Masonry components

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Synonyms: masonry materials, mechanical behavior

1. Introduction

Masonry is a non-homogeneous material, composed of units and mortar, which can be of different types, with distinct mechanical properties. The design of both masonry units and mortar is based on the role of the walls in the building. Load-bearing walls relate to structural elements that bear mainly vertical loads, but can serve also to resist to horizontal loads. When a structural masonry building is submitted to in-plane and out-of-plane loadings induced by an earthquake for example, the masonry walls are the structural elements that ensure the global stability of the building. This means that the walls should have adequate mechanical properties that enable them to resist to different combinations of compressive, shear and tensile stresses.The boundary conditions influence the resisting mechanisms of the structural walls under in-plane loading and in a buildings the connection at the intersection walls are of paramount importance for the out-of-plane resisting mechanism. However, it is well established that the masonry mechanical properties are also relevant for the global mechanical performance of the structural masonry walls. Masonry units for load-bearing walls are usually laid so that their perforations are vertically oriented, whereas for partition walls, brick units with horizontal perforation are mostly adopted.

As a composite material, the mechanical properties of masonry under different loading configurations depend on the properties of masonry components. The unit has an important contribution for the resisting mechanisms of masonry particularly in case of resisting mechanisms are associated to crushing and tensile cracking of masonry. On the other hand, mortar joints acting as a plane of weakness on the composite behavior of masonry can control the shear behavior, which is particularly relevant in case of strong unit-weak mortar joint combinations. The mortar joints has also a central role on the flexural behavior in the direction perpendicular to the bed joints, as it is tightly controlled by the tensile bond adherence. In case of experimental characterization, flexural testing of masonry in the direction perpendicular to bed joints can even be used as a means of obtaining the tensile bond strength.

Besides the review on masonry material components, it is important to present and discuss the most important mechanical properties of masonry assemblages, together with a discussion ofthe main parameters affecting the seismic performance of masonry under distinct loading configurations. Understanding the response of the basic masonry materials is essential for interpreting the seismic response of masonry structural systems.

2. Masonry Units

Masonry is a composite material composed of masonry units with a regular arrangement that are connected with mortar commonly at horizontal bed and vertical head joints. The interface between units and mortar represents in general an important role on the mechanical behavior of the composite material submitted to distinct types of loading.

The masonry units represent the fundamental material for the formation of the main body of the masonry structural element and can be made of distinct raw materials, namely clay, mud, concrete, calcium silicate and stone. However, the clay and concrete are far the most common raw materials used in structural masonry units.

The masonry units have commonly a rough rectangular shape and the dimensions are defined generally by the (length)x(height)x(width) and are laid usually according to the larger dimension (length). The length and height of the masonry units are usually multiples of 200mm (nominal dimensions), including the 10mm for the mortar thickness so that modularity of the structural elements can be achieved. The modularity is an important characteristic of masonry to make the construction technology and geometrical implementation of the structural elements (walls) with openings easier. The external vertical surface of the masonry units is known as the shell of the unit and the walls perpendicular to the face are the webs of the units (Figure 1).The top and bottom faces of the masonry units are known as the bedding areas.

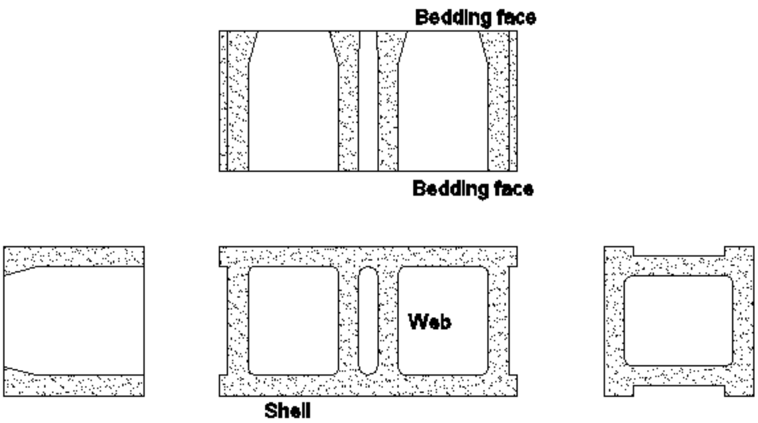
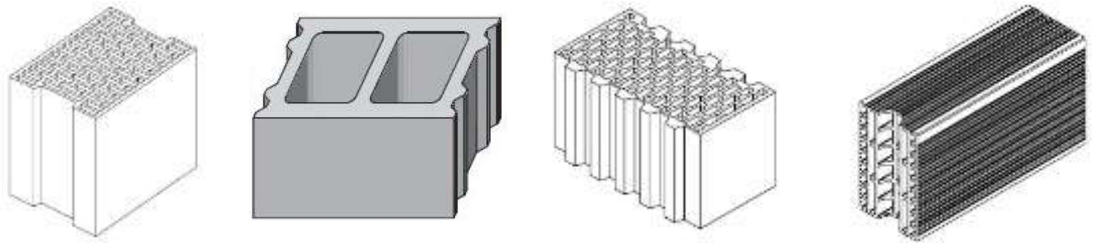


Figure 1 – Example of a masonry unit: concrete block

The masonry units can be solid or have vertical and horizontal voids/perforations known as cores with smaller dimension, and cells. Generally, solid units can have up to 25 percent of perforations in relation to their gross area. For structural purposes, it is more common that concrete or clay bricks should have vertical perforations along their full height. The horizontally perforated brick units are more common for non-structural purposes, namely for masonry infill walls typically used in some south European countries. Examples of common masonry units are shown in Figure 2. Clay units have generally a set of vertical cores with reduced area, whereas the concrete blocks commonly have large hollow cells, as seen in Figure 2(a). In vertical perforated units, the faces are called as face shells connected by the internal solid parts called as webs. When the perforation does not go through the entire height of the unit, it is called a frog. This has usually a conical shape. Sometimes, the units have indented ends over the full height and are called as frogged ends. When it is intended to have dry vertical joints, without the addition of mortar, tongue and groove or interlocking systems are designed, see Figure 2(c). In this case the out-of-plane resistance should rely on the combination of the bed joint resistance and on the tongue and groove system. Other times, the geometry of the units foresees the addition of mortar into vertical pockets, see Figure 2d, where, depending on the geometry, different reinforcing systems can be added to improve the resistance of masonry to in-plane and out-of-plane loads.



(a) (b) (c) (d)

Figure 2 – Examples on different types of masonry units: (a) clay brick unit; (b) concrete block unit; (c) masonry unit with tongue and groove vertical joints; (d) masonry unit with mortar pocket

The raw materials used in the manufacturing process of clay units are commonly surface clays (recent sedimentary formations) but shales formed from clays under pressure or fire clay, mined at deeper levels. All of these clays are equivalent in terms silica and alumina compounds with different types of metallic oxides. 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. The material used in the concrete units is a dry concrete composed of Portland cement, stone aggregates and water. It is also common to use other blended cements including blast-furnace cement and fly ash and inert fillers, considered commonly as by-products, aiming at reducing the percentage of Portland cement. In other instances, expanded clay aggregates are used to reduce the weight of the concrete units. Additive such as pozzolanic materials and other workability agents can be also used. The calcium silicate units are composed of sand and hydrated lime.

Besides the raw materials, the production technologies used to produce the clay, concrete masonry and calcium silicate units are very different. The clay units are normally extruded and fired at different temperatures, whereas the concrete units are produced in molds with a required geometry though a vibration and pressing process. The calcium silicate units are manufactured by pressing the mixture of sand and hydrated lime and then autoclaving them in order to produce a tightly grained unit.

2.1 Mechanical Properties

The most relevant mechanical properties of masonry units consist ofthe compressive strength, elastic modulus and tensile strength. The mechanical behavior of the masonry assemblages depends greatly on the mechanical properties of the masonry units.

The compressive strength of the unit can be seen as a measure of its quality and it is important for predicting the compressive strength of masonry assemblages. The compressive strength and elastic modulus can be obtained experimentally from uniaxial compressive tests according to European standards. The compressive strength is calculated from the loaded area, which is the gross area (length) x (width) of the unit when the units are oriented in the same way as they are intended to be laid in a bed of mortar. In general, an average value is obtained from the experimental results, being possible to calculate the characteristic value and the corresponding normalized compressive strength of the masonry unit, f_b, by multiplying the average values by a coefficient taking into account the moisture environment of the curing conditions (oven dry as a reference) and also by the shape factor, accounting for the dimensions of the width and the length. The modulus of elasticity can be calculated as a secant modulus of elasticity between zero and 33 percent of the compressive strength of masonry unit in the stress-strain diagram obtained from the uniaxial compressive tests. This property can be important if advanced modeling of masonry is required.

In case of modern clay and concrete masonry units, considerably high values of compressive strength can be achieved, being generally higher than the strength requirements for units to be used in seismic zones. It is common to have average compressive strength higher than 10MPa. It should be noted that the compressive strength of masonry units is different from the compressive strength of the raw material due to the effect of the shape and geometry of the units. In spite of attempts that have been made to obtain the complete stress-strain diagram of masonry units in compression, it is hard to obtain the post-peak branch of the stress-strain diagrams describing the high rate crack damage progress of the units after the maximum load is attained(see Figure 3a). It should be also noticed that the compressive strength of the masonry units can differ significantly according to the loading direction, namely in the directions perpendicular and parallel to the laying and in the direction perpendicular to the face. According to the work carried out by Lourenço et al. (2010), it was observed that compressive strength is considerably higher in the direction perpendicular to the bed joints, due to the orientation of vertical perforations, in comparison with when the direction is parallel to the bed joints. A reduction of more than 30 percent in the normalized compressive strength obtained in the parallel direction to the bed joints was also found experimentally for concrete units, as seen in Figure 3b. This difference is attributed mainly to the geometry of the masonry units with distinct arrangements of the internal perforations and cells. This results naturally in the different compressive behavior of masonry under compression for the different loading directions. The failure modes recorded in clay and concrete masonry units confirm its brittle character. In clay units with vertical perforation, it is common to observe cracking and splitting of the internal webs and shells. In case of concrete masonry units, the failure mode has a commonly pyramidal-trunk (Gihad et al., 2007, Haach 2009), see Figure 4. The first cracks appear vertically in corners of the units.

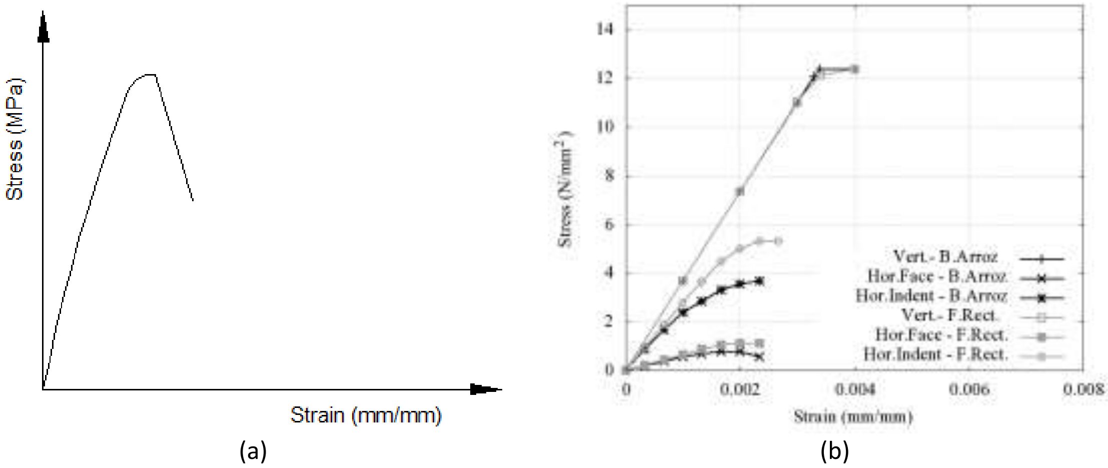


Figure 3 – Details about compression behavior of masonry units: (a) typical stress-strain diagrams; (b) effect of loading direction on the compressive strength of units

With increase of the load, there was a tendency of the connection of vertical cracks by a horizontal crack in the upper region of the unit. This behavior can be explained by the lateral restrictions caused by the steel plates in top and bottom of the specimen, generating friction forces. This horizontal crack occurs because the upper part of the units slides over the pyramidal-trunk surface of rupture. In some specimens near the collapse limit, a vertical crack also appeared in central region of the unit. The brittle failure mode of the masonry units can influence the seismic performance of the masonry under shear walls due to local failures determining the failure mode of the walls (Tomazevic, 2006).

Figure 4 – Crack patterns of concrete blocks under uniaxial compression

3. Mortars for Masonry

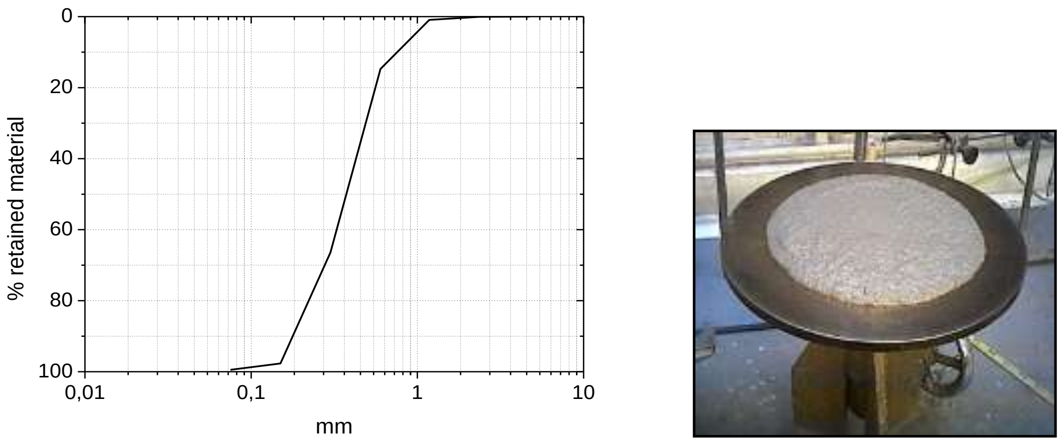
Mortar is a component of masonry and it is used to bond individual masonry units into a composite assemblage. It has a central role in the stress transfer among units when masonry is loaded by promoting and more uniform bearing and avoiding stress concentrations that can result in the premature collapse of masonry. The mortar has also the role ofsmoothing the irregularities of blocks and accommodating deformations associated with thermal expansion and shrinkage. As pointed out by Vasconcelos and Lourenço(2009) the deformability of masonry is clearly influenced by the material at the bed joints. Very distinct pre-peak behavior was found by considering dry saw unit-mortar interfaces, rough dry joints, lime mortar or dry clay resulting from sieving granitic soil. The mortar also influences the bond strength (tensile and shear) of the joints.

The mortars for laying masonry units and filling the vertical joints are commonly a combination of Portland cement, lime, sand and water in specified proportions. The strength of mortars is controlled by the cement and the workability is controlled mainly by lime and by the grading of the sand, as shown in Figure 5(a). The sand can be natural or artificial resulting from crushing stone. The size and grading of the sand particles influences both the plastic and hardened properties. More graded sand (increased variation of the size and distribution of particles) contributes to improve workability of mortars, which play a major role on the laying process of masonry units. The workability can also be improved through the use of additives like clay fillers and air entrainment. Mortar mixes can be defined by specific proportions of the compounds in volume or in weight of the cement or binder (cement and lime) content. For example the mortar mix defined by the trace 1:2:9 (cement:lime:sand) by volume means that it has double the volume of lime in relation to cement and has sand with a volume nine times the volume of cement. It can be considered also that the mortar mix has three times more sand in volume that the total binder of the mixture (cement and lime).

3.1 Properties of Fresh Mortar

The knowledge about the fresh and hardened properties of mortar is fundamental in ensuring a good performance of masonry walls. The most important properties in the fresh state of mortars are the workability, air content and setting time (rate of hardening).

The workability of mortars plays an important role on the construction process of masonry structures. Workability may be considered as one of the most important property of mortar and it is related to the process of laying masonry units and, thus, it influences directly the bricklayer's work. On the other hand, it is important to mention that the quality of the workmanship can influence considerably the mechanical properties of masonry. A workable mortar is easy to adhere to the surface of the trowel, slide off easily, spread readily and adhere easily to vertical surfaces. The workability can be improved by the addition of air entrainment agents to the cementitious materials, enhancing also the durability. The addition of lime and the use of an appropriate curve grade for the sand influence also positively the workability of mortar (Haach et al., 2011). The workability is an outcome of several properties such as consistency, plasticity and cohesion. Given that plasticity and cohesion are difficult to measure, consistency is frequently used as the measure of workability. The consistency is obtained experimentally by the flow table test, shown in Figure 5b. An acceptable value for workability for masonry construction ranges from 150 to 180mm.



(a) (b)

Figure 5 – (a) grading curve for sand; (b) measurement of mortar flow

The water retention is the property of the mortar that avoids the rapid loss of the mixing water in the masonry units and to the air and it plays a major role on the bond adherence of the mortar to the masonry units. The ability of the mortar to retain water is important to prevent the excessive stiffening of the mortar before it is used in the laying of masonry units, to ensure an adequate hydration of cement and to prevent the water from bleeding out of the mortar. The ability of the mortar to retain water is related to the masonry unit’s absorption and should be higher for higher absorption units.

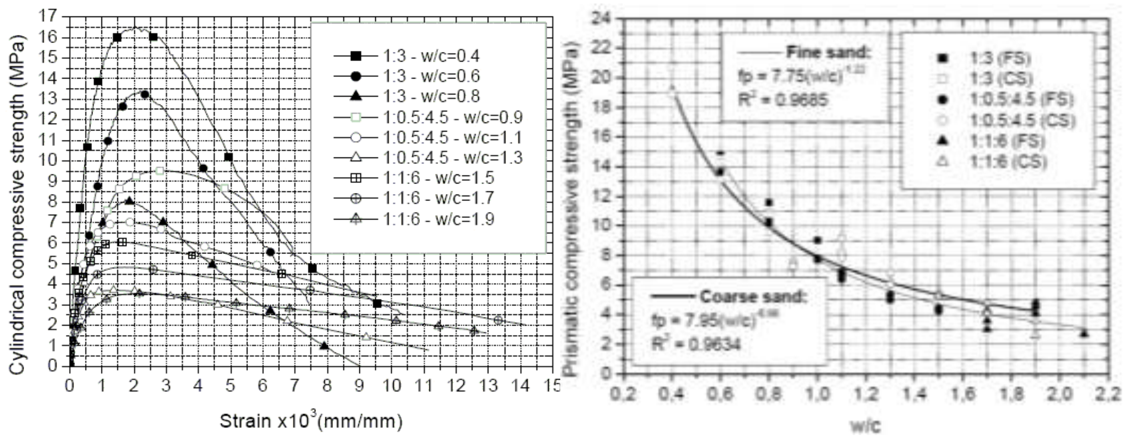
The setting time of fresh mortar relates to the hardening process of mortar. If the setting time is low, the mortar can extrude out of the joints as laying is carried out. If the setting time is high, the mortar placing on the joints can be difficult. The proper hardening rate of the mortar contributes for the adequate bond to the masonry units.

3.2 Properties of Hardened Mortar

The most important mechanical properties of hardened mortar are compressive strength and bond. The bond presents a central role, not only in the mechanical performance of masonry under different loading configurations (shear, tension) but it is also important for the durability of masonry.

The bond between mortar and masonry units develops through mechanical interlocking resulting from its adherence. The bond can in certain extent result also from chemical adhesion. Several factors influence the bond between mortar and masonry units, such as properties of masonry units, type of mortar, water-cement ratio, air content, workmanship, workability and curing conditions. The initial water absorption of the masonry units should be compatible with a good workability and appropriate water retention of the mortar to avoid rapid absorption of the water by the units from the mortar, reducing considerably the water availability for the hardening. The roughness of the masonry units is also important, being enhanced by rougher surfaces of the masonry units. More workable mortars results in better penetration through the voids of masonry units, improving the mechanical interlocking between mortar and masonry units. The additives that are placed in the mortar mix to enhance the workability also contribute to the enhancement of the bond.

Although it is known that the mortar plays a major role in the deformation of masonry under compression, it has also some influence on its compressive strength. More deformable mortar, with lower modulus of elasticity, increases the deformability of masonry under compression. The compressive strength of mortar is also used as an indicator of the workmanship quality, being common to take some mortar specimens during the construction for posterior testing and comparison with the compressive strength required. The compressive strength of mortar is affected by several factors, such as the cement content, the addition of lime and water-cement ratio. The cement gives the strength to mortar and if it is replaced by a certain quantity of lime, the compressive strength reduces, as shown in Figure 6a. Additionally, the compressive strength of mortar is also strongly reduced by the increase in the water-cement ratio (w/c) (Figure 6b).



(a) (b)

Figure 6 – Behavior of hardened mortar: (a) stress-strain diagrams and influence of the addition of lime in the compressive strength; (b) influence of the w/c ratio in the compressive strength

4. Masonry as a Composite Material

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 subjected depend on the structural element to which it belongs.

4.1 Compressive Behavior

The compressive strength of masonry is the primary mechanical property characterizing its structural quality and is fundamental for structural stability in case of load-bearing masonry walls. Compressive behavior is also important when masonry is subjected to lateral loading because the in-plane behavior 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. Masonry is a composite material made of units and mortar, so it has been largely accepted that its failure mechanism and resistance is governed by the interaction between the different components.
In case of hollow or solid units with full mortar bedding and when the mortar has lower compressive strength than the masonry units, the cracking paths and overall behavior are considerably controlled by mechanical properties of mortar and masonry units. As the mortar has generally lower modulus of elasticity than the masonry unit, it exhibits a trend to expand laterally within the mortar joints more than the masonry, being restrained by the masonry units. This interaction results in a tri-axial compression state of the mortar and on a compression-lateral tensile state on the masonry units. This stress state results in the vertical cracking of the units, as seen commonly in the experimental testing of masonry. In case of masonry units with face shell mortar bedding, it is common to find vertical cracking along the webs of the units. This is related to the non-uniform stress distribution of stresses along the height of the unit and along the thickness of the masonry and to the principal tensile stresses mainly at the top and bottom of the units (Lourenço et al., 2010).
The typical tress-strain diagram describing the compressive behavior of masonry is shown in Figure 7. The pre-peak behavior is characterized by nonlinearity beyond approximately 60 percent of the peak stress, particularly in concrete masonry. The clay brick masonry tends to present a more linear elastic behavior with nonlinearly close to the peak load, achieving also higher values of the compressive strength. Almost no post-peak is usually recorded, which is associated with the brittle character of unreinforced masonry under compression. However, the post-peak behavior of masonry is dependent on the type of units and also dependent on the mortar used. Concrete masonry specimens built with lime based mortar presents slight lower strength than masonry prisms built with cement based mortar. Additionally, higher deformations characterized the compressive behavior of masonry built with lower strength mortar. In this case, the ability deformation after peak load is higher, enabling more ductile response of masonry under compression (Haach et al. 2014). The compressive strength of masonry is always higher than the compressive strength of mortar and lower than the compressive strength of masonry unit. However, the compressive strength of masonry units takes a central role on the compressive strength of masonry. Higher strength masonry units

lead to higher strength of masonry. The relation appears to be linear in concrete block masonry (Drysdale and Hamid, 2005).

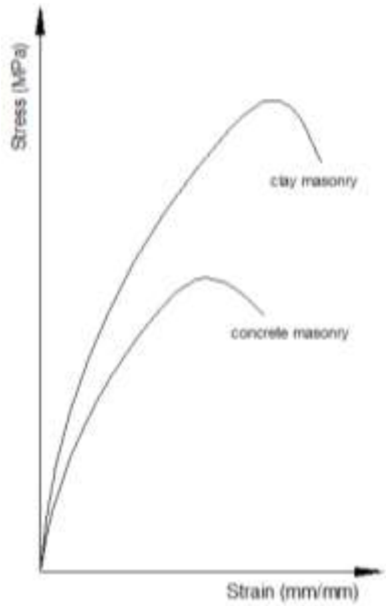


Figure 7 – Typical Stress strain diagram of concrete masonry under compression

The direction of compression of masonry units is also an important factor to take into account. Even if, in geral, masonry is load in the direction normal to bed joints, in case of masonry beams and flexural walls (out-of-plane loading), the compression in the parallel direction to the bed joints is relevant for their mechanical behavior. The compressive strength in the parallel direction to the bed joints reduces considerably in relation to the compressive strength in the normal direction to the bed joints, particularly in case of hollow units as it depends on the geometry of perforations. In case of clay brick units with vertical perforation, the compressive strength in the parallel direction to the bed joints is about 30 percent of the compressive strength of the units in the normal direction to the bed joints, resulting in the lowering of the compressive strength of masonry in this direction. The failure modes are also distinct, being the failure in the parallel direction more ductile.

4.2 Masonry under Shear

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 results in distinct failure modes (Figure 8). 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 with the development of more dominant shear resisting mechanism. The shear resisting mechanism is associated with diagonal cracks in the alignment of the compressive strut related to the tensile stresses developed in the perpendicular direction of the strut. Diagonal shear cracking can occur with distinct patterns, namely cracks developing along the unit mortar interfaces, or through both unit-mortar interfaces and through masonry units as a combination of joint failure or brick shear-tension splitting. In diagonal cracking along the unit-mortar interfaces, the shear behavior of the bed joints plays an important role on the response of the walls.

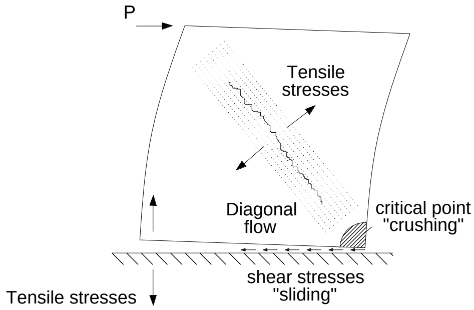
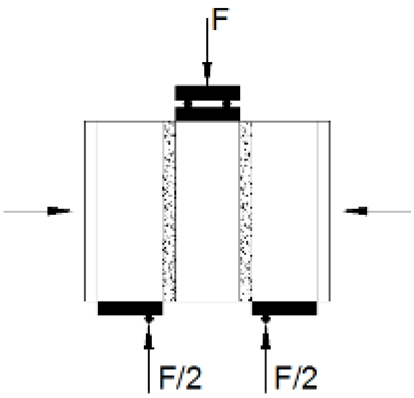


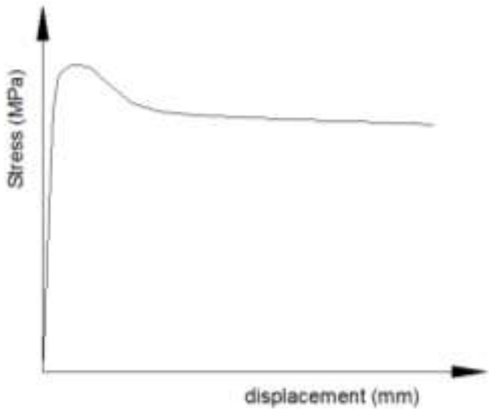
Figure 8 – Typical failure patterns that can develop in masonry walls under shear

4.2.1 Shear Behavior along the Bed Joints

The influence of mortar joints acting as a plane of weakness on the composite behavior of masonry is particularly relevant in case of strong unit-weak mortar joint combinations.Two basic failure modes can occur at the level of the unit-mortar interface: tensile failure (mode I) associated with stresses acting normal to joints and leading to the separation of the interface, and shear failure (mode II) corresponding to a sliding mechanism of the units or shear failure of the mortar joint. The preponderance of one failure mode over another or the combination of various failure modes is essentially related to the orientation of the bed joints with respect to the principal stresses and to the ratio between the principal stresses.
The shear behavior of mortar masonry joints is characterized experimentally based on direct shear tests by following the typical shear test configuration shown in Figure 9a. The typical behavior of mortar masonry joints under increasing shear load and constant pre-compression load is presented in Figure 9b. The general shape of the shear stress-shear displacement is characterized by a sharp initial linear stretch. The peak load is rapidly attained for very small shear displacements. Non-linear deformations develop in the pre-peak regime only very close to the peak stress. After peak load is attained there is a softening branch corresponding to progressive reduction of the cohesion of the joint, until reaching a constant dry-friction value. This stabilization is followed by the development of large plastic deformations.



(a)



(b)

Figure 9 – Typical shear stress-slipping diagram of mortar masonry joints under shear

After peak load is attained there is a softening branch corresponding to progressive reduction of the cohesion of the joint, until reaching a constant dry-friction value. This stabilization is followed by the development of large plastic deformations.

In case of moderate pre-compression stresses, for which the nonlinear behavior of mortar is negligible and the friction resistance takes the central role, the shear resistance of masonry bed joints is linearly dependent on the compressive stress (see Figure 10), and is given by the Coulomb friction criterion:

$$\tau = c + \mu\sigma \quad (1)$$

Where *c* is the shear strength at zero compressive stress (usually denoted by cohesion) and μ is the friction coefficient or tangent of the friction angle. For dry joints, the cohesion is obviously zero. It should be kept in mind that the failure envelope given by Equation (1) describes only a local failure of masonry joints and cannot be directly assumed as the shear strength of the walls submitted to in-plane horizontal loads (Mann and Müller, 1982; Calvi et al., 1996). In any case, the shear bond strength of masonry joints assumes a major role on the shear resistance when it can be described by the Coulomb friction criterion (diagonal cracking along the unit-mortar interfaces). The shear bond strength of masonry units can be seen as the initial shear strength used to calculate the shear strength according Coulomb friction criterion, as suggested by Eurocode 6 (2005).

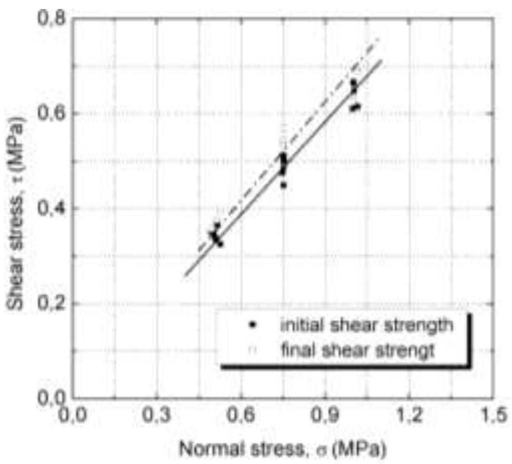


Figure 10 – Relation between shear stress and normal stress

The strength values, particularly the cohesion are greatly dependent on the moisture content, porosity of the units, initial rate of absorption of the units, on the strength and composition of mortar as well as on the nature of the interface (Amadio and Rajgelj, 1990). More plastic mortar enhances shear behavior of joints by promoting better adherence. Binda et al. (1994) pointed out that when strong mortar is considered, the strength of the units can also determine the shear behavior of the joints. In case of hollow concrete masonry, the mortar placed on the internal webs contributes considerably to the increase of the shear strength as it increases the mechanical interlocking. This implies that a wide range of shear strength values may be pointed out for various combinations of units and mortar. Mann and Müller (1982) indicated a mean friction coefficient of approximately 0.65 on brick-mortar assemblages and a cohesion ranging from 0.15MPa up to 0.25MPa, depending on the mortar grade. From the results of direct shear tests carried out by Pluijm (1999), the coefficient of internal friction ranges between 0.61 and 1.17, whereas cohesion varies from 0.28MPa up to 4.76MPa, depending on different types of units and mortar.

Another important issue regarding shear tests is the dilatant behavior of masonry joints. The dilatancy represents the difference between the variation on the normal displacements of the upper and the lower unit, Δv, as a result of the variation of the shear displacement Δu, see Figure 11. The opening of the joint is associated with positive dilation, whereas negative values of dilatancy represent the compaction of the joint. The dilatancy of rock joints is mostly controlled by the joint roughness. In conjunction with the cohesion and the friction angle, the dilatancy is also required as a parameter for micro-modeling of masonry. As pointed out by Lourenço (1996), dilatancy in masonry wall structures leads to a significant increase of the shear strength in case of confinement.

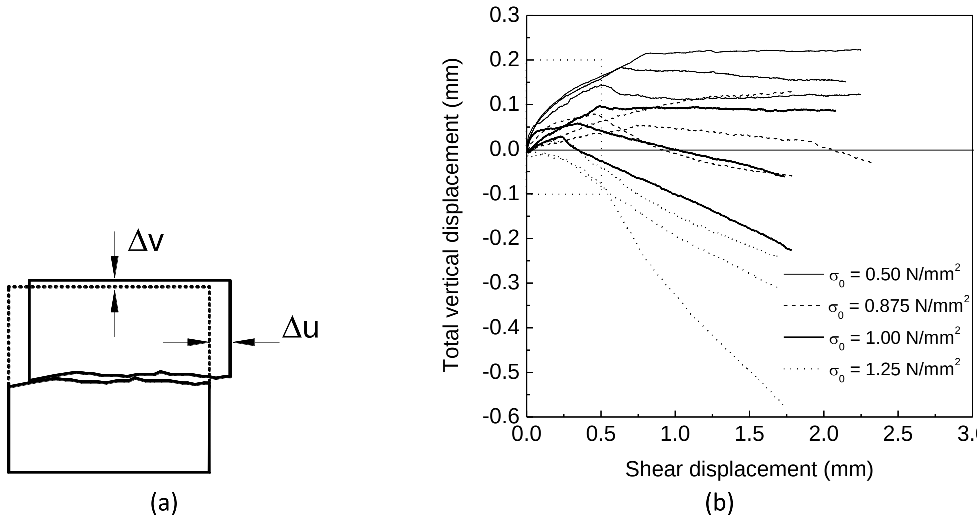


Figure 11 –Dilation of shear mortar joints; (a) definition; (2) effect of vertical pre-compression on the dilation

4.2.2 In-plane Tensile Strength

The other approach for the shear resistance of masonry shear walls is based on the Turnšek and Sheppard (1980) criterion, which is based on the assumption that diagonal cracking occurs when the maximum principal stress at the center of the wall reaches the tensile strength of the masonry.

The stress state is calculated by assuming that masonry is an isotropic and homogeneous material, which does not correspond to its actual behavior, since tensile strength is dependent on the orientation of the principal stress regarding the mortar bed joints. For height to width ratios (*h*/*l*) higher 1.5, from which walls can be considered as a solid in the Saint Venant sense, the tensile principal stress can be calculated by Equation 2:

$$\sigma_t = \sqrt{\left(\frac{\sigma_0}{2}\right)^2 + \tau^2{}_{\max}} - \frac{\sigma_0}{2} \qquad (2)$$

being the vertical stress considered as the average stress, σ_0, calculated as the ratio between the compressive load (N) and the area (txl) of the walls *N*/(*txl),* and the horizontal stress is negligible. This assumption was confirmed by using photo-elastic analysis as reported by Turnšek and Čačovič (1971).

Considering that the maximum shear stress, τ_{max}, assumes a parabolic distribution, the horizontal shear force corresponding to the opening of shear cracks, H_s, is derived by Equation 2, presenting the following expression:

$$H_s = \frac{f_t \ lt}{b}\sqrt{1+\frac{\sigma_0}{f_t}} \quad (3)$$

where f_t is taken as the tensile strength of masonry. The variable *b* takes the value of 1.5 for walls with height to length ratios larger than 1.5. In case of height to with ratios (*h*/*l*) ranging between 1.0 and 1.5, the shear stress distribution deviates from the parabolic shape and the horizontal normal stress becomes different from zero. In case of unreinforced masonry, this force is considered as the shear resistance when the failure mode corresponds to the cracking involving the cracking of units along the diagonal compression strut.

The in-plane tensile strength of masonry, f_t, can be obtained experimentally through diagonal compression tests by following the recommendation of standard ASTM E519 (2002). The tensile strength of masonry is calculated through Equation 4, assuming that in the center of the panel a pure shear stress state develops corresponding to the tensile strength to the maximum principal stress given by Equation 4:

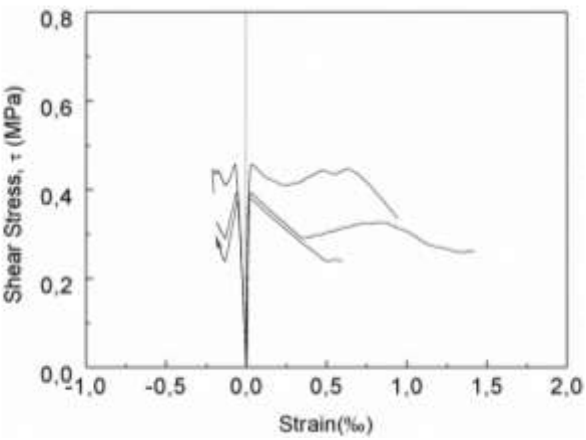
$$f_t = 0.707 \times \frac{P}{A} \quad (4)$$

Where *P* is the vertical load applied and *A* is the horizontal gross section of the specimens. The shear deformation is calculated based on Equation 5, where ΔH and ΔV are the deformation measured along the compression and tension diagonals and g is the width of the diagonal of the panel. The shear modulus is calculated by the ratio between the shear stress and the shear deformation (Equation 6).

$$\gamma = \frac{\Delta V + \Delta H}{g} \quad (5)$$

$$G = \frac{\tau}{\gamma} \quad (6)$$

The typical failure mode found in current modern unreinforced masonry composed of regular units and submitted to diagonal compression load results from the opening of a stair stepped crack along the unit-mortar interface developing in the direction of load. The crack is developed in the perpendicular direction to the tensile stresses, which means that it appears when the tensile stress in masonry is reached. The failure of unreinforced masonry occurs suddenly in very brittle style, see Figure 12a.



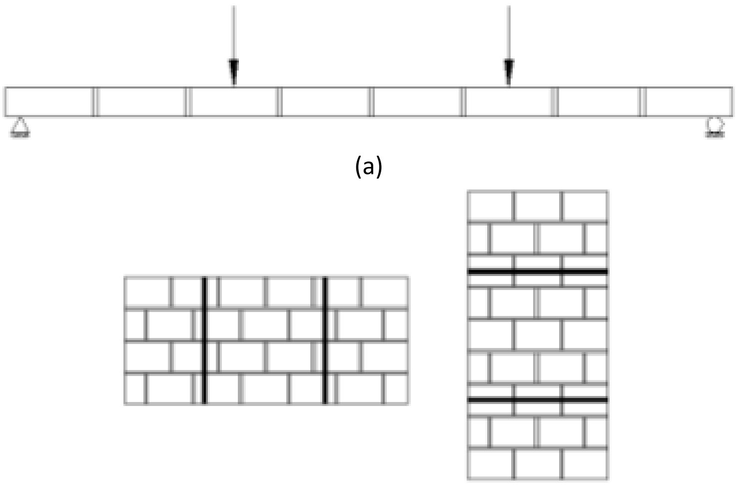
(a) (b)

Figure 12 – Details of diagonal compression tests on unreinforced masonry; (a) failure patterns; (2) typical shear stress-strain diagrams (negative values corresponds to vertical strains)

According to Haach (2009), the non-filling of vertical joints appears not to significantly influence the crack patterns and failure modes of unreinforced masonry, even if it can clearly influence the shear strength of masonry. The mortar type also influences the tensile strength as it influences the tensile and shear bond strengths of masonry joints, particularly in case of cracks develops along the unit-mortar interfaces. The tense strength of units influences the values of the tensile strength when the crack passes through the units.

4.3 Flexural Tensile Strength

The flexural strength of masonry assemblages subjected to out-of-plane bending relates to the resistance of walls submitted to lateral loads from wind, earthquakes or earth pressures. Depending on the boundary conditions and wall geometry, the bending can develop about vertical axis, about the horizontal axis or about both directions. Thus, the tensile strength is referred to the direction of the tension that can develop in the direction normal to the bed joints, f_{tn}, or in the direction parallel to the bed joints, f_{tp}.
The flexural strength of masonry units can be obtained experimentally according to EN 1052-2 (1999), by considering a four-point load testing configuration, see Figure 13a, being the load applied typically according to the scheme shown in Figure 13b to obtain the flexural strength in the parallel and perpendicular direction to the bed joints



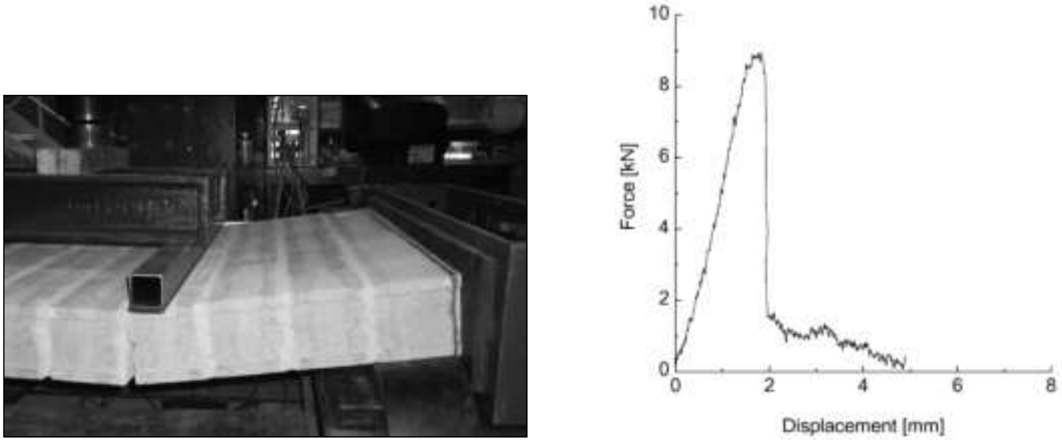
(a)

(b)

Figure 13 – Loading configuration for the experimental determination of the flexural strength of masonry; (a) geral scheme; (b) bending parallel and in the normal direction to the bed joints.

The unreinforced masonry under flexure is characterized by a very brittle behavior, which is associated with the localized central crack involving the failure of the unit-mortar interface and the units, see Figure 14a. When the flexure develops in the normal direction to the bed joints, usually the crack patterns develops along a bed joint (de-bonding of the mortar from the masonry unit). In flexure parallel to the bed joints, the usually observed crack patterns are: (1) stepped cracks along the unit-mortar interface, when masonry is made with strong units and weak mortar joints; (2) cracks passing through head joints and masonry units. The flexural strength in the perpendicular direction to the bed joints can be also taken as the tensile bond strength of mortar joints. The typical force-displacement diagram relating the vertical load applied and the maximum displacement measured at mid span, presented in Figure 14b

confirms the brittle nature of masonry under flexure. After peak load has been attained there is an abrupt reduction of the bearing capacity, meaning that the masonry loses almost all resistance with no increment of displacement. The pre-peak regime is characterized by an elastic range with only a small nonlinearity very close to the peak load.
The flexural strength depends on the type of mortar, especially on the resistance and tensile bond strength. Also here the workability of mortar plays a major role as the tensile bond strength depends on the adequate adherence of the mortar to the unit. The flexural strength depends also on the tensile strength of the masonry units, particularly when flexure develops in the parallel direction to the bed joints.



(a) (b)

Figure 14 – Details about the flexure behavior of unreinforced masonry; (a) crack pattern in flexure in the normal direction to the bed joints; (b) typical force-displacement diagram (direction parallel to bed joints).

4.4 Brief Code Considerations

The compressive strength of masonry can be estimated through empirical formulas generally based on the results of experimental tests. European masonry code (Eurocode 6, 2005) proposes Equation 7 to estimate the compressive strength of masonry:

$$f_k = k f_b^{0.7} f_m^{0.3} \tag{7}$$

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, *k* is 0.45.
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. It can be also estimated from the compressive strength of masonry. According to Eurocode 6 (2005) the elastic modulus can be obtained from Equation 8:

$$E = k_E f_k \tag{8}$$

Where k_E is recommended to be 1000.

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 (Eurocode 6, 2005).
In terms of shear, the Eurocode 6 (2005) suggests that the shear strength of masonry is calculated through Equation 9:

$$f_{vk} = f_{vk0} + 0.4\sigma_d \tag{9}$$

where f_{vk0} is the characteristic initial strength of masonry, obtained for zero compressive stress, and σ_d is the average normal stress.
The value of the characteristic shear stress should not be higher than $0.065f_b$ (f_b is the normalized compressive strength of masonry units) neither exceed f_{vlt}, which should be defined in the National Annex.
The values of the initial shear strength given in Eurocode 6 (2005) depend on the type of unit (clay, calcium silicate, concrete, stone) and on the type of mortar (general purpose mortar, lightweight mortar or thin layer mortar).
The characteristic flexural strength of masonry can be obtained by experimental tests or alternatively through the values suggested in Eurocode 6 (2005), depending on the type of unit and type of mortar. Typically, the characteristic flexural strength in the direction normal to the bed joints ranges from 0.1 to 0.2 MPa and the characteristic flexural strength in the direction parallel to the bed joints ranges from 0.2 to 0.4 MPa.
There are requirements for the masonry units and mortar to be used in earthquake prone regions. In case of masonry units, the normalized compressive strength should be higher than 5 MPa in the normal direction to the bed joints and 2.0 MPa in the parallel direction to the bed joints. The recommended values for the compressive strength of mortar are 5.0 MPa for unreinforced masonry and 10.0MPa for reinforced masonry (Eurocode 8, 2004).

5. Summary

In this section, a review on the masonry components and on mechanical properties of masonry under distinct loading configurations has been made. Additionally, some code considerations about the design mechanical properties of masonry are provided.
The masonry units have a wide range of possibilities either from the viewpoint of raw materials or from geometrical configurations. The geometrical configuration should comply with thermal and mechanical requirements to optimize the performance both from the mechanical and physical point of view. Besides the strength, it is required that the mortar should present an adequate workability and water retention ability so that an adequate mechanical behavior of masonry in attained. These properties play a major role on the bond strength of masonry (tensile and shear bond strength), which in turn have an important contribution on the shear and flexural resistance of masonry.
The compressive strength of masonry is clearly dependent on the mechanical properties of the components, the masonry unit being more important than mortar, which contributes mainly to the deformability of masonry. Depending on the failure patterns, which are dependent on the level of vertical load applied and boundary conditions, the shear response of masonry walls under in-plane loading can be largely dependent on the shear bond strength (failure load

described by the Coulomb friction criterion) or on the in-plane tensile strength of masonry (failure load described by the Turnšek and Čačovič criterion. The bond strength of the masonry joints and the in-plane tensile strength of masonry play an important role on the flexural resistance of masonry. The tensile strength is more important than the flexural strength in the direction parallel to the bed joints and the tensile bond strength of primary importance in case of the flexural strength in the normal direction to the bed joints.

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