EXPERIMENTAL ASSESSMENT OF STONE MASONRY MATERIAL PARAMETERS FOR SEISMIC ASSESSMENT OF HERITAGE WALL BUILDINGS

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Abstract

Eastern Canada has a large stock of old unreinforced masonry (URM) buildings with architectural heritage value and their seismic resistance is a concern for architects and engineers involved in defining preservation strategies. Existing (URM) wall structures require upgrading solutions that restore the wall integrity and provide sufficient resistance to earthquake loads. The current challenge in selecting efficient upgrading solutions is the evaluation of the lateral resistance and performance of existing URM walls. This evaluation is the first necessary step in the selection of an optimal strengthening strategy that reduces the potential earthquake induced damage. In Eastern Canada, however, there is limited reported information regarding the mechanical properties of those URM walls, leading to difficulty in providing a reliable prediction of their seismic resistance. This paper presents an experimental assessment of shear and compressive strength parameters for stone masonry assemblies composed of lime-stone blocks joined with cement/lime mortar which were commonly used in heritage buildings construction in Eastern Canada. The paper presents the testing program, analysis and discussion of the results including: compressive strength of lime mortar, lime-stone blocks, joint shear bond strength and diagonal shear strength parameters.

Keywords: Stone masonry; compressive strength; shear strength; heritage buildings.

1. Introduction

Worldwide post-earthquake damage surveys showed that unreinforced masonry (URM) buildings are typically associated with the highest proportion of damage [1], [2], [3], [4], [5]. Eastern Canada has a large stock of old URM buildings with architectural heritage value and their seismic resistance is a concern for architects and engineers involved in defining rehabilitation and preservation strategies for those old URM load bearing wall structures. These walls are often multi-leafs, made of two or three layers of materials of different quality and properties. The strength of the masonry assemblies is typically compromised by the degradation of the mortar joints, resulting in potential deficiencies in their resistance to earthquake induced loading. Existing (URM) wall structures require upgrading solutions that restore the wall integrity and provide sufficient resistance to earthquake loads that conform to the current building code provisions. The current challenge in selecting efficient upgrading solutions is the evaluation of the lateral resistance and performance of existing URM walls. This evaluation is the first necessary step in the selection of an optimal strengthening strategy that reduces the potential earthquake induced damage and preserves the esthetical characteristics of buildings with architectural heritage value [6].

In Eastern Canada, however, little is known about the characteristics of load bearing walls in historical structures, such as wall composition, geometry and materials [6], [7]. There is also limited reported information regarding the mechanical properties of those URM walls, leading to difficulty in providing a reliable prediction of their seismic resistance. Moreover, analytical models for the prediction of the lateral resistance of historical masonry walls requires site-specific shear and compressive strength values of the masonry assembly for reliable seismic performance assessment [8]. With accurate material data and models in the evaluation process, realistic results are obtained and hence cost-effective strengthening solutions can be adopted.

This paper presents an experimental assessment of shear and compressive strength parameters for stone masonry assemblies composed of lime-stone blocks joined with cement/lime mortar commonly used in heritage buildings construction in Eastern Canada. The testing program is described and the results are analyzed and discussed. Results include: compressive strength of lime mortar and limestone blocks, compressive strength of the stone masonry assembly, joint shear bond strength and diagonal shear strength parameters. The obtained results are particularly useful for seismic vulnerability studies of traditional unreinforced stone masonry buildings, as well as for preservation engineers in the evaluation of seismic resistance and the decision-making process of selecting efficient upgrading solutions of heritage stone masonry buildings.

2. Characterization of the stone masonry walls and experimental program

The analysis of the documentation on 5 projects on the rehabilitation and conservation of heritage stone masonry buildings in Montreal and Ottawa helped in the identification of a typical URM wall cross-section considered as potentially vulnerable to earthquake loading. Fig. 1 shows the elevation and cross-section of a representative three-leaf stone masonry wall. The wall section is typically composed of limestone blocks joined with hydraulic lime and cement mortar. The dimensions of the stone were selected to represent average values obtained from the investigated conservation projects. Such wall configuration is potentially vulnerable to in-plane and out-of-plane failure due to earthquake loading. This is mainly attributed to the lack of proper connection and interlocking mechanism that prevent the walls from responding as a composite unit. In addition, the presence of weak mortar joints may increase the wall vulnerability and can lead to its disintegration under strong ground motion, as observed during past worldwide seismic events [9].

The experimental program included three distinct phases. The first phase consisted in characterizing the mechanical properties of the stones and the mortar, as well as the compressive and joint shear sliding strength of the stone-mortar assembly. The second phase consisted in evaluating the diagonal shear strength of stone masonry wall specimens. The third phase consisted in evaluating the lateral force-deformation behavior of the representative wall specimens in Fig. 1. This paper presents the results of Phases I and II only.

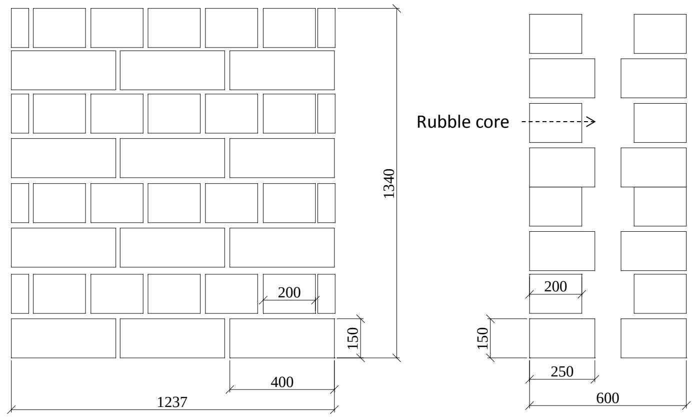

Fig. 1 – Elevation (left) and cross-section (right) of a representative three-leafs stone masonry wall.

3. Tests on stone and mortar specimens

The experimental program is carried out on stone masonry representative of traditional unreinforced masonry walls made of limestone from St-Marc-des-Carrières in Quebec. Three stone cubes with nominal dimensions of (100 mm × 100 mm × 100mm) were tested in compression to determine the average compressive strength of the stone. The average measured compressive strength was 100.6 MPa with a standard deviation of ± 13.1 MPa. This value is within the compressive strength range reported by Sorour [7] for similar limestone specimens, which range from 99 to 106 MPa. Fig. 2 shows the test setup and the failure mechanism at the end of the test for the limestone cubes with splitting cracks, spalling and crushing of the stones.

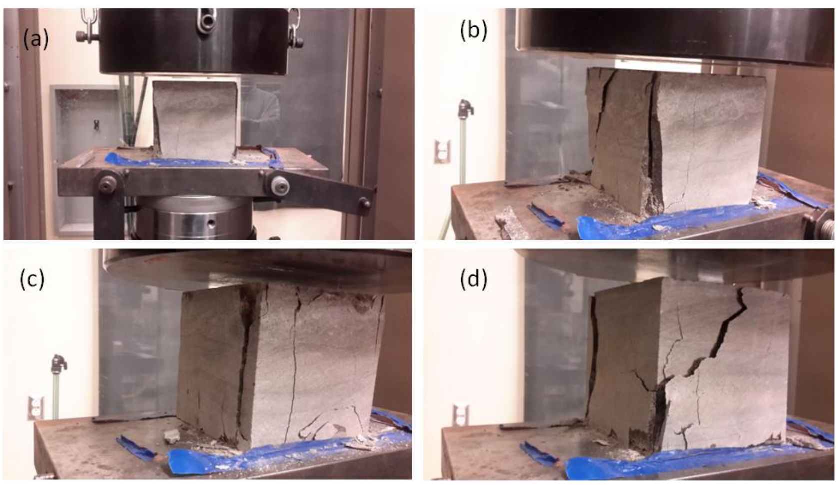

Fig. 2 – Compression tests on limestone: (a) Test setup; (b), (c) and (d) Failure mechanism for the three tested stone cubes.

The composition of the mortar was determined from the documentation on projects related to the rehabilitation of heritage buildings and after consultation with a specialized mason working on stone masonry conservation project. The type of mortar selected is typically used in conservation projects since it provides compatible properties to old URM assemblies [10]. The hydraulic lime/cement mortar mix consisted of air entrained bondcrete lime and white Portland cement with water/binder ratio equal to 0.83. The proportion of the mortar mix by volume of the components (cement: lime: sand) was (1:2:8). Bomix sand was used with particle size distribution compatible with the recommendations provided by CSA -A179-04 [11].

During the construction stage of the stone masonry specimens, mortar cube samples were retrieved from each batch. These mortar cubes were tested on the same day as the corresponding masonry specimens (e.g. compression and shear tests). Compression tests were conducted on 50 mm cubes according to ASTM specifications ASTM-C109 [12]. The measured average compressive strength was 3.30 MPa with a standard deviation of ± 0.2 MPa.

4. Tests on masonry assembly

This section presents the test setup and results on stone masonry assembly constructed in the laboratory. To complete Phase I of the project six (6) specimens were tested in compression to determine the compressive strength of masonry (f'_m) and twelve specimens were tested to determine the joint shear strength (f_s). In Phase II three panels were tested to determine diagonal shear strength (f_{dt}).

4.1 Compression tests

Masonry specimens consist of 3 stacked stone blocks with 2 mortar joints. The specimens have a height to thickness ratio of 3.2 which is within the limits recommended by ASTM-C 1314-14 [13]. A total of 6 stone masonry specimens were constructed with average dimensions of approximately (100 mm × 100 mm × 320 mm) (see Fig. 3a). The tests are performed on a "MTS Rock Mechanics Testing System". The top reaction plate is supported by a spherical cap ensuring the application of a concentric load on the top unit of the specimen. The specimen is placed at the centre of the base plate. Two LVDTs are mounted one on each side to cover the central unit and two mortar layers. The average base length of these measurements is 226 mm for the stone assembly. The test is carried out in displacement control mode. The load is applied at a slow displacement rate of 0.5 mm/min until the peak force is reached. When the force starts to decrease (the softening part), the displacement rate is increased to 1.0 mm/min. until the force drops to 50% of the maximum compression force. The onset of softening of the specimen is caused by vertical splitting cracks in the central block. This is typically followed by more cracking and crushing of the mortar layers until the specimen fails. Crack patterns at the end of the test are shown in Fig. 3b.

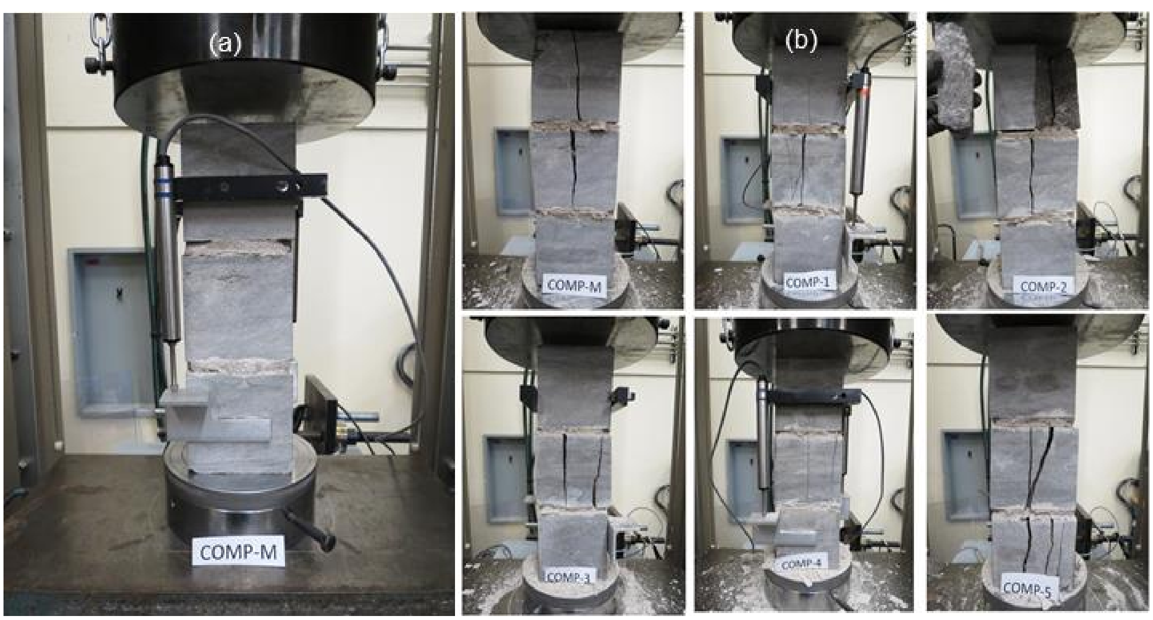

Fig. 3 – Masonry compression tests: (a) Test setup; and (b) crack pattern at the end of the tests.

Table 1 presents the compression test results for stone masonry specimens: compressive strength (f'_m), modulus of elasticity (E_m) evaluated as the secant stiffness to 33% f'_m, and the ratio of the modulus of elasticity to compressive strength (E_m/f'_m). The average compressive strength is 33.2 MPa with a standard deviation of ± 3.2 MPa.

Table 1 – Compression test results for stone masonry specimens

Specimen-ID	**f'_m (MPa)**	**E_m (MPa)**	**E_m/f'_m**
COMP-M	28.04	2920	104
COMP-1	31.65	2693	85
COMP-2	33.54	2814	84
COMP-3	33.53	2634	79
COMP-4	37.69	3145	83
COMP-5	34.91	2732	78
Average ± St.dev	33.2 ± 3.2	2823 ± 186	85.5 ± 9

In the literature, most of the theoretical models for the determination of f'_m were developed for brick masonry [14]. For regular contemporary stone masonry, according to the Eurocode-6 provisions [15], the characteristic compressive strength of stone masonry can be calculated from the compressive strengths of the stone block and mortar as follows:

$$f'_m = 0.45 f_{bs}^{0.7} f_j^{0.3} \tag{1}$$

Using the experimental compressive strength for the stone (f_{bs} = 100.6 MPa) and the mortar (f_j = 3.30 MPa), the compressive strength for stone masonry predicted with Eq. (1) is 16.2 MPa. This predicted value is approximately 50% of the observed value from the masonry assembly tests (33.2 MPa). This variation between the observed and predicted values highlight the need for more experimental data on the mechanical properties of stone masonry assembly and its components, and the need for site specific characterization of the material parameters.

4.2 Joint shear bond tests

This section presents the test setup and results for joint shear bond tests on masonry specimens made of 3 stacked stones with mortar joints. A total of 12 stone masonry specimens were constructed. Fig. 4 shows the support conditions of the stone masonry specimens within the testing machine. At the base, the specimen is supported at the inner edge of the outer units on two 30 mm wide aluminum blocks, which have the same length as the stone units. At the top, two aluminum blocks introduced the reaction force of the testing machine at the outer edges of the middle unit. During the test, two LVDTs – on each face – measure the relative displacements between the outer and middle units. The shear tests are conducted at three different normal stress levels, where normal refers to the direction perpendicular to the mortar joints: 0.3 MPa, 0.7 MPa and 1.1 MPa. The normal forces are applied by means of two D15 mm steel rods. The force in the rods is monitored with two compression load cells. Once the cracks have formed the shear stress remained approximately constant and the test is ended when a shear displacement of approximately 10 mm is reached.

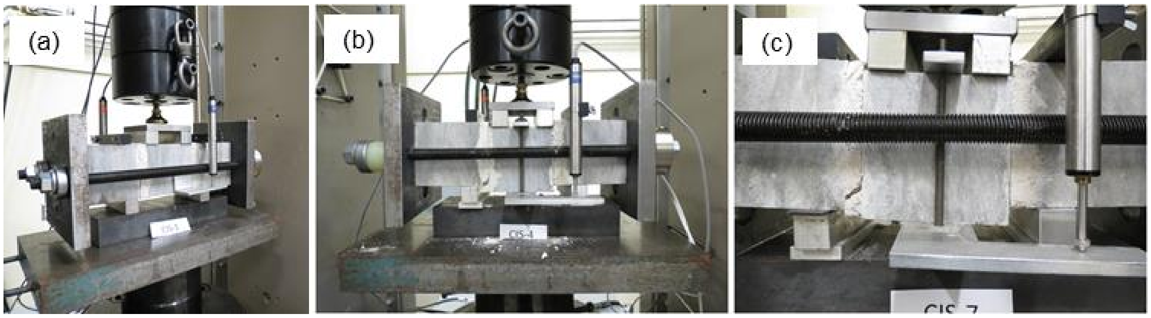

Fig. 4 – Masonry joint shear bond tests: (a) Test setup; (b) and (c) crack pattern at the end of the tests.

The peak shear stress, that is the maximum measured shear stress, is determined for all tests. The shear stress is defined as the applied shear force divided by the gross cross section area of the two mortar beds. The corresponding normal stress (measured by the compression load cells) at peak shear stress is recorded for the evaluation of the Mohr-Coulomb failure envelope (Fig. 5). The obtained value of the cohesion (C) is 0.56 MPa and the coefficient of friction μ is 0.85. There are limited sources in the literature regarding the values for the cohesion and coefficient of friction for stone masonry. Vasconcelos and Lourenço [16] reported values of 0.36 MPa for cohesion and a coefficient of friction of 0.63 for stone masonry made of granite and lime mortar. Binda et al. [9] reported values for sandstone and calcareous stone masonry with lime mortar: cohesions (C) were 0.33 MPa and 0.58 MPa, respectively, and coefficients of friction μ were equal to 0.74 and 0.58, respectively.

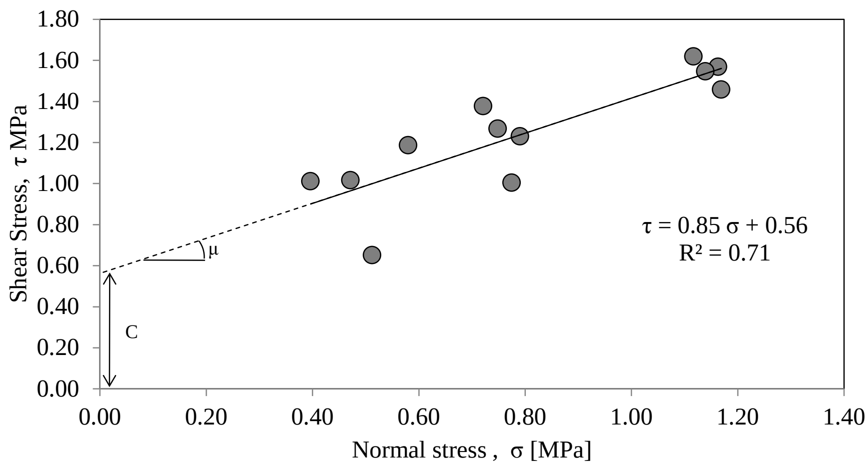

Fig. 5 – Shear stress-normal stress pairs for stone masonry test units and Mohr-Coulomb envelope.

4.3 Diagonal shear tests

This section presents the test setup and results for diagonal shear tests on stone masonry specimens. The tests were conducted according to the procedures of ASTM E-519 [17] for diagonal compression tests on square masonry panels. Two square stone masonry panels with average dimensions of (618 mm x 618 mm) and a thickness of one stone block (100 mm) were constructed in horizontal direction (Fig. 6a) and then rotated 45 degrees and placed under the testing frame (Fig. 6b). Therefore, the compression force was applied on the diagonal direction of the panel to induce the shear failure mechanism.

The compression force was applied by a servo-hydraulic actuator installed on the testing frame. The strain shortening of the vertical diagonal and the extension of the horizontal diagonal were measured using displacement transducers which were placed on both sides of the masonry panels. The gauge length for the strain measurements was 630 mm. The observed failure pattern was characterized by the stair-stepped cracking along the mortar joints as shown in Fig. 7.

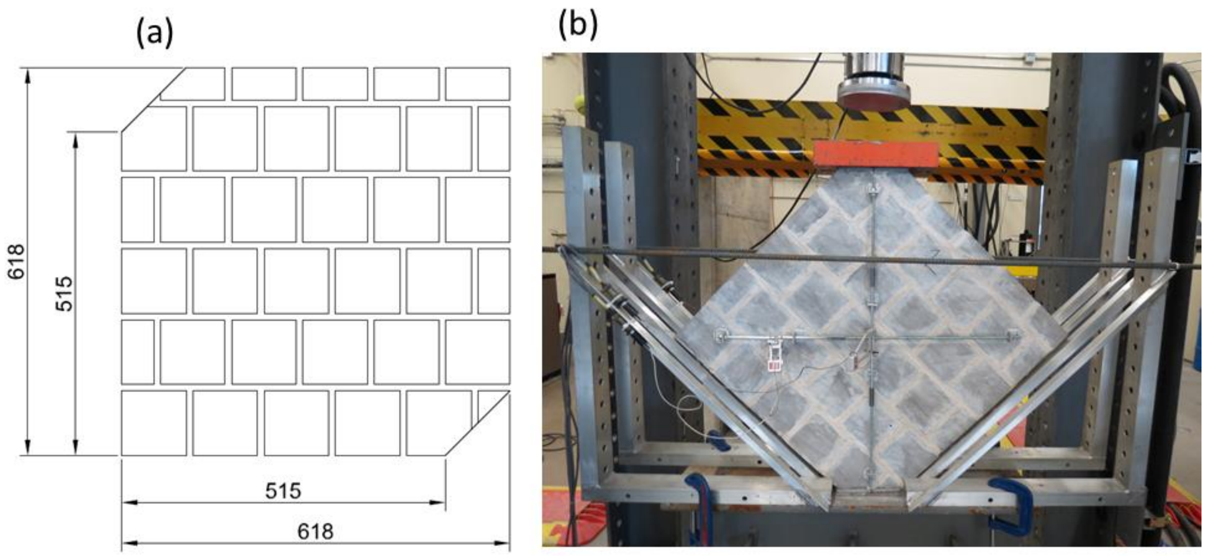

Fig. 6 – Diagonal shear tests on stone masonry panels: (a) panel dimensions (mm) and (b) test setup.

Fig. 7 – Failure pattern at the end of the diagonal shear tests on stone masonry panels.

The diagonal shear strength (f_{ds}) is calculated using ASTM E-519 [17] as follows:

$$f_{ds} = \frac{(\cos 45^o)P}{A_n} = \frac{0.707P}{A_n} \;, \qquad A_n = \frac{(w+h)}{2}.t.n \tag{2}$$

where P is the maximum applied force; A_n is the net area of the panel; w is the panel width; h is the panel height; t is the thickness of the panel; n is percent of the gross area of the unit that is solid expressed as a decimal, in this case n = 1.

The shear strain (γ) is calculated with Eq. (3), as follows:

$$\gamma = \frac{\Delta V + \Delta H}{g} \tag{3}$$

where ΔV is the vertical shortening of the panel (measured from the gauge deformation); ΔH is the horizontal extension of the panel (measured from the gauge deformation); g is the gauge length of the vertical and horizontal displacement measurements. ASTM E-519 does not provide specific recommendations about which point the elastic shear modulus should be calculated on the shear stress-shear strain curve. Milosevic et al. [18] and Magenes et al. [19] suggest that the elastic shear modulus (G) be measured from the shear stress-shear strain curve with at one third (33% f_{ds}) of the maximum shear stress. Table 2 presents the results of the experimentally obtained diagonal shear strength of the tested panels and the shear modulus at 33% of the maximum stress. The average diagonal shear strength is 0.37 MPa and the average shear modulus is 487.17 MPa. The shear modulus is around 17% of the modulus of elasticity E_m (2823 MPa, see Table 1) which is within the range of observed values for stone masonry [14]. It should be noted that Mazzon [20] observed a large scatter in the range of values reported in the literature for the shear strength and shear modulus of un-strengthened stone masonry obtained from laboratory investigations: the shear strength varied between 0.06 to 0.37 MPa and the shear modulus varied between 79 to 837 MPa.

Table 2 – Diagonal shear strength and elastic shear modulus of the stone masonry panels.

Panel	**f_{ds} (Mpa)**	**0.33 f_{ds} (Mpa)**	**γ (0.33f_{ds})**	**G (MPa)**
1	0.41	0.14	0.0263%	516.29
2	0.34	0.11	0.0249%	458.06
Average ± St.dev	0.37±0.05	0.14±0.03	0.0256%±0.001%	487.17±9.60

5. Conclusions

This paper presented an experimental assessment of shear and compressive strength parameters for stone masonry assemblies composed of lime-stone blocks joined with cement/lime mortar which were commonly used in heritage buildings construction in Eastern Canada. The testing program was described and the results were analyzed and discussed, including: compressive strength of lime mortar, compressive strength of the lime-stone blocks, compressive strength of stone masonry assembly, joint shear bond strength and diagonal shear strength parameters of the masonry. The measured average compressive strength for stone masonry was 33.2 MPa corresponding to an assembly of stone blocks with compressive strength of 100.6 MPa and mortar joints with compressive strength of 3.3 MPa. These results are approximately 50% higher than the compressive strength using Eurocode-6 equation. Joint shear tests results measured a cohesion value 0.56 MPa and a friction coefficient of 0.85 between the stone and mortar. These values are consistent with the results of similar studies in the literature. The average measured diagonal shear strength obtained from the diagonal compression tests was 0.37 MPa, which is in the upper range of the values reported in the literature, while the average shear modulus of 487.17 MPa is consistent with the results from similar studies. The experimental program highlighted the need for more experimental data on the mechanical properties of stone masonry assembly and its components and the need for site specific characterization of the stone masonry material parameters.

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