INFLUENCE OF DIFFERENT TYPES OF UNITS AND MORTARS ON SEISMIC RESISTANCE OF MASONRY WALLS

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ABSTRACT

The influence of different types of units and mortars on seismic resistance of masonry walls has been studied. Hollow clay and autoclaved aerated concrete (AAC) masonry units have been used for the construction of testing walls. The units were either laid in general purpose mortar and thin layer mortar or glued together by polyurethane (PU) glue. Altogether ten walls have been tested as fixed at both ends by subjecting them to constant vertical and in-plane acting cyclic shear load. No significant difference in main parameters of seismic behavior, such as resistance, displacement and energy dissipation capacity has been observed in the case of the clay block masonry laid in both, general purpose and thin layer mortar. However, gluing the hollow clay units with PU glue significantly changed the behavior. In the case of AAC masonry, replacing the thin layer mortar with PU glue had little effect on the seismic performance.

KEYWORDS: masonry, seismic resistance, mortars, cyclic shear

INTRODUCTION

In the last decade a number of new masonry unit types and construction technologies have been introduced in European market, with improvements motivated by construction simplicity and environmental concerns rather than by structural stability. Due to their thickness and material properties, masonry joints filled with traditional general purpose mortar represent thermal bridges. In addition, traditional construction using general purpose mortars, is slow. To improve thermal insulation properties and simplify the construction, new types of units have been developed, laid in thin layer mortars with only mechanical interlocking at the head joints. Dimensional regularity of units, especially the evenness of bedding surfaces, is required in the case that thin layer mortars are used. Recently, polyurethane (PU) glue was introduced [1], representing an alternative to thin layer mortars. As specified by the producer, the construction using PU glue is faster, cleaner and can be performed at lower outside temperatures, thus extending the construction season.

Because of high volume of holes ratio, porosity of material, and thin shells and webs, hollow clay masonry units become brittle when the wall is subjected to a combination of high vertical and seismic shear loads. Therefore, alternative materials with similar thermal properties have been introduced. One of them is autoclaved aerated concrete (AAC). Because masonry units from AAC are solid units without holes, brittleness and robustness of units do not represent a problem. Because of high porosity, thermal properties of AAC masonry are good, however the compressive strength is low. Originally, AAC masonry is built with thin layer mortar, however attempts have been made to use PU glue also for the construction of AAC masonry.

In this paper, an attempt has been made to compare the behavior of typical representatives of modern masonry when subjected to seismic loads. The results of an experimental study, carried out at Slovenian National Building and Civil Engineering Institute, will be presented and discussed.

MATERIALS AND TEST SPECIMENS

Masonry units. Hollow clay masonry units with dimensions 25 cm/25 cm/30 cm (length/height/thickness) and vertical holes of 48 % of the gross volume, belonging to Group 2 masonry units according to Eurocode 6 [2], and AAC solid units with dimensions 62.5 cm/25 cm/25 cm (length/height/thickness), belonging to Group 1 units, have been used for the construction of walls. Hollow clay units had ground bed surfaces for the use with thin layer mortar or PU glue.

Compressive strength of hollow clay and AAC masonry units, determined by testing, was 12.1 MPa and 2.4 MPa, respectively.

Mortars. General purpose mortar consisted of lime/cement/sand in volumetric proportion of 1:3:9. Compressive strength, determined on cubes with side length of 7.07 cm, and bending strength, determined on prisms 16/4/4 (in cm), amounted to 3.9 MPa and 1.1 MPa, respectively. Actual thickness of general purpose mortar in the bed-joints of the walls varied from 7 to 15 mm (average 10 mm).

Thin layer mortar used for the construction of hollow clay masonry walls was a commercially available dry powder ready mix mortar supplied with the units. Compressive and bending strength determined on cubes and prisms, were 12.5 MPa and 4.6 MPa, respectively. The average thickness of thin layer mortar in the bed-joints was 1 mm.

Thin layer mortar used for the construction of AAC masonry walls was also a commercially available dry powder ready mix, but from a different producer. Compressive and bending strength were 8.8 MPa and 3.7 MPa, respectively. The average thickness of mortar was 1 mm.

Commercially available PU glue, designed for the construction of masonry walls, was used. The measured thickness of the glue in the bed-joints walls was less than 1 mm.

Walls. Ten 100 cm long and 100 cm high walls were built on r.c. foundation blocks. On the top of each wall, a reinforced concrete bond beam was constructed for the application and distribution of compressive (vertical) and horizontal loads. Six hollow clay and four AAC units' walls have been built.

In the case of the walls built of hollow clay units, head-joints were of mechanical interlocking type, not filled with mortar or glue. Only the bed joints were filled with either general purpose or thin layer mortar, or glued with PU glue. In the case of the walls built of AAC units, however, both bed and head joints were filled with thin layer mortar, but only bed joints were glued with PU glue. Each type of masonry walls was tested at two levels of constant pre-compression. In the case of the clay masonry units, the pre-compression ratio was 0.10 and 0.20 (10 % and 20 % of the compressive strength of masonry), whereas in the case of AAC units, the walls have been tested at pre-compression ratio 0.15 and 0.30. The test matrix is given in Table 1.

Table 1: The characteristics of tested walls

Wall	Pre-compression ratio [%]	Units	Mortar	Dimensions (l/h/t; in cm))
B-t-10	10	Clay	Thin	100/100/30
B-t-20	20	Clay	Thin	100/100/30
B-g-10	10	Clay	PU glue	100/100/30
B-g-20	20	Clay	PU glue	100/100/30
B-m-10	10	Clay	General purpose	100/100/30
B-m-20	20	Clay	General purpose	100/100/30
AAC-t-15	15	AAC	Thin	100/100/25
AAC-t-30	30	AAC	Thin	100/100/25
AAC-g-15	15	AAC	PU glue	100/100/25
AAC-g-30	30	AAC	PU glue	100/100/25

DESCRIPTION OF TESTS

Cyclic shear tests with in-plane application of horizontal loading were performed in a test setup shown in Fig. 1, which made possible the walls to be tested as symmetrically fixed at both ends. Test setup consisted of a steel reaction frame, fixed to the r.c. strong-floor of the laboratory, and hydraulic actuators for simulation of vertical and horizontal loads.

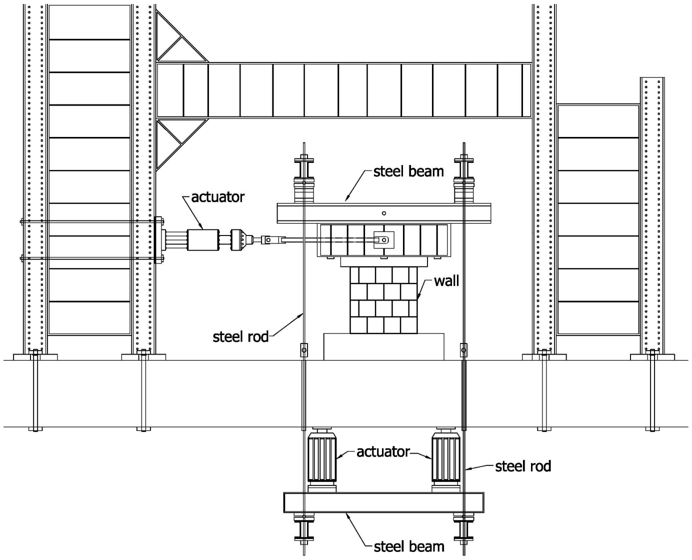

Figure 1: Cyclic Shear Test Setup

The horizontally placed servo controlled actuator, used to impose lateral displacements according to a pre-programmed protocol, was fixed to the reaction frame. Two vertically placed actuators to impose constant vertical loading, however, were fixed to the strong-floor. At each step of testing, the amplitude of horizontal loading in the form of prescribed displacements in positive and negative direction was repeated three times. Vertical actuators induced the axial load through a system of steel rods and steel beam, which was fixed to the bond beam at the top of the tested wall. The actuators were controlled by a regulation loop to impose constant vertical force at zero rotation of the beam.

Compressive strength. The compressive strength and modulus of elasticity for each of the considered types of masonry were determined according to European standard EN 1502-1. The results of tests are presented in Table 2. The measured elastic modulus of masonry walls built from clay units and using PU glue is surprisingly low. This can be explained by the fact, that, according to the standard, the modulus is evaluated at 1/3 of the ultimate strength. Tests show that stiffness increases beyond about 25 % compressive strength level. To check the obtained value, the elastic modulus of masonry was evaluated also on the basis of the measured elastic compression of walls, measured during the application of pre-compression load before cyclic shear tests. Similar values have been obtained in both cases.

Table 2: Compressive Strength and Elastic Modulus

Walls	Units	Mortar	Comp. strength [MPa]	Elastic modulus [MPa]
B-t	Clay	Thin	6.7	5600
B-g	Clay	PU glue	5.3	1500
B-m	Clay	General purpose	4.8	4800
AAC-t	AAC	Thin	1.5	1300
AAC-g	AAC	PU glue	1.3	780

Tensile strength of the interface. Tests to study the effect of mortar on the tensile strength of the interface were performed by loading the interface in direct tension by the so called couplet test using bolts through holes [3]. The fixing of the units into the hydraulic actuator was achieved by placing bolts through holes, which were drilled through the units, and steel plates, as shown in Figure 2a.

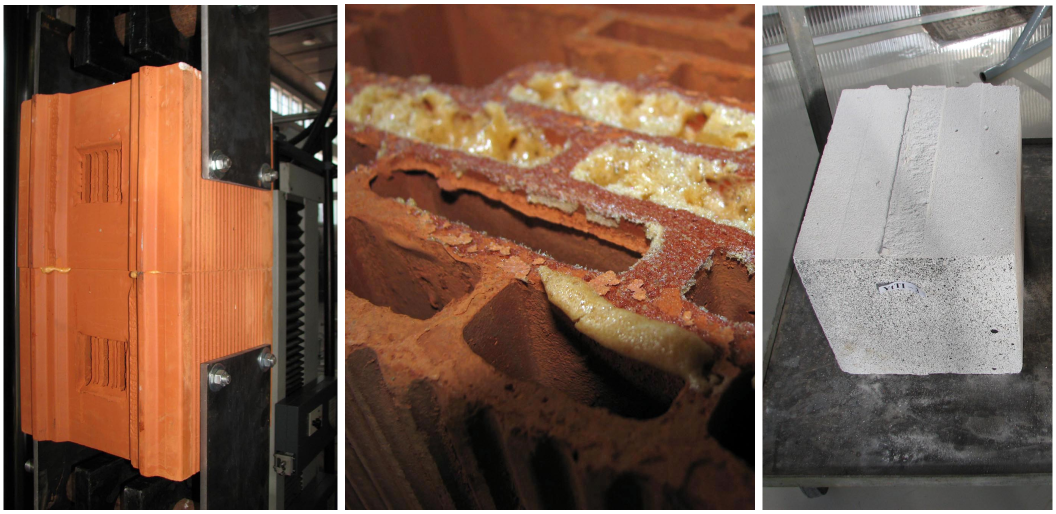

Figure 2: Tensile test: a) Setup; b) Failure in the PU Glue; c) Failure in Mortar

In the case of masonry units glued with PU glue, the glue was applied in two strips along the length of the unit, as in the actual construction of the walls. Samples for testing bond tensile strength of AAC units with thin layer mortar, on the other hand, were prepared with only a 5 cm wide strip of mortar along the center of the sample as shown in Figure 2c. If mortar was applied over the entire surface of the samples for tensile testing, the failure would not occur in the joint, but through a plane passing through the holes for bolts. AAC masonry walls were constructed with mortar over the entire surface of the bed joint.

The bond tensile strength was determined by taking into consideration the gross surface area of the unit, except for the case of AAC with thin layer mortar, where the net area of mortar was considered. The values are given in Table 3. The failure occurred in the mortar or PU glue (see Fig. 2b) if clay masonry units were used, and in the material of the unit if AAC was used (see Fig. 2c).

Table 3: Tensile Strength of the Interface

Walls	Units	Mortar	Tensile. strength [MPa]
B-t	Clay	Thin	0.08
B-g	Clay	PU glue	0.12
B-m	Clay	General purpose	0.03
AAC-t	AAC	Thin	0.19*
AAC-g	AAC	PU glue	0.07

* net area

SEISMIC RESISTANCE

Observed response. The first damage that developed in clay masonry (regardless of the type of the mortar used) was in the form of cracks in the bed joints. Later on, the cracks in the units developed and propagated diagonally in a typical diagonal shear pattern. The major strain plot obtained by an optical system is shown in Figure 3a. The failure mode of clay masonry is due to shear damage, with diagonal shear cracks running through the units and joints and heavy damage to the units.

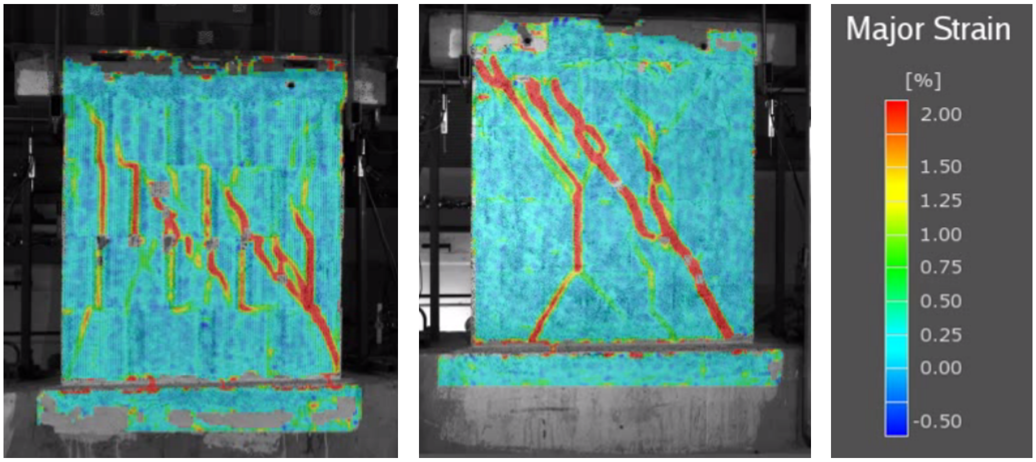

Figure 3: Plot of major strain: a) Wall B-g-20; b) Wall ACC-t-30

The first damage that developed in AAC masonry was diagonal cracking in the units. The cracks later propagated so that, before collapse, a clear diagonal shear pattern with cracks running directly through the units has been observed. Major strain plot of a typical damage pattern obtained by an optical system in shown in Fig. 3b.

The envelopes of hysteretic relationships between shear, *H*, and lateral displacement, *u*, are shown in Fig. 4. The envelopes of general purpose and thin layer mortar are similar, but the envelope of hollow clay unit masonry with PU glue is significantly different. Higher displacement capacity, however lower shear resistance has been observed.

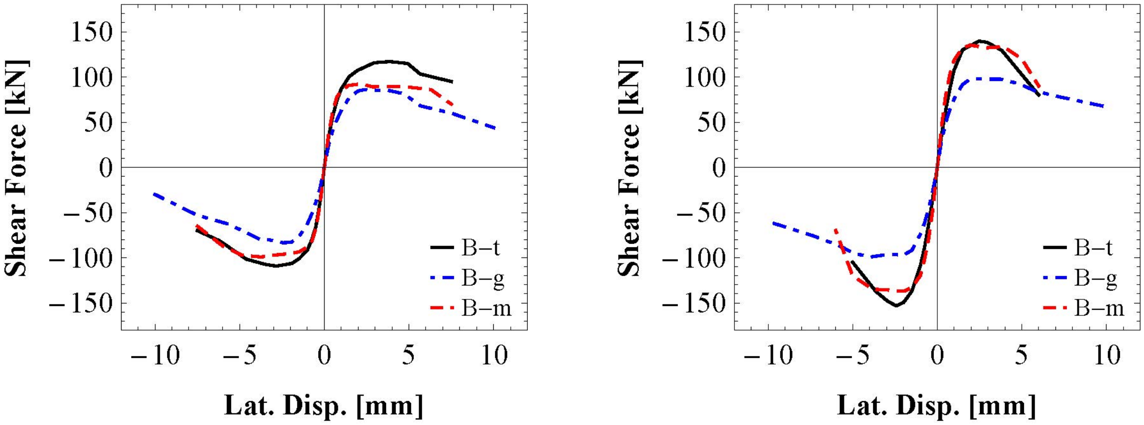

Figure 4: Response Envelopes of Clay Masonry Walls: a) Low Compression; b) High Compression

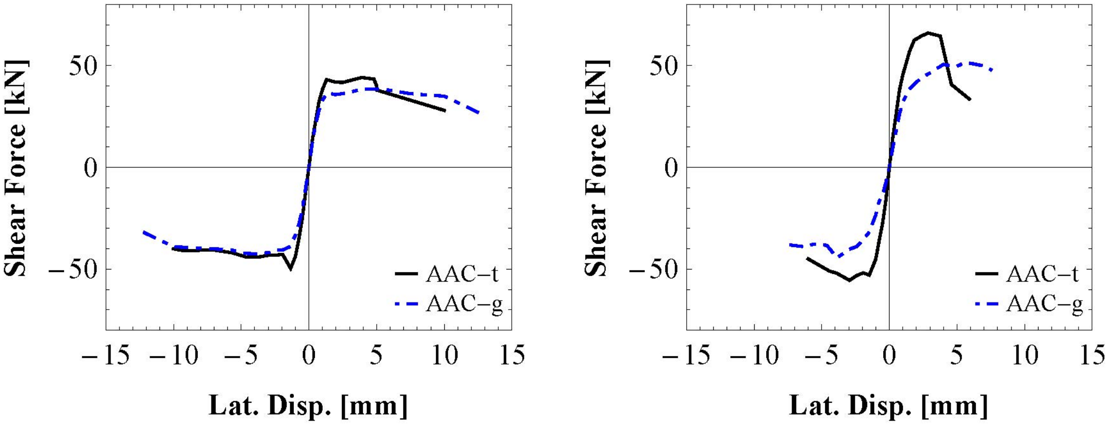

Figure 5: Response Envelopes of AAC Masonry Walls: a) Low Compression; b) High Compression

As can be seen in Fig. 5, which shows the envelopes of lateral load - displacement hysteretic relationships, the use of PU glue instead of thin layer mortar in AAC masonry results in increased displacement capacity and decreased resistance capacity The effect is small in the case of the lower but substantial in case of the higher pre-compression.

To assess the effect of different materials, the resistance and displacement capacity of the walls at three limit states are compared, namely crack (damage) limit state, where the first cracks occur in the walls, causing evident changes in the stiffnesses of the walls, maximum resistance, and ultimate limit state of collapse, defined by severe degradation of resistance at repeated lateral load reversals or collapse in the walls. The results are summarized in Table 4, where the values of lateral load, displacement and rotation $\Phi = d/h$ (in % of h; h = height of the wall), at characteristic limit states are given. As expected, due to stronger units, the resistance of hollow clay unit masonry is much higher than the resistance of AAC masonry. As mentioned, the walls made of each type of masonry were tested at two levels of pre-compression. The effect of higher pre-compression is similar in all cases: maximum shear resistance increases, but occurs at smaller drifts and at the cost of reduced deformation capacity and ductility of the walls. In Table 5, the dimensionless capacities of the walls with respect to maximum resistance limit state are presented. The highest ductility can be observed in the case of the hollow clay masonry with PU glue, whereas the lowest is in the case of hollow clay masonry with thin layer mortar.

Table 4: Limit States

Wall	Crack/damage			Max resistance			Collapse		
	u [mm]	H [kN]	Φ [%]	u [mm]	H [kN]	Φ [%]	u [mm]	H [kN]	Φ [%]
B-t-10	1.00	89.2	0.09	3.35	113.1	0.31	7.50	67.1	0.70
B-t-20	2.00	144.2	0.19	2.45	146.4	0.23	4.51	63.2	0.42
B-g-10	1.00	62.5	0.10	2.41	84.7	0.24	10.00	31.1	1.00
B-g-20	1.00	74.9	0.10	3.19	98.6	0.30	10.00	59.0	0.95
B-m-10	0.75	80.1	0.08	2.84	95.5	0.28	7.50	63.7	0.75
B-m-20	1.00	119.2	0.10	2.20	136.2	0.22	6.34	51.1	0.63
AAC-t-15	1.00	41.1	0.10	2.62	46.9	0.26	9.99	36.0	1.00
AAC-t-30	1.50	54.9	0.15	2.91	60.7	0.29	5.98	41.7	0.60
AAC-g-15	1.00	33.1	0.10	4.25	40.5	0.43	12.49	30.8	1.25
AAC-g-30	2.00	38.7	0.20	4.74	48.1	0.47	6.03	40.6	0.60

Table 5: Deformation and Resistance Capacity

	Crack/damage		Collapse	
	$H / H_{\max}$	$\Phi \ / \ \Phi_{\max}$	$H / H_{\max}$	$\Phi \ / \ \Phi_{\max}$
B-t-10	0.79	0.3	0.59	2.24
B-t-20	0.98	0.8	0.43	1.84
B-g-10	0.74	0.41	0.37	4.15
B-g-20	0.76	0.31	0.60	3.13
B-m-10	0.84	0.26	0.67	2.64
B-m-20	0.88	0.45	0.38	2.88
AAC-t-15	0.88	0.38	0.77	3.81
AAC-t-30	0.90	0.52	0.69	2.05
AAC-g-15	0.82	0.24	0.76	2.93
AAC-g-30	0.80	0.42	0.75	1.58

The dissipated hysteretic energy of hollow clay and AAC masonry is shown in Figs. 6 and 7, respectively. Graphs showing the hysteretic energy as a function of cumulative displacement demonstrate the highest capacity of energy dissipation of PU glue for brick masonry. Based on the resistance envelopes of walls B-t and B-m in Fig. 4a, the cumulative displacements of walls B-t and B-m in Fig. 6a should be the same. However, due to a different lateral loading protocol in the case of wall B-t (some phases were omitted), these displacements are not the same. The total hysteretic energy is similar, though.

For AAC masonry, the effect of mortar is different for the higher and lower level of pre-compression. In case of the lower pre-compression, more energy is dissipated by walls with PU glue than by those with thin layer mortar. It is vice versa for the case of the higher compression.

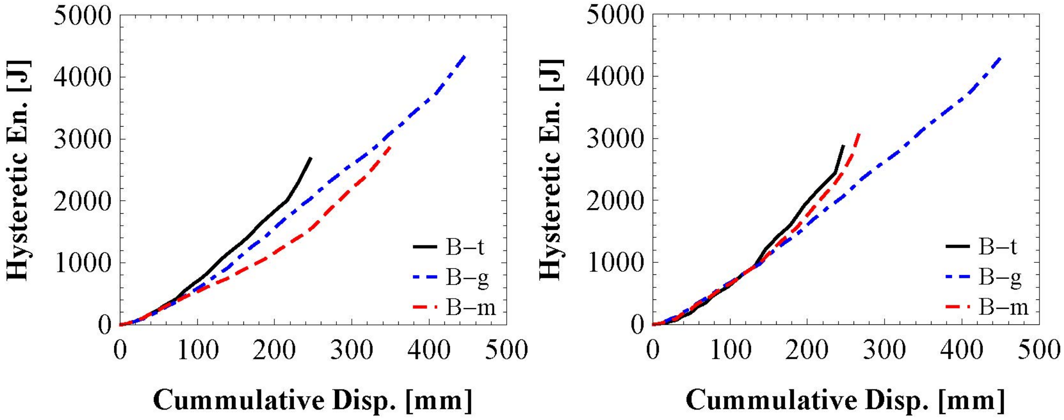

Figure 6: Hysteretic Energy of Clay Masonry Walls: a) Low Compression; b) High Compression

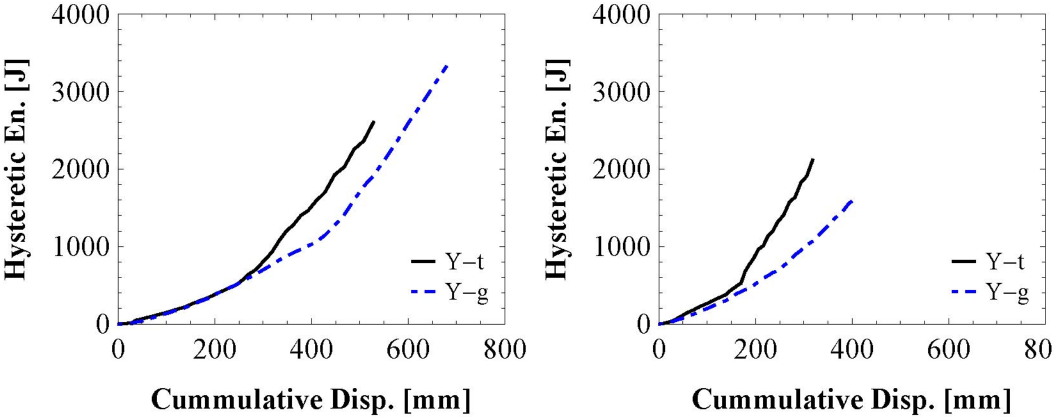

Figure 7: Hysteretic Energy of AAC Masonry Walls: a) Low Compression; b) High Compression

CONCLUSIONS

The effect of different masonry units and mortars on seismic resistance of walls has been experimentally investigated. Ten walls built from either hollow clay or AAC masonry units and using different kinds of mortar (general purpose and thin layer mortar) or PU glue have been tested.

Regardless of masonry units and mortar, shear behavior and shear failure prevailed. However, whereas in the case of the hollow clay unit masonry the first cracks developed in the joints, AAC unit masonry started cracking in the units.

The replacement of general purpose mortar with thin layer mortar in clay masonry was found to have little overall influence on any of the considered parameters of seismic resistance, despite about double tensile strength of the joint. On the other hand, in the particular case studied, the PU glue increased the ductility of the walls but reduced the shear resistance.

In the case of AAC masonry, PU glue had little effect at low level of compressive stress. At higher compression, however, shear resistance was smaller than in the case of thin layer mortar, but the deformation capacity was higher.

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