The design and performance of high-performance perforated fired masonry bricks

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Abstract

Fire perforated clay masonry units have been extensively used through years in masonry structures, particularly in masonry walls both for loadbearing and non-loadbearing purposes (partition walls and enclosures). The location of the masonry walls as external enclosure brings some physical requirements, which together with mechanical requirements are the basis of the design of hollow clay bricks.

This chapter provides an overview of the design requirements and design concepts of hollow clay bricks, together with some recent trends arising in the framework of obtaining more sustainable constructive materials. It discusses the main issues related to the mechanical performance of the units and of the masonry assemblages under distinct loading conditions. As often the unreinforced hollow clay masonry is built in seismic prone regions, an emphasis is given to the seismic behavior of hollow clay brick masonry under combined vertical and lateral in-plane loading, being discussed the main seismic performance parameters.

Keywords: perforated clay units, masonry, design requirements, thermal efficiency, mechanical performance

1 Introduction

The use of fired clay hollow bricks in the construction of masonry walls, both in loadbearing and non- loadbearing walls is much common in Europe and other countries (Mosele et al., 2006). In Portugal and other south Mediterranean countries, where reinforced concrete technology prevails in the construction of low to medium rise buildings, the use of hollow clay masonry walls has been limited to the construction of non-loadbearing walls (partitions and enclosures). Typical advantages of hollow clay masonry system as a loadbearing solution are the reduction of execution time, the solution for thermal and acoustic insulation, the significant reduction of thermal bridges, the fire protection and the reduction of coating thickness. In fact, the energy efficiency of buildings and energy saving are aspects to take into consideration when construction materials are designed both from the economic and environment point of view. The building stock is responsible for large amount of energy consumption, representing almost one third of the total amount of energy (Sutcu et al., 2014), which is related mainly to cooling and heating of the indoor environment. Being the hollow clay bricks one of the main units used for the enclosure masonry walls, if they are improved by proper processing, they can significantly reduce the thermal conductivity, which result in lower heat losses through the masonry walls. Aiming at improving the thermal behavior of masonry walls, different geometries and geometrical configurations for the hollow clay bricks have been proposed over the last years (Del Coz Diaz et al. 2008; Morales et al., 2011a), together with the use of more efficient raw materials that are able to induce internal porosity, thus reducing the thermal conductivity and transmittance through the walls (Sutcu et al., 2014).

The design of hollow clay bricks walls should comply with distinct physical and mechanical requirements. Given that the masonry walls (loadbearing and non-loadbearing) are acted by in-plane and out-of-plane loadings due to seismic events, it is important that the clay hollow bricks give to the masonry walls an adequate mechanical behavior when the masonry walls are built in seismic prove regions (Tomazevic et al., 2006). Besides the resistance, it is also important that masonry walls exhibit adequate deformation capacity to accommodate the deformations imposed by the external loading without the development of extensive damage that prevents its repair after earthquakes.

This chapter aims at giving and overview of the fired hollow clay units mostly used in the construction of masonry walls, namely with respect to the geometry, physical and mechanical requirements. The traditional raw materials and the production technology are reviewed and an overview of the recent trend for the incorporation of waste materials in the composition of the brick is provided. Often, the introduction of waste materials aims not only at improving the environmental sustainability of clay bricks by reducing the quantity of clay but also at improving the thermal capabilities of the brick that results is more cost effective solutions. The mechanical performance of hollow bricks and it its influence on the mechanical behavior of masonry is analyzed. In terms of the mechanical behavior of hollow clay masonry distinct loading configurations are also highlighted, namely to compression and cyclic lateral shear. In addition, the main mechanical parameters describing the seismic performance are also pointed out.

2 Conception of fired clay units

Masonry units (concrete blocks, bricks, stone pieces, etc.) are fundamental elements in the definition of geometry and modularity of dimensions, which should be a multiple of the dimensions of the half unit. The clay and concrete are far the most common raw materials used in structural masonry units.

In particular, the hollow clay units have commonly a rough rectangular shape and are characterized geometrically by the global (nominal) dimensions (length x height x thickness). The length and height should be selected to allow for modular construction, being usually multiple of 200mm (nominal dimensions), including the 10mm for the mortar thickness. The modularity is an important characteristic of the masonry units to make the construction technology and geometrical implementation of the structural elements (walls) with openings easier.

2.1 *Design requirements for fired perforated clay units*

The design of clay units should comply with distinct requirements at the level of physical and mechanical properties. Basically, the geometry of the clay brick should be defined based on three main parameters: (a) structural behavior associated to requirements of the constructive system; (b) thermal performance; (c) ergonomics. Additionally, physical parameters should be also taken into account, particularly to control the conditions of use and durability.

In terms of mechanical properties, the quality of the units is much based on the compressive strength in the perpendicular and parallel direction to the bed joints. According to European code requirements, in case of clay units are to be used in buildings located in high seismic prone regions, minimal values for the compressive strength in the perpendicular and parallel direction to the bed face of respectively 5.0N/mm^2 and of 2.0N/mm^2 should be ensured (EC8, 2004). Additionally, an adequate robustness of the units should be also ensured to allow for a suitable behavior of a masonry walls submitted to combined vertical and horizontal in-plane loading. This can be achieved by adequate raw material mix and adequate mould design, avoiding straight angles between shells and webs (Tomazevic et al., 2006). In terms of geometry of clay bricks, the european code (EC6, 2005) provides also requirements related to the geometry of the units, namely the percentage of holes (both vertical and horizontal holes), from which it is possible to attribute a masonry unit group, see Table 1. The masonry unit group is also an important characteristic in the point of view of the hollow clay brick masonry design as some fundamental mechanical parameters such as shear, flexural and compressive strength of clay masonry can be estimated one the group unit is known. Other geometrical features of the hollow clay units are related to the transversal surface of any hole (both deep and through holes), thickness of the webs and shells and combined thickness of webs and shells, see Table 1. The flatness of the faces of brick masonry units should be also ensured. This property can be determined through European standard EN 772-20 (2005).

The physical requirements needed to be considered in the design of clay masonry units are summarized in Table 2. Regarding the density of the clay masonry units two classes are identified, namely low gross dry density (LD units with a gross dry density lower or equal to 1000kg/m^3) and clay units with high gross dry density (HD units with a gross dry density higher than 1000kg/m^3). Some typical units of each class, defined according to EN 771-1 (2005) are shown in Fig. 1 and Fig 2. The porosity can also be determined when it is intended to know the distribution of pores volume in respect to their diameter. The porosity can influence the freeze-thaw resistance.

When the intended use of the units assures a complete protection against water penetration no reference to freeze-thaw is required. On the other hand, when the intended use of the units assures only a partial protection against water penetration and in countries where there is a requirement for freeze and thaw resistance, it shall be evaluated and declared according to the provisions valid for the place where units are applied, see Table 2. In case of HD units, due to its potential use in exterior walls, the freeze-thaw resistance should be declared.

The requirement to declare the active soluble salts content is intended to ensure that under particular service conditions, the damage to the masonry units does not occur. The soluble salts inducing sulfate attack are the sodium, potassium and magnesium. The damage is dependent on the risk of moisture exposition. Three categories are defined according to the requirement associated to the limitation of the soluble sulfates (EN 771-1, 2005), which are also associated to the risk of exposure to moisture.

Immediately after firing, clay products begin to absorb moisture from the environment. This moisture absorption causes complex chemical reactions within vitrified clay itself, leading to moisture expansion. The moisture expansion is increasing with time, being high at early ages and continues very slowly even after many years (Drysdale and Hamid, 2005; Hall and Hoff, 2012). The raw materials, firing temperature and firing time affect the amount of moisture expansion.

The absorption of moisture by capillary action (initial rate of absorption) in the unit produces a suction effect that draws water from mortar to the unit. Too low or too high values can be detrimental in terms of bond strength at the brick-mortar interfaces, resulting in cracks, delamination and soluble salts concentration leading to irreversible deterioration processes (Anand et al., 2003). High values of the initial absorption of the units results in the formation of a dry thin layer of mortar next to the unit. The mortar can stiffen rapidly avoiding a proper setting of units. Thus, appropriate value of initial rate of absorption should be ensured.

For units intended to be used in external elements, the water vapor permeability can be important. This is related to water vapor diffusion coefficient (EN 1745, 2012). Knowledge of the thermo-hygrometric performance of building materials is fundamental to avoid the formation of superficial moisture due to environmental and or construction factors (e.g.

humidity absorption from air, capillary rise) as well as to assess the extent of condensation phenomena (Dondi et al., 2003).

For units to be used in elements subject to fire requirements the classification of the clay units should be provided. If the percentage of organic compounds is lower than 1% (in volume or weight) the units are classified as Class A1 without the need of testing. The masonry units with organic compounds higher than 1% (in volume or weight) need to be classified according to EN 13501-1 (2002).

Complementary to the mechanical requirements, the thermal efficiency takes a major role on conception of the clay bricks. With the new thermal regulations and aiming at achieve more sustainable solutions that result in the saving of energy consumption, additional demand was put in the design of the geometry of the perforated bricks. For example, in Portugal the reference values for the global thermal performance of enclosure walls doubled, with respect to the previous thermal regulation. The environment sustainability of the hollow clay units is much related to the geometry and internal arrangement of the internal cells aiming at obtaining an adequate thermal conductibility coefficient, which is an important criterion as it influences the heat losses from building enclosure walls. Values of thermal conductibility, λ less than 0.55W/(m.K) can be found for normal clay bricks but for lightened clay bricks the thermal conductivity can be less of 0.3W/(m.K) (EN1745, 2012).

2.2 *On the design of the geometry and shape for hollow clay bricks*

The geometry and shape of the hollow clay brick units is directly related to the thermal efficiency required for a certain climatic region. According to Li et al. (2008), the equivalent thermal conductivity depends on the heat transfer processes, namely by convection within the enclosures, radiation between holes surfaces and heat conduction through the solid clay. The optimum number of holes and its arrangements depend on the dominated heat transfer process. With the increase in holes numbers, generally the natural convection and the surface radiation will be deteriorated in some extent due to the increased thermal radiation shield or space limitation for the developing of natural convection. On the other hand, the increase in holes leads to the increase of heat conduction area in solid skeleton with higher thermal conductivity. The final outcome depends on which factor is prevailing. With respect to the internal configuration of the internal voids (ether vertical or horizontal perforations), it is important that thermal bridges are avoided to improve the thermal performance of the brick (Del Coz Diaz et al. 2008; Morales et al., 2011a; Antoniadis et al., 2012). The shape of vertical holes can have distinct configurations, from rectangular voids to triangular or rhomboid voids. Non-rectangular shapes of the voids tends to present greater resistance to the heat transfer and thus to exhibit lower thermal conductivity. Besides, non-rectangular shapes allow for more rows in the same brick leading to lower percentage of voids keeping the same partition thickness, and enabling to achieve lower values for the equivalent conductivity coefficient (Morales et al., 2011b, Lourenço et al. 2010). In Fig. 3, an example of clay bricks with different internal voids shape is given to which different thermal conductivity coefficients are associated. An equivalent thermal conductivity, U, of 0.57W/m^2.K was achieved for rice shape, of 0.56W/m^2.K for lozenges shape and of 0.60W/m^2.K for the rectangular shape of the internal cells (Lourenço et al., 2010). In relation to horizontal perforation, studies have been also carried out in the analysis of the internal configuration of the voids (Antoniadis et al., 2012; Costa, 2014), being in general variable the configuration of the rectangular perforations.

Other aspects that can affect the thermal efficiency are the presence of tongue and grooves at the vertical joints and the assembly at the bed joints. The design of dry vertical joints (tongue and groove) is much common aiming at simplifying the construction technology and avoiding the addition of mortar at the head joints. The tongue and groove head joints tends to decrease the thermal efficiency as it works as a continuous thermal bridge, like the continuous internal ribs (Morales et al., 2012). Thus, a way to avoid the thermal bridges is to break it by extending the voids to the tongue and grove area, thus improving remarkably the thermal behavior. The more breaks there are in the heat flux through the tongue and groove system, better is the thermal performance of the brick assemblages.

Usually, ordinary cement mortars (general purpose mortars) used for building walls constitutes approximately about 5–7% of the total surface area. As the ordinary cement mortar has high thermal conductivity compared to the masonry bricks, the type of mortar joints and the conductivity of the mortar used for laying the brick units take also an important role in the thermal transmittance of brick wall. The results pointed out by Al-Hadhrami and Ahmad (2009) showed that thermal resistance of the walls prepared with insulating mortar increased by about 23–46% compared to that of the samples prepared with ordinary cement mortar. On the other hand, thin layer joints with bond mortar with low thermal conductivity can reduce considerably the thermal transmittance of a brick wall (Juárez et al., 2012; Morales et al., 2014). According to Juárez et al. (2012), the thermal performance of a wall built with a particular type of brick using thin horizontal joints improves by 30% to 37% in relation to a wall made of the same bricks with standard mortar and full-bed joints, depending on their internal geometry. The obtaining of fired clay bricks with perfect laying faces implies a more accurate production technology, which can increase the prices of the units. Besides, the possibility for grinding the bed joint surfaces is related to the clay used in the manufacture of the clay blocks.

3 Raw materials used in the production of perforated fired bricks

3.1 *Conventional raw materials and production technology*

The raw materials used in the manufacturing process are a mixture of natural clay, silt and sand. The clays (recent sedimentary formations) and shales formed from clays under pressure or fire clay, mined at deeper levels are commonly used in the production of fired hollow clay units. All these clays are equivalent in terms silica and alumina chemical composition, which are the main chemical compounds of clay, with smaller amounts of iron, calcium, sodium and other elements. The surface clays present a great variability and in some cases a mixture of clay of distinct locations can be used to reduce the variability (Drysdale ad Hamid, 2005).

The production process of hollow clay bricks encompasses the following steps: (1) disassembly of clay. After the assessment of the quality of raw material, the clay is laid in layers on stockpile and is kept outside for a certain period of time to ensure consistency; (2) processing of clay. In this stage, the clay is collected from the stockpile and shoveled into the box feeder, being mixed with sand, other additive materials and water in the mixer to achieve a correct consistency. After this, the clay is fed into the grinder, where it is reduced in size to small granules and after the transport, the mixed clay is dropped into the extruder; (3) extrusion. The brick mass is pushed through a die and then cut into individual bricks; (4) drying. After the extrusion, the drying takes up to 36 hours for thinner bricks and up to 45 hours for thicker. Moisture content of a brick drops about from 20% to 2%. After the process of drying the bricks automatically transferred to the kiln by kiln cars; (5) firing. The dried bricks are then fired for 6-36 hours in the kiln, which is usually heated by natural gas or coal at a temperature higher than 900°C. The firing of the clay bricks intends to improve durability through sintering, which can be seen as the bonding mechanism of clay particles.

3.2 *Use of byproducts and other additives in the production of fired bricks*

As the production technology based on the firing process contain high embodied energy, due to the need of reducing the natural source material and aiming at obtaining also more efficient solutions in the thermal point of view, several research studies have been studying the possibility of adding distinct byproducts as a substitution of part of the raw clay material. In fact, the conventional bricks are produced from clay with high temperature kiln firing, leading to high energy consumption and release of greenhouse gases. The clay bricks have an embodied energy of 2.0kWh and release in average 0.41kg of carbon dioxide (CO2) per brick (Venkatarama Reddy and Jagadish, 2003). On the other hand, the quarrying operations for obtaining clay are energy consuming and generate high levels of wastes. Therefore, the idea is often to obtain modified clay brick blends with waste and byproducts and use the traditional technology for the production of hollow bricks. It is also expected that no remarkable differences on the general properties of hollow clay bricks, such as compressive strength and water absorption, are obtained.

With this respect, very different byproducts have been used to replace the clay with reasonable results in terms of physical and mechanical properties, mainly as related to compressive strength of the fired material. A general overview of the different residues that have been used in the recent past can be found in Raut et al. (2011) and in Zhang (2013). It should be stressed that fly ash (particularly class F) has been largely used by different authors (Sutcu and Akkurt, 2009; Gorban and Simsek, 2013; Demir et al., 2005). All the authors found that the fly ash can replace clay at high volumes ratios. In general, the compressive strength of modified clay bricks is higher than in standard clay bricks and the water absorption presents lower values. Additionally, it was seen that the bond strength, durability (resistance to freeze-thawing cycles) is also better than in standard clay bricks. The use of stone residues such as granite sawing wastes (Menezes et al., 2005), granite-basalt fine quarry residues (Sutcu and Akkurt, 2009), waste marble powder (Bilgin et al., 2012) revealed also to be adequate for replacing conventional clay raw material. The granite sawing wastes have similar physical and mineralogical characteristics to conventional clay raw materials and demonstrated to lead to final products with characteristics fitting the requirements of Brazilian standardization. In general, the use of these residues revealed to be adequate taking into consideration the needed physical and mechanical requirements.

The thermal conductivity of a hollow brick is related to the geometry of the hollow cells, and can be optimized according to different geometries of the hollow cells, as discussed in section 2.2. Additionally, the thermal performance of hollow clay bricks is also dependent on the thermal conductivity of the bulk of the material that constitutes the brick. In this way, the thermal performance of the hollow clay bricks can be also improved by acting on the thermal conductivity of the solid part. The enhancement (reduction) of the thermal conductivity of the material can be obtained by the addition of pore-forming agents to the brick material before firing, like wood sawdust, polymers, leather residues, paper-making sludge, powered limestone, polystyrene (Zhang, 2013). Lourenço et al. (2010) refers the use of organic wastes from wood and paper industry, namely sawn dust from wood (SD), cork dust (CD) and paper mill sludge (PM). In this work, distinct percentages of the organic wastes were added to the paste in order to decide for an optimum composition. From Fig.4 it is observed that an increase on the percentage of organic waste leads to a reduction of the specific mass and of the thermal conductivity. The introduction of industrial paper residues was also investigated by other authors (Raut et al., 2011; Sutcu et al., 2014). The raw materials blends containing up to 30 wt% of wastes, experienced a reduction of the thermal conductivity of approximately 50% without the decreasing of the compressive strength below the recommended values. Of course that a balance between mechanical performance and thermal insulation of the brick has to be found as, in general, the addition of wastes results in the decrease of the compressive strength. In the work carried out by Demir et al. (2005), it was confirmed that the addition of kraft pulp residues in clay brick production can be effectively used as an organic pore-forming in clay body without any detrimental effect on the other brick manufacturing properties. Both density and compressive strength reduces but these are still higher than the ones required by codes. After the work carried out by Gorban and Simsek (2013), it was seen that the thermal conductivity can also be improved by adding rice husk in a proportion between 2.5 and 5% to the clay, being effective as a pre-forming agent in the clay body.

4 Mechanical characteristics of perforated fired bricks

The most important mechanical characteristic of masonry units and particularly of hollow clay units is the compressive strength. This property is an indication of the quality of the brick and provides information about the adequacy for the use of hollow clay bricks in loadbearing or in non-loadbearing walls. As already discussed, the masonry units should comply with compressive strength requirements when used in seismic prone regions (EC8, 2004).

The compressive strength of masonry units is obtained from uniaxial compression tests based on standardization that defines the loading protocols, equipment and procedure (EN 772-1, 2000). The uniaxial compression tests can be carried out in force or displacement control, but the latter is preferred if the behavior of the hollow brick after the peak load is required.. An example of the typical uniaxial compressive behavior of hollow clay bricks (300mm x 300mmx 200mm) considering two distinct configurations according to the process for the laying of the masonry units on full mortar bed joints (FBM) or as partly (“shell”) bedded (SBM) is presented in Fig. 5 (Lourenço et al., 2010). The shell bedded joints can be preferred to ensure an adequate behavior to water infiltration from rain by avoiding humidity bridges for example. For partly bedded units two strips of 90mm of general purpose mortar were considered, being the vertical load applied only in the thickness of the mortar strips through two steel plates with the same thickness. Normalized compressive strengths, f_b, of 13.9N/mm^2 and 10.5N/mm^2 were obtained for full bedded and shell bedded units respectively, meaning that the shell bedded brick presents a reduction of about 25% on the compressive strength. The lower compressive strength of the shell bedded masonry unit is associated to the higher tensile stresses developed in the perpendicular direction to the applied load as is shown in Fig. 6, where the distribution of the tensile principal stresses obtained from numerical simulation is illustrated (Lourenço et al., 2010). The highest tensile stresses are distributed on the vertical perforations along lines corresponding to the end of loaded area. These tensile stresses are associated to tensile strains, which leads to the cracking and lateral splitting of the units, according to what was observed from the experimental failure modes.

The analysis of the stress-strain diagrams indicates that the post-peak behavior of the hollow bricks could not be recorded due to its brittle nature under compression. In fact, both types of bedding exhibit brittle behavior accompanied by vertical cracking and splitting of the internal webs, with failure occurring by splitting of the external shells of the units. The pre-peak regime is also similar, even if the scatter on the compressive strength is higher and the cracking before failure is more extensive for partial bedded clay units.

In spite of the compressive strength parallel to the vertical perforations (perpendicular to bed joints) corresponds to the majority of the loading solicitation, it should be noticed that the compressive strength in the parallel direction to bed joints is important for masonry beams, which are considered as structural elements connecting the masonry piers between openings (Vladimir et al., 2012). The compressive numerical behavior of clay units with rice grain and rectangular shape of the vertical perforations pointed out in Lourenço et al. (2010) under compression for the three main loading directions (one perpendicular and two parallel to bed joints) can be made through Fig. 7. It is observed that hollow clay units present a considerable anisotropic behavior, being the strongest direction parallel to the vertical perforations as expected. The response under uniaxial compressive loading of both clay units is similar in the direction perpendicular to bed joints. However, the hollow clay unit with rectangular perforations presents higher stiffness and compressive strength in both directions parallel to bed joints. The anisotropic behavior is a result of the geometry of the clay units and is essentially associated to the higher stiffness and higher net area in each distinct direction. The anisotropy degree between the compressive strength normal and parallel to the bed joints is close to the value presented by Tomazevic and Weiss (2012) of 0.3 for the ratio between the compressive strength in the parallel and perpendicular direction to the bed joints.

Despite it is not very usual to obtain the tensile and shear strength of the masonry units, Tomazevic and Weiss (2012) presented the values of the tensile and shear strength of different hollow clay blocks obtained based on splitting and diagonal compression (tensile strength) and shear tests (shear strength). It was found that the values of the shear strength of hollow clay units are higher than the tensile strength, being the ratio between the normalized shear and compressive strength in range between 0.10 and 0.20. The ratio between the normalized tensile and compressive strength is the range between 0.03 and 0.09. Both shear and tensile strength appears to be related to the combined thickness of the shells and webs, presenting a trend for increasing with higher percentage of the combined thickness and decreasing volume of holes.

It should be stressed that the mechanical characteristics of hollow clay units are particularly important when walls are submitted to combined in-plane vertical and horizontal loading

(Tomazevic et al., 2006), as the ductility and energy dissipation of the walls depends on the local behavior of the clay bricks.

5 Masonry assemblages with fired perforated brick masonry

The masonry is considered as a composite material composed of units and mortar and unit-mortar interfaces and its mechanical behavior depends on the mechanical characteristics of the elements and also on its arrangements. The loading configurations to which masonry is submitted depend on the structural element to which it belongs. In case of masonry walls, where hollow clay units are almost exclusively used, compressive and in-plane lateral loads are the most important loading configurations when the mechanical behavior of masonry is analyzed.

5.1 *Mechanical performance of brick masonry under compression*

Several experimental, numerical and simplified analytical studies have been carried out in order to increase the knowledge about the compressive behavior of masonry (McNary and Abrams, 1985; Khalaf et al., 1994; Page and Shrive 1988; Gihad and Lourenço, 2007). Being masonry a composite material made of units and mortar, it has been largely accepted that its failure mechanism and resistance is governed by the interaction between the components. The evaluation of compressive behaviour plays a major role in the characterization of masonry as a structural element since compression is a primary loading to which structural walls are subjected. Compressive behaviour is also important when masonry is subjected to lateral loading since the in-plane behaviour depends on the compressive properties of masonry, especially if flexural resistance mechanisms predominate (Haach et al., 2011). The finite element numerical analysis of masonry walls based on macro-modelling also requires the data regarding the mechanical behavior of masonry under compression and the key mechanical properties, namely the compressive strength, elastic modulus and fracture energy.

The compressive behavior of masonry is usually determined based on experimental testing, generally according to the standards (EN 1052-1, 1999). An example of the typical compressive behavior of hollow clay masonry is shown in Fig. 8. The stress-strain diagrams were obtained under displacement control and describe the compressive behavior of full bedded masonry specimens (FBM) and partial (“shell”) bedded masonry (SBM) built with prebatched mortar M10 (group 2 units) and unfilled vertical joints. From the stress-strain diagrams it is possible to determine the compressive strength and modulus of elasticity of masonry. It is seen that the behavior of the full bedded masonry is relatively brittle, as no post-peak behavior was found. The response of partly bedded masonry is more ductile in the sense that no abrupt failure occurs, which corresponds to a higher capacity to redistribute compressive stresses within the specimen. A considerable reduction on the compressive strength of the shell bedded masonry was recorded, even if no significant change on the shape of the pre-peak behavior (and thus on the initial stiffness) was detected in relation to full bedded masonry. The stress-strain diagrams are very close to the stress-strain diagram obtained by Tomazevic an Weiss (2012) on hollow clay masonry made of different hollow bricks with distinct arrangement of the internal holes. The pre-peak behavior is characterized by some nonlinearity much close to the peak resistance and almost no post-peak was recorded. Similar behavior was also pointed out on clay masonry (with clay blocks with rectangular vertical perforations with a volume percentage of 46% - group 2) tested by Mojsilovic (2006). In this case, the normalized compressive strength of units is considerably high (between 28.6MPa and 42.0 MPa), which should result in a brittle failure. It is interesting to notice that the masonry built with clay units belonging to the group 1 (EC6,

2005) present a more ductile behavior under compression, which should be associated to lower percentage of volume of holes and higher combined thickness of the shells and webs (Tomazevic and Weiss, 2012).

Cracking of the hollow clay masonry is predominantly vertical, developing in the internal webs and shells of the units (Lourenço et al., 2010; Tomazevic et al., 2006; Mojsilovic, 2006, Da Porto et al., 2011a) and the failure is characterized by spalling, buckling and separation of the shells and vertical splitting and crushing of the webs, see Fig. 9. This behavior can also be attributed to the lateral tensile stresses induced in the units by the distinct deformation characteristics of masonry units and mortar at the bed joints (McNary and Abrams, 1985; Khalaf et al., 1994) and to the bucking of the vertical webs in case of horizontal perforation.

5.1.1 Prediction of the elastic properties of masonry under compression

The compressive strength of masonry can be estimated through empirical formulas generally based on the results of experimental tests (Kaushik et al., 2007; Dymiotis and Gutlederer, 2007; ACI, 1999). European masonry code (EC 6, 2005) proposes the eq. 1 to estimate the compressive strength of masonry:

$$f_k = k f_b{}^{0.7} f_m{}^{0.3} \qquad [1]$$

where k depends on the type and shape of units and mortar at bed joints, f_b is the normalized compressive strength of the unit and f_m is the characteristic compressive strength of mortar. For hollow clay units of group 2 and general purpose mortar, the value of k is 0.45. The application of this formula resulted in the overestimation of the compressive strength of group 2 units (Lourenço et al., 2010) and particularly in case of bricks of group 1 (Tomazevic and Weiss, 2012). However, more recently, it was shown that several empirical formulas applied to a great amount of experimental data generally gives compressive strength values of masonry on the safety side (Garzon-Roca et al., 2013).

The modulus of elasticity of masonry can be determined based on the experimental results, generally by taking the tangent value at 1/3 of the compressive strength of masonry in the stress-strain diagrams or by considering the secant values in a range between 0.1 and 0.4 of the compressive strength (Da Porto et al., 2011a). It can be also estimated from the compressive strength of masonry. According to EC6 (2005), the elastic modulus can be obtained from the eq. 2:

$$E = k_E f_k \tag{2}$$

Where k_E is recommended to be 1000.

The comparison of the values of the elastic modulus estimated based on eq. 2 and the experimental values obtained in full and partial bedded hollow clay brick masonry provided by Lourenço et al. (2010) revealed that the difference is reasonable, being of 15% and 3% for full and partly bedded masonry, respectively.

On the other hand, the values of shear modulus, G, used for example in the calculation of the lateral stiffness of masonry walls, can be estimated by multiplying the modulus of elasticity by 0.4 (EC6, 2005). However, according to Tomazevic (2009) the values of the shear modulus of clay brick masonry are considerably lower, and can be fixed in 10% of the modulus of elasticity. These results were obtained based on the in-plane experimental tests carried out on hollow clay brick masonry walls.

5.2 *Mechanical performance of brick masonry under shear*

In case of modern masonry, where the connections between walls and between walls and rigid diaphragms are ensured, the global stability of the masonry buildings, when submitted to seismic action, is essentially guaranteed by the resisting mechanism of masonry walls that behaves predominantly in shear. This justifies the relevance that has been given to the analysis of the behavior of masonry walls under in-plane cyclic loading.

5.2.1 Solutions for hollow clay brick masonry walls

Several constructive systems based on hollow clay units for new masonry have been proposed recently (Mosele et al., 2006). To become the construction technology easier, different types of head and bed joints have been proposed. The advances on the production technology of hollow clay units and accurate dimension of the units led to use thin layer mortar instead of general purpose mortar (Da Porto et al., 2009). Besides, given that structural masonry walls or even enclosure non-loadbearing hollow clay masonry walls are composed of only one leaf, due to the great width of the brick to comply with thermal requirements, it is proposed that the mortar at bed joints is placed by strips to improve the performance of the walls to humidity (face shell masonry) (Lourenço et al., 2010) see Fig.10. On the other hand, there is a trend to use unfilled vertical joints to make the construction faster and novel shapes for the hollow clay tongue and groove for head joints are adopted (Lourenço et al., 2010; Da Porto et al., 2009; Da Porto et al., 2011b). The hollow clay units with tongue and grove head joints enable the consideration of dry masonry head joints due to the interlocking between units at the head joints to ensure the resistance of the walls for out-of-plane loading. Even if unfilled vertical joints are not recommended in masonry walls built in seismic prone regions (EC8, 2004), there has been an attempt to study the possibility of using unfilled joints, unfilled joints with interlocking or partially filled head joints with mortar in pockets, as some freedom in given in the national annexes European countries (Tomazevic et al., 2006).

It is also common to reinforce hollow clay masonry by adding steel reinforcement at bed joints or in the vertical direction located in vertical holes formed by the frogged ends of the masonry units (Lourenço et al., 2010; Da Porto et al., 2010), where mortar is introduced to ensure appropriate adherence of the reinforcements to the masonry.. The addition of reinforcement at the walls intends not only to improve the lateral resistance of the walls, but also the deformation capacity in the nonlinear range and the ability to dissipate energy during cyclic loading. The hollow brick masonry with mortar pockets can be classified as having fully filled head joints as mortar is provided over a minimum of 40% of the unit width. Hollow clay brick with C shape and H shape have been proposed to make the construction of the reinforced masonry easier (Da Porto et al., 2011a). The horizontal reinforcements can also be placed in recesses made in the brick units (Da Porto et al., 2011b) to improve the in-plane cyclic performance.

5.2.2 Experimental characterization of hollow clay brick masonry walls

In the scope of seismic experimental research, distinct testing approaches have been used for unreinforced masonry structures, namely quasi-static monotonic or cyclic tests, dynamic shaking table tests and pseudo-dynamic tests. According to Calvi et al. (1996), despite dynamic tests simulate with more accuracy the seismic action, cyclic quasi-static tests enable more accurate measurements of forces and displacements and the record of damage evolution becomes easier. The quasi-static cyclic tests are typically carried out on walls submitted to a combination of vertical loads, simulating the permanent loads and monotonic or cyclic horizontal loads simulating in a simply way the seismic loading. Typical fixed-fixed or fixed-free cantilever walls are adopted in the static tests. Although the latter do not represent real boundary conditions, it renders the interpretation of results and testing setup easier. This testing configuration has been adopted in several research programs (Bosiljkov et al., 2003; Vasconcelos and Lourenço, 2009; Haach et al., 2010).

The main resisting mechanisms that are characteristic of the response of the masonry walls submitted to combined in-plane loading are shear and flexure, which result is distinct failure modes (Fig. 12). The predominance of the shear or flexure is associated to distinct factors, namely the geometry of the walls (height to length ratio), level of pre-compression loading, boundary conditions, masonry materials and masonry bond. In general, in squat walls shear resisting mechanism predominates and in slender walls, the flexural resistance mechanism plays the major role. Low pre-compression load levels are associated to flexural resisting mechanisms and high pre-compression load levels are in general associated to the development of more important shear resisting mechanism. In case of cantilever walls, the lateral load applied at the top of the wall leads to the generation of a diagonal flow of compressive stresses from the load application point up to the opposite bottom corner. Diagonal tensile cracks develop often in the alignment of the compressive strut associated to the tensile stresses developed in the perpendicular direction of the strut (Fig.12a). The progressive concentration of compressive stresses at bottom corners results in most cases in their crushing. Fixed ends walls present also the diagonal flow of compressive stresses, but here the stresses concentration can occur at the top and bottom corners of the wall, resulting in the possible crushing. On the other hand, this configuration of stresses results in more common diagonal tensile cracks, meaning that for this boundary condition the shear behaviour is more predominant (Haach et al., 2011).

The typical experimental behavior of masonry walls is described based on the force-displacement diagrams relating the force applied at the top pf the wall and the displacement at the top of the wall. Fig. 13 shows the typical force-displacement diagrams obtained in unreinforced hollow clay brick masonry with full and partially bedded masonry and with filled and unfilled vertical joints with an aspect ratio of 0.91 and tested in cantilever boundary configuration under a pre-compression load of 0.07 and 0.1 % of the compressive strength. The full bedded masonry wall with filled vertical joints (FBM-FVJ) presents clearly a predominant flexural (rocking) mechanism associated to the S shape of the force-displacement diagrams. The limitation of the lateral displacement is associated to masonry crushing of the bottom corners. The maximum lateral displacement of shell bedded masonry (SBM-FVJ and SBM-UVJ) is lower than the full bedded masonry in case of unfilled vertical joints and particularly in case of filled vertical joints, which exhibits a very brittle behavior. It is seen that the maximum lateral force is attained for low lateral displacements and failure occurs soon after the maximum load is reached. The in-plane cyclic behavior of full and shell bedded masonry with filled vertical joints is characterized by: (a) opening of horizontal crack at the bottom bed joint, (b) rocking mechanism over the lower corners and (c) crushing of the bottom corners, see Fig. 14.

It should be mentioned that in general the in-plane behavior of the unreinforced hollow clay masonry with units belonging to group 2 (EC6, 2005) is described by force-displacement diagrams close to the ones presented in Fig. 13, with a predominant S shape and somewhat narrow hysteretic loops, at least up to peak lateral resistance (Tomazevic et al., 2006; Da Porto et al., 2009). After the peak load resistance is attained there is a sudden degradation of the lateral resistance, corresponding to the brittle failure of the masonry walls. This behavior is in part explained by the brittle nature of the hollow blocks. It should be stressed that an important issue related to the in-plane behavior of hollow clay masonry walls is the robustness of the hollow clay bricks as the local failure of the bricks can result in a brittle collapse of the walls and lead to deficient responses in terms of energy dissipation and ductility. The robustness of hollow clay units can be particularly relevant in reinforced masonry, in which the exploitation of the tension capacity of reinforcements is desired. The idea for the need of robustness of the hollow clay bricks was introduced in EC8 (2004), when dealing with seismic behavior of new masonry structures, even if no quantitative criterion is given to evaluate the robustness. However, according to the recent results of Tomazevic and Weiss (2012), it was concluded that the requirements and recommendations for sufficient robustness of the hollow clay units for the intended use in seismic regions are only partly a function of the units type as they behave reasonably in the walls submitted from low to moderate levels of pre-compression load and present a brittle response for high levels of pre-compression levels.

5.2.3 Seismic performance indexes for hollow clay brick masonry

The evaluation of the seismic performance of unreinforced stone masonry shear walls is carried out in terms of performance indexes, including the ductility and energy dissipation capacity. The ductility is a useful measure that makes possible the reduction of elastic seismic design actions by means of a behavior factor, since it gives an indication of the ability of the structure to dissipate energy (Tomaževič, 1999; Da Porto et al., 2009).

The idealized bilinear envelop of the force-lateral displacement diagrams has been widely reported in the literature as a simplified method of evaluating the in-plane seismic performance (stiffness, strength and ductility) of masonry walls under cyclic loading (Shing et al., 1989; Magenes and Calvi, 1997; Bosiljkov et al., 2003). The experimental envelop is defined by considering the force-displacement points of the hysteresis loops for which the displacement exceeds the previous maximum displacement (Schultz et al., 1998). According to Tomaževič (1999) three limit states need to be defined in order to idealize the experimental envelope, see Fig. 15, which are identified through three characteristic points in the force-displacement diagrams. The crack limit state corresponding to the formation of the first significant cracks is defined with the point (H_{cr}, d_{cr}). The maximum resistance is identified by the couple (H_{max}, d_{Hmax}) and the ultimate state is related to the maximum displacement attained during the cyclic test and is associated to the point (H_{dmax}, d_{max}). The initial secant slope in the elastic-plastic diagram, K_e, at the formation of flexural cracks, is calculated as the ratio between the lateral force, H_{cr}, and lateral deformation, d_{cr}. The value of the ultimate resistance of the elastic-plastic diagram, H_u, is obtained by ensuring equal energy dissipation of the idealized diagram and the monotonic experimental envelope. The ultimate idealized displacement, d_u, is commonly defined as the intersection of the idealized bilinear diagram with the softening branch of the experimental envelope (Tomaževič, 1999).

Table 3 summarizes the values of indicative points of the non-linear response of hollow clay masonry the masonry walls tested under in-plane cyclic loading by different authors, namely the ratio between H_u and H_{max}, and the rotation angles corresponding to the maximum load, θ_{Hmax}, and to the ultimate load, θ_u, calculated as the ratio between the top displacement measured in the walls and the height of the wall. In terms of ultimate load, H_u, obtained in the idealized bilinear diagram for the hollow clay brick masonry, equivalent to monotonic experimental envelop, it is observed that the a value of 0.89 (H_u/H_{max}) was obtained for partly bedded masonry SBM-UVJ (Lourenço et al. (2010), which is close to the value pointed out by Tomaževič (1999) for walls failing in shear. For the specimen FBM-FVJ, a value of 0.95 was observed, which is directly related with the typical flexural envelop. For specimen SBM-FVJ, the value of 0.83 is associated to the very brittle behavior found, which means that a higher reduction of the experimental maximum load should be considered. These values are very close to the ones pointed out by Da Porto et al. (2009) for hollow clay brick masonry walls with tongue and groove head joints, and walls with mortar pockets. In relation to the deformation, it can be seen that apart from the low value of the rotation angle at the maximum resistance (θ_{Hmax}) for the hollow clay brick masonry walls submitted to pre-compression levels of 30% of the compressive strength (walls BM0.3), in all the other cases the rotation angle at the maximum lateral resistance are in the range of 0.3-0.6 mentioned in Tomazevic and Weiss (2012) for the rotation angle corresponding to maximum resistance. It is observed also that the hollow clay brick masonry walls BM0.3 present a rotation angle at the ultimate state, θ_u, of 0.7, which appears no to be acceptable when compared to the range mentioned also by Tomazevic and Weiss (2012) of 1.0-1.2% for the ultimate rotation angle. This value is lower the one recorded in walls submitted to a compression vertical load of 15% of the compressive strength (BM0.15). It is interesting to notice the remarkable influence of the vertical pre-compression level on the in-plane behavior of hollow clay brick masonry walls (BM), for which a great difference on the lateral deformation of the walls were found, being the highest pre-compression levels associated to a much brittle behavior. According to Da Porto et al. (2009), for nonlinear analysis of shear walls, the Italian code proposes a maximum horizontal displacement of 0.4% of the wall height in walls failing in shear and a maximum horizontal displacement of 0.8% of the wall height in walls failing in flexure.

Another index for the evaluation of the seismic performance of masonry walls under in-plane loading is the dissipation of energy during the hysteretic response of the wall. A dissipative structure can mean the reduction of the seismic response and, consequently, the reduction of the ductility demand (Shing et al., 1989). On the other hand, more dissipative structures have associated higher reduction factors used for the calculation of the reduced elastic seismic forces when using the equivalent elastic static method of analysis for structural analysis. The energy that is dissipated at each loading cycle, E_{diss}, is obtained by integrating numerically the force-displacement hysteresis loop between two consecutive displacement peaks, see Fig. 16. The input energy is the energy needed to deform the masonry walls from the equilibrium position until a certain level of displacement previously defined. It is calculated as the area under the straight line connecting the origin and the peak force of the hysteresis loop, see Fig. 14. The values of hysteretic dissipated energy are low in case of narrow hysteresis loops of the force-displacement diagrams or when “pinching” effect is visible, which happens when force-displacement diagrams present an S shape. This is the case of the results pointed out by Da Porto et al. (2009) for hollow clay brick masonry walls with different types of bed and head joints and also in case of walls tested by Lourenço et al. (2010). The relation between input and dissipated energy pointed out by Tomazevic et al. (2006) for the hollow clay brick masonry walls with distinct perpend joints was also low, which could be attributed to the brittle nature of the walls resulting from the local failure of the hollow clay bricks. In fact, the premature collapse of the hollow clay bricks resulted in average values of ratio of the dissipated and input energy of about 0.17 at maximum resistance and of about 0.26 at ultimate state. This values were clearly lower the values of 0.3 and of 0.4-0.5 at maximum and ultimate states respectively when the walls do not present local brittle failure of the bricks. The study carried out by Tomazevic and Weiss (2012) on the influence of the geometry of the units on the performance of in-plane behavior of brick masonry walls indicated that the ratio between input and dissipated energy, both at maximum resistance and at ultimate load, does not depend on the geometry of the units, at least if the hollow clay bricks belong to the same group according to EC6 (2005). This study concluded also that the dissipated energy is more related to the levels of pre-compression level that determine the failure mode of the masonry walls, and thus the ability of the walls to dissipate energy.

6 Concluding remarks

The hollow brick masonry is a material widely used in the construction of masonry walls of buildings that work as loadbearing and non-loadbearing walls. As enclosure walls, the hollow brick masonry walls should comply with appropriate physical properties that assure its functional behavior under service loads. This Chapter discussed the main physical and mechanical requirements that should be taken into account in the design of hollow brick masonry units so that an appropriate physical and mechanical behavior of masonry is achieved. An overview of the behavior of hollow brick masonry under distinct loading configuration was also provided and the relation with the mechanical performance of the brick was established.

Among the physical properties, the thermal conductivity play a central role as it is required that the masonry walls present heat losses that result in high energy consumption. The thermal efficiency of the hollow brick can be enhanced both at the level of geometry either by designing an appropriate internal arrangement of the perforations and by introducing changes on the compound raw materials. With this respect, organic materials have been considered as after the firing process they naturally induce porosity that reduces the thermal conductibility and thus the transmittance of the brick masonry walls.

Another aspect that should be taken into account when designing the hollow brick units consists of the mechanical performance, mainly as related to the compressive strength. The compressive strength of units is mobilized not only under vertical loading but also under lateral in-plane and out-of-plane loading. For in-plane loading, besides the resistance, it is important that walls have adequate deformation capacity in the non-linear range so that premature damage is developed and brittle response of the brick masonry walls is prevented. This is much related to mechanical properties of brick masonry, which are directly related to the mechanical performance of the hollow brick.

7 Future trends

The need for a more sustainable construction has been putting additional demand on the design of more efficient construction materials. In this scope, two main approaches have been followed by researchers, namely: (1) achieving more sustainable materials with incorporation of wastes and byproducts (Vasconcelos et al., 2013) by the reduction of natural raw materials and by reducing the embodied energy; (2) more efficient solutions in the point of view of the energy saving by reducing energy consumption in cooling and heating on the environment indoor of buildings. Both approaches have resulted in several studies on alternative raw materials and on the geometrical configurations (internal holes arrangement) of hollow brick masonry units aiming at optimize the thermal efficiency of the bricks.

It is considered that in the point of view of the physical and mechanical efficiency of hollow bricks, additional work is expected to carry out in the evaluation of the possibility of using nanotechnology for achieving smart hollow bricks, namely (1) to improve its resistance and deformation ability that ensure more effective responses of masonry walls under earthquake induced loads; (2) to enhance its thermal insulation ability; (3) to control the cracking that develops under service loading conditions; (4) to give sensing and self-repairing ability after damage that can be induced by low to medium earthquakes. In case of hollow blocks used in veneer walls, it should be also possible to combine new geometries with functionalized surfaces by acting either on the raw materials or on the surface coatings that promotes self-cleaning and hydrophilic surfaces aiming at improving thermal performances through the buildings skin.

It is also stressed that the development of improved hollow bricks to be used in loadbearing and non-loadbearing walls should be thought in an integrated context of a development of a constructive system for masonry walls.

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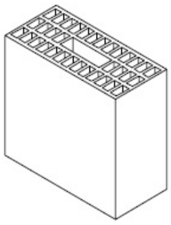

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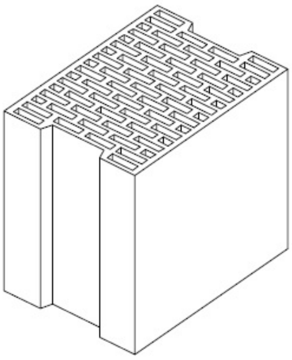

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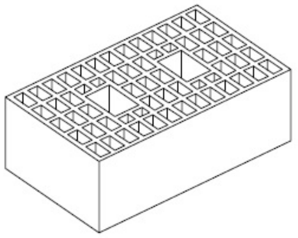

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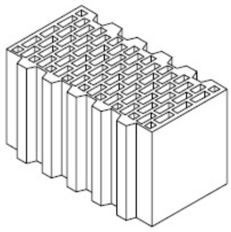

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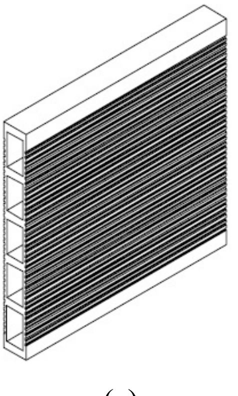

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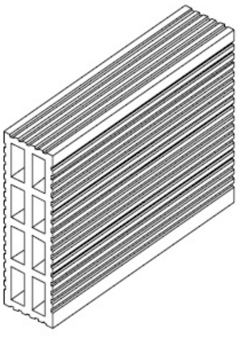
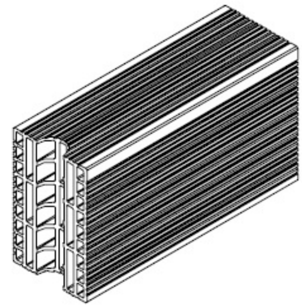
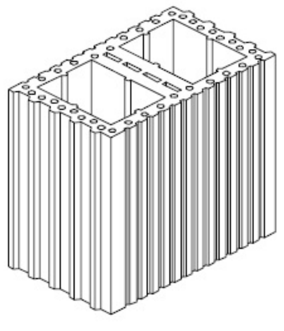
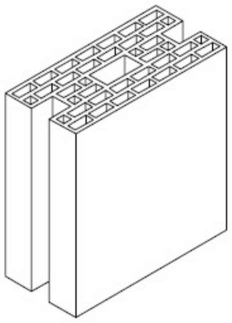


(f)



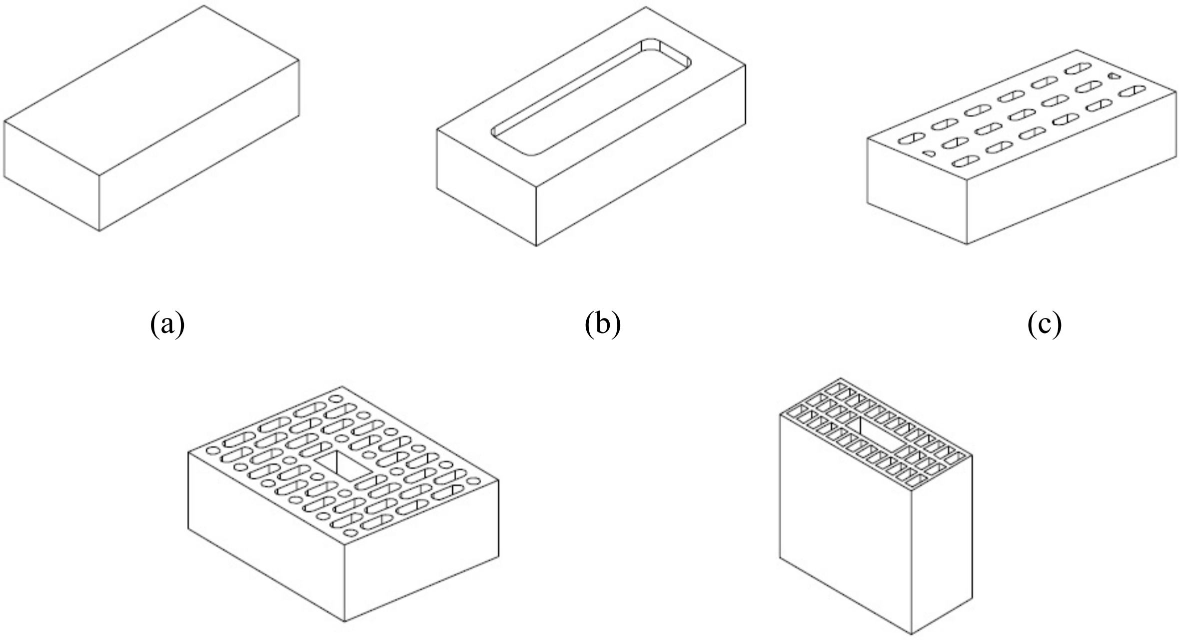




(g) (h) (i)

Fig. 1

LD clay units; (a) vertically perforated unit; (b) vertically perforated unit with mortar pockets; (c) vertically perforated unit grip holes; (d) vertically perforated unit with tongue and groove; (e) horizontally perforated unit for partitions walls; (f) horizontally perforated unit with rendering keyways; (g) horizontally perforated unit with mortar pocket; (h) unit for concrete or mortar infill; (i) unit for masonry panels;



(a) (b) (c)

(b) (c)

Fig. 2

HD clay units; (a) solid unit; (b) frogged units; (c) vertically perforated unit; (d) vertically perforated unit; (e) horizontally perforated unit

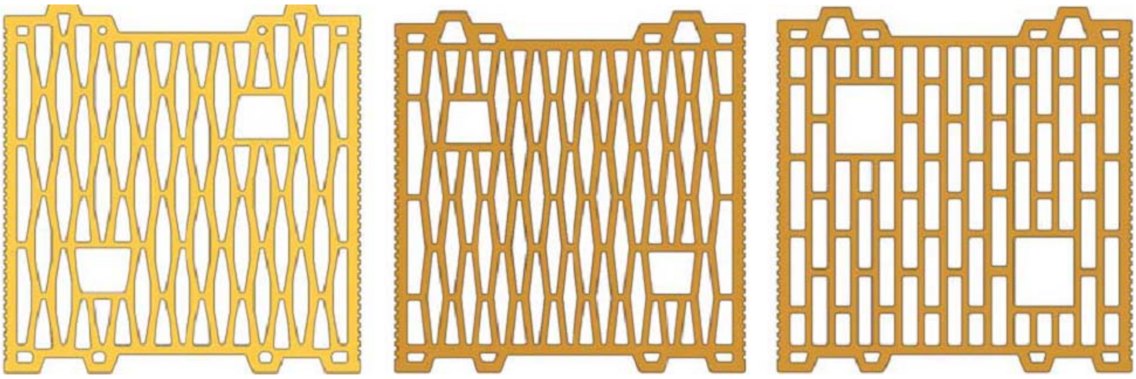
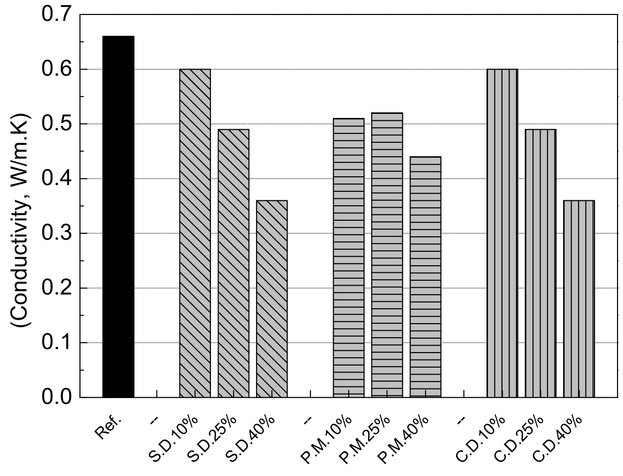
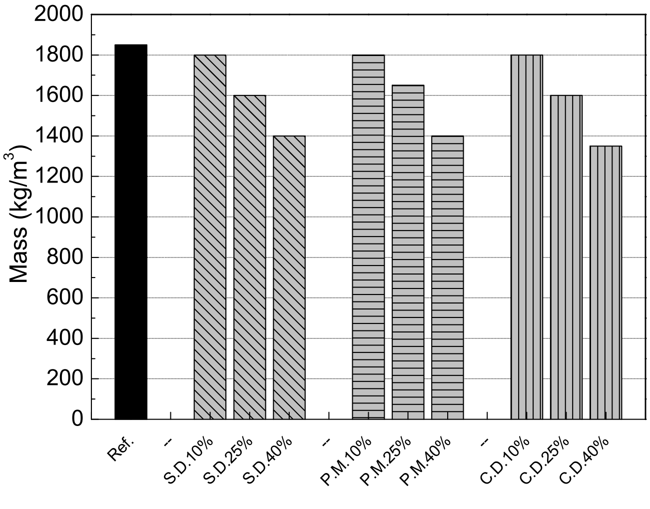

(a) (b) (c)

Fig. 3

Distinct shapes for the internal voids of a brick masonry; (a) ; (b); (c) rectangular shape



(a)



(b)

Fig. 4

Evaluation of different additives on the physical and mechanical behavior of the clay material: (a) conductivity; (b) mass. Here, the reference solution is a clay paste without any additives.

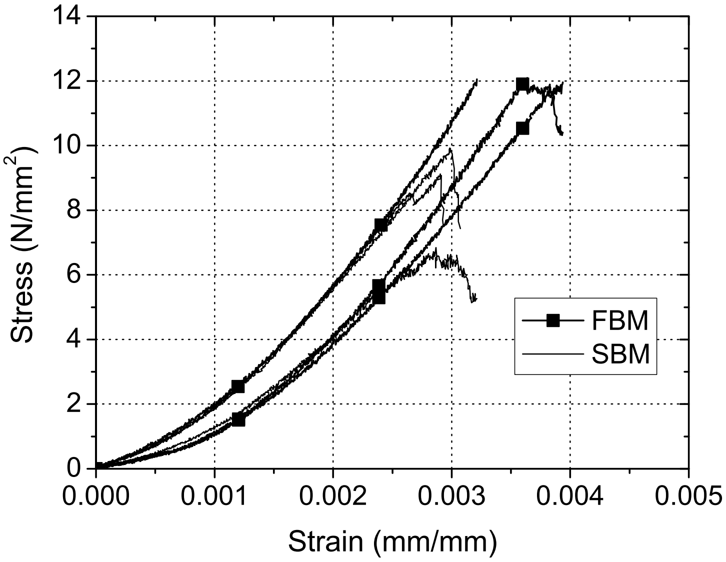
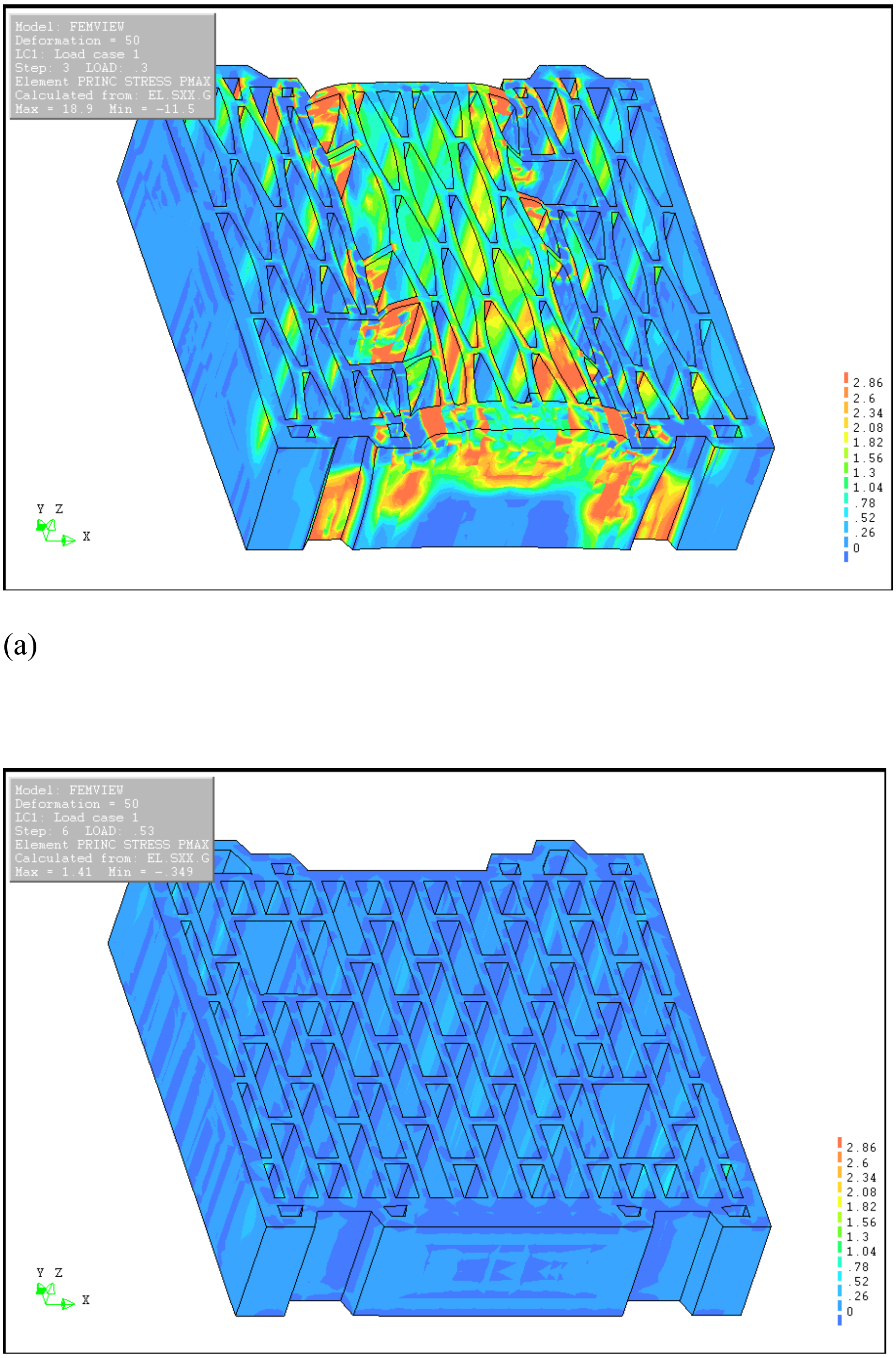


Fig. 5

Typical stress-strain diagrams under uniaxial compression



(a)

(b)

Fig. 6

Distribution of principal tensile stresses (units inN/mm^2); (a) shell bedded clay unit; (b) full bedded clay unit.

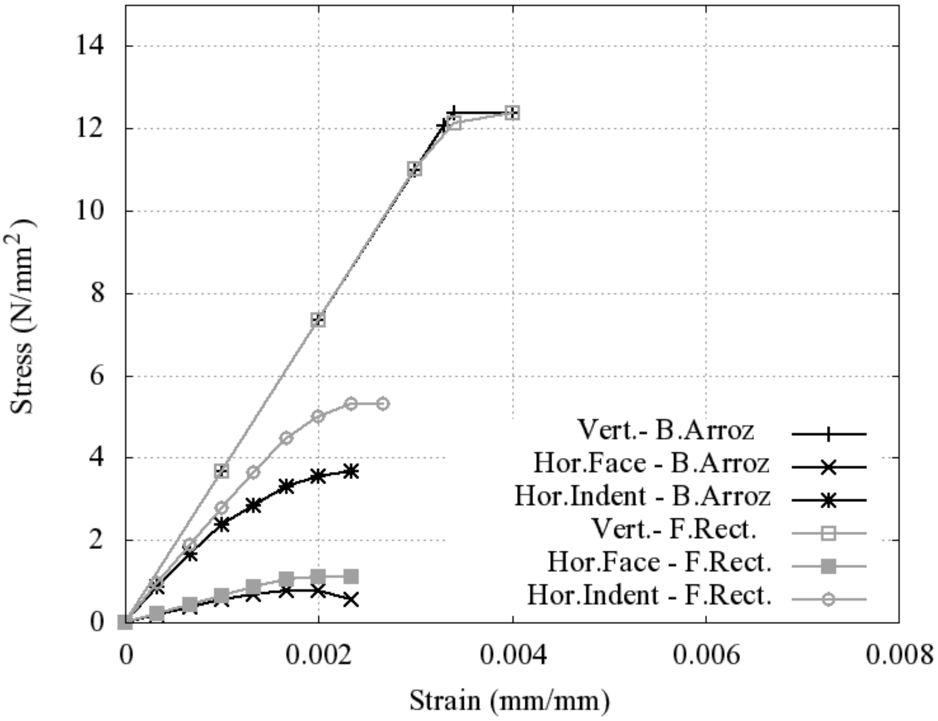


Fig. 7

Stress–strain diagrams in three main loading directions

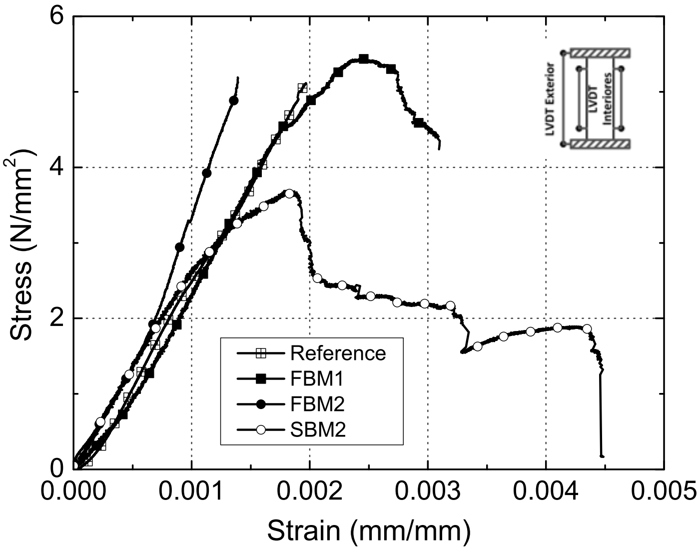


Fig. 8

Typical stress–strain diagrams of clay brick masonry under compression

Fig. 9

Typical failure modes of clay masonry under compression

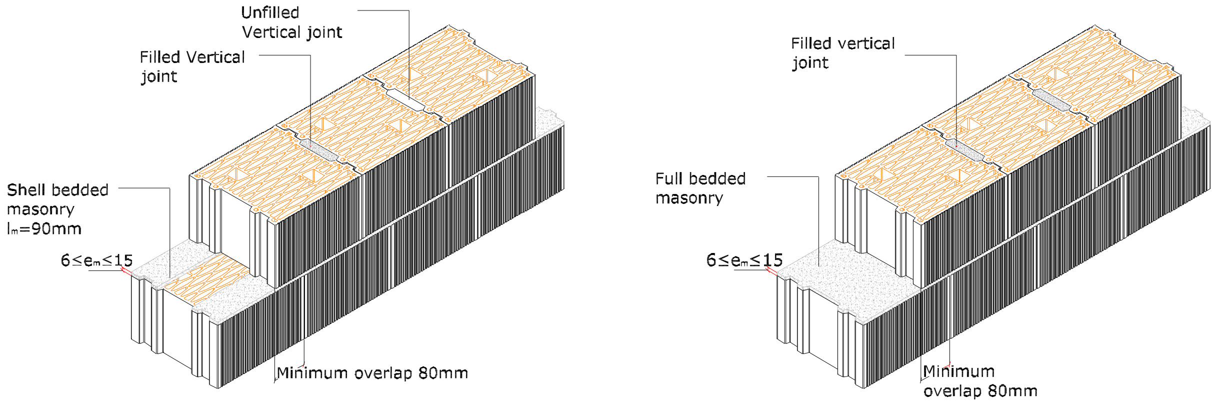


Fig. 10

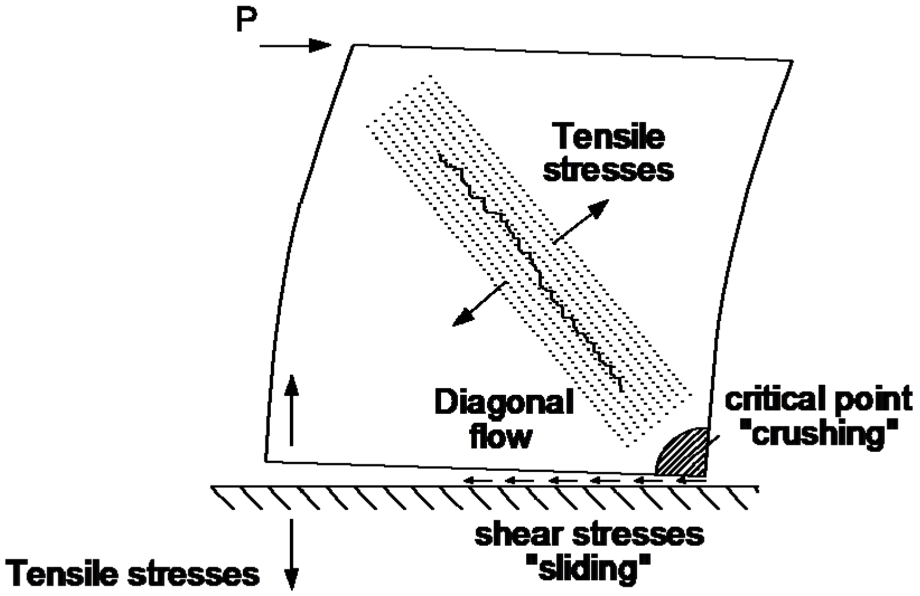
Constructive system with hollow clay units fully and partly (shell) bedded with unfilled and filled vertical joints

(a)

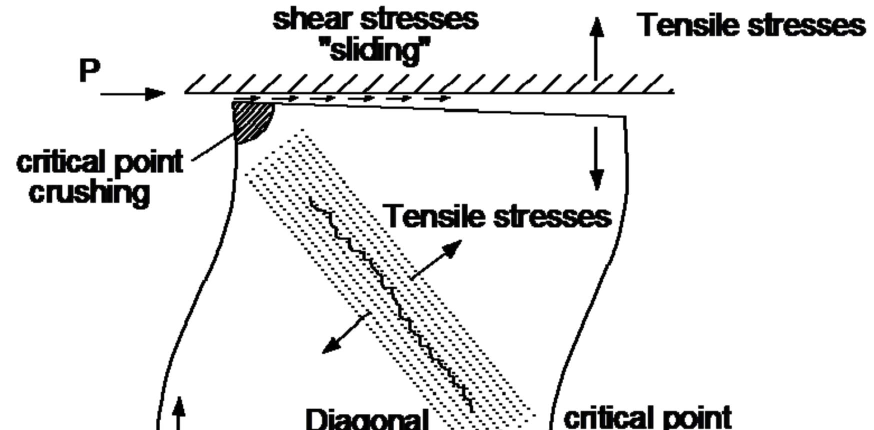
(b)

Fig. 11

Constructive system with hollow clay units; (a) tongue and groove head joints; (b) mortar pockets at head joints



(a)



(b)

Fig. 12

Typical failure modes of masonry shear walls; (a) fixed-free boundary conditions; (b) fixed-fixed boundary conditions

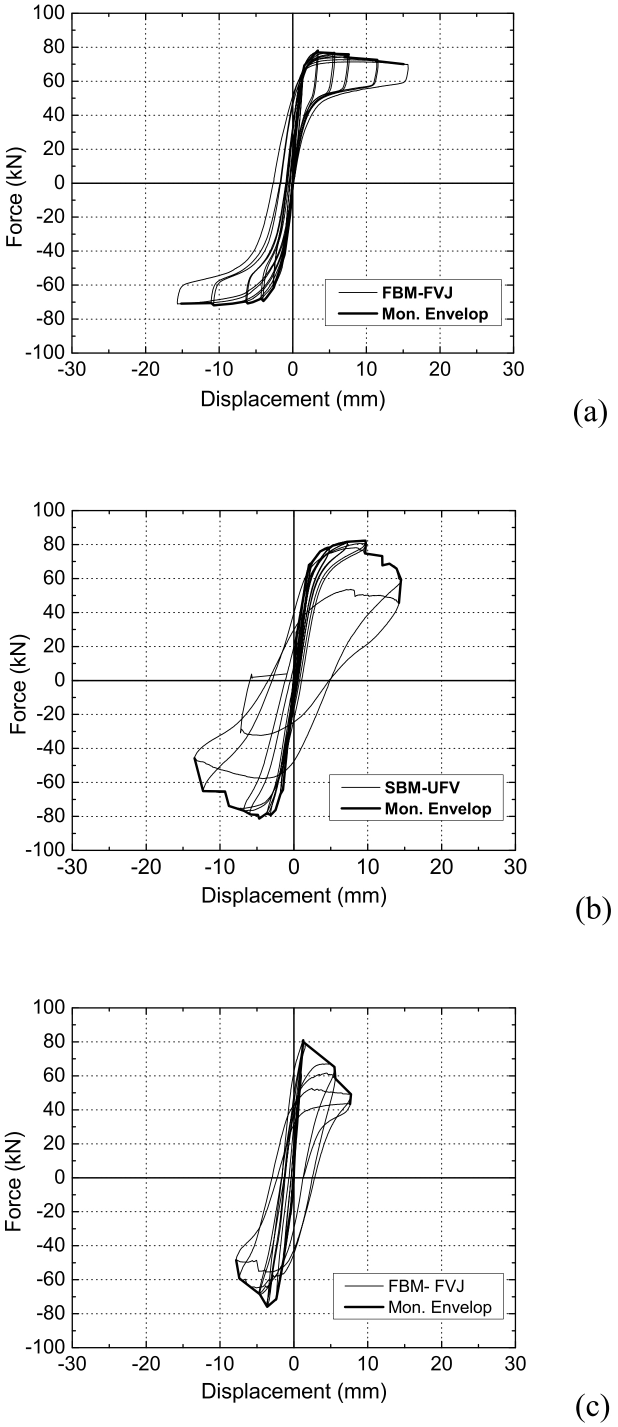


Fig. 13

Typical force-lateral displacement of masonry walls; (a) full bedded masonry with filled vertical joints; (b) full bedded masonry with unfilled vertical joints; (c) full bedded masonry with filled vertical joints

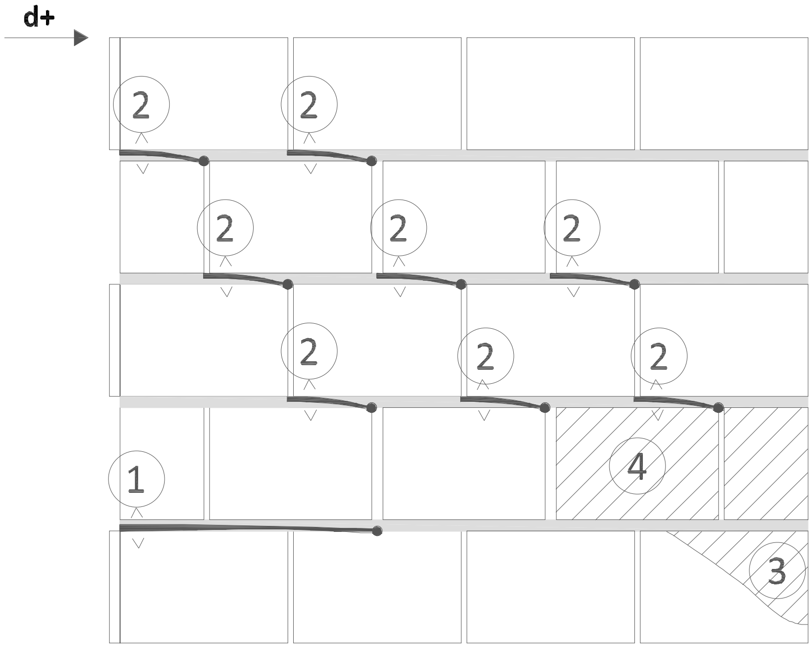


Fig. 14

Typical crack patterns for hollow clay masonry under in-plane loading

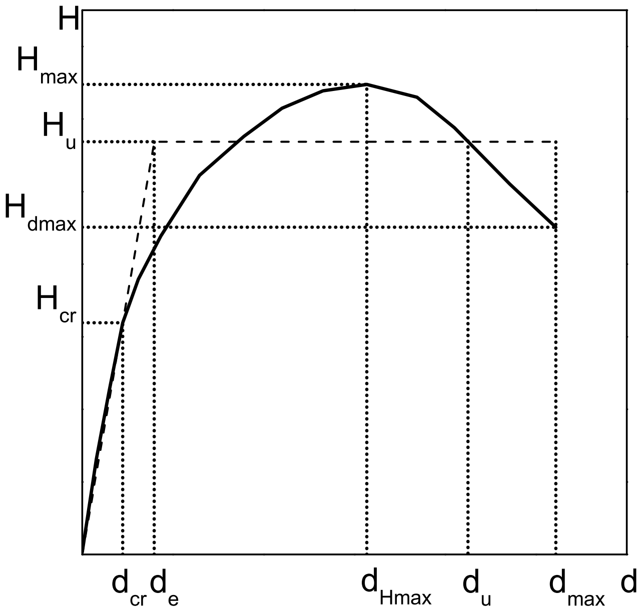
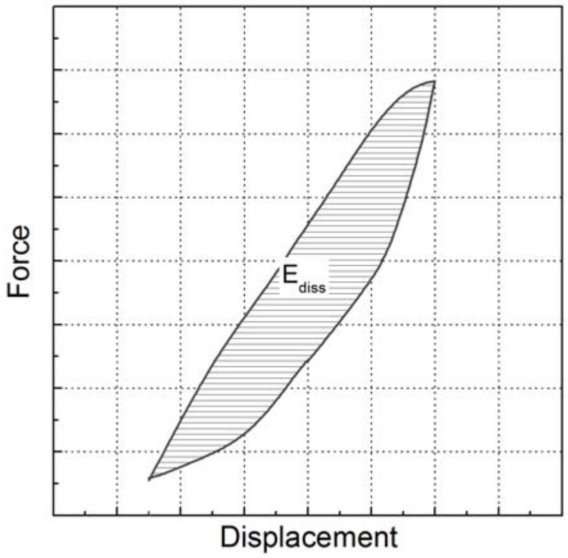
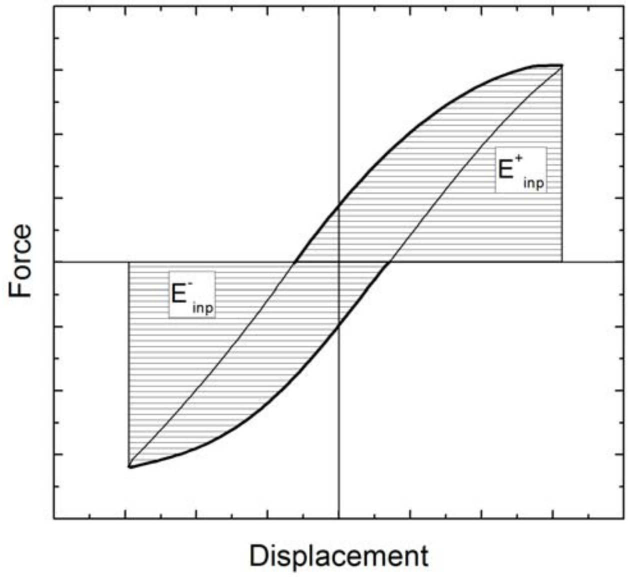


Fig. 15

Bilinear idealization of the monotonic experimental envelop



(a)



(b)

Fig. 16

(a) Schematic representation of the energy dissipated in a hysteresis loop; (b) schematic representation of the input energy