



Effects of Test Specimens on the Shear Behavior of Mortar Joints in Hollow Concrete Block Masonry

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Abstract. The shear characteristic of mortar joint is the most important factor which decides the behavior of masonry structures subjected to lateral in-plane loading. This article focuses on the experimental study of shear behavior of mortar joint in hollow concrete brickwork. In this experimental program, two types of specimen prepared according to two different standards (RILEM and European standard) were tested in order to study the influence of some formal parameters of test specimens to the shear behavior of mortar joint in hollow concrete brickwork. The test results showed that no matter whether there are horizontal joints in test specimens or not, an important dispersion is highlighted both in shear behavior and in shear failure criterion of mortar joint in hollow concrete block masonry assembly. However, the presence of horizontal joints may cause artifacts which have effect on the redistribution of stress and therefore on the correct transmission of lateral compression to the shear mortar joint. This effect tends to impact the damage and failure mechanism and therefore the failure criteria. In consequence, the Mohr-Coulomb criterion is only verified (with a coefficient 99% regression) for the case of test specimens without horizontal mortar joints although this verification is restrictive in terms of a low number of valid tests.

Keywords: Hollow concrete masonry · Shear pull-out test · Shear behavior · Mortar joint

1 Introduction

Hollow concrete masonry structure has been widely used worldwide. This structure can be subjected to in-plane shear loading cause by seismic, wind or by an accidental loading (settlement or car crush). Under this loading condition, the failure mode of masonry structures could be shear type characterized by cracks across mortar joints caused by shear stress. The comprehension of the shear behavior as well as the shear failure criteria

of mortar joint in hollow concrete brickwork is therefore necessary and that has been significantly scrutinized in several studies in the literature. However, the effect of test specimens on the shear behavior of mortar joint in hollow concrete brickwork which has not been addressed before will be focused on in the present study.

For the study on the shear behavior of mortar joint in brickwork, numerous test configurations are proposed in the literature (couplet or triplet) to characterize the shear behavior of mortar joints. The direct shear tests on couplets were used in many studies [1–6]. Whereas, the shear tests on triplets in accordance with standard NF EN1052-3 [7] or according to standard RILEM TC-76 LUMB5 (1991) [8] were used in [9–15]. The configurations are distinguished by the assembly loading dispositive, by the quantity of bricks, by the number and position of mortar joints in the assemblies. These numerous configurations were based on the objective to obtain the compromise, difficult to find, between a simplicity of carrying out the tests and the desire to ensure uniform distribution of normal and shear stresses in the assemblies [6]. Among all the proposed configurations, a comparative study between two types of shear tests on triplet was carried out: one established according to the RILEM recommendation [8], the other based on the study of triplets, in accordance to standard (NF EN1052-3 (2003) – [7]). The main difference between these two test set-up bases on the difference in the test assemblies: there are horizontal mortar joints in the test specimens according to the first recommendation while they are absent in the test specimens manufactured according the other one.

2 Experimental Program

2.1 Materials

The bricks used in the present study are halved lengthwise of hollow concrete brick; class B40 (the characteristic compressive strength is 4 MPa - according to the Eurocode 6 [16]) whose dimension is $500 \times 200 \times 75 \text{ mm}^3$. The dimension of one brick unit is therefore $250 \times 200 \times 75 \text{ mm}^3$. The uniaxial compressive test was performed at laboratory (according to the European standard EN 772-1:2000 [17]) and shows that the average compressive strength of these bricks is 6.5 MPa.

The mortar used in our study is a Portland cement-based mortar (CEM I 52.5), of which the formulation is shown in Table 1.

Table 1. Mortar formulation

Type	Proportions by mass		
	Cement	Sand 0/4	Water
Mortar based on CEM I 52,5	1	3	0,5

The uniaxial compressive tests and flexural tests were performed at our laboratory with nine prismatic specimens measuring $40 \times 40 \times 160 \text{ mm}^3$ manufactured according to the European standard (EN 1015-11) [18]. These tests were done on the 3 specimens after 31 curing days with the result of average compressive strength equals to 48 MPa.

2.2 Shear Pull-Out Test of Masonry

2.2.1 Specimens

In order to study the influence of test specimens to the shear behavior of mortar joint in hollow concrete brick masonry, this shear pull-out test is performed on specimens constructed according to both the European standard (NF EN1052-3(2003)) [7] and the RILEM recommendation (RILEM (1991d)) [8]. Both specimens are the type of triplet. The main difference between these two types of assembly is that there are horizontal mortar joints in the test specimens according to the RILEM recommendation while they are absent in the assemblies manufactured according to European standard. The average thickness of both horizontal and vertical mortar joints is 10 mm. The detail and the dimension of both specimens are represented in Fig. 1.

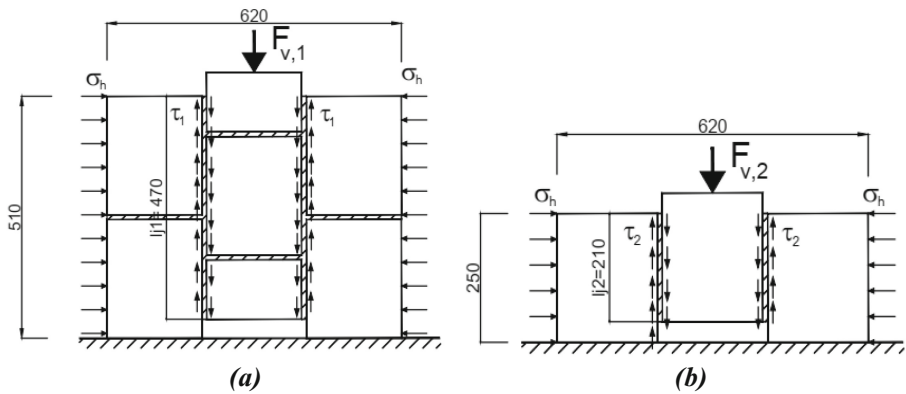


Fig. 1. Specimens of shear pull-out test: (a) – according to RILEM recommendation and (b) – according to European standard.

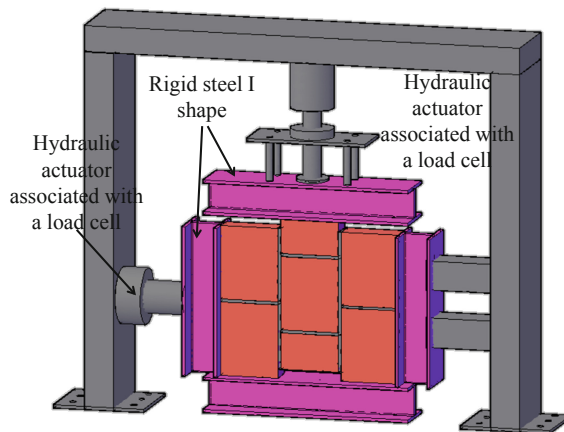


Fig. 2. Shear pull-out test set-up

2.2.2 Test Set-Up

The test set-up of these shear pull-out tests is presented in the Fig. 2. This test set-up permits to apply simultaneously both lateral compressive stress and shear stress on the mortar joints. The device used to apply the lateral compressive stress consists of a hydraulic actuator associated with a loadcell, supported on a rigid frame. In addition, the rigid IPE profiles are positioned on either side of the assemblies.

The vertical shear load is provided by a very rigid loading frame on which a hydraulic actuator with a capacity of 50 tones is supported, associated with a vertical loadcell. This vertical load is applied and distributed uniformly on the upper face of the central brick of the triplet using a very rigid steel I shaped beam.

The instrumentations adopted aim to measure the relative displacement between two adjacent bricks during loading process: four LVDT sensors ± 10 mm (referenced C1 to C4) are symmetrically positioned on both faces of the test specimens (two of them are glued in the front face and the two others are on the behind face), Fig. 3.

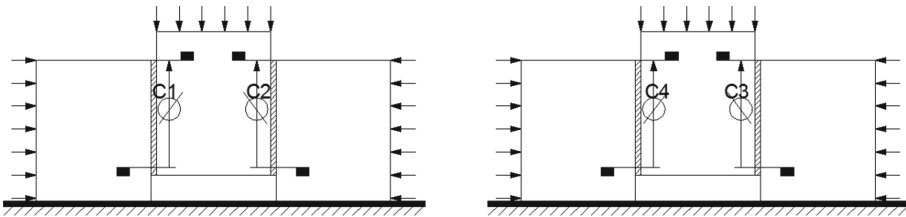


Fig. 3. Position of LVDT sensors on two faces (front face and behind face)

Regarding the testing procedure, first the lateral compressive load is applied up to the desired value, then this load is identically kept and the vertical shear load is gradually applied up to the failure by displacement control with the speed of 0.05 mm/min. A total of 32 specimens (17 specimens constructed according to the RILEM recommendation and 15 specimens constructed according to the European standard) were tested with different lateral compressive stress varied between 0 and 30% compressive strength of bricks (correspond to 0 and 1.2 MPa) in order to avoid the influence of bricks' significant damage on the results.

2.2.3 Results and Discussions

a) Failure modes

The failure modes observed for both two cases of assembly in these shear pull-out tests are generally divided into 4 following modes, Fig. 5:

- Mode a, fracture plane of the brick-mortar interfaces.
- Mode b, fracture plane of brick-mortar interface accompanied by cracking of mortar joint;

Table 3. Failure modes and shear strengths obtained in the shear tests according to European standard (specimens without horizontal mortar joints).

Lateral compressive stress (Mpa)	0.00			0.30			0.60			1.00			1.20		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S4	S5	S1	S2	S3	
Specimens	S1	S2	S3	S1	S2	S3	S1	S2	S3	S4	S5	S1	S2	S3	
Failure modes (*)	(a) (b)	(a)+ (b)	(b)	(a)+ (c)	(b)	(a)+ (b)	(a)+ (d)	(b)	(a)+ (b)	(a)+ (b)	(d)	(c)	(a)+(d)	(a)+(b) +(c)	
shear strength (MPa)	0.18	0.99	0.72	0.65	1.03	1.4	-	1.3	1.49	0.9	-	-	-	-	
Residual shear strength (MPa)	-	-	0.50	0.38	0.78	-	-	-	1.17	-	-	-	-	-	

() The failure modes identified from the Figure 4.*

in comparison the results between two cases of assembly; it is worthy noted that the two latter failure modes (mode c and mode d) tend to appear at lower lateral compression levels (about 20% of compressive strength of masonry) for the specimens with horizontal mortar joints than for the specimens without horizontal mortar joints (about 35% of compressive strength of masonry). Indeed, it is likely that this multiplicity of failure modes in the case of assemblies with horizontal joints is also linked to the difficulties of filling these joints during the implementation of assemblies. Thus, the lack of filling of certain joints can cause artifacts in the distribution of the stresses having repercussions on the failure mode.

b) *Shear behavior of mortar joint*

The shear behavior of mortar joint is represented by the evolution of shear stress versus relative displacement recorded by the LVDT sensors.

The shear stress along the shear mortar joint is calculated by the following equations:

- For the case specimens with horizontal mortar joints:

$$\tau_1 = \frac{F_{v1}}{2 \times l_{f1} \times t} \quad (1)$$

- For the case specimens without horizontal mortar joints:

$$\tau_2 = \frac{F_{v2}}{2 \times l_{f2} \times t} \quad (2)$$

Where:

F_{v1} , F_{v2} are vertical shear load recorded during the test for two cases with and without horizontal mortar joint respectively (see Fig. 1).

l_{f1} , l_{f2} are the length of vertical shear mortar joint corresponding to the case with and without horizontal mortar joint respectively (see Fig. 1).

t , is the thickness of specimens, equal to 75 mm for both cases.

Figure 5 shows this evolution for some different lateral compression levels for both types of specimen. It is worthy of note that all the specimens whose failure modes contain mode (c), and mode (d) could not be considered because they are worthless in this shear behavior study of mortar joints.

It is highlighted from these figures that there is dissymmetrical behavior of two vertical mortar joints. In addition, the shear failure of these hollow concrete bricks assemblies is not sudden but is affected by “jerks” which result in several peaks in the evolution curves. The dissymmetrical behavior and the “jerks” can correspond to a non-simultaneous failure of the two vertical joints and to the different failure mechanisms described above in Fig. 4.

Additionally, in considering the evolution of one vertical joint, three phases can be identified: the first elastic phase which is generally characterized by an extremely high rigidity, followed by a hardening phase until reaching the maximum stress. Then, if a

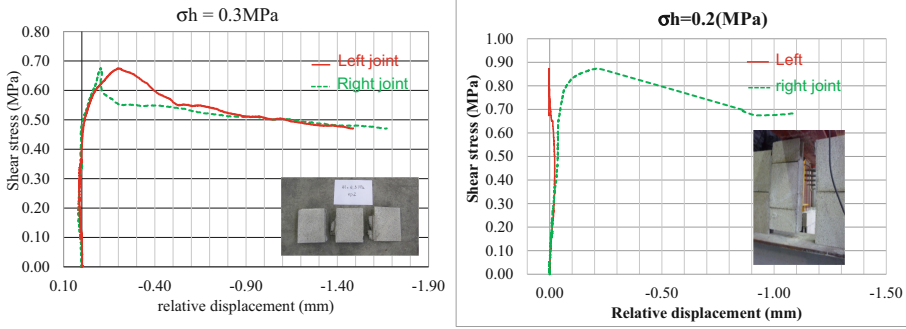


Fig. 5. Shear stress versus relative displacement for both two types of assembly

lateral compressive stress is applied, a softening post-peak phase appears, characterized by a residual plateau. In this study, this residual level is more or less marked or identifiable depending on the test specimens: this residual plateau is associated with a sliding mechanism between two adjacent bricks which was not always happened in this study (often observed in the case of test specimens without horizontal joints but only observed at low pre-compression levels for test specimens with horizontal joints). The complexity of damage mechanisms at higher lateral compressive stress results in more disordered post-peak phases.

c) Evolution of shear strength in function of lateral compression stress

The shear strength and the residual shear strength for different level of lateral compression stress (correspond to the maximum value and the residual value calculated from Eq. (1) and (2)) are represented in Table 2 (with horizontal joints) and Table 3 (without horizontal joints). It is useful to recall that only the results correspond to failure types of mode (a) and or mode (b) should be considered in this analysis.

From these results, the evolution of shear strength (τ_{max}) in function of pre-compressive stress (σ_h) was identified and presented in Fig. 6 (for the test specimens with horizontal mortar joints) and Fig. 7 (for the test specimens without horizontal mortar joints).

Despite the high dispersion in the results, the failure curves established in the plane (τ_{max} , σ_h) show an increasing trend which means that the shear strength of mortar joint increases with increasing of the lateral compression stress and this result is consistent with the scientific literature. However, most authors in the literature noted that the mortar joint obeyed the Mohr-Coulomb failure criterion, establishing a linear relationship between the shear strength and the lateral compression stress. The results of the present study for both cases, admittedly very dispersed, do not tend to support this conclusion. Indeed, Fig. 6 and Fig. 7 plot the linear trend curves with the relative small of linear regression coefficient (0.53 and 0.56 respectively for specimens with and without horizontal joints).

However, a refined analysis (the same analysis as previously) was performed in considering only the results correspond to the presence of residual shear strength which

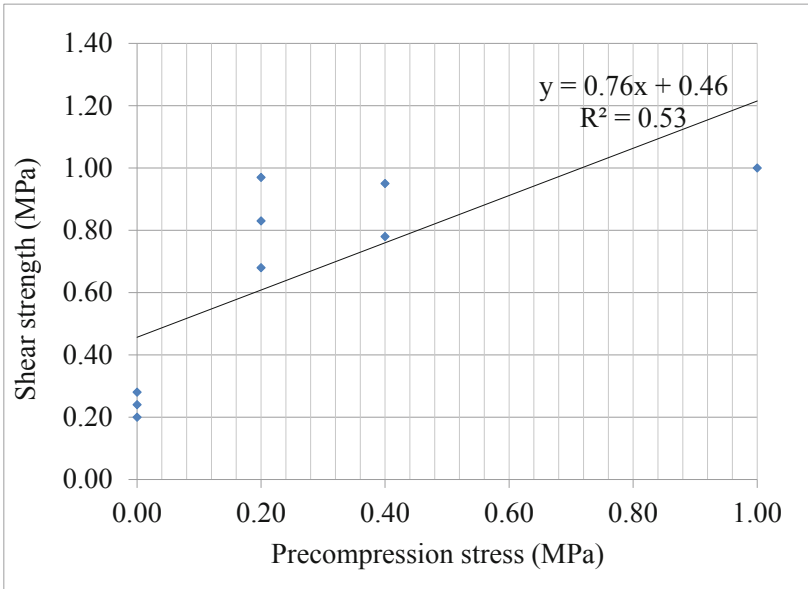


Fig. 6. Evolution of shear stress in function of pre-compression stress (for the test specimens with horizontal mortar joints)

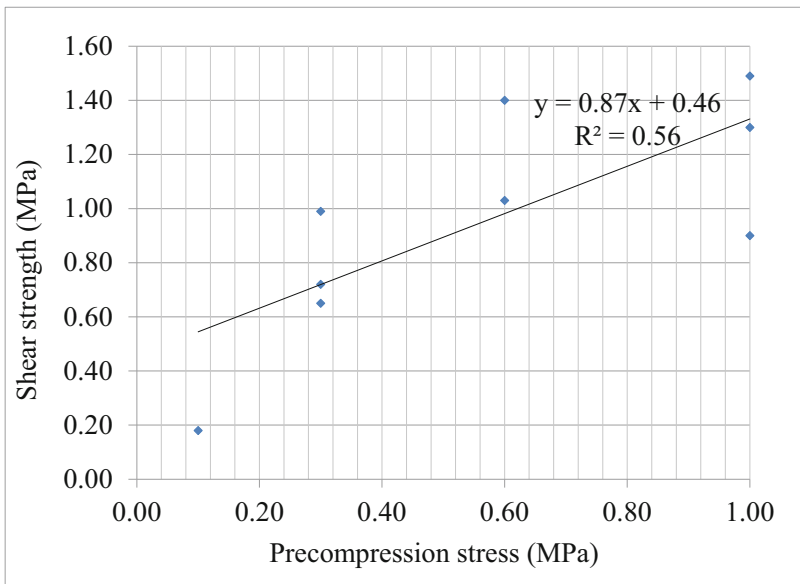


Fig. 7. Evolution of shear stress in function of pre-compression stress (for the test specimens without horizontal mortar joints)

reflects a correct transmission of the lateral compressive stress on the shear joint studied. This refined analysis, admittedly restrictive in terms of test specimens (only in some test specimens without horizontal mortar joints), leads to a verification of the Mohr-Coulomb criterion with a coefficient 99% regression (Fig. 8). The analysis of the residual shear strength also leads to a linear evolution of the residual strength as a function of the lateral compression stress.

These linear relations reflect the Mohr-Coulomb criterion by the expressions:

$$\tau_{max} = \sigma_h \cdot \tan(\phi_{max}) + c_{max} \tag{3}$$

and

$$\tau_r = \sigma_h \cdot \tan(\phi_r) + c_r \tag{4}$$

Where:

τ_{max} , τ_r : ultimate and residual shear strength of mortar joint

ϕ_{max} , ϕ_r : ultimate and residual internal friction angle

c_{max} , c_r : ultimate and residual cohesion

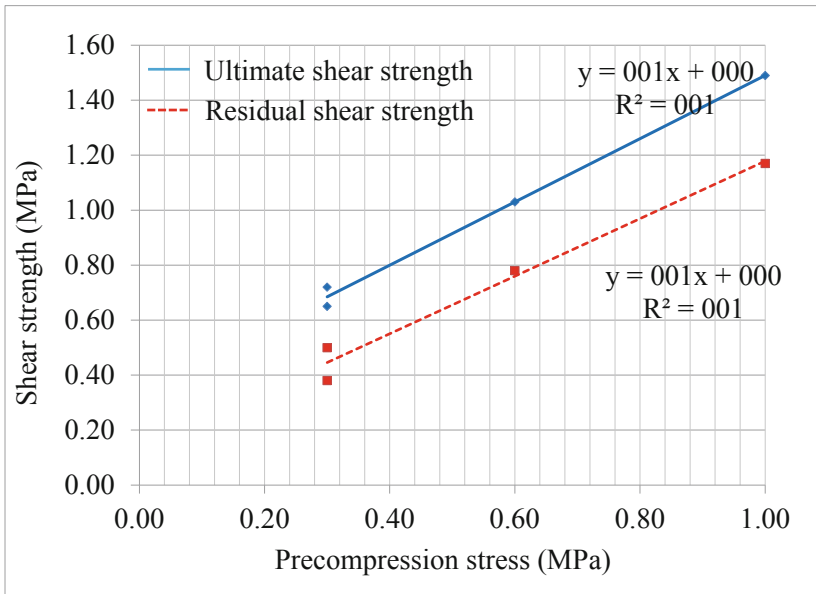


Fig. 8. Evolution of ultimate shear strength and residual shear strength of mortar joint for the specimens without horizontal mortar joints.

The obtained values characterize the Mohr-Coulomb criterion of these mortar joints are represented in Table 4.

The obtained values of $\tan\phi$ (both ultimate and residual) seem to be acceptable as they range within the usual interval of variation found in the literature (this range varies

Table 4. Shear characteristics of mortar joints

Characteristics	Ultimate	Residual
Cohesion (c, MPa)	0.34	0.13
Tan ϕ	1.15	1.05

between 0.7 and 1.2 – [2]). Furthermore, it appears that the residual cohesion in this case is non-zero and it can be explained by the penetration of mortar in the holes, which avoids the separation of bricks. In addition, the residual cohesion value equal to about 38% the ultimate cohesion which is in line with the results found in the literature ([3]).

3 Conclusions and Perspectives

This experimental study based on shear pull-out tests on triple with two types of assemblies according two different standards (RILEM and European) helps to point out several findings related to the effects of test specimens as follows:

No matter whether the test specimens contain horizontal mortar joints or not, an important dispersion is highlighted both in shear behavior and in shear failure criterion (based on the evolution of shear strength in function of lateral compression stress) of mortar joint in hollow concrete block masonry assembly. The main effect of test specimens lays on that the presence of horizontal joints in the test specimens may cause artifacts which have influence on the redistribution of stress and therefore on the correct transmission of pre-compression (lateral compression) stress to the shear mortar joint. Consequently, the damage and failure mechanism and therefore the failure criteria might be impacted. Indeed, the refined analysis leads to a verification of the Mohr-Coulomb criterion with a coefficient 99% regression (with the shear characteristics are in range within the usual interval of variation found in the literature) only for the case of specimens without horizontal mortar joints. However, this verification is restrictive in terms of a low number of valid tests. This restriction proposes a continuous study in the future with numerous tests specimens without horizontal mortar joints (use the same test set-up according to the European standard) to verify the shear failure criterion of mortar joint for this type of masonry.

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