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THE MECHANICAL BEHAVIOUR OF MORTARS IN TRIAXIAL COMPRESSION

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Abstract. *Most commonly the mechanical behaviour of the masonry composite is derived from the complex mechanical interaction in between the masonry units, stone and/or brick, and the mortar joint. While mortars generally are described by means of their mechanical properties in standardised uni-axial compression, equilibrium within the masonry composite most often results in the presence of a horizontal confinement within the mortar joint. A series of tests on mortar samples in a state of triaxial compression evidence a clear change in mechanical behaviour and failure mechanism compared to the mechanical behaviour of the mortar in uni-axial compression. Depending upon the importance of the horizontal confining pressure, within the mortar joint, the mechanical behaviour of the mortar can shift from a very brittle material to highly elasto-plastic, while in the mean time a pore collapse mechanism is induced.*

In order to describe the mechanical behaviour of the masonry composite from the individual materials, an adequate modelling of the mechanical behaviour in triaxial compression of the mortar becomes necessary.

This paper gives an overview of the mechanical behaviour of mortars in uni-axial and triaxial states of stress. The phenomenological approach and the first step towards the modelling of the mortar structure are presented.

1 INTRODUCTION

The main objective for the presented study is to understand the differences in material behaviour of the composite masonry constructed with different mortar types; e.g. putty lime, hydraulic lime, cement or lime-cement mortars. While lime mortars generally obtain a lower uniaxial compressive strength, determined in a standardised way, than nowadays cement-based mortars, its influence on the overall strength of the masonry structure is minimal and the possibility of the former to adapt to settlements is extraordinary and still not understood[i,ii].

Masonry is a composite material, built up of brick or natural stone units and a mortar as binder matrix. Both composing materials are different in nature. Both brick and natural stone can be considered as an elastic brittle material with a certain compressive strength and some tensile strength, which is often considered only one tenth of its compressive strength. Mortar is generally also considered an elastic brittle material, however, with a much higher deformability with regard to the brick or natural stone units. Due the composite nature of masonry and the important difference in deformability of the composing materials, the stresses and strains will be divided in a complex manner between the brick units and mortar matrix, if masonry is subjected to an external loading[iii]. Most common masonry is loaded by the dead load of the structures it bears. The vertical loads result in a horizontal confining pressure on the mortar inside the horizontal joint, as the mortar tries to move out horizontally from between both bricks due to its elevated deformability. Equilibrium in the composite masonry results in horizontal tensile stresses in the brick[iv,v] (figure 1).

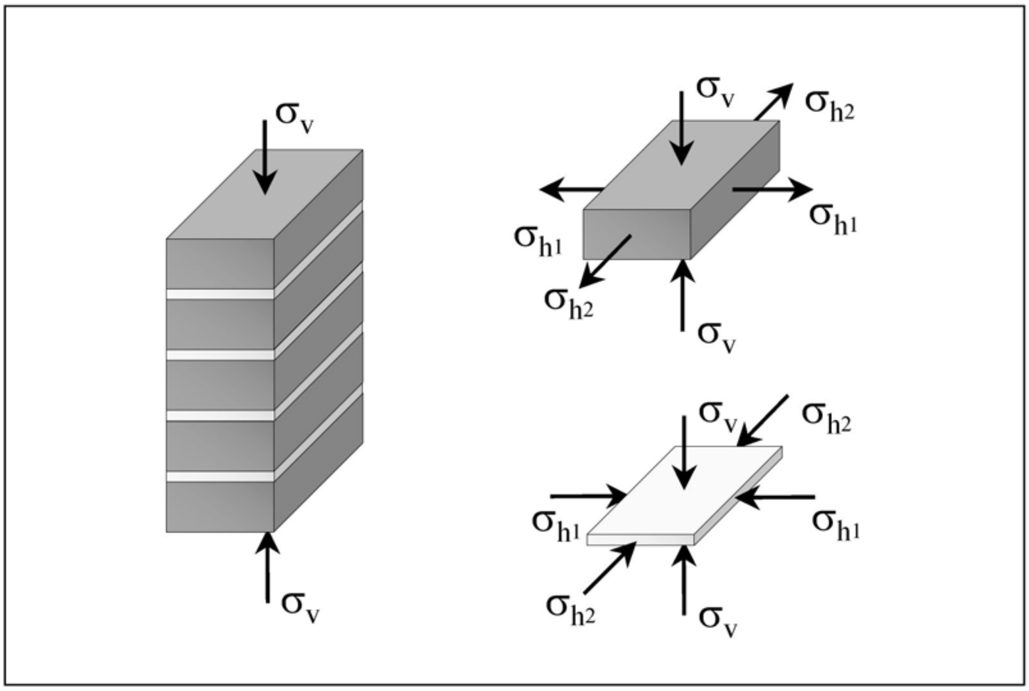


figure 1: Stress redistribution in a masonry composite

2 THE MATERIAL BEHAVIOUR IN COMPLEX LOADING CONDITIONS

2.1 Introduction

The following paragraphs outline the change in material behaviour and failure mechanism of a mortar upon triaxial loading. It is important to note that, apart from the actual values of compressive strength and the associated deformations, no important differences are found for different mortar types upon their overall mechanical behaviour in triaxial compression[vi,vii]. The analysis of the influence of the triaxial loading condition on the material behaviour is therefore valid for mortar in general, independent of the type and composition of the mortar (e.g. putty lime, hydraulic lime, cement or lime-cement mortar).

2.2 From brittle to elasto-plastic deformation

Upon triaxial loading an evident change in material behaviour can be discerned, as is demonstrated in figure 2, where the deformations of a putty lime mortar are represented in both uni-axial and triaxial loading conditions. From the analysis of the development of the stress-strain relationship with an increasing σ_h/σ_v-ratio – the ratio σ_h/σ_v will further on be denoted as κ – the following observations can be deduced:

- a change in material behaviour is observed from brittle in uni-axial loading to a combined elastic and plastic behaviour in triaxial loading, from rather low confining pressures up to hydrostatic compression. From κ as low as 0.15 the influence of the rather limited confining pressure is important, resulting initially in some post-peak plastic behaviour and gradually, as

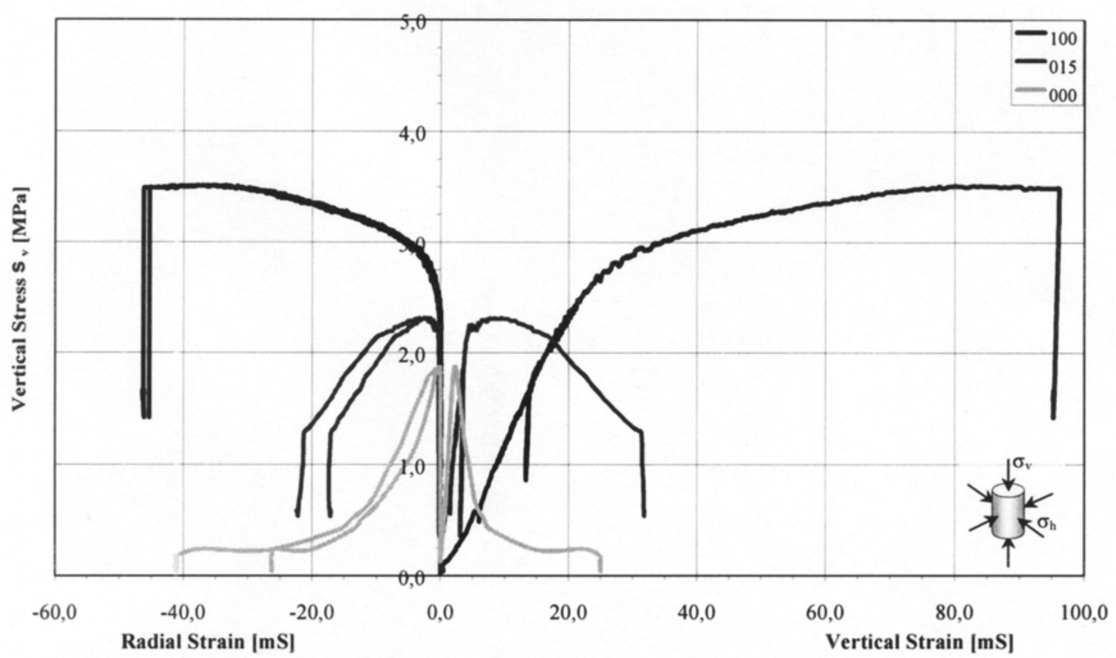


figure 2: Vertical and horizontal deformations in uni-axial and triaxial loading conditions. The legend represents κ in hundredths of a unit

κ increases, altering the mechanical behaviour to an elasto-plastic material. A similar change in material behaviour has been recorded for several other materials as e.g. porous chalk[viii], porous sandstone[ix] and concrete[x].

- an important increase in strength is observed with only a slight increase in the contribution of the horizontal confining pressure on the overall loading condition. This is fairly evident in the graphical representation of the corresponding horizontal and vertical loading conditions at failure, the triaxial yield criterion in the $\sigma_{II} = \sigma_{III} = \sigma_h$ plane, in figure 3.
- a tendency towards an increase in deformability in the elastic region at higher κ-values. The collected data is however rather limited and too scattered in order to formulate a relationship between the change in modulus of elasticity and κ.

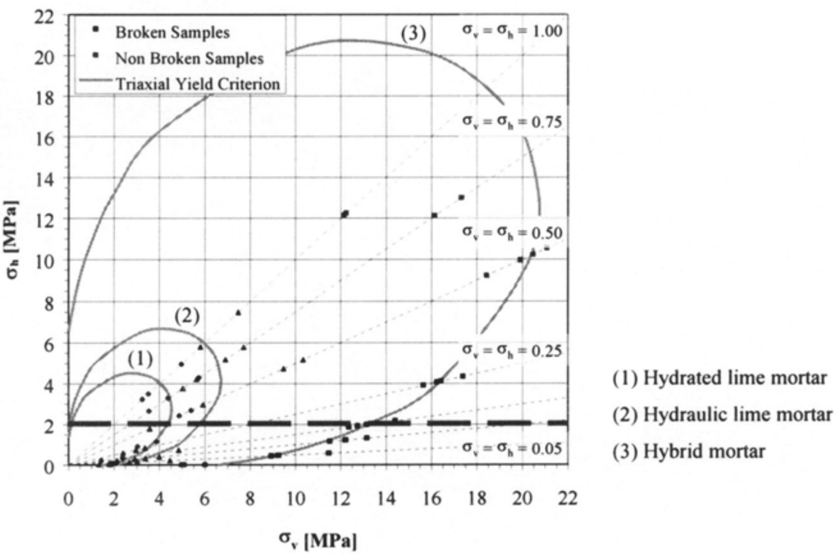


figure 3: Triaxial yield criterion

2.3 From shear failure to pore collapse

Analysis of the volumetric deformation upon triaxial loading, represented in figure 4 for a moderately hydraulic lime mortar, evidences a change in failure mechanism at values of κ above 0.25 (at κ equal to 0.25 both failure mechanisms have been observed for the different mortar types).

Under uni-axial loading or triaxial loading conditions with a relative limited horizontal component (κ < 0.25), the recorded volumetric deformations, as well as the evolution of the Poisson's ratio throughout the test, evidence the existence of a shear failure mechanism. After an initial decrease in volume, probably due to the closing of existing cracks and anomalies within the mortar structure, an increase in volume is rather soon observed as a network of very fine vertical cracks starts to grow and shear bands develop. The mortar sample finally collapses along diagonal shear bands accompanied by a substantial increase in volume over the middle section of the cylindrical mortar sample.

For triaxial loading conditions with an important horizontal confining pressure (κ > 0.25), failure of the mortar no longer coincides with an increase in volume. Hence, no shear failure mechanism is observed. In stead a rather constant decrease in volume is observed right to the end of the triaxial test, setting forward the possibility of a pore collapse mechanism. The existence of such a pore collapse mechanism has been demonstrated in the case op porous rocks[xi,xii]. In most cases the triaxial tests had however to be terminated before the actual failure of the mortar was observed, due to the limited measurement range of the triaxial test apparatus (these points are referred to as non broken in figure 3), at least if failure is defined as a decrease in bearing capacity of the mortar sample. Careful study of the mortar samples after the triaxial tests proved that, although the bearing capacity of the mortar was unaffected, the internal structure of the mortar was almost completely destroyed and the mortar internally was turned to powder. Failure itself, therefore, was not observed as a decrease in bearing capacity, but rather by the collapse of the internal structure of the mortar. If and how the bearing capacity of the mortar finally will fade away, could not be derived from the current study.

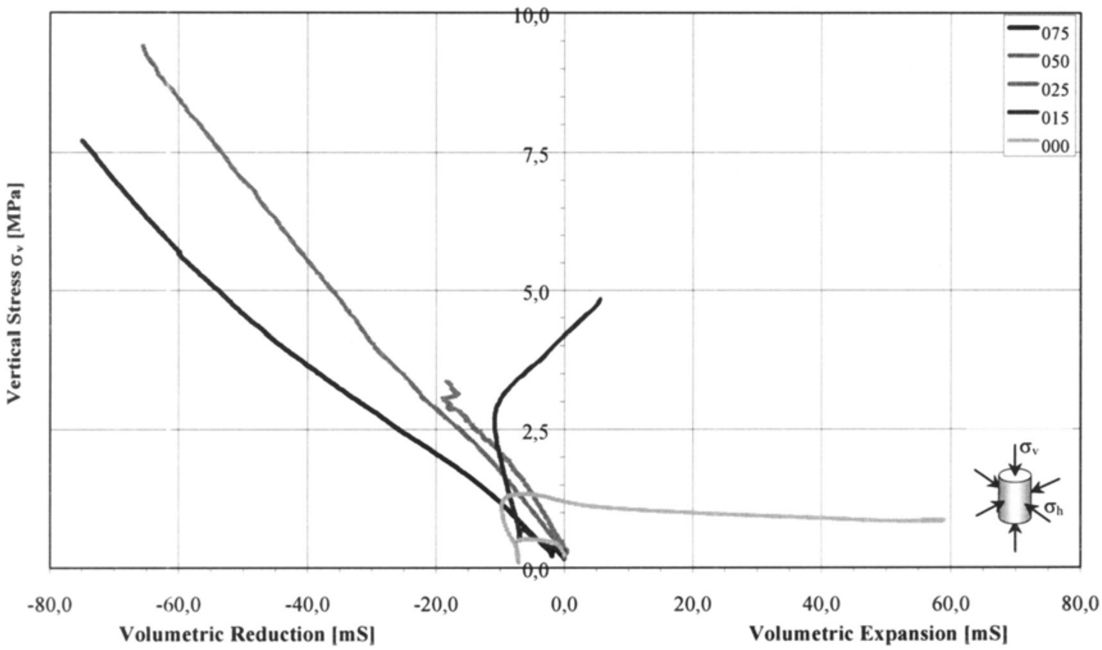
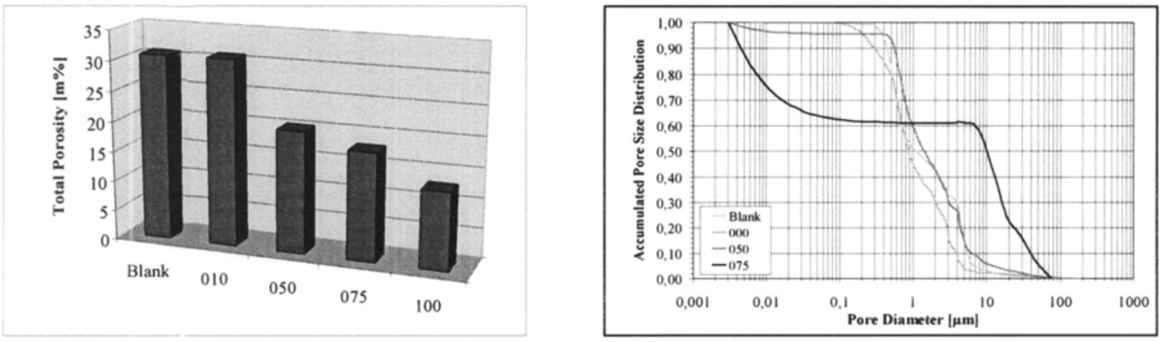


figure 4: Volumetric deformations in uni-axial and triaxial loading conditions.
The legend represents κ in hundredths of a unit

2.4 Evidence for a pore collapse mechanism

The study of the internal pore structure of very weak lime mortars, let alone the study of a deteriorated lime mortar after triaxial compression, is a problem on its own which faces a lot of problems regarding the validity of the test results. The most important issue is the influence of the test conditions on the pore structure of the weak sample. In order to at least put forward some evidence of a pore collapse mechanism several tests were explored and combined; the determination of the total pore volume through vacuum submersion and the analysis of the pore structure by means of mercury intrusion and scanning electron microscopy.



(a) (b)

figure 5: a) Total pore volume by vacuum submersion, b) Pore size distribution by mercury intrusion
The legend represents κ in hundredths of a unit

The results obtained are represented in figure 5a, for the total porosity by vacuum submersion in the case of an hydraulic lime mortar, and figure 5b, for the pore size distribution by mercury intrusion in the case of a putty lime mortar. Both studies show some evidence for the alteration of the internal pore structure of the mortar upon triaxial loading conditions for κ above 0.50. For the hydraulic lime mortar the decrease in total porosity, even considering a normal variation in material properties of the material, is substantial. The study of the pore structure by mercury intrusion on the other hand shows that the internal structure of the -putty lime- mortar undergoes an important transformation. The triaxial loading condition, again in the case of the presence of an important horizontal component, is responsible for the formation of both a network of fine to large cracks and the closing of the medium sized pores. This was also recorded by means of the SEM-images, where indeed the formation of a network of fine cracks from grain to grain was confirmed.

The main objective is the understanding of the material behaviour of masonry, constructed either with an age-old low strength, highly deformable lime mortar, or with a modern high strength, stiff cement mortar. The differences in material behaviour and especially the total amount of deformation of the masonry cannot be attributed to the material properties of the mortar alone. While lime-based masonry exhibits several times more deformation upon failure in comparison to cement-based mortar, their difference in Young's modulus accounts for only an increase in deformability of about 30% (Taking in consideration that a Young's modulus of 100 MPa is a lower limit for lime-based mortars and 800 MPa a higher limit for cement-based mortars). The explanation of the higher deformability of the limed-based masonry, therefore, has to be found elsewhere.

3 BACKGROUND FOR THE CHANGE IN FAILURE MECHANISM

The occurrence of intersecting diagonal shear bands in uniaxial vertical compression is generally attributed to the formation of a network of interacting vertical cracks, which are induced by the stress concentrations occurring around pores, anomalies or existing flaws within the internal structure of the mortar upon compression (figure 6). The analytical solution for the 2-dimensional stress distribution surrounding a circular hole in an infinite plate is well known. The structural discontinuity of the hole leads to the occurrence of both compressive and tensile stress concentrations at its edge. In uniaxial compression a compressive stress, 3 times the applied uniaxial stress, appears at the holes' edges in a direction perpendicular to the externally applied stress, while tensile stresses, in absolute value equal to the applied stress, occur at the holes' edges parallel to the loading direction. The occurrence of such tensile stresses in a low tensile strength material leads gradually, as the external loads increase, to the formation of an increasing number of cracks parallel to the applied load at pores, anomalies and existing flaws within the mortar structure. The mechanical interaction of these individual cracks finally leads to the occurrence of diagonal shear bands, inducing failure of the mortar sample.

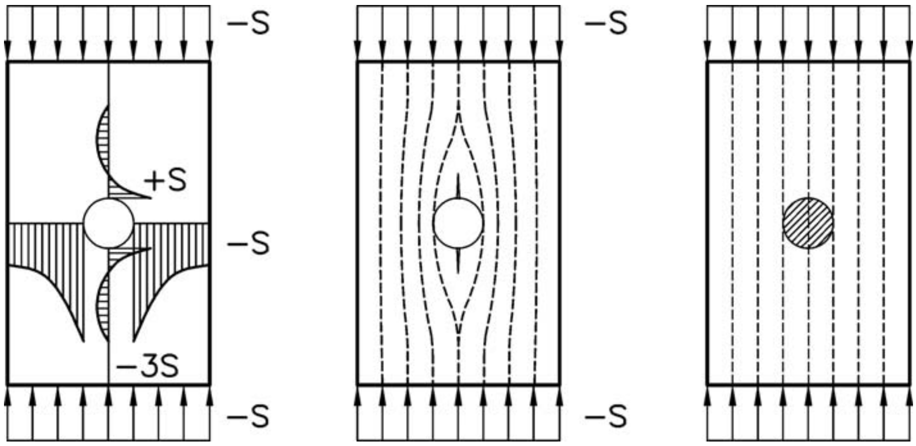


figure 6: Stress distribution and the onset of crack formation for a circular hole in an infinite plate in uniaxial compression

In the case of a triaxial loading condition, the horizontal confinement will of course counteract the horizontal tensile stresses induced by the main 'vertical' load. Returning to the analytical solution of the stress distribution around a hole, one can determine that at a kappa value of 0.25 the maximum tensile stress at the holes' edge has already diminished considerably. In order for a crack to form and the adhered shear band to develop, the main 'vertical' load has to increase accordingly. At a kappa value of 1/3, the tensile stresses within the holes' neighbourhood even disappear completely. Hence, failure along shear bands becomes by definition impossible. Regarding the fact that the internal structure of a material always presents at least some tensile strength, the formation of shear bands will practically be already inhibited at a somewhat earlier stage. The observation of the disappearance of the failure phenomenon along shear bands at a κ-value of 0.25 is therefore confirmed.

4 MASONRY AND THE COMPLEXITY OF A COMPOSITE MATERIAL

Looking at the results of the triaxial analysis, the difference in material behaviour of the masonry can neither be attributed to a difference in material behaviour of the mortars. There is a difference in actual deformation of the mortars upon triaxial loading, but however not to such an extent that it can account for the large difference in deformability of the masonry. Since the difference in deformability for the different types of masonry apparently cannot be attributed to the material behaviour of the mortar, the explanation has necessarily to be found in the composite nature of the masonry where the triaxial interaction occurs as a result of the brick-mortar interaction. As said before, the ultimate state of the masonry upon failure is determined by the tensile strength of the brick or natural stone and/or the shear strength on the brick/stone-mortar interface. The development of the stresses and strains upon loading of a masonry wall can, for the moment being, not be explained. However, based on the present analysis of the triaxial behaviour of the mortar, the ultimate state of the masonry at the moment of failure of the brick can be examined.

The observation of the material behaviour of the masonry is based upon the triaxial yield criterion for the mortars, represented in figure 3, and the assumption that the tensile strength of the brick or natural stone and not the shear strength on the brick/stone-mortar surface is determinative for the failure of the masonry structure. Looking at the frequent occurrence of vertical cracks within the brick or natural stone units of load-bearing masonry walls, this seems a valuable assumption. The tensile strength of the bricks, found in ancient brickwork, is generally about 1 to 2 MPa. Considering, for example, a 2 MPa strong brick, the ultimate state of compression of the mortar in the masonry upon failure of the brick is represented in figure 3 by a horizontal line at σ_h equal to 2 MPa. In the case of limed-based masonry, this horizontal line intersects the failure envelope for the lime mortar in a triaxial compression state with κ of about 0.50. At failure of the masonry, the lime mortar, therefore, behaves as a elasto-plastic material with an activated pore collapse mechanism. Hence, large deformations of the mortar, and consequently the masonry, can be observed. The lime-cement mortar, on the other hand, is situated at a κ-value of around 0.15 on the verge of the plastic-viscous material behaviour. Around peak stress already to some extend an increased plastic deformation of the mortar occurs, however without the initiation of the pore collapse mechanism. No cement mortars were tested, due to the high strength of the mortar in respect to the attainable confining pressure within the triaxial test apparatus. From the knowledge gained in the study of the three other mortar types and the ultimate strength of the cement mortar in uni-axial compression (~15 MPa), an imaginary envelope in the triaxial yield criterion can be imagined, intersecting both axes at $\sigma_h = \sigma_v = 15$ MPa. The ultimate state of the masonry will in such a case be defined by a triaxial state of compression with κ around 0.05 to 0.10, where the cement mortar is thus a more or less brittle material with only the elastic deformation being addressed. This agrees with earlier test results on masonry walls, where for lime-based bedding mortars important plastic deformations were recorded, before collapse of the masonry structure, and none for the masonry structures based on pure cement bedding mortars[xiii]. The increase in deformability of the different types of masonry is thus not explained by the difference in elastic properties of the mortar, but rather by a difference in material behaviour when applied in the composite masonry. The issue of mechanical compatibility, upon applying new materials in historic masonry, therefore, should not focus on maximising the strength characteristics of the new material, but instead turn to the evocation of the plastic material behaviour in triaxial compression. Weaker mortars will be able to address their plastic deformation much more, compared to stronger mortars, before subjecting the bricks to tensile stresses, which will break the latter. As such the restored masonry will employ fully its ability to adapt to the imposed settlements.

5 CONCLUSIONS AND FURTHER RESEARCH

The change in mechanical behaviour of mortar from a brittle material in simple uniaxial compression to a elasto-plastic structure in triaxial compression has been demonstrated experimentally. Additionally, the adhering change of failure mechanism from the occurrence of diagonal shear bands, attributed to the formation of a large number of interacting vertical cracks forming the shear bands, to a mere pore collapse of the internal structure is observed as well. A theoretical approach, based upon the initiation of the network of vertical cracks within the shear bands, tends to confirm the observed value of κ at which the change in failure mechanism is observed experimentally.

The initial presence of a shear failure mechanism puts forward the use of a non-associated Mohr-Coulomb or Drucker-Prager failure criterion[xiv], while the changes in pore structure could probably be modelled with an alteration of the parameters, due to an increase in damage, of the description of the mortar as a cohesive-frictional material. The elaboration of such a material model is foreseen in the near future. The confrontation of such a material model within a FEM-model of the composite masonry structure with a series of test results on the development of the strains and stresses within single leaf masonry walls, which are currently being processed, will be useful to understand the development of the elastic and plastic deformation of the composite structure. Hence, a better understanding of the mechanical behaviour of historic masonry structures will be gained.

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