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On the mechanical behavior of masonry

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ABSTRACT:

In this chapter, a review on the mechanical behaviour of masonry is presented. The aim is to establish a base of knowledge and understanding of masonry that will underpin its mechanical characteristics and will inform the decisions towards the selection of the computational tool used which are going to be described in the following chapters. Initially, a brief description of the factors that influence the mechanical response of masonry and the variation of the material properties are discussed. The review then considers the possible causes of cracking in masonry and the different failure modes that may occur during loading. Principal findings from the review are summarised at the end of the chapter.

Keywords: Masonry, Mechanical Behaviour, Cracking, Bond Strength

1 INTRODUCTION

Masonry is a very common and traditional form of construction that has been used for centuries and around the world. Some of the most important cultural and historical monuments (like Parthenon, Pyramids, Colosseum; Segovia aqueduct etc.) have been constructed using masonry. Masonry constructions also represent the vast majority of the traditional buildings like church domes (Hagia Sophia, Istanbul; Maria del Fiore in Florence, Italy; St Peter in Rome, Italy) and gothic structures (Amiens Cathedral; Beauvais Cathedral). Most of these historic and heritage structures are old and are deteriorating over time. Research in the area of masonry constructions is therefore essential to understand their structural capacity, how they behave with the application of external load, to assess their design levels, their design potential and retrofitting measures. In spite the urgent need to understand the mechanical behavior of masonry, only recently researchers have shown interest in studying the behavior of structural masonry in detail. This is mainly due to: a) the high complexity of masonry behavior when compared to other construction materials such as concrete and steel; and b) the absence of solid and comprehensive experimental and numerical research.

Masonry is a heterogeneous brittle material that consists of units and mortar joints. Masonry units usually consist of fired clay, concrete or calcium silicate bricks; concrete or fired clay blocks; adobe or various types, sizes and shapes of naturally occurring stones. The composition of the mortar joints is usually expressed in terms of the volume or weight ratio of the binder and the sand (or fine aggregate). The most commonly used binder in modern construction is Ordinary Portland Cement (OPC). This is sometimes supplemented by a small amount of hydrated lime which aids workability and cohesiveness. Water is added, not only to react with the OPC to produce the hydration products responsible for strength development, but also provide workability of the mortar in the fresh state. It is usually up to the mason or bricklayer to add the required quantity of water to obtain the desired workability. The strength of the mortar is classified as per the composition of its constituents e.g. parts of OPC to parts of sand to parts of water (OPC : sand : water).

From the different combinations of masonry units, mortars and unit bonding patterns, a large number of geometric arrangements and strength characteristics can be obtained. Generally, the main mechanical features of masonry can be characterised by the rigid nature of the masonry units which have a high resistance to compression; the deformability of the mortar joints with a low resistance to tension and the frictional properties of the unit/mortar joint interface. However, the characteristics and the mechanical properties of masonry may vary significantly even within the same structure. Extensive studies have been carried out in the past to investigate the factors influencing the mechanical behaviour and strength of masonry under loading, understand their specifications and how they behave and how to assess their structural capability and to design potential retrofitting and repair methods (Hendry, 1998; Rots, 1997; Van der Pluijm, 1999). The most important factors influencing the mechanical response of masonry are: Unit characteristics; mortar joint characteristics; brick/mortar bond characteristics; curing processes and workmanship. These are considered in more detail below.

2 FACTORS INFLUENCING THE MECHANICAL RESPONSE OF MASONRY

2.1 Unit characteristics

Masonry is composed of individual units laid in and bound together by mortar. The common materials of units are brick, stone and concrete blocks. Masonry is generally a highly durable form of construction. The properties of the bricks in any typical structure will vary. Such variations may have an effect on the mechanical response to applied load or environmental changes (e.g. humidity and temperature). Some of the factors that may be responsible for variations in the bricks include: a) the brick making process; b) the natural variation in the composition and quality of the raw materials used in the brick making process; and c) deterioration due to ageing effects. The shape of the bricks will also vary as a result of differences in contraction during and after firing and moisture expansion.

According to McKibbins et al. (2006), bricks that are fired at the centre of a clamp in the kiln are subjected to burning and baking at higher temperatures than the rest and are of better quality and durability. Moreover, as the brick raw materials (i.e. clay or shale) are variable in moisture content, each batch of bricks will require a different amount of water to be added to the mix to ensure the right consistency at the end of the mixing process. Stone inclusions that may be found in the raw materials can also vary the mechanical properties of clay bricks, in some cases increasing the compressive strength. Beyond their original variability, the process of ageing and deterioration of bricks in old structures is another factor which can influence the current condition and physical characteristics of masonry.

Stone masonry construction is known since ancient times and can be seen all over the world. The type of stones used for the construction is usually variable and highly dependent on the local availability. Stone structures built without mortar rely on the skill of the craftsmen and the forces of gravity and frictional resistance. The primary function of masonry elements is to sustain a vertical gravity load. However, structural masonry elements are required to withstand combined shear, flexure and compressive stresses under earthquake or wind load combinations consisting of lateral as well as vertical loads. Stones of different shapes and types have been used in the past for the construction of walls, arches, flat roofs and domes. Usually historical buildings were built with: (i) sawn drystack or dry-stone masonry without bonding mortar; (ii) irregular stone masonry with bonding mortar; (iii) rubble masonry with irregular bonding mortar thickness; and (iv) a combination of the three techniques. When bonding mortar was used, it was usually of low strength. Masonry with mortar joints can experience a significant loss of mortar due to combined chemical, physical and mechanical degradation and the behaviour of these constructions can then become similar to those made of dry joint masonry. The type of stone, the shape and size and the exposure to extreme environmental conditions will influence significantly the strength properties of the masonry construction.

Masonry units could also be made of concrete. Concrete blocks may be produced with hollow canters to reduce weight or improve insulation. Concrete blocks are usually come in many sizes and specifications to allow special construction features. U-shaped blocks or knockout blocks with notches to allow the construction of bond beams or lintel assemblies, using horizontal reinforcing grouted into place in the cavity. Blocks with a channel at the end, known as "jamb blocks", allow doors to be secured to wall assemblies. Blocks with grooved ends permit the construction of control joints, allowing a filler material to be anchored between the un-mortared block ends. Other features, such as corners known as "bullnoses" may be incorporated. Concrete masonry units may be formulated with special aggregates and thus their strength properties and characteristics will vary.

2.2 Mortar joint characteristics

The quality of mortar can also vary significantly even within the same structure. Some factors that may cause such variations are: a) the composition and quality of the materials used during the mortar making process; b) the interaction of the mortar with the adjacent bricks in the structure; c) the orientation of the joints in the structure and d) deterioration due to ageing effects.

Most mortars are a mix of cement, lime, sand and water. As a result the composition of the mortar may not be completely uniform throughout the structure, due to a lack of consistency in the batching of the mix constituents. Also, the properties of the mortar are influenced by the units surrounding them. According to Brocken and Pel (1995), mortar joints between masonry units with a high moisture content will cure in a different way to those between units of a lower moisture content.

Also, the characteristics of the mortar joints at different orientations could vary. According to Dialer (1990), the strength of the head or perpend joints is usually lower than the strength of the bed joints. This is a result of the greater degree of mortar shrinkage in the perpend joints and because these joints are often not filled fully with mortar. According to Mann and Muller (1982), such a reduction in strength and stiffness of the perpend joints can generate a discontinuous or non-uniform stress distribution in masonry subjected to in-plane loading. This is illustrated in Figure 1, in which σ_x is the normal stress, $\Delta\sigma_x$ is the change in normal stress and τ_{xy} is the complementary shear stresses. In addition, the processes of ageing and deterioration of mortar especially in old structures is another factor which can influence the current condition and physical characteristics of masonry. The reader should also be aware that construction of masonry wall systems is possible without the use of mortar. It occurs sometimes in stone masonry and it can be found in places where the lime was not locally available (or it was too expensive). In this case, the mechanical behaviour and strength of masonry construction will be completely different to that containing mortar joints.

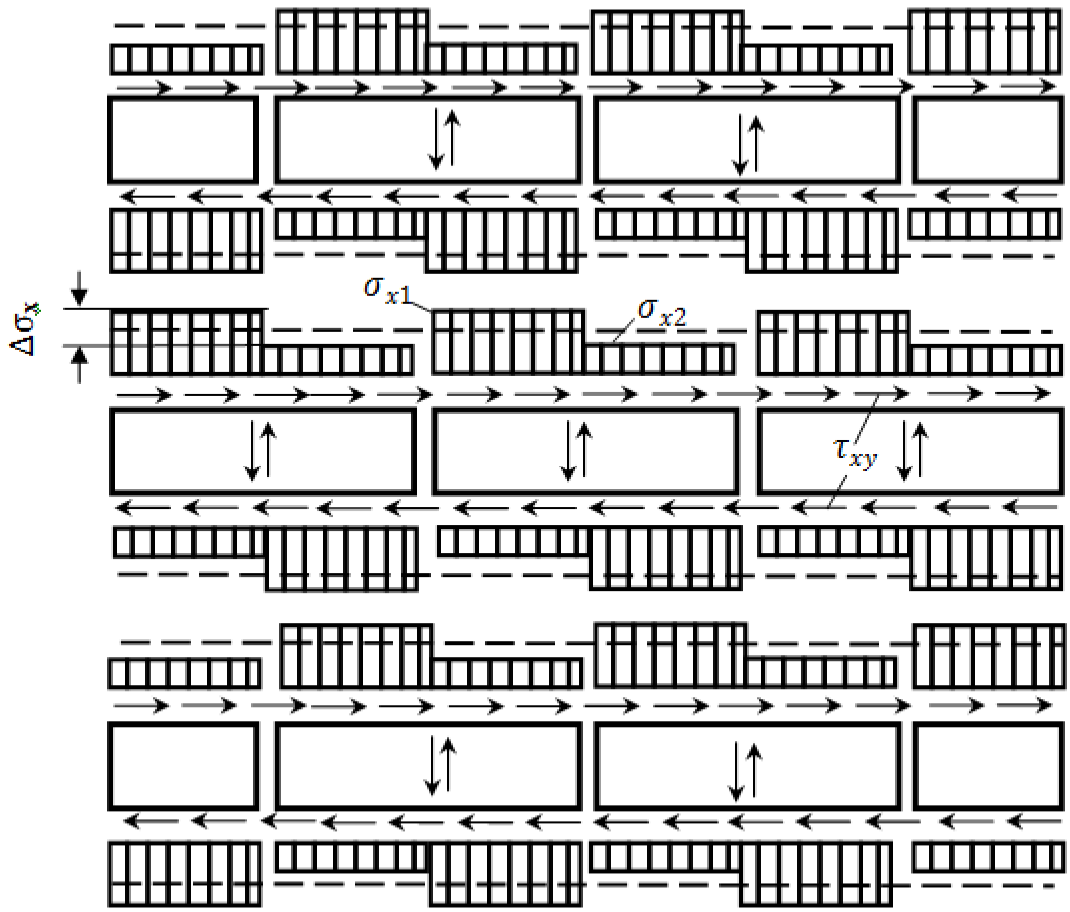


Figure 1 Stress variations in a masonry wall subjected to in-plane loading as a result of differences in the bed and perpend joints (Schlegel and Rautenstrauch, 2004)

2.3 Brick/mortar bond characteristics

The interaction between the bricks and the mortar joints is important in the mechanical behaviour of masonry as it has a considerable effect on load transfer and cracking. The value of the bond strength at the unit/mortar interface is very variable and has a large influence on brickwork's tensile strength and therefore its resistance to cracking. According to Grandet et al. (1972) and Lawrence et al. (1987) bonding of the brick and mortar is initially caused by the mechanical interlocking of the Calcium-Silicate Hydrates (C-S-H) and/or $Ca(OH)_2$ crystals which form in the surface micro-pores and cracks in the brick. The analysis of the bond interfaces using X-Ray and scanning electron microscopy techniques revealed no evidence of chemical reactions between the mortar and the brick materials. Furthermore, investigations by many researchers (Lawrence et al., 2008; Reda and Shrive, 2000; Sugo et al., 2001) have demonstrated that the formation of bond between the bricks and mortar is mechanical involving the transport of mortar fluids and fines to the brick/mortar interface followed by the hydration of the cementing materials.

Several researchers (Anderson and Held, 1986; Goodwin and West, 1982; Jung, 1988; Kjaer, 2010; Lawrence and Cao, 1988; Ostergard, 2010; Vermeltfoort et al., 2007) have investigated the factors that influence bond strength. Based on their studies, the most important factors are:

- The surface texture and the suction behaviour of units;
- The mortar composition;
- The grain size distribution of the aggregate in mortar;
  and
- The type of binders and the use of admixtures and additions for the preparation of the mortar.

The water suction of the masonry units is perhaps the most important intrinsic factor affecting the fresh mortar and, consequently, the properties of the hardened mortar and the properties of the brick/mortar interface. According to Hendry et al. (2004), bricks with a high suction rate will tend to remove water from the mortar leaving insufficient water for efficient hydration and the formation of C-S-H and $Ca(OH)_2$ required for high bond strength. If the suction rate is too low, the hydration products do not penetrate deep enough into the pores and the bond strength is reduced. Tensile bond strength is highly variable with moisture content of the bricks at the time of laying, as indicated in Figure 2.

Vermeltfoort et al. (2007) found that for a mortar of given consistency, the maximum bond strength was achieved when the brick contained an optimum amount of water. This occurred when the amount of “free” water in the mortar matched the initial rate of suction of the brick, which in turn is dependent on the amount of water in the brick at the time of laying.

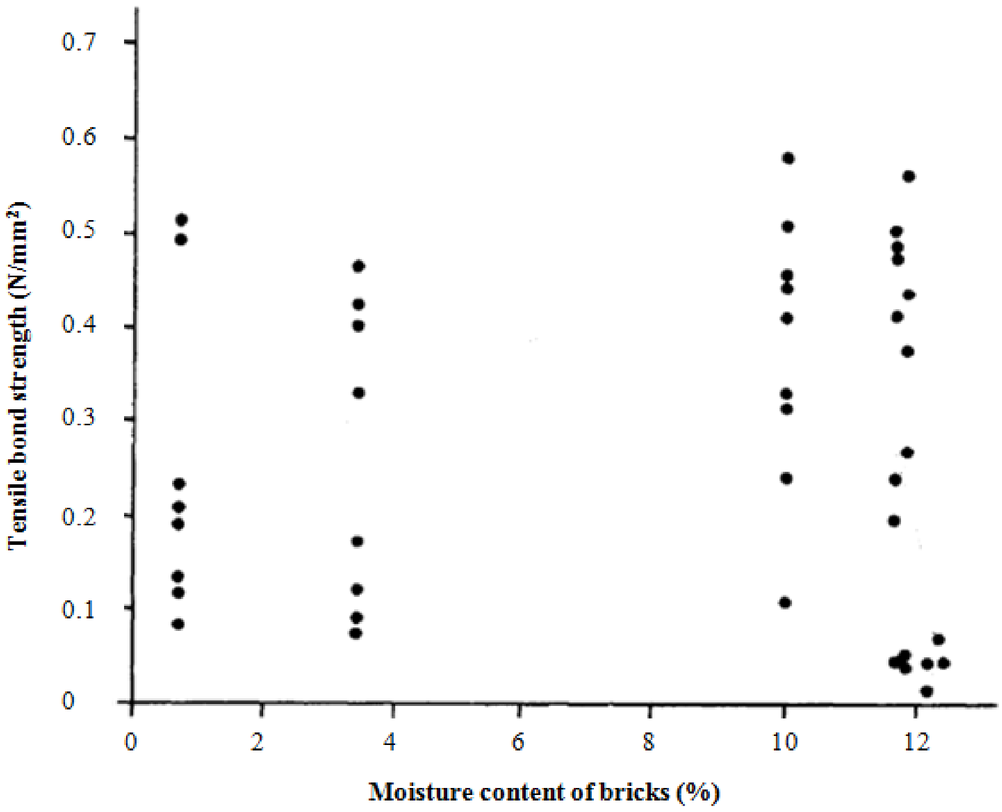


Figure 2 Variation of the brick/mortar tensile bond strength with moisture content of the bricks at the time of laying (Hendry et al., 2004)

In addition, the use of lime and plasticiser or air entraining agent increases the workability of mortar. Studies of the microstructure at the interface between the bricks and mortar and brick/mortar bond by Lawrence and Cao (1988) showed that the effect of lime on the interface microstructure is to facilitate the formation of the initial calcium rich film and to increase the amount of calcium hydroxide at the interface. The addition of lime enhances bonding but also increases the water demand of the mortar. However, due to this increase in water content, the strength of lime mortar tends to be low. The interface between bricks and mortar containing an air entraining agent has been found to contain a significant number of voids/air bubbles which can have a significant effect on the resulting bond. According to (Anderson and Held, 1976; Jung, 1988; Schubert, 1988) the general trend is that an increase in air content of the mortar will lead to a decrease in unit-mortar bond strength. However, recent studies have revealed that it is the structure of the air content which determines and influence the bond strength rather than the amount of air (Kjaer, 2010).

Studies carried out by Ostergaard (2010) have demonstrated that the grain size distribution of aggregates for mortar has a significant effect on the bond strength of the unit/mortar interface. It was concluded that there is a decrease in bond strength with an increase in the grain size distribution of the mortar joints and this effect is noticeable for mortar with high cement content.

Finally, sand faced bricks are often used in construction for aesthetic reasons and/or for de-moulding the bricks from the steel plates during the brick making process. According to Vermeltfoort et al. (2007) bond strength is lower for sand faced bricks. It was found that the sand from the faces of the brick was well bonded to the mortar but readily separated from the brick thereby causing low bond strength. It was also found that the sand obstructs the transport of the binder (cement, lime) to the solid brick mass which further contributes to the low bond strength.

2.4 Curing process

Moist curing of masonry after construction helps to ensure the maximum hydration of the cement in the mortar, thereby improving the bond, particularly to high suction bricks. The effects of curing conditions on the masonry strength have been investigated by many researchers (Anderson and Held, 1976; James, 1973; Marquis and Borchelt, 1986). They concluded that air cured masonry specimens have lower flexural bond strength compared with those wrapped in polyethylene sheeting or sprayed with a concrete curing compound. The difference in flexural bond strength between cured and not cured masonry increases for bricks with a high initial rate of suction (James, 1973). Also, as expected, masonry built on site, or in similar conditions, has lower flexural bond strength than masonry built in the laboratory (Marquis and Borchelt, 1986). However, even when masonry is constructed in environmentally controlled conditions in the laboratory, variations in curing and the properties of the masonry can still occur.

2.5 Presence of moisture content

The mechanical behaviour of masonry is highly variable. The presence of moisture in masonry, mainly conveyed by rising damp, is extremely frequent and plays a key role in the deterioration state of old masonry structures, owing to salt crystallisation, frost damage etc. In addition, the presence of moisture in the brick and mortar material pores may also directly influence the mechanical characteristics (compressive and tensile strength, elastic modulus) due to the interactions with the pore surface, enhancement of crack propagation velocity and other mechanisms. The contribution of moisture presence to the collapse of masonry built with ferruginous stone ashlars has been studied in Verstrynge (2014). From such studies, the presence of water in masonry found to lower both the compressive strength and stiffness of the stone. In the case of sandstone, which is a highly porous material, similar trends obtained. Blocks made of sandstone found to swell due to the water and hence decrease the internal friction of the stone Erguler 2009).

A decrease of the elastic modulus in highly moisture conditions was also found in other literature papers for different kinds of clay bearing rocks and buildings stones (see, e.g. Fjær 2009; Jimenez-Gonzalez & Scherer 2004; Martìnez-Martìnez et al. 2011; Sassoni et al. 2013; Vásárhelyi & Ván 2006 and Vasarhelyi 2003). Among these studies, several mechanisms were observed to play a role in decreasing the mechanical performance of saturated clay bearing stones. These include: fracture energy reduction, capillary tension decrease, pore pressure increase, frictional reduction and chemical and corrosive deterioration (Erguler 2009). It is worth mentioning that, in some cases, decrease in compressive strength and elastic modulus of up to 90% were registered for saturated clay beraring rocks in comparison with the oven dried ones (Gentilini et al. 2012 and Franzoni et al. 2014). In relation to the shear behaviour of masonry in wet and dry conditions, studies suggest that saturation causes deterioration in strength and stiffness of up to one half.

2.6 Quality of masonry work

The strength of masonry is also highly affected by the quality of construction, i.e. site workmanship. The most obvious workmanship factors that may affect the mechanical characteristics of masonry include:

- incorrect proportioning and mixing of the mortar;
- incorrect or incomplete filling of the joints between the bricks with mortar;
- incorrect area of adhesion between bricks and mortar e.g. frogged bricks should always be installed with the frog uppermost so that they are fully filled with mortar;
- the quality of the craftsmanship of the bricklayer or mason, e.g. ability to build walls to "*line and level*";
- unfavourable curing conditions; and
- disturbance of the masonry units or joints after laying.

In particular cases, these defects will present in varying degrees and the overall behaviour of the brickwork will reflect their combined effect. Assessing the overall effect of workmanship on the behaviour and strength of brickwork is not a straightforward issue. West et al. (1986) investigated the effect of bad workmanship. According to the study, the greatest effects of bad workmanship were found in masonry construction using mortar mixes weaker than 1:0.25:3 (OPC:lime:sand ration) parts of mortar mix properties. It is assumed that variations due to workmanship factors will be more heightened when using very weak mortars.

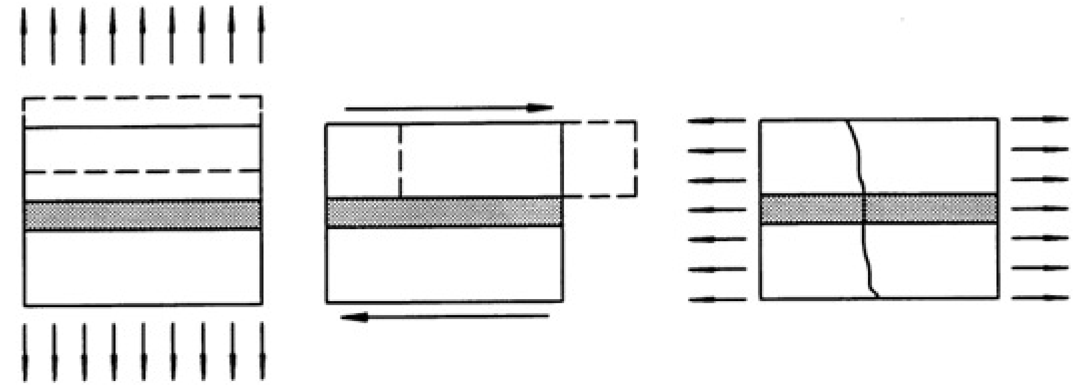
Variations in masonry properties due to bad workmanship effects are unavoidable even under closely controlled laboratory conditions. An extensive investigation on the degree of variation due to workmanship effects in masonry can be found elsewhere (Hendry, 1998).

3 FAILURES IN MASONRY

Movements in masonry may arise from the application of external load, foundation settlement, temperature changes, creep, and chemical reactions in the materials such as chemical attack or corrosion of any carbon steel components embedded in the mortar such as ties or reinforcement (Hendry, 1998). Restraining the movement of a brittle material such as masonry can result in cracking. Cracking and crushing in masonry structures may occur in:

a) the units;
b) the mortar;
c) the brick/mortar interface;
and/or in
d) all of the above.

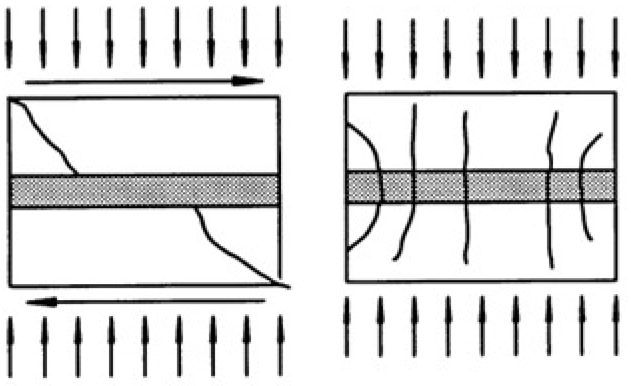
Cracks in masonry may not open uniformly but may close and open according to the type of stresses applied to them over a period of time. Usually cracks of 0.2 mm and wider are assumed to be significant because they are visible to the naked eye. If such cracks open up and propagate through the structure they may reduce its load carrying capacity and could lead, eventually, to collapse. The five basic failure modes of masonry as observed by Lourenço and Rots (1997) are shown in Figure 3. They identified that the occurrence of one of the modes of failure depends on the magnitude and direction of the shear and normal stress on the masonry. From Figure 3 it can be seen that (a) and (b) are joint mechanisms, (d) is a unit mechanism and (c), (e) are combined mechanisms involving the units and joints. However, variation in the stress-state within masonry can lead to combined failure modes in the structure (Garrity, 1995 & 2004; Melbourne and Tomor, 2005; see also Figures 4 & 5). Experimental evidence (Abdou et al., 2006; Adami and Vintzileou, 2008; Garrity et al., 2010) has shown that at low values of normal stress, the principal failure mode of masonry with low strength mortar is either in the brick/mortar interface or in the mortar itself, resulting to joint opening due to cracking (Figure 3a) and/or frictional sliding along a bed or perpend joint (Figure 3b). The behaviour of masonry under tensile and combined compression and shear are considered further below.



a) Joint tensile cracking

b) Joint slip

c) Cracking of unit in direct tension



e) Unit diagonal tension crack

d) Masonry crushing

Figure 3 Masonry failure modes (Lourenço and Rots, 1997)

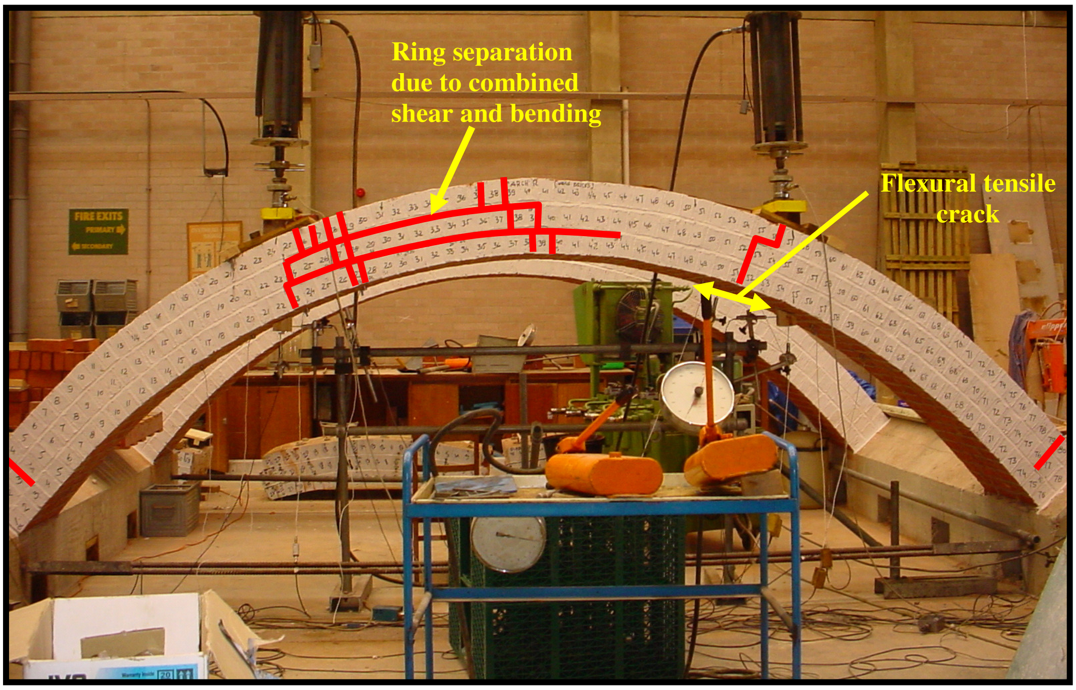


Figure 4 Crack patterns and failure modes for an arch constructed with brickwork (Melbourne and Tomor, 2005)

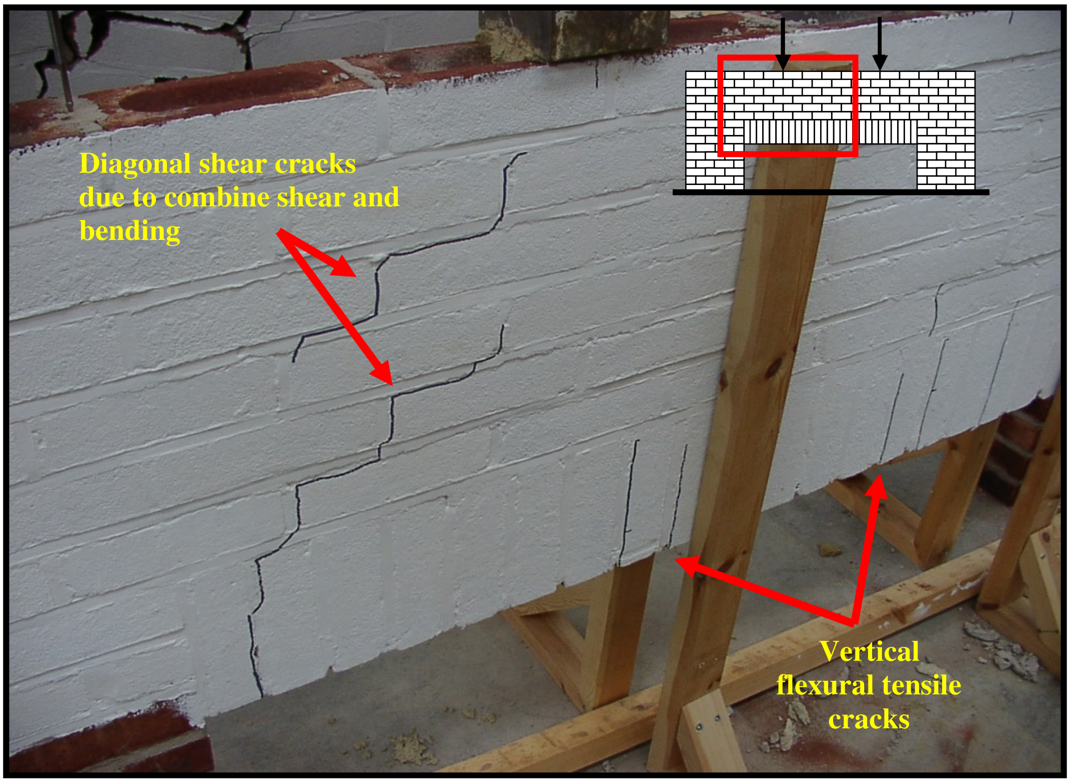


Figure 5 Cracking in a masonry wall panel due to flexural tension and combined shear and flexure (Garrity, 2004)

4 COMPRESSIVE STRENGTH OF MASONRY

Under uniaxial compressive loading, mortar tends to expand laterally more than the brick, because it has weaker mechanical properties. Due to the continuity between the bricks and mortar, ensured by cohesion and friction, mortar is confined laterally by the bricks. Shear stresses will then develop at the brick-mortar interface which produce a triaxial compressive stress state in the mortar and a bilateral horizontal tension coupled with vertical compression in the brick (see figure 6). In this way, failure usually occurs by the development of cracks in the bricks, parallel to the loading direction.

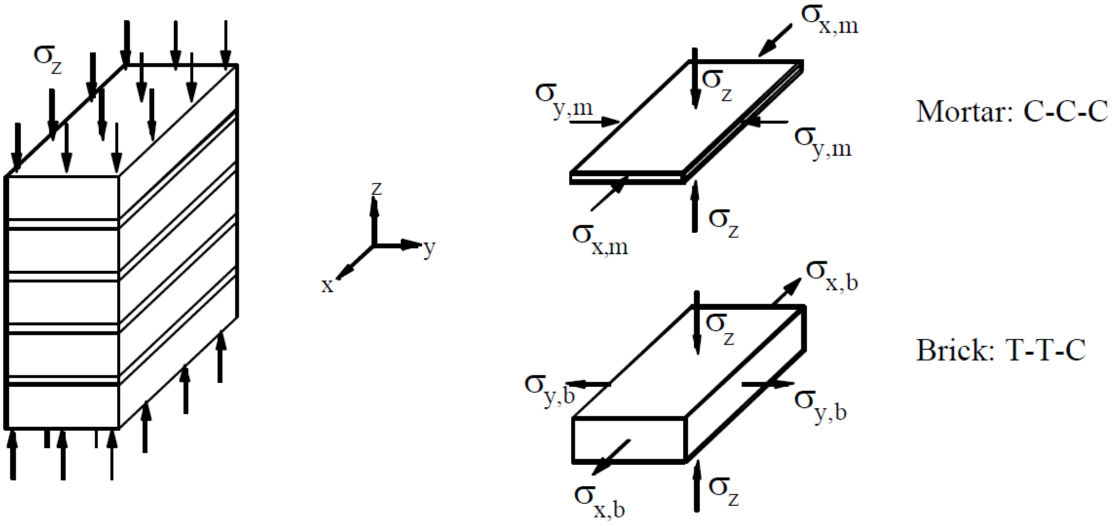


Figure 6 Masonry prism under compressive loading vertical to bed joints and stress states of brick and mortar elements (C: compression; T: tension) (Oliveira 2003)

5 TENSILE STRENGTH OF MASONRY

Masonry has a relatively high resistance to compressive stress but has little resistance to tensile stresses. From the literature (Adami and Vintzileou, 2008; Lawrence et al., 2008), the tensile strength (i.e. the resistance of masonry to tensile stresses) is highly dependent on many factors including the type of masonry unit, the composition of the mortar, the admixtures that may be included in the mortar and workmanship. In order to evaluate the behaviour of masonry under tension, different types of tests have been set up. According to Jukes and Riddington (1997), tensile strength tests can be divided into two main categories: i) direct tensile strength tests (as shown in Figure 7a & d) and ii) flexural tensile strength tests as shown in Figure 7 (b & c).

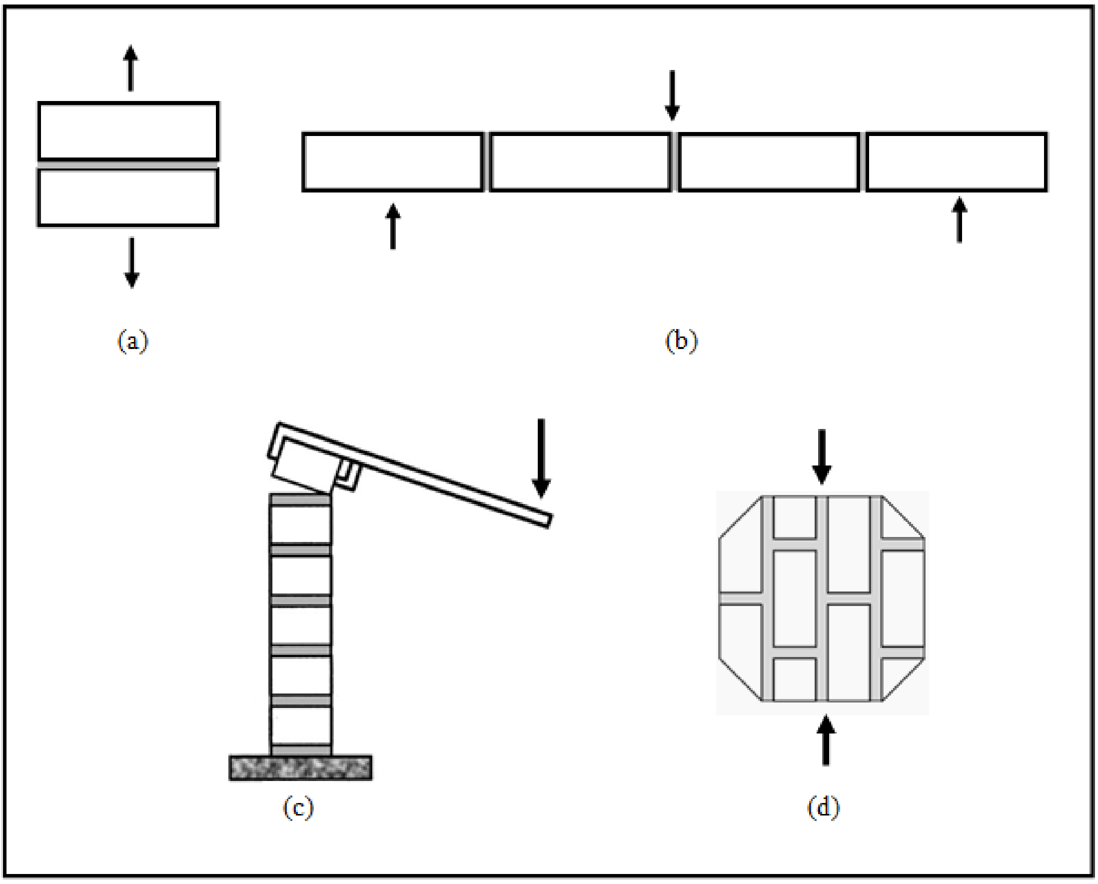


Figure 7 Different tensile bond strength tests: (a) direct tensile bond strength test; (b) flexural bond strength test; (c) bond wrench test; (d) splitting test

Tensile strength

Tensile stresses can occur in masonry as a result of in-plane loading effects caused by eccentric gravity loads, thermal or moisture movements, foundation movement etc. For a tensile test, the relationship between the applied tensile stress and the elongation of the test specimen shown in Figure 8 can be obtained. This shows some tension softening behaviour after tensile failure. The behaviour prior to attaining the peak load is a close approximation to linear elastic behaviour.

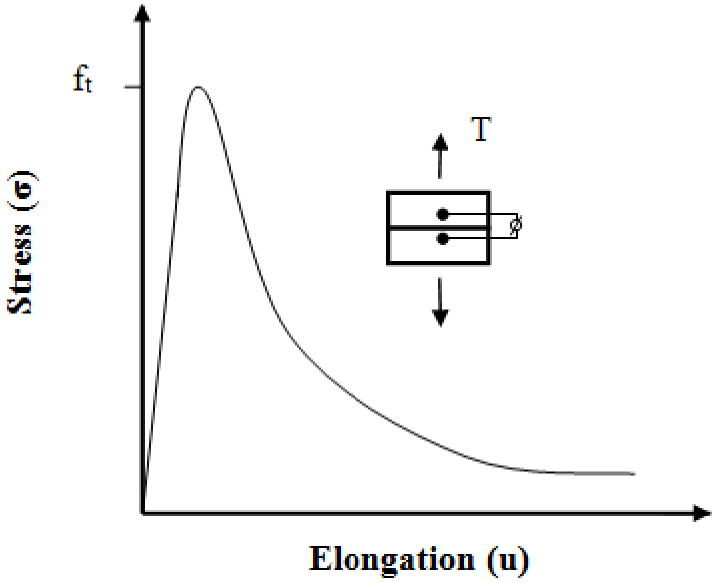


Figure 8 Schematic diagram of a deformation controlled tension test (Van der Pluijm, 1999)

Also, numerous experimental studies have shown that the tensile resistance of masonry is low and variable. As discussed previously, the tensile strength of brick masonry is governed mainly by the strength of the bond between bricks and mortar joints and the strength of the mortar. Van der Pluijm (1999) carried out tensile tests on masonry specimens made from solid clay units. A visual inspection of the failure surfaces showed that the bond area at failure was smaller than the full possible contact area. From Figure 9, the net bond area seems to be concentrated in the inner part of the specimen which can be attributed to a combined effect of poor workmanship. The difference in the net bond areas can significantly scatter in pre- and post-peak masonry behaviour which demonstrates the vast variability of masonry properties.

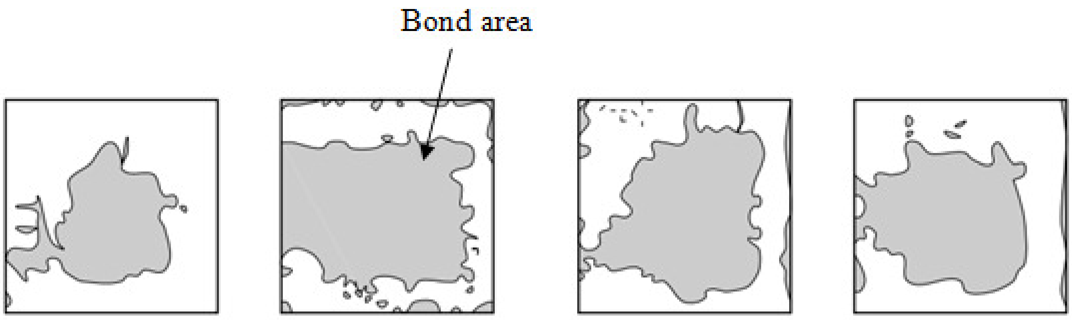


Figure 9 Tensile bond surface of soft mud clay brick with 1:2:9 (OPC:lime:sand) mortar (Van der Pluijm, 1999)

Tensile failure can occur either at the interface (Figure 10a & b) or in the mortar itself (Figure 10c). Failure modes of typical masonry units failed during tensile testing are shown in Figure 11.

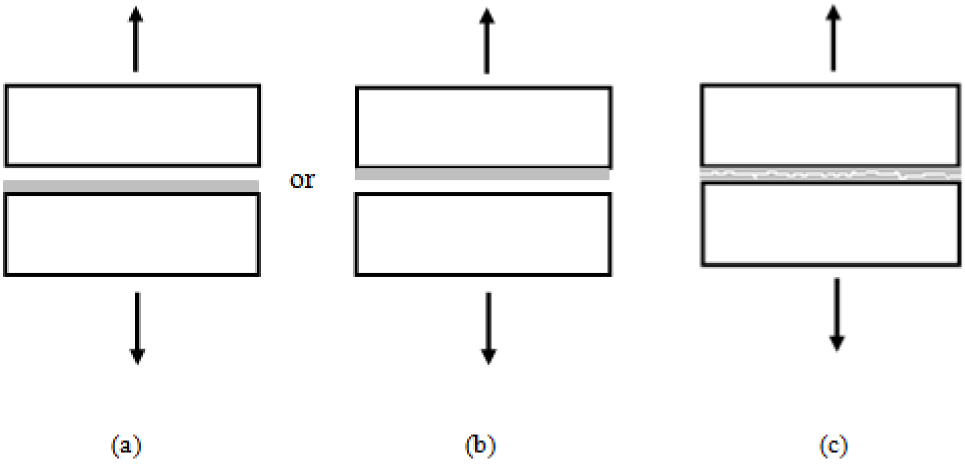


Figure 10 Typical tensile test failure modes: (a) bond tensile failure of the top interface; (b) bond tensile failure of the bottom interface; (c) tensile cracking of the mortar

The significance of the result obtained from tensile testing depends on the mode of failure. If failure occurs at the interface, the result obtained from the test represents the tensile bond strength, if, however, the mortar joint cracks then the test result gives the tensile strength of the mortar. In general, it is difficult to predefine the mode of failure in a tension test and there is no clear or reliable relation that exists between the tensile stress and the mode of failure.

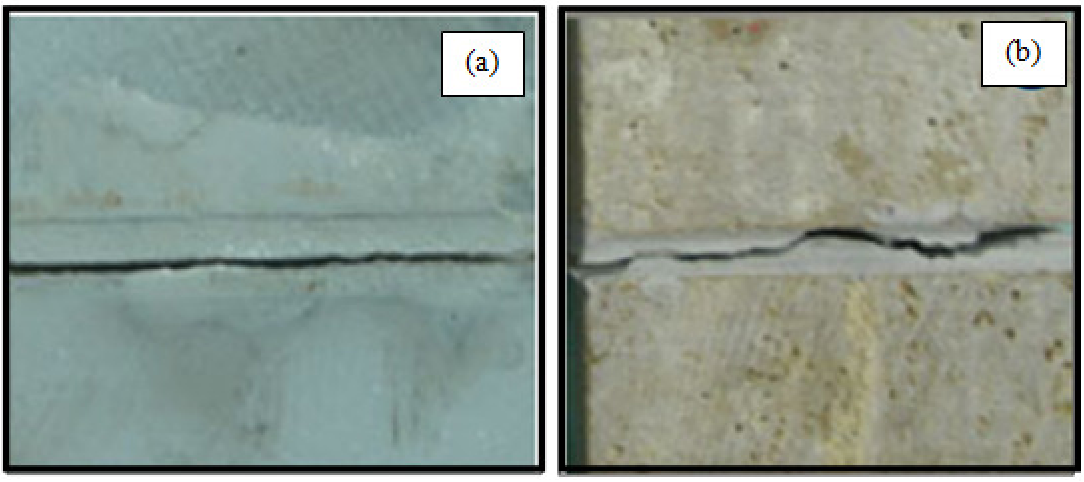


Figure 11 Tensile failure modes: (a) bond tensile failure of bottom interface; (b) tensile cracking of mortar (Adami and Vintzileou, 2008)

From the literature (Hendry, 1998; Van der Pluijm, 1999), the tensile strength of brickwork typically ranges from 0 to 1N/mm^2. However, the variability of this property even in the same structure has to be kept in mind.

Flexural bond tensile strength

The flexural bond strength of masonry is needed particularly for the design of masonry walls subjected to horizontal forces applied normal to the face of the wall, such as wind forces. As in the case of tension, the strength developed is dependent on the absorption characteristics of the bricks and also on the type of mortar used. Flexural tensile strength tests can also be used to obtain tensile bond strength data. However, as identified by Oliveira (2003), flexural tests measure the bond strength at the edge of the mortar joint, but the strength at that point may not be representative of the strength of the full depth joint. Flexural tensile failure modes can either be in the mortar or at the brick/mortar interface, see Figure 12. According to Hendry et al. (2004), the flexural tensile strength of clay brickwork ranges from about 0.8 to 2.0 N/mm^2 depending on whether the plane of failure is parallel or perpendicular to the bed joint.

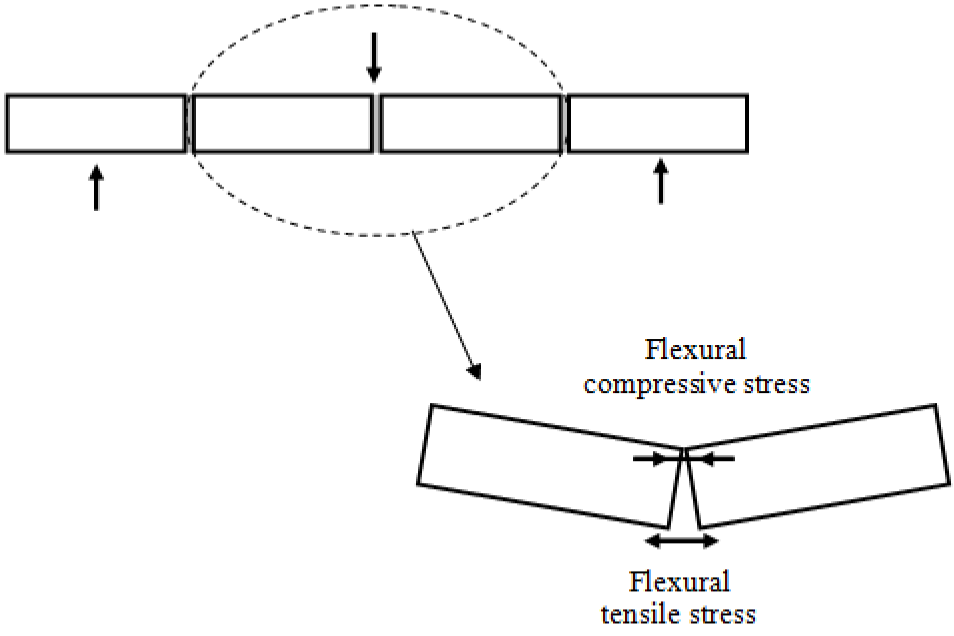


Figure 12 Flexural tensile stresses in a masonry panel (plane of failure perpendicular to the bed joints)

6 COMBINED COMPRESSION AND SHEAR STRENGTH OF MASONRY

The strength of masonry in combined shear and compression is of importance in relation to the resistance of masonry to lateral loading. Several tests on masonry panels and specimens subjected to this type of loading have been carried out to understand its behaviour and to identify limiting stresses to be used in design, see Figure 13. A discussion regarding the adequacy of the different test methods will not be given here; the reader is referred to Atkinson et al. (1989) and Jukes and Riddington (1997) for further information.

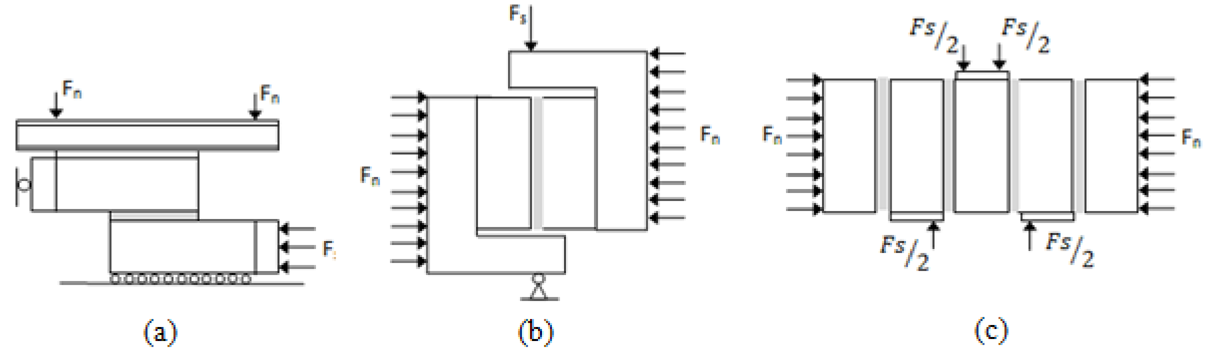


Figure 13 Different types of shear tests a) direct shear test, b) Van der Pluijim test (Van der Pluijim, 1999) and c) triplet test

From the tests, it has been found that the shear strength depends on the mortar strength and results from the combination of two mechanisms: a) bond strength and b) frictional resistance. Typical results of the shear stress plotted against normal pre-compression for a shear test are shown in Figure 14. From Figure 14, the failure behaviour of masonry joints under shear accompanied with vertical pre-compression levels can be represented by the Coulomb friction law. The relationship between the shear stress (τ) and the normal stress (σ) is linear and is given by:

$$\tau = c + \sigma \tan \varphi \tag{1}$$

, where c represents the cohesion or shear bond strength and is the shear strength at zero pre-compression and $tan\varphi$ is the tangent of the friction angle of the interface between unit and mortar joint and is not necessary equal to the coefficient of dry friction (Van der Pluijm, 1992). However, for high normal compressive stresses, the validity of the Coulomb failure is lost and cracking/crushing of the units occurs. According to Hendry (1998), for clay bricks, this limit is about 2N/mm^2. For a shear test with normal pre-compression, the relationship between the shear stress and the shear displacement is of the form shown in Figure 15. The descending part of the graph between ultimate shear strength of a test τ_u and τ_{fr} is described by Van der Pluijm (1999) as softening of the cohesion.

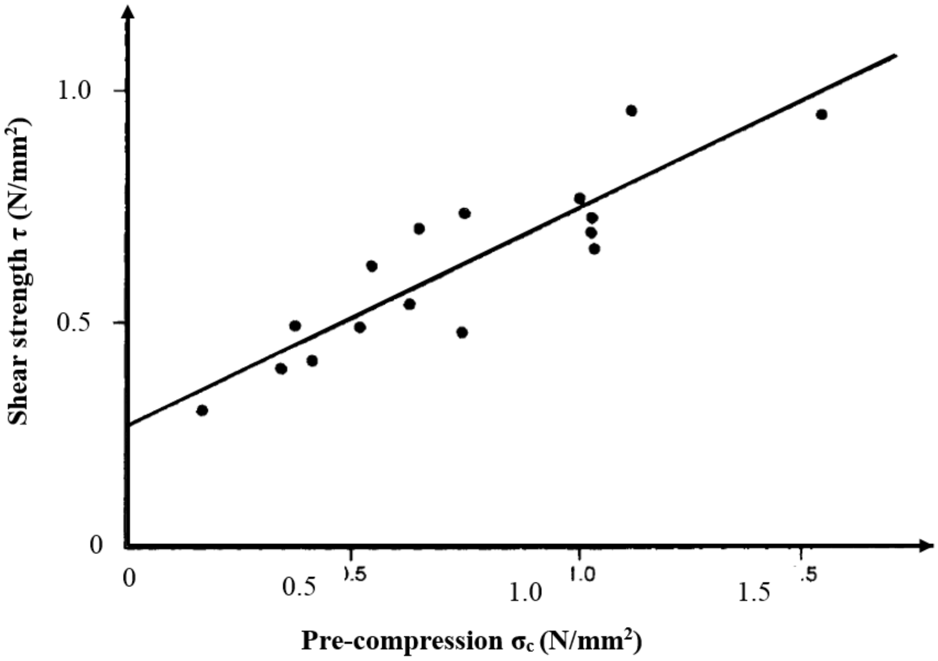


Figure 14 Typical relationship between the shear strength of brickwork and the vertical pre-compression obtained from a shear test (Hendry et al., 2004)

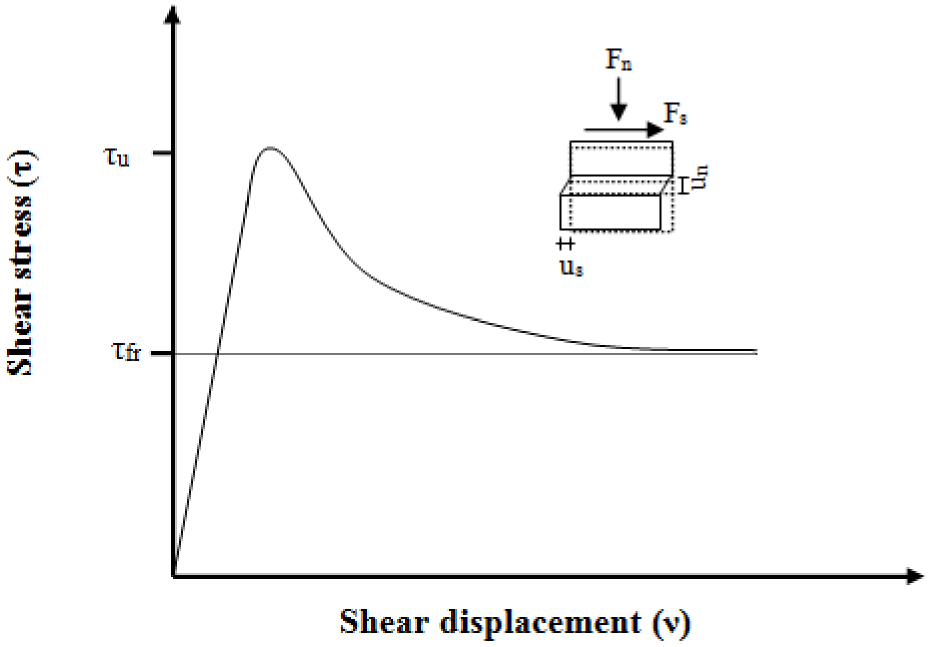


Figure 15 Schematic diagram of a deformation controlled shear test under constant normal compression (Van der Pluijm, 1993)

The values of cohesion and friction angle that define the brick/mortar interface may vary considerably according to the different unit/mortar combinations (Sarhosis et al. 2015). BS5628

(2005) gives design values for cohesion ranging from 0.35N/mm^2 to 1.75 N/mm^2 and tanφ equal to 0.6 for mortar designation (i), (ii) and (iii). In EC6, a table is provided which gives values for cohesion for different unit/mortar combinations and a constant value of tanφ equal to 0.4. In the literature, the value of tanφ usually varies between 0.7 and 1.2 (35^0 to 50^0) depending on the materials used (Lourenço et al. 2004). The published values of the cohesion parameter are reported to vary between 0.1 and 1.8 N/mm^2 (Lourenço, 1998b; Hendry, 1998; Jukes and Riddington, 1994; Van der Pluijm, 1999). According to experimental studies on masonry wall panels having a height to length ratio of 1.0 or more and units with a compressive strength of between 20 and 50 N/mm^2 laid in 1:1:6 (OPC:lime:sand) mortar, the value of cohesion has been estimated to be equal to 0.2 N/mm^2 (Hendry et al., 2004).

Another relevant feature of masonry joints is the so-called dilatancy angle (ψ). This is a measure of the volume change upon shearing. From Figure 15, the ratio between the normal displacement (u_n) and the shear displacement (u_s) gives tanψ. The dilatancy angle is positive but tends to zero upon increasing normal confining stress (Van der Pluijm, 1999). A typical relationship between the normal stress and the dilation angle is illustrated in Figure 16.

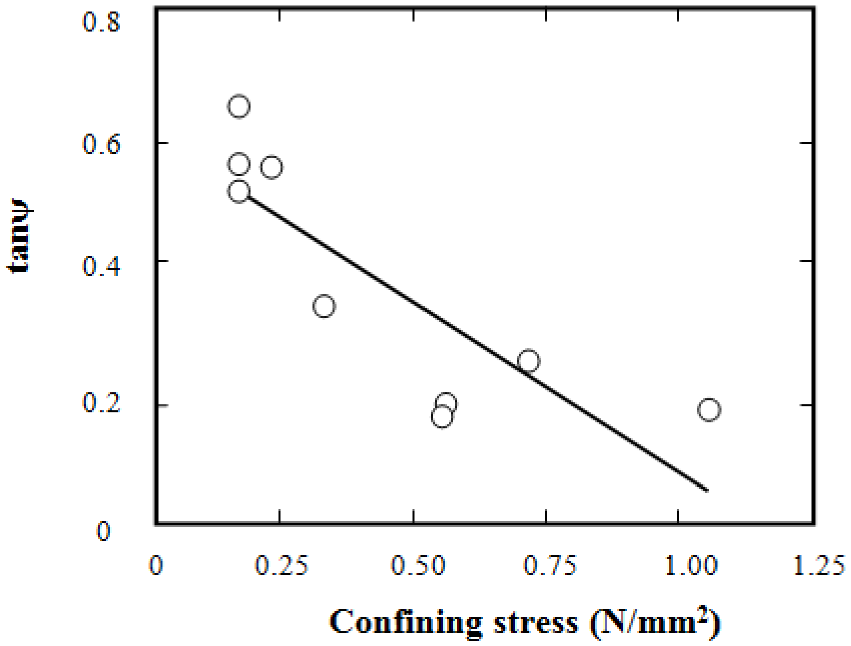


Figure 16 Effect of normal stress on the dilation angle (Van der Pluijm, 1993)

The failure modes generally recorded during shear tests for masonry with low strength mortar are:

Mode a: shear failure of the top/bottom interface

Mode b: a fracture plane at each brick-mortar interface accompanied by a vertical crack in the mortar.

These failure modes are schematically represented in Figure 17 and shown in Figures 18 & 19.

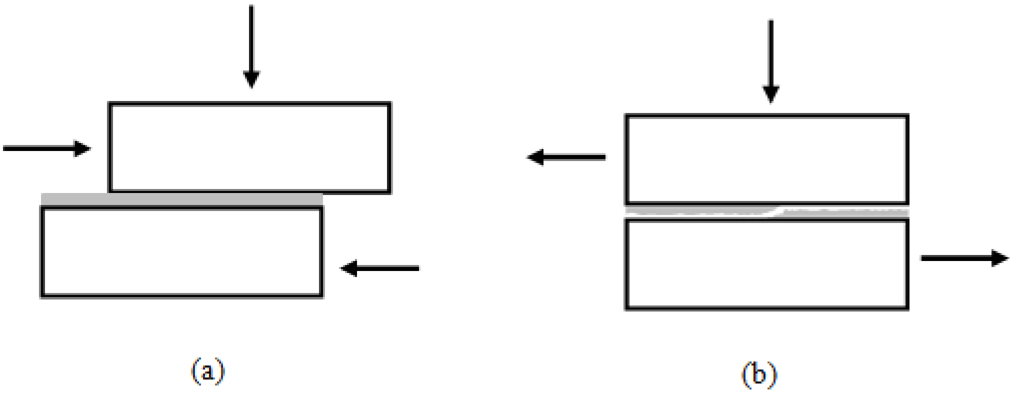


Figure 17 Typical shear failure modes: (a) shear failure of the top interface; (b) shear failure of mortar. Arrows indicate forces in the brick specimen

Figure 18 Failure mode during shear test (Abdou et al., 2006)

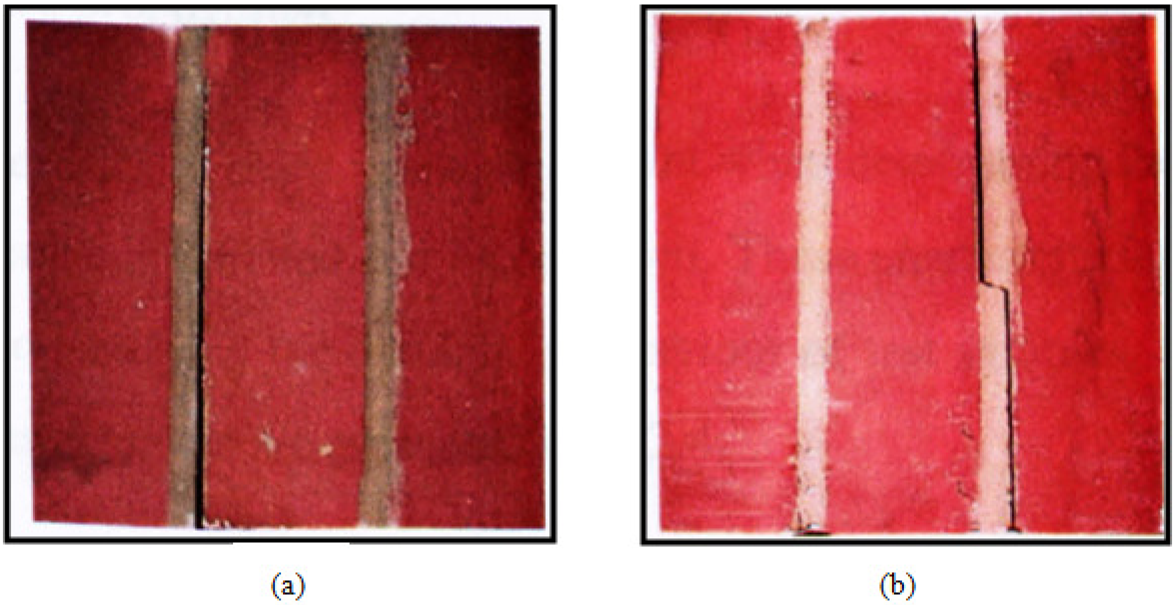


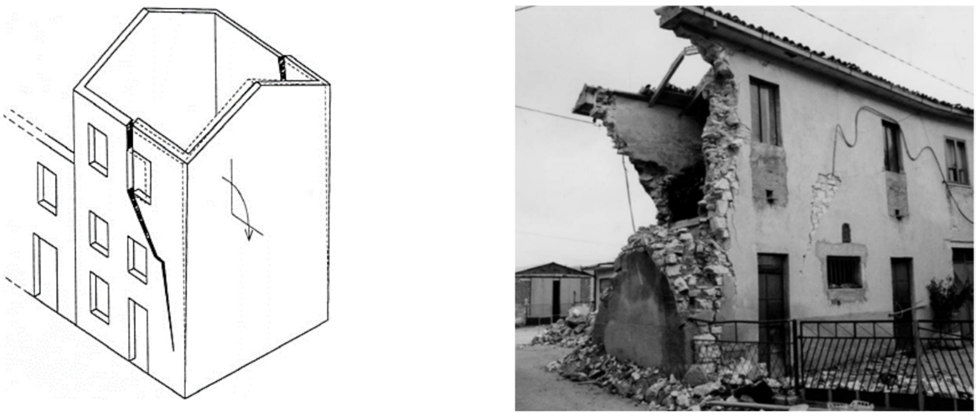
Figure 19 Failure modes (a) and (b) from the triplet shear test (Beattie, 2003)

The mode of failure that may occur during shear testing is determined by the shear bond strength at the unit/mortar interface and the shear strength of the mortar joint in relation to the amount of shearing under vertical pre-compression. However, as far as the author is aware, there is no evidence of any research into the relationship between the mode of failure and the amount of vertical compressive stress for very low values of compression. When evaluating the results of shear tests, the shear strength will be the lower value of the mortar strength or the brick/mortar bond strength (i.e. whichever fails first).

Overall, for masonry subjected to in-plane combined axial loading and shear where the levels of compressive stress are sufficiently low to avoid a crushing failure, it seems that the behaviour of the masonry can be best described by a constitutive law which is based on or encompasses the Mohr-Coulomb failure criterion.

7 OUT OF PLANE BEHAVIOUR

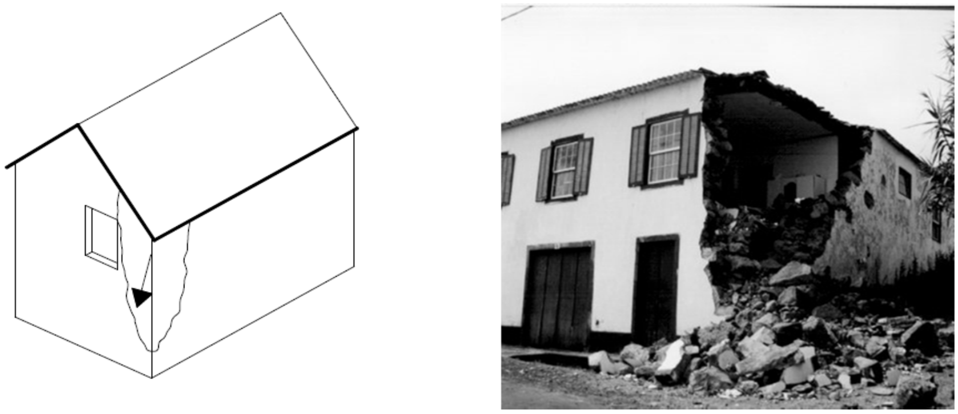
Out of plane loading refers to the response of masonry to horizontal actions perpendicular to their plane. Such loading can be due to wind or earthquake. Experience has shown that masonry structures are most vulnerable to the out of plane loading. The major mode of failure is due to overturning (Casarin 2006). Most of the times, such failure is happening in structural elements of the building which may lead in total collapse. Typical out of plain failure modes are presented in Figure 20. Figure 20a shows the out of plane failure of the façade of a building due to poor connection between the diaphragms and the external walls. An out of plain failure with the overturning of some of the façade walls of the top of building due to Christchurch earthquake in 2011, is shown in Figure 20b. The lack of connection between external and internal walls of the buildings did not allow the box behaviour to develop and led to catastrophic collapse. As we can see, the walls have completely detached. Figure 20c shows a partial overturning of façade at the weakest component (openings). Last, Figure 20d illustrates overturning of a corner wedge due to ineffective connection between external walls, insufficient anchoring of the floors to the perimeter walls and the presence of openings near the edges. As can be seen from Figure 20d, the crack pattern follows the opening of the façade.



(a)

(b)

(c)



(d)

Figure 20 Failure modes due to out of plane loading during earthquakes: (a) Overturning of façade; (b) Overturning of portions of the façade; (c) Partial overturning of façade (effect of openings) (Binda et al. 2006); (d) Overturning of corner wedge (Lagomarsino 1998; Beolchini et al. 2002).

8 CONCLUSIONS

Masonry is a heterogeneous, anisotropic composite material. The non-linear behaviour of masonry is controlled by the mortar joints which act as planes of weakness. The characteristics and the mechanical properties of masonry may vary significantly even in the same structure. Brick properties may vary due to the brick making process; variation in the raw material or as a result of deterioration. Mortar joint properties may also vary considerably due to the variability of the mixed constituents and their position (horizontal or vertical) in the structure. There may be non-uniform distributions of stress due to applied loading caused by differences in the stiffness of the perpend and bed joints. The most important factors that influence the mechanical response of brick masonry are: a) the brick characteristics; b) the mortar joint characteristics; c) the brick/mortar bond characteristics; d) the curing process; and d) the quality and workmanship. Restraining the movement of a brittle material such as masonry can result in cracking. Cracks in masonry can occur in the masonry units, in the mortar, at the unit/mortar interface or in all of these. Cracks in masonry may not open uniformly but may close and open according to the type of applied stress. Possible failure modes that can occur in masonry are: joint tensile cracking, joint slip cracking, masonry unit tension cracking and masonry crushing. The main mechanical features of masonry can be characterised by the rigidity of the masonry units which have a comparatively high resistance to compression, the deformability of the joints with a weak resistance to tension and the frictional properties of the brick/mortar interface. Experimental investigations carried out by several researchers have demonstrated that the occurrence of cracks and the modes of failure depend on the direction and magnitude of shear and normal stress applied to the masonry. For low strength masonry (such as historic masonry structures), cracking tends to be along the brick/mortar interfaces and failure usually results from de-bonding or separation of the bricks from the mortar joints. At low values of normal stress, the principal failure modes of masonry built with low strength mortar are either: a). De-bonding at the brick mortar interface or b). Tensile failure of the mortar resulting in an opening of the joint (i.e. cracking) and frictional sliding. Several small scale tests have been carried out in the past by many researchers to investigate the strength of masonry in tension and in combined compression and shear. However, depending on the type of test and the materials tested a large variation in the tensile and shear strength has been obtained. Values of tensile strength can range from 0.0 to 1.0 N/mm^2. Values of cohesive strength are reported to vary from 0.1 to 1.8 N/mm^2 depending on the materials tested and the test method used. For masonry subjected to in-plane combined axial loading and shear, where the levels of compressive strength are sufficiently low to avoid crushing failure, the behaviour of masonry can best be described by a constitutive law which is based on or encompasses the Mohr-Coulomb failure criterion.

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KEY TERMS AND DEFINITIONS

Brickwork: Masonry produced by laying one brick over the other separated with or without mortar.

Load: External forces applied to the structure.

Tensile strength: Max stress that masonry can withstand while being stretched or pulled and before fail.

Compressive strength: Max compressive force resisted per unit area of net cross sectional area of masonry.

Dilation angle: Is the angle which measures the uplift of one unit (i.e. brick or block) over the other.

Friction angle: Force resisting the relative motion of two surfaces of solid blocks.

Bond strength: The strength that keeps building material and mortar together.