 x 22	1/2	50 x 67 x 5.5	IW
W10		Fired	cut	4 x 4 x 16 (c)	1/2	50 x 67 x 4	IW
W11				5.5 x 5.5 x 22	1/2	50 x 50 x 5.5	SW
W12			reused	4 x 4 x 16 (r)	1/2	50 x 67 x 4	IW
W13				5.5 x 5.5 x 22	1/2	50 x 50 x 5.5	SW
W14				5.5 x 5.5 x 22	1/4	50 x 67 x 5.5	IW
W15				5.5 x 5.5 x 22	1/6	50 x 67 x 5.5	IW
W16			reused	4 x 4 x 16 (r)	2/1	50 x 67 x 4	IW
W18	FRS	Fired		4 x 4 x 16	2/1	50 x 67 x 4	IW
W17	LRS	Unfired		4 x 4 x 16	2/1	50 x 67 x 4	IW
W19	NRS	Unfired		4 x 4 x 16	2/1	50 x 67 x 4	IW

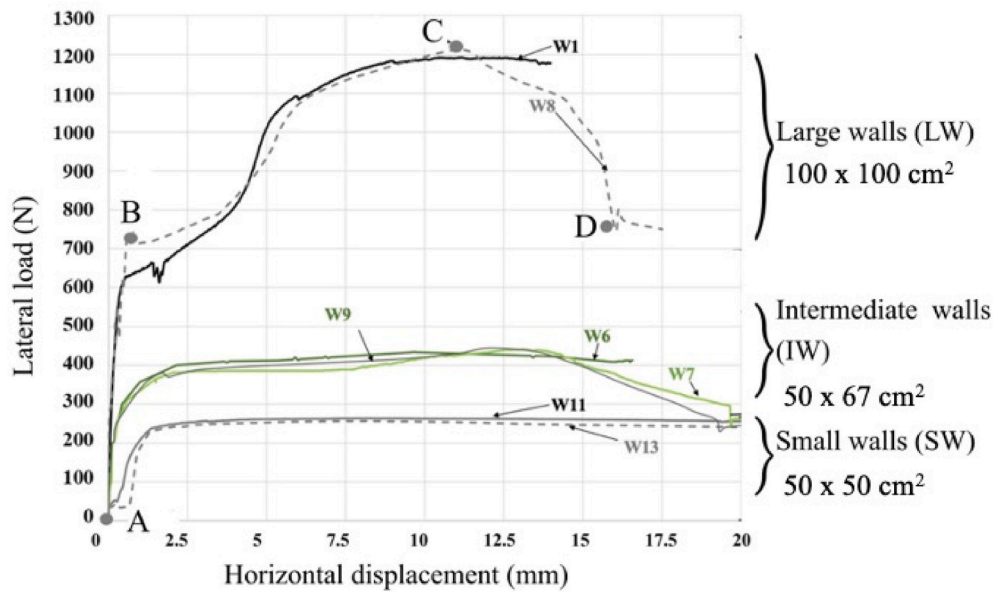


Fig. 4. Effect of wall size observed in pushover tests. Case of walls built with reference fired bricks (FR, brick dimensions  $5.5 \times 5.5 \times 22 \text{ cm}^3$ ) jointed with  $L/S = 1/2$  mortar.

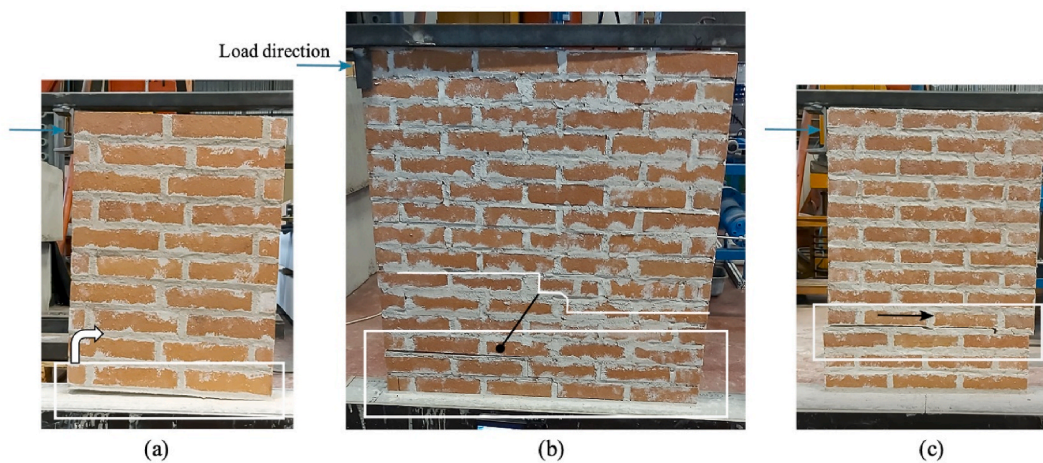


Fig. 5. The failure modes: a) rocking failure, b) shear failure, c) sliding failure.

Three (FR) W13, W14, W15 built with 3 ratios of mortars  $L/S = 1/2, 1/4$  and  $1/6$ , are also tested to study the influence of mortar strength on the wall behaviour.

Three intermediate walls (IW) are built using  $4 \times 4 \times 16 \text{ cm}^3$  river sediment-based bricks: (1) wall, W18, made of (FRS) bricks, (2) W17 wall made of (LRS) bricks and (3) W19 wall made with (NRS) bricks. Notice that W18 is more difficult to build due to the heterogeneity of brick size and shape resulting from shrinkage phenomena during firing.

The selected of mortar ratio considers the UCS value of the bricks of the wall built as abovementioned. If the UCS strength of the mortar is lower than the compression strength of the bricks, then the compression strength then the compression strength of a masonry wall is invariably higher than the mortar compression strength. As the compressive strength of (FRS), (LRS) and (NRS) bricks is relatively low (Table 4), it is decided to select a mortar joint more resistant with a ratio  $L/S = 2/1$ . Table 6 summarizes the wall characteristics prepared to perform the pushover tests.

## 4. Results

### 4.1. Behaviour of walls made of the fired reference bricks (FR)

The load-displacement curves recorded from the pushover tests show a clear repeatability in walls testing. All the walls were built with same sized-bricks and same joint mortar ( $L/S$  constant). Wall tests are duplicated for each type of wall (LW, SW) or triplicated for intermediate walls (IW). According each wall size, similar trends are observed in pushover load-displacement.

The curves show a typical behaviour pattern: (1) a linear behaviour (from A to B, in Fig. 4), which corresponds to the linear elastic range from the unloaded state A to its effective yield B. Then, an inelastic reduced (ductile) stiffness from B to C is observed. This path BC corresponds to the appearance of the first cracks within the mortar at the base of the walls (Fig. 5). Beyond point C towards D, a sudden reduction in the load resistance appears. Depending on the size of the wall, the different paths are more or less marked. Maximum loads (peak values) and failure modes are reported in Table 7.

Three different failure modes are observed along the pushover tests:

**Table 7**  
Maximum loads and failure modes for (FR) bricks walls pushover testing.

Wall reference	Wall size (width x height) cm <sup>2</sup>	Brick size cm <sup>3</sup>	Mortar Ratio L/S	Maximum load (N)	Failure mode*
W1	100 × 100	5.5 x 5.5 x 22	1/2	1206	Rocking, 1st
W8		5.5 x 5.5 x 22	1/2	1212	Shear 3 to 2
W6	50 x 67	5.5 x 5.5 x 22	1/2	434	Shear: 2 to 1
W7		5.5 x 5.5 x 22	1/2	449	Rocking 1st row
W9		5.5 x 5.5 x 22	1/2	444	Rocking F
W11	50 x 50	5.5 x 5.5 x 22	1/2	263	Rocking F
W13		5.5 x 5.5 x 22	1/2	263	Rocking F
W10	50 x 67	4 x 4 x 16 (c)	1/2	117	Rocking 1st
W12		4 x 4 x 16 (r)	1/2	101	Sliding, 3rd row
W14	50 x 67	5.5 x 5.5 x 22	1/4	257	Rocking F
W15		5.5 x 5.5 x 22	1/6	192	Rocking F
W16		4 x 4 x 16 (r)	2/1	172	Rocking F

\* Note: The number after the failure mode indicates the row (from the base of the wall) where failure is initiated – F: foundation. Rocking F: indicates that there is a rocking failure at the level of the foundation of the wall Shear 2 to 1: indicates that failure is initiated at the level of the 2nd row and runs down to the 1st row.

- a) Most of the walls (W1, W7, W9, W10, W11, W13 to W16) experience rocking failure, which is initiated either at the junction between the wall and the foundation or at the base of the first row of bricks (Fig. 5a);
- b) Shear failure is observed for two walls (W6 and W8) with a fracture line starting from the first or the second row of joint and running down to the foundation beam (Fig. 5b);
- c) The last failure mode is the sliding failure (W12), for which the fracture line is initiated horizontally at mortar level. Above this fracture line, the whole upper part of the wall slides over the bottom part of the wall (Fig. 5c).

For all the modes, collapse is due to mortar failure always occurring at the base of the walls.

#### 4.2. River sediment-based brick wall behaviour

In this section, walls were made with the three different types of river sediment-based bricks. Dimensions of bricks ( $4 \times 4 \times 16 \text{ cm}^3$ ) and walls ( $50 \times 67 \text{ cm}^2$ ) tested are constant. Bricks are jointed with constant L/S (=2/1) mortar.

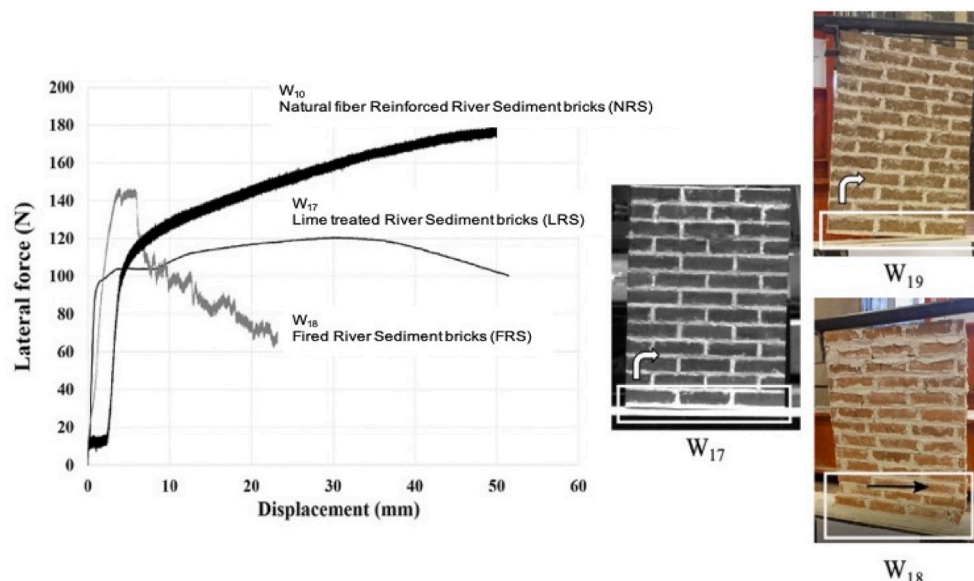
##### 4.2.1. Fired river sediment-based bricks (FRS) wall

During the pushover test, the wall (W18) shows an elastic phase (Fig. 6). The first cracks appear within the mortar joint at the level of the first row of bricks from the wall base but only on one side of the wall. This reveals the beginning of inelastic but linear response of stiffness. Soon afterwards, the wall response reaches a small plateau during which the load remains constant and corresponds to the maximum recorded load of 140 N. Then, the first cracks begin to appear on the other side of the wall. A sudden reduction in the load resistance is observed and the upper part of the wall begins to slide as the load decreases.

A sliding failure is observed with a final horizontal displacement of 4 cm and the fracture of a piece of brick at the base of the resisting wall (Fig. 6).

##### 4.2.2. Lime treated river sediment-based bricks (LRS) wall

Wall (W17) is made with lime stabilized Mexican (LRS) bricks. During the pushover test, the wall exhibits two behaviour phases: (1) an elastic part and (2) an inelastic phase resulting in a large plateau. The load continues to increase slowly until reaching a maximum of 120 N (Fig. 6). During the applied loading, the rocking failure is observed.



**Fig. 6.** Pushover tests on the sediment-based brick walls.



**Table 8**

Maximum load and failure mode observed during the pushover tests carried out on the walls made of  $4 \times 4 \times 16 \text{ cm}^3$  Mexican bricks.

Wall reference	Brick type	Brick nature	Mortar L/S ratio	Maximum load (N)	Failure mode <sup>a</sup>
W18	FRS	Fired	2/1	146	Sliding 1st
W17	LRS	Unfired	2/1	120	Rocking F
W19	NRS	Unfired	2/1	–	Rocking F

F: foundation, Rocking F: indicates that rocking failure is observed at the level of the foundation of the wall.

<sup>a</sup> The number after the failure mode indicates the row of bricks (from the wall base) where failure begins.

#### 4.2.3. Natural fiber reinforced river sediment-based bricks (NRS) wall

Bricks (NRS) reinforced with natural fibres served to build the wall (W19). During the pushover test, the first cracks appear at the base of the wall between the foundation beam and the wall while the load remains constant around 15 N (Fig. 6). Then, the load increases steeply and rapidly. A linear behaviour is observed, which is consistent with the fact that the crack line moves continuously and the wall starts rocking. At the end of the elastic phase, around 100 N, the load continues to increase slowly while rocking (or tilting) increases, the wall only holds at the load plate on the upper wall corner. The test is stopped when rocking reaches 4 cm for the vertical displacement. However, no bricks are found to have fractured during the test. Indeed, as shown by Magenes and Calvi (1997), in the case of pure flexural responses where a rocking response is observed, very large displacements can be obtained.

The maximum load supported by the walls made of the river sediment-based bricks as the corresponding failure modes are presented in Table 8. While the fired sediment bricks have a compressive strength twice higher than the lime-treated sediment bricks, the maximum load values that the walls can withstand, are very close. As reported by Pandey and Meguro (2004), damages appear on masonry walls as cracks in the mortar joints at a very early stage of the loading phase. Indeed,

cracks appear within mortar at a much lower loading level than in brick units. The initiation of cracks in the mortar joints in masonry walls indicates an inelastic response rather than failure. Masonry walls then show a good resistance, after the first cracks appearing, thus allowing for frictional sliding, which contributes to energy dissipation. Although a more resistant mortar is used for the sediment-based brick walls than for the reference brick walls, in both cases, failure always appears at the mortar level. No failure is observed in bricks.

## 5. Analysis and discussion

### 5.1. Influence of addition of lime in joint mortar composition on wall behaviour

Five pushover tests are conducted on  $50 \times 67 \text{ cm}^2$  (width x height) walls made of  $5.5 \times 5.5 \times 22 \text{ cm}^3$  (FR) bricks. Three of them (W6, W7, W9) are built with a mortar ratio  $L/S = 1/2$ . For walls W14 and W15 the mortar ratio  $L/S$  is  $1/4$  and  $1/6$ , respectively (Fig. 7). The supported load clearly increases with the rate of lime used shown in Fig. 7, which seems to attenuate as it goes from  $1/6$  to  $1/2$ . This underline the significant role of the lime quantity used, on the raise of supported pushover load by the wall.

### 5.2. Influence of brick dimensions on lateral pushover loading

The influence of the brick dimensions is clearly observed on Fig. 8. It should also be noted that the volume of the small bricks ( $4 \times 4 \times 16 \text{ cm}^3$ ) is equal to  $256 \text{ cm}^3$ , about one third of the volume of the larger bricks ( $5.5 \times 5.5 \times 22 \text{ cm}^3$ ), which is equal to  $665.5 \text{ cm}^3$ .

Considering the behaviour of both brick dimensions tested, the larger bricks used for walls W6, W7 and W9 induce a positive impact on wall performances. The averaged pushover load is (442 N) while the lowest brick dimensions are used for the wall W10 are able to support a load of (117 N). Thus, for a brick volume difference equal to 38%, a load

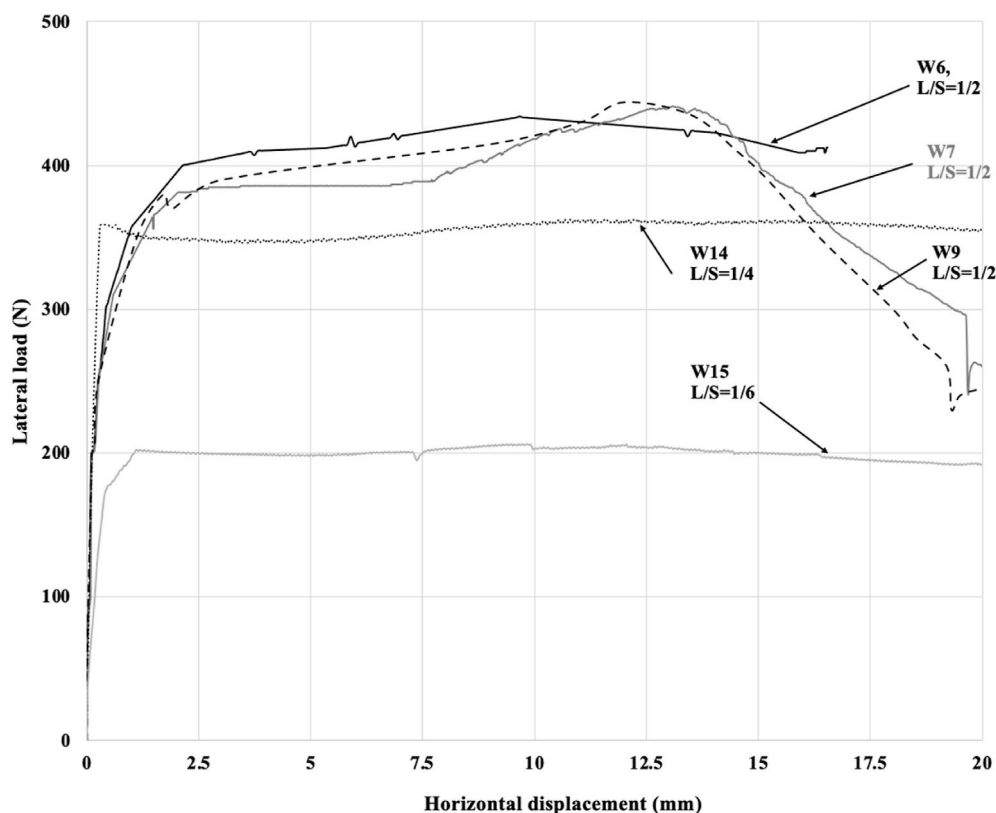


Fig. 7. Effect of L/S ratios in mortar composition in pushover testing on (FR) bricks. (brick dimension:  $5.5 \times 5.5 \times 22 \text{ cm}^3$ ) walls (IW,  $50 \times 67 \text{ cm}^2$ ).

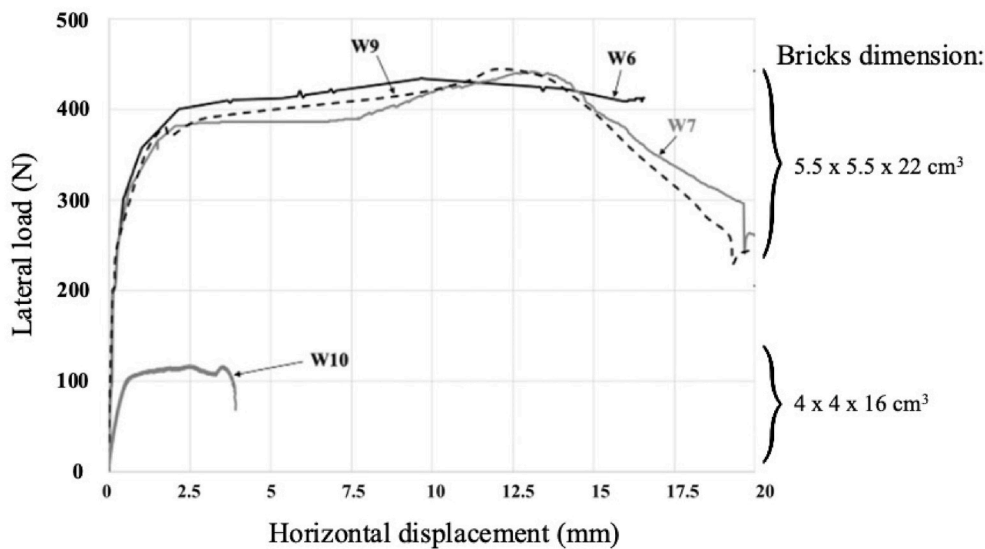


Fig. 8. Brick size effect: pushover testing on intermediate walls ( $50 \times 67 \text{ cm}^2$ ). Made of different-sized (FR) bricks ( $5.5 \times 5.5 \times 22 \text{ cm}^3$  and  $4 \times 4 \times 16 \text{ cm}^3$ ).

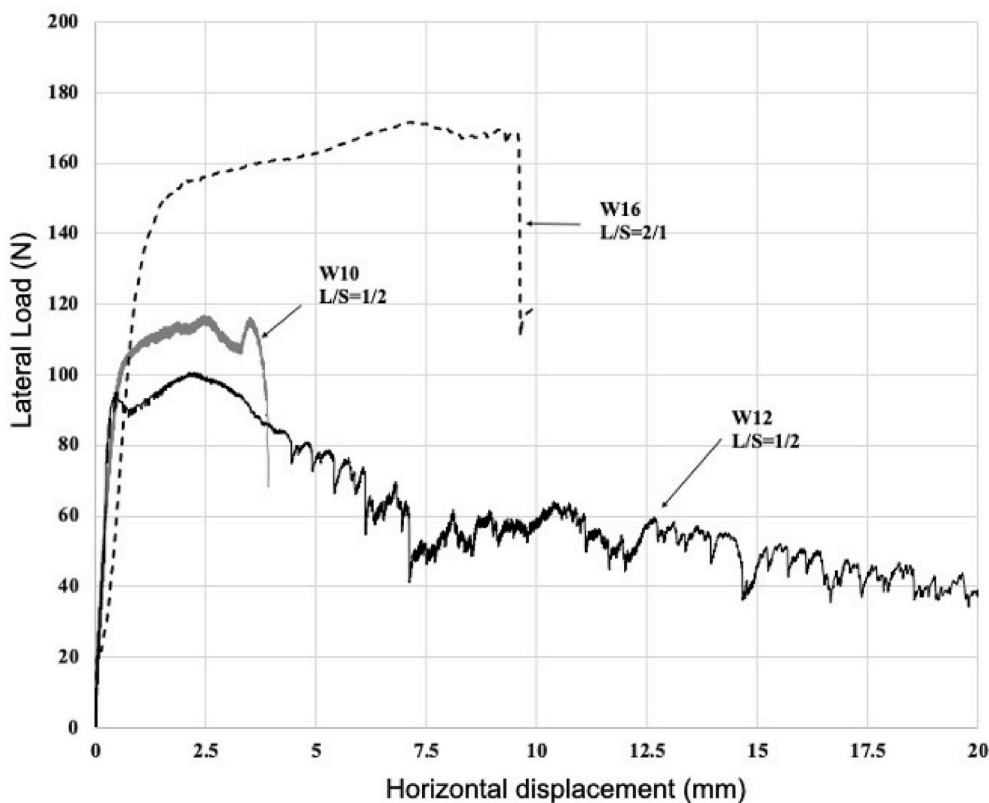


Fig. 9. Effect of use of new and reused bricks: pushover testing on (FR). Bricks ( $4 \times 4 \times 16 \text{ cm}^3$ ) on walls ( $50 \times 67 \text{ cm}^2$ ).

difference of 26% is measured, this difference is not negligible but remains in the same order of magnitude.

### 5.3. Reuse of bricks

For circular economy point of view, the potential reuse of the bricks after demolition is fundamental. The results in Fig. 9, show a little decrease in pushover performance between W10 and W12 noting that W10 was built with new bricks and W12 with reused bricks.

To overcome the loss of pushover performance for reused bricks,

there is still the possibility to adjust the L/S mortar ratio. Considering previously a use of  $L/S = 2/1$  for the wall W16 for what results greatly improved to reach a maximum lateral load of 172 N.

The modification of mortar ratio L/S remains an interesting possibility. Considering the results given in (Table 5) and above discussed, the use of ratio  $L/S = 2/1$  is recommended.

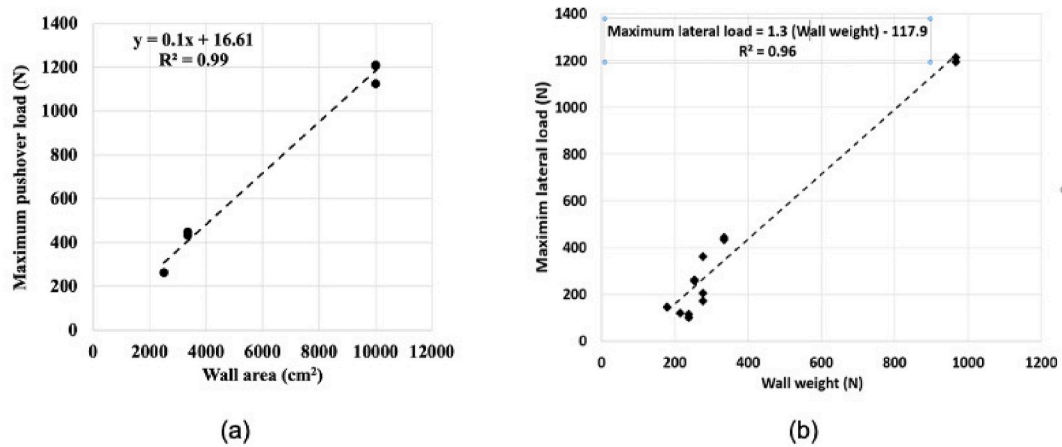


Fig. 10. (a) Correlation between maximum pushover loads and wall area, (b) Maximum pushover load versus wall weight.

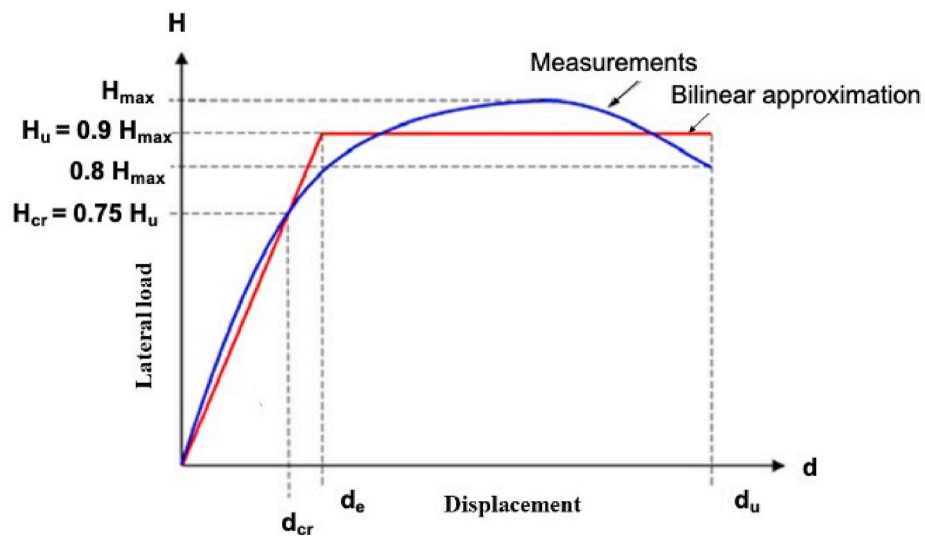


Fig. 11. Parameters of the wall response to in-plane solicitations according to (Allen et al., 2016).

5.4. Correlation between maximum pushover lateral load and (a) wall weight and (b) wall size

In the range of load applied during pushover tests, a linear

correlation is established between the maximum pushover load supported by the structure and the load application wall area of the tested wall (Fig. 10a).

The weight of tested walls is calculated by considering the types of

Table 9  
Ductility and stiffness parameters of walls tested.

Wall reference	Wall size	Brick type	Mortar L/S	Hmax (N)	0.8Hmax (N)	De (mm)	Du (mm)	M (-)
<b>Fired Reference brick - size: 5.5 × 5.5 × 22 cm<sup>3</sup></b>								
W1	LW		1/2	1193	954	4.8	18	3.8
W8	LW		1/2	1212	970	5.2	15.5	3.0
W6	IW		1/2	434	347	0.9	16.1	17.9
W7	IW		1/2	441	353	1.3	16.8	12.9
W9	IW	FR	1/2	444	355	1.1	16.3	14.8
W11	SW		1/2	263	211	1.0	25.0	25.0
W13	SW		1/2	257	205	1.1	51.5	46.8
W14	IW		1/4	362	290	0.2	48.6	243.0
W15	IW		1/6	206	165	0.4	40.1	100.3
<b>Fired Reference brick - size: 4 × 4 × 16 cm<sup>3</sup></b>								
W10	IW		1/2	116	93	0.5	3.9	7.8
W12(r)	IW	FR	1/2	101	80	0.3	4.4	14.7
W16(r)	IW		2/1	172	138	1.1	9.6	8.7
<b>Sediment-based brick - size: 4 × 4 × 16 cm<sup>3</sup></b>								
W18	IW	FRS	2/1	146	117	2.4	6.3	2.6
W17	IW	LRS	2/1	120	96	1.3	52	40.0
W19	IW	NRS	2/1	(Hmax could not be measured)				

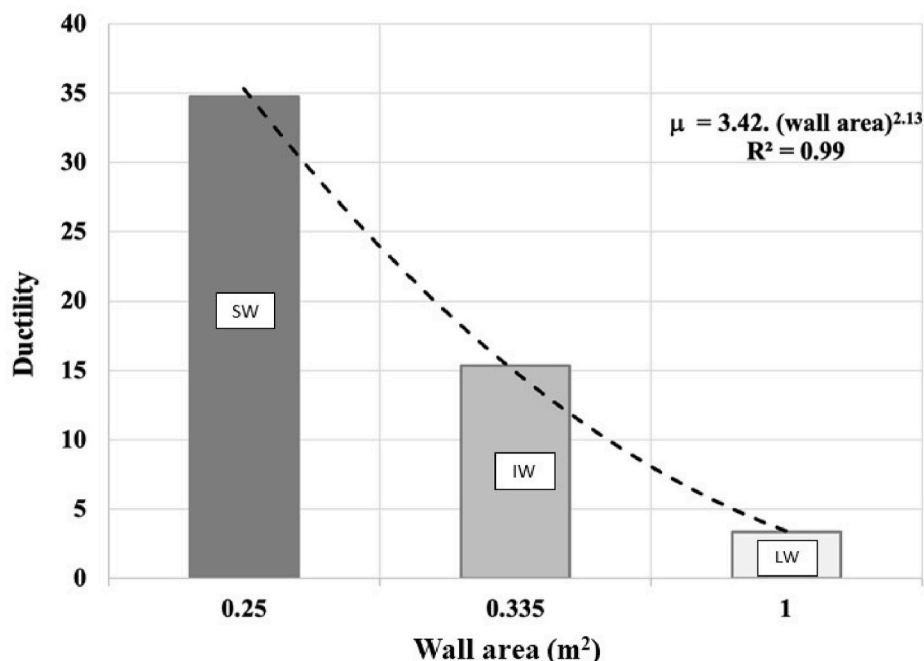


Fig. 12. Ductility parameter versus wall area (height by length) for (FR) walls pushover tested with same brick dimensions ( $5.5 \times 5.5 \times 22 \text{ cm}^3$ ) and same joint mortar ratio ( $L/S = 1/2$ ).

brick, mortar ratios and the wall dimensions. A satisfying correlation is found between the maximum pushover loads and the corresponding wall weight as shown in (Fig. 10b).

### 5.5. Ductility of the walls

The ductility of a structure is an important factor in the design of construction in high seismic regions. The ductility corresponds to the ability of a structure or its components to provide resistance in the in-elastic domain of response without a significant reduction of stiffness (Pauley and Priestley, 1992).

The ductility of the walls tested is analyzed in terms of behavioral response during pushover testing *i.e.* from the load-displacement curves analysis. The area below the lateral-force displacement curve shows the energy consumption of the structure. Ductility is defined as the ratio  $\mu$  between two displacements,  $du$  and  $de$ , corresponding to a load equal to 80% of the maximum load ( $H_{max}$ ) (Eq. (1)) (Allen et al., 2016; Magenes and Calvi, 1997) (Fig. 11):

$$\mu = \frac{du}{de} \quad (1)$$

The ductility and stiffness parameters obtained from testing data are summarized in Table 9. The level of ductility describes the energy absorption capacity of the structure and its ability to deform under lateral loading. Therefore, the selection of ductile materials is an important safety issue in earthquake zones (Zengin and Koçak, 2017). The results analysis shows that the size of the wall affects the ductility: the larger the wall area, the smaller its ductility and thus, the less it can withstand earthquakes (Fig. 12).

The ductility of the sediment-based fired bricks wall ( $\mu = 2.6$ ) is lower than the wall built with the fired reference bricks ( $\mu = 8.7$ ) with the same mortar ratio ( $L/S = 2/1$ ). This indicates that the fired sediment-based bricks walls have a lower energy absorption capacity and would therefore be more sensitive to earthquakes. Regarding ductility, the walls made with lime treated sediment-based bricks ( $\mu = 40$ ) suits seismic zones better than fired sediment-based bricks walls ( $\mu = 2.6$ ). In the case of the (LRS) bricks walls, maximum loads could not be measured.

A correlation between the wall area and the ductility parameter according to the criteria of Allen et al. (2016) for fired bricks and for a joint mortar ratio of 1/2 is established (Fig. 12). This relationship must be confirmed for other wall configurations.

## 6. Conclusions

The objectives of the present study were to develop a suitable mortar for wall construction with different types of Usumacinta River sediment-based bricks. Moreover, the wall should be tested under seismic scenarios and more specifically in-plane response for reduced scale walls. Thus, pushover tests were performed by applying a lateral load to these different types of walls. From all the tests and observations made, it was found that:

- the role of the amount of lime used to strengthen the mortar has been clarified. The unconfined compressive strength increases from 0.59 to 1.81 MPa when the volume ratio of lime to sand goes from 1/6 to 2/1. Thus, a higher lime dosage is suitable for sediment-based bricks with lower resistance.
- experimental procedure for building walls has been implemented so as to a horizontal load applied with constant velocity.
- Considering the bonding of bricks and of various types of mortar joints, it was found that for all ratios 1/6, 1/4, 1/2 and 2/1, failure of the pushover test occurs in mortar joints.
- All experiments allowed studying the effect of: wall size, brick type, mortar type on the wall behaviour under lateral load.
- walls with fired reference bricks (FR) having the same bricks size and the same ratio of mortar exhibit a maximum load of 1200 N for large walls, while intermediate and small walls reach a mean value of 440 N and 260 N, respectively.
- for reference fired bricks (FR) walls a rocking failure is the most observed, while shear and sliding failures are less observed.
- a L/S ratio of 2/1 is used for walls with sediment-based bricks, as a result a maximum load of 130 N is measured. Moreover, the sediment-based fired brick has a sliding failure mode while the unfired brick has a rocking failure.

- all the failure modes initiated always in the mortar joints near the base of wall.
- the dimensions of the brick influence the lateral loading of the wall; thus, larger bricks result in a higher maximum lateral load.
- fired bricks that have already been used in experiments can be reused, but to overcome the loss of cohesion of the bricks, it is suggested to use a mortar with a higher ratio of lime to sand L/S (2/1) in order to increase the friction between the interface brick/mortar.
- The ductility largely depends on the area of the wall, the nature and type of brick. Therefore, the ductility parameter of unfired sediment-based bricks stabilized with lime is 15 times higher than that of fired sediment-based brick wall. This indicates that these walls have a lower energy absorption capacity and will therefore be more sensitive to earthquakes. Lime treated walls and reinforced natural fibers provide the desired ductility properties.

This study shows all the importance of using bricks made of sediment in light buildings.

- in the range of pushover maximal loads observed, linear correlations are found between the maximum load of the wall and the corresponding wall area and wall weight with high  $R^2 = 0.99$  and  $0.96$  respectively. More walls must be tested to confirm this statement.
- the obtained pushover loads are not very high but sufficient for light constructions; different kinds of mortar can be investigated to improve this behaviour and to follow how the wall behaviour evolves.
- The durability of the sediment-based bricks must be also investigated in the future.

The three types of the Usumacinta river sediment-based bricks *i.e.* fired, stabilized and fiber-reinforced, used in the construction of test walls, offer sustainable solutions that meet the needs in terms of rational use of material resources and available energy considering the drastic reduction of sediment transport.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

The authors do not have permission to share data.

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