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EXPERIMENTAL INVESTIGATION ON THE TORSION-SHEAR BEHAVIOUR AT THE INTERFACES OF INTERLOCKING MASONRY BLOCK ASSEMBLAGES

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Abstract. *This paper presents an experimental investigation on the initial shear (cohesion) and torsion-shear strengths at the interface of an interlocking masonry block. An interlocking block is a rigid unit with locks avoiding the block to slide. This improves the seismic response of dry jointed assemblages of masonry structures subjected to in-plane and out-of-plane loading. The experimental investigation is designed and carried out for the corrugated interface having one lock with rectangular cross section, i.e. the specimen is an interlocking unit composed of a main body and a lock located on the upper face of the main body. Cement-based mortars are selected to reproduce the specimen, casted using a mould provided by a 3D printer, and both the lock and the main body are kept rigid during the tests. The initial shear and torsion-shear capacities of the interface at which the lock is connected to the main body are assessed together with its quasi-brittle fracture and registered in terms of load-displacement curves. In the designed setup, the horizontal force is applied to the rigid lock until it is disjointed from the rigid main body of the block, while the effect of rocking during the shear test is avoided. The force and the displacements are measured using a load cell and Linear Variable Displacement Transducers (LVDTs), respectively. The experimental programme includes four different sets with different load application points and different load directions, each set repeated on a number of similar specimens. Empirical formulations between the initial shear and compressive strengths of the lock interface are also evaluated.*

1 INTRODUCTION

Under seismic loading, unreinforced masonry walls can fail due to in-plane or out-of-plane loading. In traditional masonry block structures subjected to seismic loading, the joints between the masonry units act as planes of weakness due to their low tensile and shear bond strength. The mechanical behaviour at the joint interfaces has widely been studied within different methods of analysis, e.g. discrete or finite element analysis [1-3] and limit analysis with infinitive [4], or finite isotropic associative [5] and non-associative [6] frictional resistances. In particular, experimental investigation was carried out on 3D dry-stacked units to evaluate yield domains in shear, torsion-shear and torsion-shear-bending moment interactions [7] and on the validation of frictional resistances of shear block walls [8].

Increasing interest has recently been devoted to interlocking blocks/interfaces capable to enhance the sliding resistance of masonry joints to external forces. The interlocking blocks are rigid block units which, on their faces, have locks keeping the blocks together and preventing blocks from sliding. Experimental and numerical tests [9,10] investigated the in-plane and out-of-plane capacity of masonry walls composed of blocks with corrugated interfaces. Out-of-plane behaviour of osteomorphic blocks and interfaces with cross shaped locks were also experimentally investigated by Dyskin et al. [11] and Ali et al. [12], respectively. Similarly, experimental and numerical investigations were carried out on the different behaviour of wooden joinery connections with different geometric properties [13-16]. A digital tool to design structurally feasible masonry structures composed of interlocking blocks is being developed by some of the presenting authors [17-19].

One of the key factors that influence the behaviour and capacity of the conventional mortared block masonry is the bond strength between the mortar and the units. Similarly, the shear strength between the lock and the main body of the interlocking block is of utmost importance for dry masonry with interlocking interfaces. This means that, if the interlocking blocks are composed of cohesive material at their interfaces, the Mohr–Coulomb criterion can be adopted for both systems, for which the bond strength itself depends on the initial shear strength (cohesion) and the coefficient of friction as well as the level of normal stresses.

In order to determine the initial shear strength and the coefficient of friction, only European Standard EN 1052-3 [20] test method is available yet. However, the scientific literature shows that generally researchers have developed and conducted their own domestic test method, indicating the difficulty of finding a general consensus [21].

In this paper, a novel and alternative test method is proposed to evaluate the initial shear and torsion-shear capacity of a single lock belonging to an interlocking block, while the coefficient of friction and shear in presence of normal forces are beyond its scope. The test setup is similar to that used for dry-stacked tuff blocks [7], but with a different application of the load and different constraints, in order to allow the absence of normal force on the cohesive interface between the two parts of the block (lock and main body) kept rigid during the tests. The block was specifically designed to reproduce a particular interlocking block shape. The material properties of two selected cement-based mortars were also experimentally evaluated in order to define or confirm empirical relationships between their compressive and initial shear strengths.

2 EXPERIMENTAL INVESTIGATION

Representing the simplest interlocking model, a main body with a lock located on its upper face was designed as the specimen for this test. An ad hoc test setup was realized to estimate the pure shear and torsion-shear resistance of the interface at which the lock is connected to the main body, while keeping rigid the lock and the main body of the interlocking block.

A first phase of the research focused on finding the proper shape and dimensions for the block. A number of specimens were made by casting mortars with different mixtures in a mould, provided in the desired shape and dimension by a 3D printer. Then, four different test configurations were set up to simulate shear and torsion-shear failures, herein named sets S1, S2, S3 and S4. Besides, calibrating the mechanical properties of the appropriate mortar to be prepared was a crucial issue, both because of the limitations of the involved instrumentation, in particular the maximum capacity of the load cells, and of the necessity of obtaining a clear shear failure mode of the lock interface (cohesive crack). Therefore, trial samples composed of several specimens were casted with different cohesive materials and were tested under pure shear [22]. Finally, two mortars, namely M1 and M2, were chosen and their density, flexural and compressive strengths were experimentally determined.

In sum, eight samples, combining the four sets and the two mortars, were tested. Each of the two samples tested in pure shear, namely S1M1 and S1M2, involved four specimens, while the six samples for torsion-shear tests, comprised three specimens each, in total providing twenty-six experimental results.

The experimental investigation was carried out with standard and non-standard equipment at Laboratory of the Department of Structures for Engineering and Architecture (DiSt) of the University of Napoli Federico II (Italy).

2.1 Characterization of mortars

Two different mortars, M1 and M2, were chosen to make the specimens, whose composition and curing time are quoted in Table 1. Pozzolana, so named from the Pozzuoli town, is fine sand or loose blocks that can be easily found, in colours ranging from grey to red [23,24]; lime, supplied by Cimmino Calce s.r.l. (Naples), is a calcium-containing inorganic mineral still used in large quantities as building and engineering material. The mixtures were prepared using the amount of water required to ensure enough workability and normal consistency. According to the European Standard UNI EN 1015-2 [25], the pastes were compacted during the casting to remove any air bubbles and voids. Curing was performed in ambient laboratory conditions (relative humidity 60 ± 10% and 20 ± 5°C) until the test day.

Table 1: Composition of the tested mortars

Mortar	Pozzolana	Sand	Cement	Lime	Curing Time
M1	50%	24%	2%	24%	28 days
M2	47%	38%	15%	-	28 days

These non-standard mixtures were chosen to prepare specimens in the first phase of the experimental program, aimed to obtain: 1) failure load values compatible with the designed setup and within the valid range of the employed instrumentation; 2) failure modes corresponding to instantaneous and clear cutting of the lock from the main block. So, before defining M1 and M2, the traditional pozzolana based mortar [24], obtained with three parts of pozzolana and one of lime, was first employed to cast five specimens, cured in water for 28 days, and tested with pure shear setup. As the limit load (500N) of the load cell was reached before any failure on the lock, a new attempt was made by reproducing the same experimental phase in which only the curing time was reduced to 14 days. Applying this change, collapse was achieved in all the specimens, but a relatively concave shape was observed at the failure interface. Then, other mixtures were tested, adding cement with different ratios of components, with sets of five specimens cured in air for different curing times, and finally M1 and M2 mortars were chosen.

Standard specimens, i.e. rectangular parallelepipeds of 40x40x160mm were also prepared to characterize the mechanical properties of the M1 and M2 mortars, i.e. four for each mortar. Those specimens were measured with a digital calliper and weighted with an electronic weighting machine, to obtain the density of the mortars.

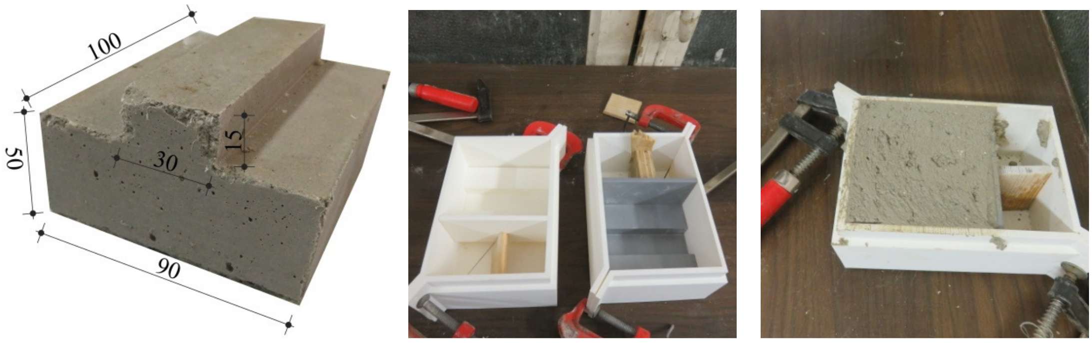
Then, flexural and compressive tests were carried out with standard equipment, following the UNI EN 1015-11 [26]. The mean values of the measured density and strengths are summarized in Table 2.

Table 2: Experimental mechanical properties of the tested mortars

Mortar	Flexural strength [MPa]	Compressive strength [MPa]	Density [kN/mc]
M1	1.05	2.69	12.7
M2	0.37	0.75	14.0

2.2 Specimen shape and test setup for shear and torsion-shear strengths evaluation

The designed specimen is composed of a main body, which is a 100x90x50mm cuboid, with a 100x30x15mm cubic lock located on its upper face (Figure 1a). It was made of the mortars described in the previous section, casted by using an ad hoc formwork to make the customized lock dimensions. The formwork was composed of pieces made by a 3D printer (Figure 1b).



(a) (b) (c)

Figure 1: (a) Designed specimen; (b) printed moulds; (c) curing phase

The test setup was specifically designed to pursue pure shear and torsion-shear resistances of the lock interface, overcoming some related issues. In fact, with the aim of minimizing the effect of bending usually experienced during shear tests [21] and of avoiding the pre-compression force, which are the main challenges of the traditional experimental setup [20], a new setup was developed for the experimental tests.

Actually, a horizontal load was applied directly on the front face of the lock by the static gravity load via a pulley system, while its main body was held fixed, until the collapse of the lock occurred. Meanwhile, the test setup, other than measuring pure shear resistance, ought to be efficient in evaluating also torsion-shear failure, by simply changing the load eccentricity. This task was accomplished by changing the position and direction of the designed pulley system.

The test setup is schematically shown in Figure 2a: the horizontal point-load was applied to the side face of the specimen lock by means of an electric hydraulic jack, monotonically increasing until the failure mechanisms. As shown in Figure 2b, the block was fixed to a wooden board to avoid sliding and to the upper support to avoid rotation, while the board was fixed to the upper support against sliding as well.

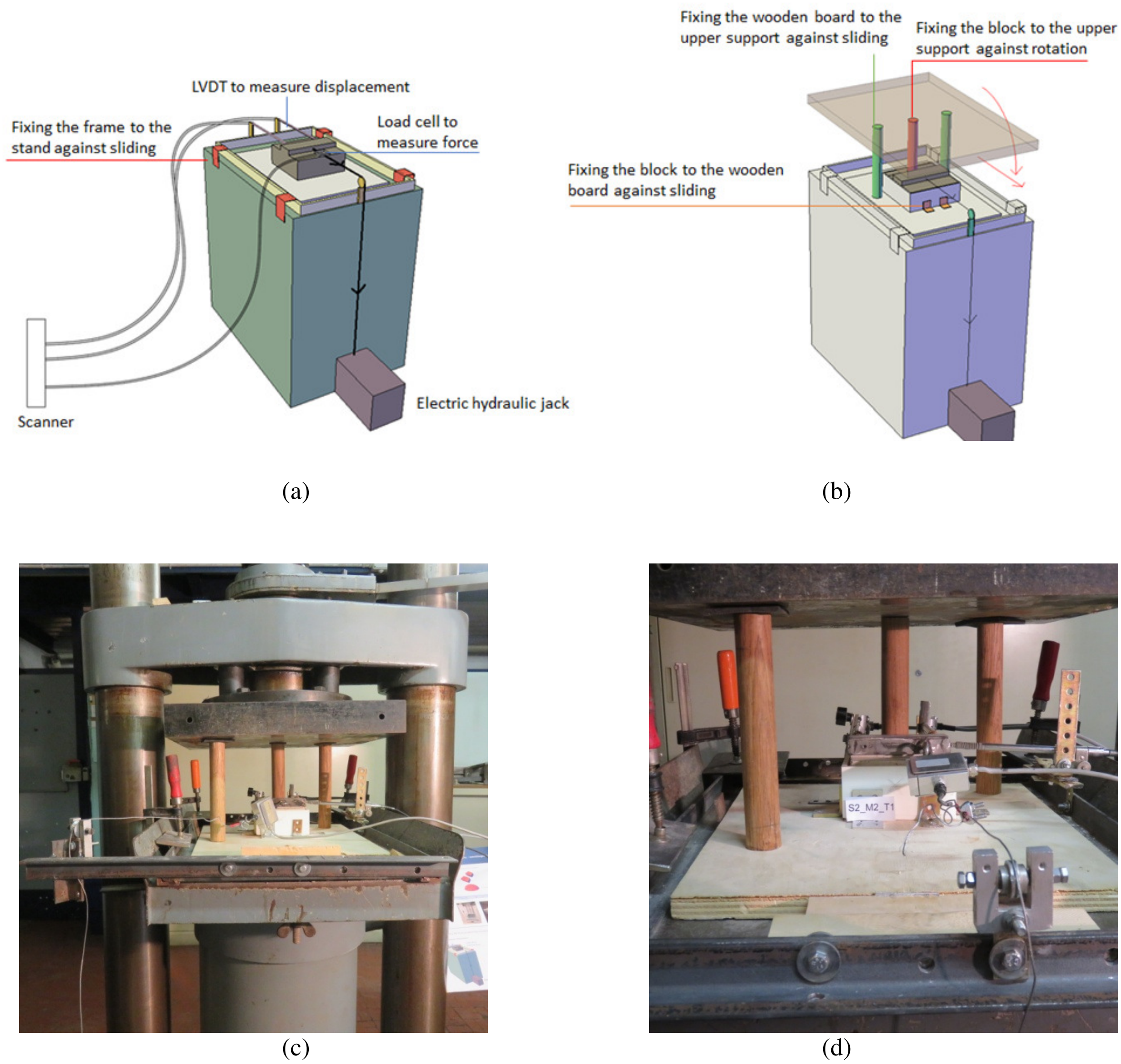


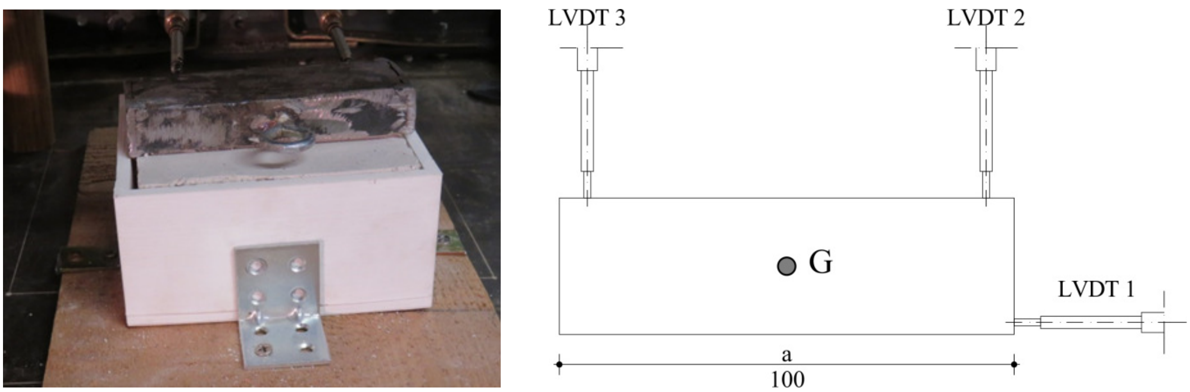
Figure 2: Test setup. (a) Displacement and load measurement; (b) constraints; (c,d) realized torsion-shear setup

The application of an iron cup on the lock allowed both the simulation of this part as a rigid block and the distribution of the applied shear force along the whole lock face (Figure

3a). On the other hand, the main body of the interlocking block was kept rigid during the tests by using a rigid cup-shaped container, still provided by a 3D printer. The load was applied under displacement control at a constant rate of 3mm/min.

Forces were measured using a load cell with a maximum capacity of 500N and an acquisition frequency of 10 Hz, while displacements were measured using Linear Variable Displacement Transducers (LVDTs) with a displacement range of ± 50mm. A digital scanner, distributed by Vishay Measurements Group, was employed to acquire transducers data.

With the aim of capturing both pure shear and torsion-shear failures, three LVDTs, supported by a steel frame, were positioned to the lateral and back sides of the lock and numbered as shown in Figure 3b.



(a) (b)

Figure 3: (a) Interlocking block with steel cup; (b) LVDT's position in the plan view

2.3 Testing program

The experimental program was planned in order to analyze the shear resistance of the lock interface in case of pure shear (S1) and torsion-shear (S2-3-4). The horizontal force, representing the shear force *V*, was applied at variable eccentricity and direction in the midplane of the lock.

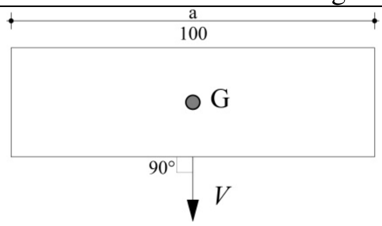
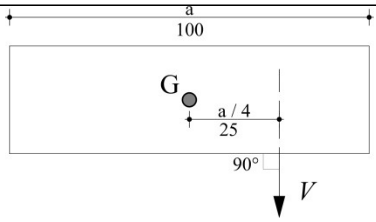
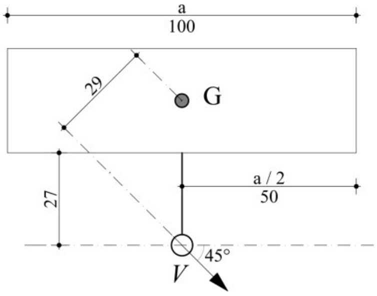
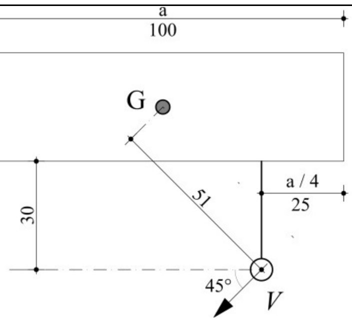
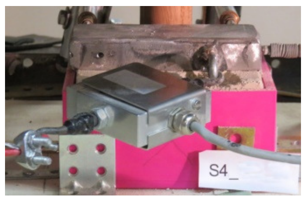
As introduced above, the specimens made of two chosen mortars, M1 and M2, were tested with four setups, resulting in eight samples (Table 3), i.e.:

- S1M1 and S1M2 for pure shear strength evaluation, each comprising four specimens;
- S2M1, S2M2, S3M1, S3M2, S4M1, S4M2 for torsion-shear strength evaluation, each comprising three specimens.

As shown in Table 3, the shear setup (S1) was modified to allow torsion-shear behaviour, in different ways:

- for S2, the force application point was moved on the lock, with *V* still orthogonal to the lock front side, applying the eccentricity e = 25mm from point G;
- for S3, the force application point was only spaced from the lock with reference to S1, with *V* rotated 45° counterclockwise, applying the eccentricity e = 29mm;
- for S4, the force application point was moved on and spaced form the lock, with *V* rotated 45° clockwise, applying the eccentricity e = 51mm.

Table 3: Experimental set configurations (the distances are in mm)

Set	Configuration	
S1M1 S1M2	 PURE SHEAR	
S2M1 S2M2	 TORSION-SHEAR (e = 25mm)	
S3M1 S3M2	 TORSION-SHEAR (e = 29mm)	
S4M1 S4M2	 TORSION-SHEAR (e = 51mm)	

3 EXPERIMENTAL RESULTS

3.1 Pure shear strength of the two mortars

In order to determine the pure shear strength (cohesion) of the two mortars, a total of 8 tests were made out for M1 and M2 mortar samples. Using the S1 shear test setup described in the previous section, it was possible to define the force causing the shear collapse of the specimens. The values of this force for the two M1 and M2 mortars are collected in Table 4.

The coefficients of variation (CV) show a low dispersion of the frequency distributions and therefore a good reliability of the test setup. The average values of the limiting forces related to pure shear failure are equal to 431N and 240N for the M1 and M2 mortar, respectively. The greater shear resistance of the M1 mortar compared to M2 is in good agreement with similar trends for the compressive and flexural strength results shown in Table 2.

Table 4: Pure shear resistance of the two M1 and M2 mortars for S1 tests

Mortar	Shear resistance *V* [N]				CV [%]	Average *V* [N]
	T1	T2	T3	T4		
M1	399	472	408	445	6.8	431
M2	250	242	226	243	3.7	240

For this setup (pure shear), two LVDTs were used to verify the effective displacements of the lock in the absence of torsion. Figure 4 shows the load-displacement curves referred to some of the four tests performed on each of the M1 and M2 mortars, i.e. T2 Test in Figure 4a, and T1 and T3 Tests in Figure 4b. From these figures it is first evident the quasi-brittle behaviour of the material for both mortars. It is then worth emphasizing that the displacements of the two LVDTs, registered as channels Ch.2 and Ch.3 in the figure, substantially tend to overlap for each test. This result confirms once again the reliability of the setup realized ad hoc in the laboratory; in fact, the specimens collapsed in pure shear as there was no torsion effect. The maximum capacity values shown in the graphs correspond to the limiting forces collected for the corresponding tests in Table 4.

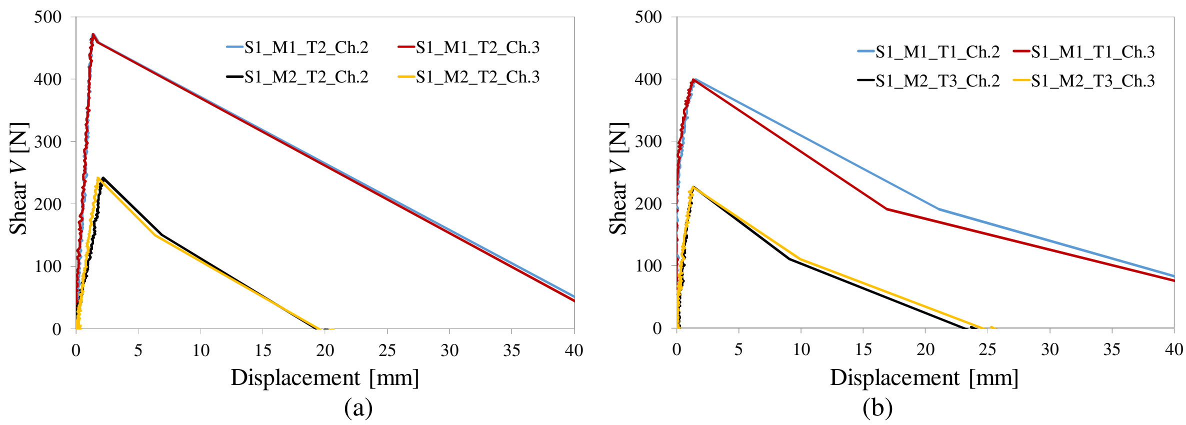


Figure 4: Load-displacement curves for S1 tests: (a) M1_T2 – M2_T2 and (b) M1_T1– M2_T3

Assuming a uniform distribution of the limiting shear force along the interface (100x30mm) between the lock and the main body of the specimens, the mean shear strength f_v can easily be derived for each tested mortar. The relationship between the experimental shear and compressive strengths are reported in Table 5, taking into account the values in Table 2. These results seem to confirm the reliability of the empirical formulation developed by Ali et al. [27], which fits experimental results on standard triplets of masonry and mortar and provides a relation between the mean bond shear strength in absence of normal stresses (cohesion), and the compressive strength of mortar. The formulation is:

$$f_v = 0.06\, f_m^{0.8389} \tag{1}$$

where f_m is the compressive strength of mortar.
In fact, although this formulation was tested for mortars with compressive strengths greater than those of M1 and M2, the pure shear strengths obtained with this formulation for M1 and M2 are very close to the experimental results, as reported in Table 5.

Table 5: Relation between pure shear and compressive strengths of the two M1 and M2 mortars for S1 test

Mortar	Shear strength [MPa]	Compressive strength [MPa]	Shear strength/compressive strength ratio	Shear strength according to Eq. (1) [27] [MPa]
M1	0.15	2.69	5.6%	0.14
M2	0.08	0.75	10.7%	0.05

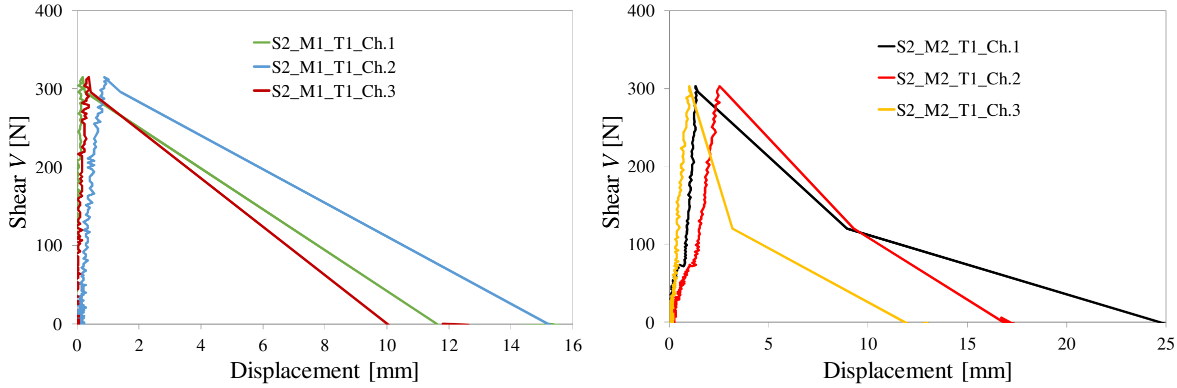
3.2 Torsion-shear strength of the two mortars

The S2-3-4 setups were developed to analyze the torsion-shear resistance of the lock. These setups differ from each other in the eccentricity of the applied force. To determine the torsion-shear strength of the two mortars, a total of 18 specimens, three per each set and mortar, were made out on the M1 and M2 mortar samples, as reported in Table 6. The first interesting remark is that the values of the forces V related to torsion-shear failure of each mortar decrease with increasing eccentricity, as expected. The small coefficients of variation CV, except one, still show quite a good reliability of the setup adopted.

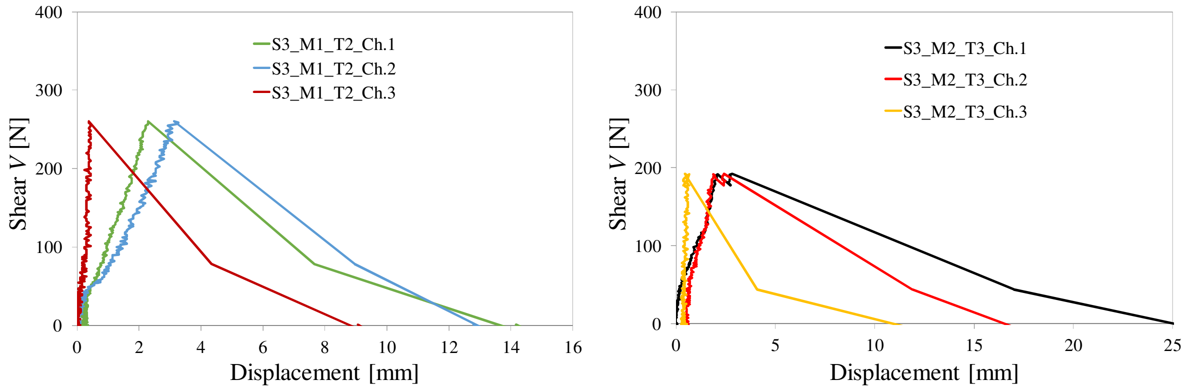
Table 6: Torsion-shear resistance of the two M1 and M2 mortars for S2-3-4 tests

Set	ecc. [mm]	Mortar	Shear force *V* [N]			CV [%]	Average *V* [N]
			T1	T2	T3		
2	25	M1	314	300	330	3.9	315
		M2	213	203	181	6.7	199
3	29	M1	243	260	276	5.2	260
		M2	181	193	192	2.9	189
4	51	M1	79	177	195	33.9	150
		M2	118	133	106	9.3	119

On the other hand, through the load-displacement curves in Figure 5, it is possible to confirm the quasi-brittle behaviour of the involved materials and to analyze the rotation of the lock until collapse and its consistency with the eccentric load applied. Unlike the curves for pure shear in Figure 4, where the displacements of LVDT 2 and 3 tend to coincide, for the torsion-shear condition the displacements are very different from each other. Specifically, the displacement of the LVDT Ch.3 is generally between ± 0.5 mm, while the displacements recorded by the LVDT Ch.2 are even six times higher. Using three LVDTs allows to record three final displacements at the moment of the lock failure and therefore to build the final deformation. Further investigation will be carried out to define the pure torsion strength as well, so that analytical yield domains in torsion-shear interaction can be experimentally validated, similarly to what developed by Casapulla and Portioli [7] for dry-stacked tuff blocks.



(a)



(b)

Figure 5: Load-displacement curves for S2 and S3 tests and: (a) M1 and (b) M2 mortars

12 CONCLUSIONS

Interlocking blocks/interfaces are capable to enhance the shear resistance of masonry joints to external forces, including seismic loading. If the interlocking blocks are composed of cohesive material at their interfaces, the mechanical behaviour is governed by the Mohr-Coulomb criterion for which the bond strength at these interfaces depends on initial shear strength (cohesion) and the coefficient of friction as well as the level of normal stresses.

This paper describes the experimental investigation carried out on the simplest interlocking block, composed of a main body with a prismatic lock located on its upper face and subjected to lateral loading in absence of normal force. An ad hoc test setup was realized to estimate the initial shear and torsion-shear strengths at the lock interface, with results reported in terms of load-displacement curves. Two cement-based mortars were used for specimens, casted using moulds provided by a 3D printer.

The first interesting experimental outcome is that the proposed domestic test method is reliable enough compared to others existing in the literature to assess the shear and torsion-shear strength of cement-based mortars with low compressive and flexural strengths. In fact, using three LVDTs in key positions, pure translation of the lock was registered in the case of pure shear failure and twisting deformation was possible to be captured in the case of torsion-shear condition. Another interesting remark is that the relation between the experimental initial shear and compressive strengths of the lock interface is very close to the empirical formulation developed by Ali et al. [27], which fits experimental results on standard triplets of masonry and mortar. This result can be very useful when analysing limit conditions of assemblages of masonry interlocking blocks composed of material of known compressive strength. Further work is under development to evaluate the torsion-shear yield domain for the single lock interface and to extend the test method to interlocking blocks composed by a number of locks.

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