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EXPERIMENTAL STUDY OF SHEAR BOND STRENGTH OF TRADITIONAL MASONRY

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Abstract

The failure of the masonry's joints, under horizontal loads, is attributed to the development of the shear and tensile stress that lead to the rupture of the brick - mortar interface of the joint. In this paper shear bond strength of the brick - mortar interface was measured on two types of traditional masonry prisms in form of triplets. Triplets were made either of compressed earth bricks and mud mortars or of fired bricks and lime mortars. For that purpose, an experimental method was developed. The influence of the joint thickness, the size of the bed joint of brick and the mortar strength to the bond were studied. Bond strength and friction coefficient of the different types of masonry were investigated. Both traditional masonries showed low bond strength and joint slip in general was characterised by high ductility. Results could be useful for numerical analysis of the above masonries.

Key Words

Earth brick masonry, fired brick masonry, shear, bond strength

1 Introduction

The strength of the bed joint which characterises the brick – mortar interface is of particular concern in the case of unreinforced masonry structures, such as compressed earth brick and fired brick masonries, found in historical buildings. The available knowledge concerning shear strength and shear load displacement of these types of masonry is less advanced compared to the behaviour of the masonries in compression although shear is the dominant mode of failure observed in many masonry buildings subject to seismic loadings (Kariotis et al., 1985). The behaviour of this traditional type of masonry is of particular interest in the case of repairing (deep pointing and reconstruction) of old or monumental structures.

An extensive experimental program was implemented at the laboratory of Buildings Materials of the Aristotle University of Thessaloniki, for the comparative study of the behaviour of the traditional masonry specimens made with compressed earth bricks - mud mortars and fired bricks – lime mortars. One of the objectives of the project was

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the experimental determination of the shear bond strength between compressed earth brick and mud mortar interface in comparison with that of fired brick and lime mortar. As parameters, geometrical aspects of the prisms such as the joint thickness, the brick width (surface size of the brick-mortar interface) and the mortar composition on the shear behaviour of the masonry prisms were studied (Bei, 2004).
There are no scientific reports on shear tests under normal stress on earth brick masonry. Only a few references dealing with tests of flexural bond (bond wrench testing) exist. These tests were made by Walker (1999), who has found that the commonly flexural bond strength values were less than 0.10 MPa. Venu Madhava Rao et al (1996) have reported flexural bond strength between 0.004 to 0.14 MPa while Mehra, et al (1950) have found that the tensile bond strength for mud mortars with 5% to 10% cement ranged between 0.007 to 0.32 MPa.
Shear tests were performed according the first draft of CEN standards, and RILEM recommendations at different levels of normal stresses. The vertical and horizontal displacements on the specimens of triplet's prisms were measured.

2 Materials and Methods

The materials used for the tests with the earth brick masonry were compressed earth bricks (CEB) -compressed at 5 MPa with hydraulic press and mud mortars at the joints which were either stabilised (mud mortars with addition of cement in their composition in order to became water resistant) or not stabilised. For the fired brick masonry hand made fired solid bricks (FB), -traditional bricks with rather high water absorption- and lime mortars were used. The geometry and the mean values of the mechanical strength of bricks achieved from different experimental tests are reported on Table 1, while the mechanical characteristics of the mortars are presented on Table 2.
Triplets, three stack bonded bricks, were used in a total number of 96 specimens. Three types of triplets' specimens with CEBs and mud mortars were tested and named as A1, B1 and C1. Similarly, three types of triplets' specimens with FBs and lime mortars were named as A2, B2 and C2. The geometry of all tested triplets is indicated in Figure 1. Specimens A1 were constructed with CEB and with non-stabilised mud mortars (NSMM) and were defined as reference specimens. Group A1 was used with bricks of 250x120x80mm and joints of 10mm. Group B1 was constructed with triplets of double thickness (20mm) of joint while group C1 represented triplets with reduced width of bricks (250x90x80mm) and the same joint thickness as that of specimens A1. Triplets of group D were constructed with compressed earth bricks and stabilised mud mortar with cement (SMM). FB with lime mortar (LM) masonry followed the same geometrical combinations as CEB with mud mortars triplets (Figure 1) designated A2, B2 and C2 groups.
Triplets were constructed by suitable wetting of the bed brick interface in order to avoid water suction by the mortar for both types of bricks (CEB and FB). They were covered by plastics sheet for 14 days. Finally, an extra weight of approximately 4 kg has placed on the top of each prism in order to increase the cohesion between mortar and brick interface.

Table 1 Mechanical characteristics of the bricks used for the tests

Bricks	Dimensions(mm)	f_{bc} *(MPa)*	f_{bfl} *(MPa)*	E_b (MPa)
Compressed earth brick (CEB)	250x120x80	5,206	0,926	3645
Fired brick(FB)	250x120x80	14,22	2,255	7075

Table 2 Mechanical characteristics of the mortars used for the tests

Mortars	f_{mc}(MPa)	f_{mfl} (MPa)	f_{mt}(MPa)
Non stabilised mud mortar (NSMM)	2,69	1,463	0,469
Stabilised mud mortar (SMM)	3,66	0,870	0,123
Lime mortar (LM)	1,57	0,305	0,170

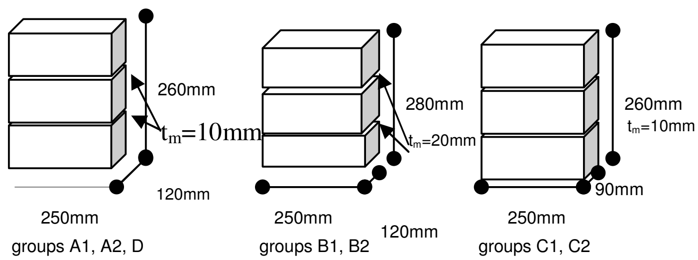


Figure 1 Geometry of triplets

Firstly, in order to evaluate the range of the normal stress in service load applied, tests under compression were carried out on the triplets.
The pre-compression load for shear tests did not exceed 0.8 MPa (load in service). Since the shear stress distribution along the brick-joint interfaces was not constant, a mean value was calculated by dividing the ultimate load by the area of the horizontal joint multiplied by two.
A testing device was designed for biaxial tests as shown in Figure 2. The triplet was placed between the testing device. The mortar's joints were parallel to the applied shear load. A hydraulic jack was placed between the specimen and the device for the horizontal normal load application at the metacenter axis. Shear load and normal stress were applied simultaneously. The tests were carried out by applying shear loads at a rate of 0,4N/mm^2/min and different levels of normal stress (0, 0.2, 0.4, 0.6, 0.8 MPa). The duration of tests was between 5 to 10 min.
Two linear voltage differential transducers (LVDTs) were used to measure the vertical absolute displacement and one LVDT measured the horizontal displacement. Although the stress was not uniformly distributed along the brick – mortar interface during the test, it was stabilised when the ultimate load was applied (Figure 2(b)).
First, the initial shear strength with zero pre-compressive (normal) loads was measured. However, when the shear load was applied at the central brick, the hydraulic jack normal stress was activated (Figure 2(a)) with the maximum value of the normal stress indicator not exceed the σ_n=0.008 MPa. This value was considered as equivalent to zero. Similarly, for the fired brick-lime mortar initial stress measurement on specimens showed that the maximum normal stress value not exceed σ_n=0.016 MPa and it was considered as zero too.

3 Results and discussion

The resulting shear stress-displacement curves for both types of masonries are shown in Figure 3. The number following the name of each group of triplets indicates the level

of normal stress applied to specimens. For example, code A1-0.4 expresses specimens of group A1 preloaded at 0.4MPa of normal stress.

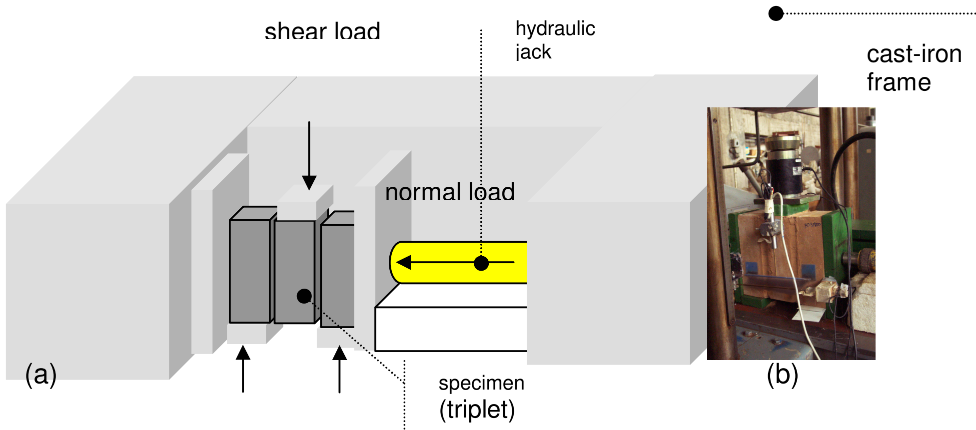


Figure 2 (a) Testing device - (b) Instrumental arrangement

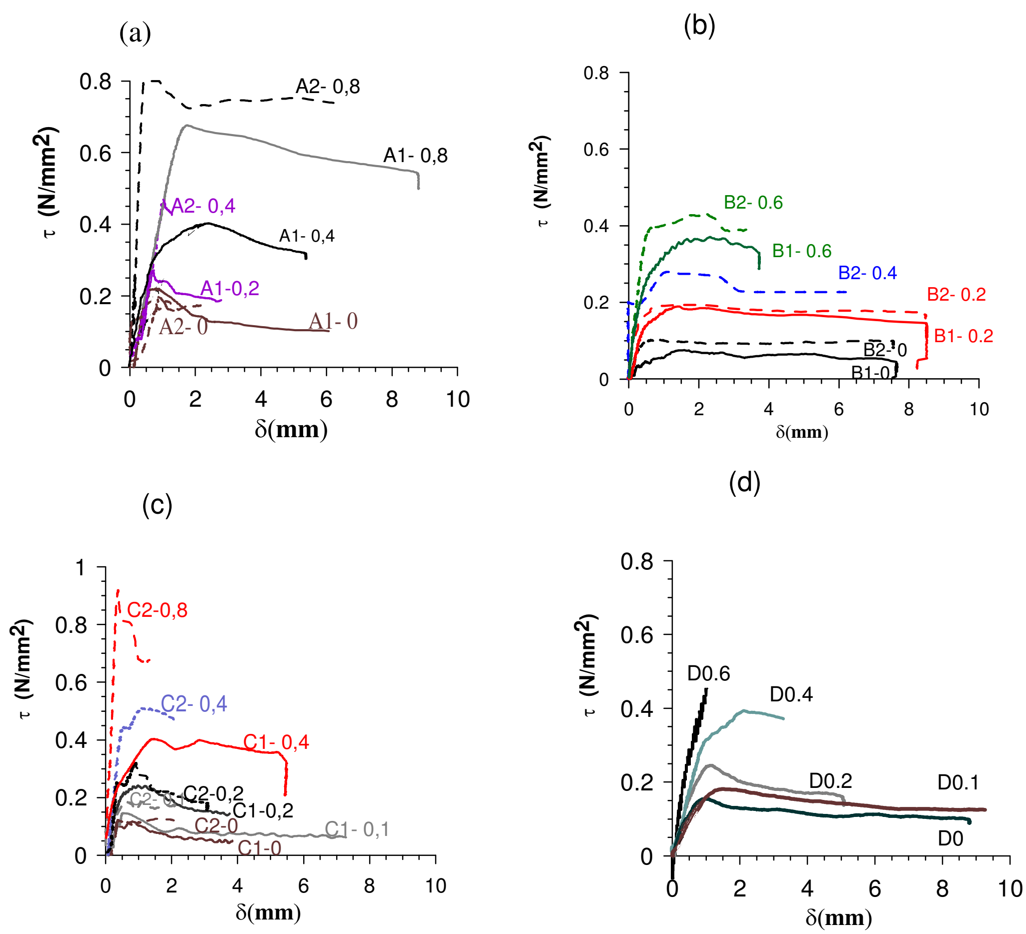


Figure 3 Shear strength – displacement (τ-δ) curves. (a) Groups A1 and A2, (b)groups B1 and B2, (c) groups C1 and C2, (d) group D

All the tested groups have shown an increase of the shear strength of the bed joint which is almost proportional to the applied normal stress (Coulomb criterion) (Mann and Müller, 1977).

Slip of joints was characterised by high ductility. After the peak failure no considerable stress drop is observed, even in cases when joint displacement δ was high as shown in Figure 3 (b) and (c) (approximately 8mm).

The slopes of the curves τ-δ at post peak failure (Figure 3) of both types of traditional masonries have shown a different behaviour compared to familiar published experimental curves that usually present drops during joints slip (Roberti, et al,1997), (Van der Pluijm, et al, 2000).

In particular, for σ_n values greater than 0.2 MPa the rate of shear stress decrease after failure was very low, especially at groups specimens presented the lowest bond strength (values at 0.103, 0.126 and 0.135 MPa, for B1, B2 and C1 groups of triplets respectively). It seemed that the bond strength loss after failure was not so evident on the τ-δ curves because of its low value. However, when pre-compression stress σ_n was 0.8 MPa (relatively high), shear stress drop was greater (Figure 3, groups specimens A2 and C2). An additional reason for the shear stress loss after joint failure is believed to be the loss of the pre-compressive stress because of the reduction of the bed joint height after the beginning of joint slip.

Joint failure envelopes are shown in Figure 4 for the compressed earth brick construction and in Figure 5 for the fired brick construction respectively. Regression lines and the corresponding equations for the experimental τ-σ_n points are presented through Eq. (1) to (7) in the form of $\tau = \mu\sigma_n + \tau_o$.

group A1: $\tau\ (A1) = 0.58\sigma_n + 0.218\ ,\qquad r^2 = 0.983$ (1)

group B1: $\tau\ (B1) = 0.43\sigma_n + 0.110\ ,\qquad r^2 = 0.959$ (2)

group C1: $\tau\ (C1) = 0.62\sigma_n + 0.172\ ,\qquad r^2 = 0.969$ (3)

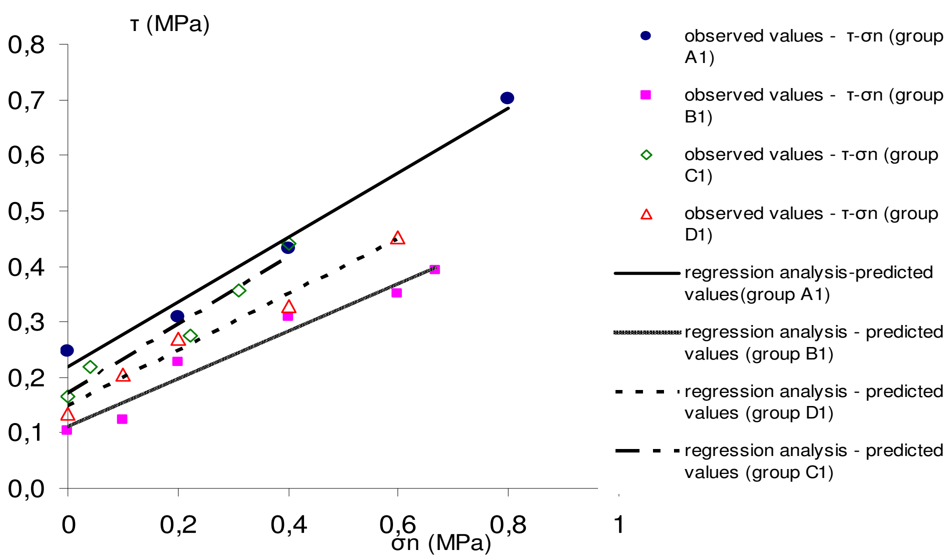


Figure 4 Failure envelopes on earth brick construction triplets

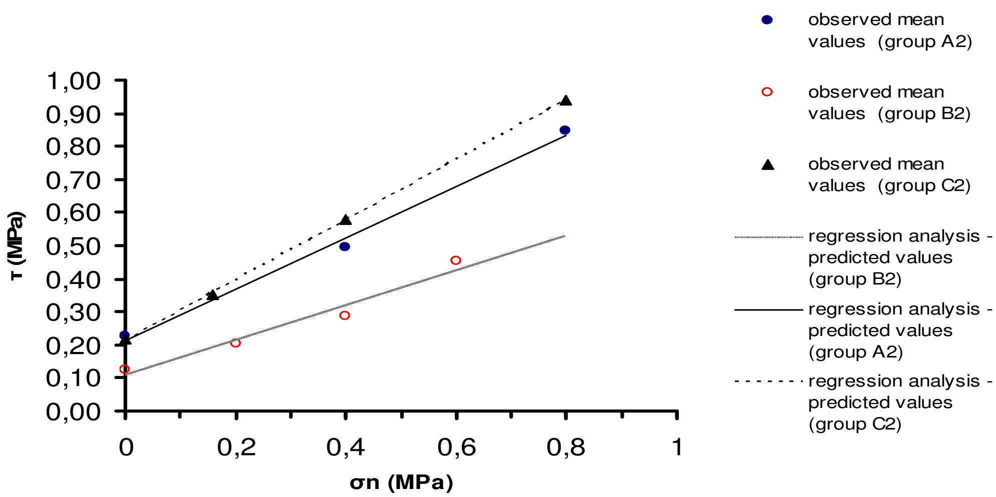


Figure 5 Failure envelopes on fired brick construction triplets

group D :	$\tau\,(D) = 0.50\sigma_n + 0.148$,	$r^2 = 0.982$	(4)
group A2:	$\tau\,(A2) = 0.774\sigma_n + 0.213$,	$r^2 = 0.994$	(5)
group B2:	$\tau\,(B2) = 0.531\sigma_n + 0.109$,	$r^2 = 0.965$	(6)
group C2:	$\tau\,(C2) = 0.900\sigma_n + 0.213$,	$r^2 = 0.999$	(7)

τ is the mean shear stress of the joint
σ_n is the applied normal stress (negative compressive stress)
r^2 is the correlation coefficient

3.1 Comparison between triplets with 10mm and 20mm of joint thickness (groups A1 - B1 or A2 - B2)

Comparisons between Eq. (1) and (2) showed that shear bond stress value of group B1 was reduced to almost the half of that corresponded at group A1. Also, the mean friction coefficient **μ** has shown a reduction from groups A1 to those of B1. Similar results were obtained for the fired bricks and lime mortars groups between A2 and B2 shown on Eq. (5) and (6). In order to keep the moisture content constant for both earth bricks triplets and fired bricks triplets the same construction procedure was followed. A1 and B1 group specimens as well as A2 and B2, were of identical mortars composition. Group B1 or B2 was as thick as twice the the thickness of A1 or A2. It seemed that joint slip occurred earlier because of the important volume of these joints. These thicker bed joints have created a lower stiffness zone in the total prism’s volume so that the brick- mortar interface failed earlier compared to groups A1 or A2.
This is in agreement with the findings of Atkinson et al (1989) who used on tests on masonries with fired clay bricks (modern and old) and concluded that thicker joints

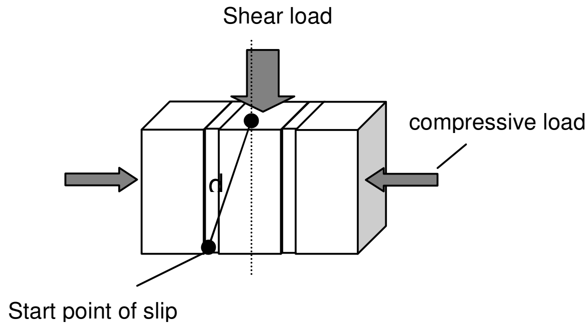


Figure 6 Mechanism of "bending moment" applied on the specimen

lead to lower stiffness than thinner ones. These researchers have also found that the bond strength is influenced by the joint thickness.
The experiments were shown that both bond strength and mean friction coefficient μ were influenced by the thicker joints of groups B1 and B2 (20mm) (Equation 2). However, the main limitation of this test is inevitably the development of a bending moment, especially when the thickness of the joint is high (Figure 6). Thus the specimen fails not only because of the shear stress but also by the flexural stress. The horizontal LVDT indicated the presence of bending deformations. Other researchers used similar testing devices reported this measurement limitation (Roberti et al, 1997), (Grimm, 1975).

3.2 Comparison between triplets with different bed joint dimensions (groups A1-C1, or A2- C2)

Comparisons between Eq. (1) and (3) and/or Eq. (5) and (7) showed that shear bond strengths τ_o were similar for both groups A1 (0.218 MPa) and C1 (0.172 MPa) and A2 (0.213MPa) and C2 (0.213MPa). The slopes on both correlated τ-σ_n curves were practical identical. It seemed that the 25% reduction of the shearing surface at the triplets of group C1 or C2 (change of the width from 120mm to 90 mm, Figure 1) do not actually influence the shear strength as long as the mortar composition and the joint thickness remain constant.

3.3 Comparison between triplets with different joint composition (groups A1 and D)

The measured average bond strength of group D is 0.148 MPa, 32.1% lower than the average bond strength of group A1. After the joint failure test, it was observed a remarkable smooth texture on the joint surface of the stabilised mortar used. It seemed that the presence of cement in mud mortar of group D restrained the clay percentage of the mortar, which was principally responsible for the development of cohesion forces between the compressed earth brick substratum and the mud mortar (Van der Waals forces).

3.4 Failure types

All specimens were photographically documented after the tests. The study of the photos permitted to identify two failure types and detect similarities, which cannot

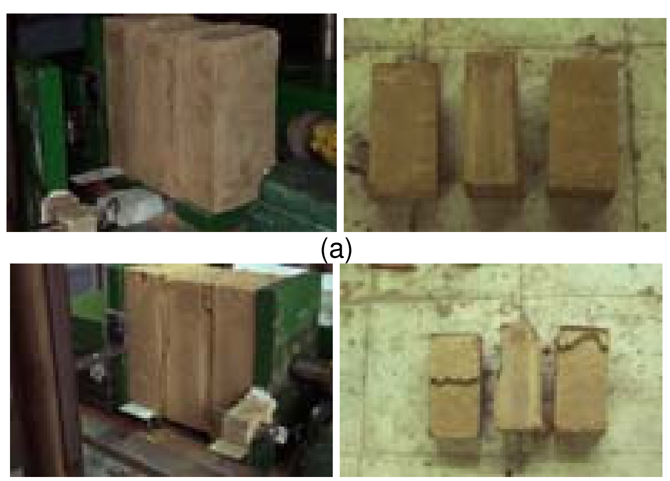
otherwise be deduced from the mechanical tests itself. The failure types observed in details are:
First failure type: This failure mechanism on the triplets appeared at the brick-mortar interface together with a typical crack at 45° through the mortar joint in *z- like* form (Figure 7(b)). Second failure mode: This failure mechanism appeared with *a parallel crack* between brick- mortar interface (Figure 7(a)).

3.5 Detachment pattern

The configuration of the debonded substratum (the “traces” of bond) is defining as *cohesion pattern* when mortar traces remain on the brick substratum and as *adhesive pattern* when no macroscopic traces of mortar left on the brick substratum.
It was observed that, when the failure type is *z-like* the detachment showed a *cohesion pattern*. This happened at the specimens of groups A1, A2 and C1, C2 when the joint thickness is 10mm. On these groups the bond strength value was recorded relatively higher (from 0.16 to 0.24 MPa) than the other remaining tested groups. The specimens at σ_n=0.8 MPa did not followed the above observation. The failure type was *parallel* and the detachment of *cohesion pattern.* This phenomenon may be due to the higher pre-compression (0.8 MPa) that forced joint mortar at higher tightening before shear cracks occurred. This leaded the mortar mass to a total slip by reducing the bond strength of the interface instantaneously.
In addition, it was observed that when the failure type is of *parallel type* the detachment showed an *adhesive pattern* as indication of poor bond between mortar and brick substratum. This happened at the specimens of groups B1, B2 and at the specimens of group D where the average bond strength value was measured low (from 0.103, to 0.126 MPa). The above groups (B, D) presented high ductility after the beginning of slip, possibly correlated to the above failure type.

4 Conclusions

The shear strength can be described on the basis of Coulomb’s friction failure criterion ($\tau = \tau_o - \mu\sigma_n$). The shear stress – displacement curves have shown similarities between both types of traditional masonry prisms (earth bricks-mud mortars triplets and fired bricks -lime mortars triplets). The main difference between the two is that compressed



(a)

(b)

Figure 7 Shear tests. (a) Parallel type failure – adhesive pattern (b) z-like type failure – cohesive pattern

earth bricks masonries developed lower shear strength and higher values of slip than the fired bricks masonries. Slopes of failure envelopes for the combination of compressed earth brick and mud mortars masonries were in the range 0.43-0.62 and for the combination of fired bricks with lime mortars in the range 0.53-0.9.

Joint slip always occurred between brick - mortar interface for all specimens (load in service).

Failure type and detachment pattern of the joint may be related to the values of bond strength. Lower values of bond strength (≈0,1 MPa) are connected to *parallel* failure type and *adhesive* detachment pattern. Higher values are connected to *z-like* failure cracks on joints and *cohesive* detachment pattern.

For triplets of joint thickness of 10mm the mean value of bond strength was 0,218 MPa for compressed earth bricks - mud mortars and 0.213 MPa for fired bricks – lime mortars. Bond strength was decreased by 50% when the joint thickness was doubled. This was attributed to the increase of the lower stiffness zone by the thick joint.

The addition of cement in the mud mortar reduced the bond between the mud mortar and earth brick interface. The size of slip surface of the joint did not seem to influence the bond strength value.

Joint slip is generally characterised by the high ductility on both tested traditional masonries.

Friction coefficient $\boldsymbol{\mu}$ values presented high dispersion. In general, it was lower for the prisms with compressed earth bricks and mud mortars. However, it remained constant for $\boldsymbol{\sigma_n}$ at service load, with values between 0.48 to 0.62 for earth brick construction and values between 0.53 to 0.90 for fired brick constructions.

Eurocode's friction coefficient value $\boldsymbol{\mu}$=0.4 is lower than the measured values.

Results can be useful as input parameters for numerical analysis of the masonries of the types presented above.

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