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The effect of mortar type and joint thickness on mechanical properties of conventional masonry walls

Başak Zengin*[1], Burak Toydemir[2a], Serhan Ulukaya[3b], Didem Oktay[3c],
Nabi Yüzer[3d] and Ali Kocak[3d]

[1]*Graduate School of Natural and Applied Sciences, Yildiz Technical University, Turkey*
[2]*Istanbul Gelisim University, Turkey*
[3]*Department of Civil Engineering, Yildiz Technical University, Turkey*

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Abstract. Masonry walls are of a complex (anisotropic) structure in terms of their mechanical properties. The mechanical properties of the walls are affected by the properties of the materials used in wall construction, joint thickness and the type of masonry bond. The carried-out studies, particularly in the seismic zones, have revealed that the most of the conventional masonry walls were constructed without considering any engineering approach. Along with that, large-scale damages were detected on such structural elements after major earthquake(s), and such damages were commonly occurred at the brick-joint interfaces. The aim of this study was to investigate the effect of joint thickness and also type of mortar on the mechanical behavior of the masonry walls. For this aim, the brick masonry walls were constructed through examination of both the literature and the conventional masonry walls. In the construction process, a single-type of brick was combined with two different types of mortar: cement mortar and hydraulic lime mortar. Three different joint thicknesses were used for each mortar type; thus, a total of six masonry walls were constructed in the laboratory. The mechanical properties of brick and mortars, and also of the constructed walls were determined. As a conclusion, it can be stated that the failure mechanism of the brick masonry walls differed due to the mechanical properties of the mortars. The use of bed joint thickness not less than 20 mm is recommended in construction of conventional masonry walls in order to maintain the act of brick in conjunction with mortar under load.

Keywords: masonry wall; mortar; joint thickness; mechanical behaviour

1. Introduction

Examining the state of the constructions after major earthquake(s) has exhibited that the most remarkable damages was observed in masonry structures. Similarly, great damages were detected in the conventional masonry buildings, especially after the most recent Van (Turkey) earthquake (Sayin *et al.* 2014, Erdik *et al.* 2012, Kizilkanat *et al.* 2011). In this earthquake zone, it was clearly observed that the constructions were completed by the use of local materials, disregarding any engineering approach. However, the studies about the constructions in seismic zones have shown that such a way is unsustainable anymore and the constructions should be made in conformity with the related regulations or codes under engineering discipline (Porco *et al.* 2013, Tomazevic *et al.* 2009).

Under seismic loads, it is difficult to estimate the behavior of masonry walls that constructed through rudimentary methods. Such a similar case is observed in the infill masonry walls of reinforced concrete buildings. In fact, the infill walls contribute to the rigidity of the structure but they are among first structural elements to receive damage first from a potential dynamic movement (Koçak 2013, 2015, Asteris 2003, Asteris *et al.* 2015a, Asteris *et al.* 2015b).

The properties of the materials used in wall construction play a major role on the behavior of the infill walls. In general, the masonry units used in walls are heterogeneous and anisotropic. Since materials used in construction of the walls will affect the wall behavior, the mechanical properties of the materials must be adequately described by laboratory tests (Ravula and Subramaniam 2017). Along with these, various test methods to assess wall behavior have been performed by several researchers (Xin *et al.* 2017, Pereire *et al.* 2011, Basaran *et al.* 2015, Foytong *et al.* 2016, Bourzam *et al.* 2008, Kausnik *et al.* 2007).

In this study, the correlation between the joint thickness and mortar type was investigated to determine the behavior of the masonry walls which were randomly bonded by skilled workers, and also to construct more ductile walls. For this purpose, the mechanical characteristics of the

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*Corresponding author, Ph. D. Student
E-mail: zenginbasak@gmail.com
[a]Ph. D. Student-Lecturer
E-mail: btoydemir@gelisim.edu.tr
[b]Ph. D.
E-mail: serhanu@yildiz.edu.tr
[c]Ph. D.
E-mail: dyasar@yildiz.edu.tr
[d]Professor
E-mail: nyuzer@yildiz.edu.tr
[e]Associate Professor
E-mail: akocak@yildiz.edu.tr

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materials that used in construction of the conventional masonry walls were primarily determined. Then, the walls constructed using different joint thicknesses and different mortar types were subjected vertical and horizontal loading, simultaneously. The test results were interpreted by the plotted the load-displacement graphs, and finally, the effect of the joint thickness on ductility of the masonry walls was discussed.

2. Masonry walls

2.1 Mortar of properties

Mortar is a composite material that acts anisotropically. The role of the mortar is to ensure bonding of the masonry units to each other, and to distribute the existing stress by making the surfaces of the units smoother. The fresh properties of the mortar such as workability also affect construction process and failure mode; in other words, the adhesion of the mortar to the unit is directly related with mechanical behaviour of the walls. It is well known phenomenon that the characteristics of constituents, e.g., characteristics of aggregate, and some parameters like water to binder ratio govern both fresh and hardened properties of mortar. The compression, bending or direct tension tests are performed, in some cases with simultaneous measurement of displacements, to determine the mechanical properties of mortars (Šlivinskasa *et al.* 2016).

In a study conducted by Steil *et al.* (2001), it was experimentally observed that compressive strength increases by 78% in masonry prisms with an increase in the mortar strength by 8.8%. Cunha *et al.* (2001) have demonstrated in their study that wall strength increased at the rate of 400% with an increase of the mortar strength by 20%. It was also pointed out that the mortar acted homogeneously in masonry prisms when strong mortar was used and stress-induced damage was occurred along the joint (Mohammad *et al.* 2017). Upon examination of wall behaviour based on the use of using weak mortars, it was concluded that non-linear behavior began earlier, the walls were severely damaged and these conditions affected the axial stress of the wall (Garrity 2010, Amadio 1999). Finally, Vasconcelos and Lourenço (2009) have stated that the mechanical properties of mortars, especially existing in the bed joints, have an effect on deformability of masonry walls.

2.2 General principles of masonry wall

In masonry structures; vertical construction elements which transmit the loads from superstructure elements such as beam and slab to foundation, separate the spaces from each other in the buildings, surround the spaces and protect the building against external effects, are considered as wall. Walls lead to an increase in rigidity and energy absorption capacity and to a change of the load distribution in the plan and cross-section. It cannot be a reliable approach to explain the strength of the masonry in terms of strength of unit and mortar. In walls made of brittle materials, sudden collapses can take place under the load effect, and sudden cracks and fractures occur as soon as they exceed the load-bearing limit.

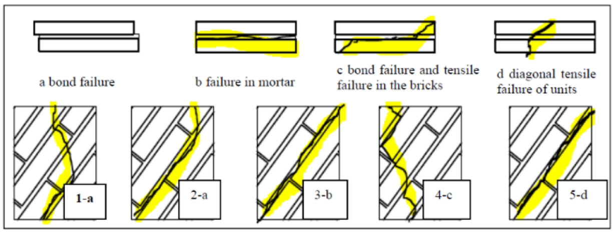


Fig. 1 Failure mechanisms for shear specimens (Van der Pluijim 1999, Schueremans 2001)

Masonry walls usually reach failure mechanism under out-of-plane effects with shearing effects. In walls with rather large cross-sections are unlikely to exhibit damages originating from normal stresses. Masonry walls commonly bear normal stresses at a very little rate of their capacities and normal stresses in the walls do not exceed 10-15% of the existing capacity. The shearing mechanism occurs owing to the fact that the mortar fails or due to adherence loss between the masonry unit and the mortar. Different failure modes can take place depending on the magnitude and direction of the normal stresses occurring in the wall (Fig. 1). Fig. 1(a) shows a bond failure mechanism while Fig. 3(b) shows mortar failure. In addition, Fig. 4(a) shows bond failure and tensile failure and Fig. 5(a) shows diagonal tensile failure of units.

Gumaste *et al.* (2007) examined the modulus of elasticity and compressive strength of the brick masonry walls under compression loads and they found that compressive strength of the masonry walls has ranged between 25 to 50% of compressive strength of the brick. They have also stated that one of the reasons of collapse of the masonry walls made with low-strength mortars was the weak zones existing at the brick-mortar interfaces. On the other hand, the lateral compression load in the bricks drops and consequently tensile rupture can be observed if shearing failure occurs due to the loss of adherence between brick and mortar. Even if one of the bricks in the wall is weak, this brick will probably be crushed due to the tensile rupture took place at other bricks. In the walls made with a high-strength mortar, however, the stresses existing in the head joint mortar can lead to shear failure at the underlying brick.

3. Experimental study

3.1 Materials

In this study, vertically perforated brick as masonry unit and two different types of mortar were used for wall production since they have been preferred commonly in production of conventional masonry walls. The bricks have dimensions of (length×width×height) 290×190×135 mm. NHL 3.5 class of natural hydraulic lime was used as binder in one of the mortars, while CEM IV/B (P) 32.5 R class cement was used as binder. The chemical composition and physical and mechanical properties of the binder materials are given in Table 1.

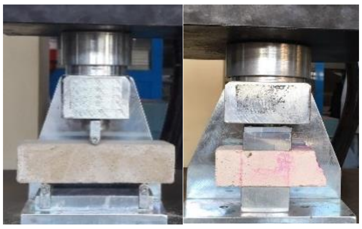
Table 1 Chemical composition, physical and mechanical properties of the binder materials

Components (weight %)	CEM IV/B (P) 32.5 R Cement	NHL 35 Natural Hydraulic Lime
SiO_2	35.9	11.4
Al_2O_3	9.8	0.4
Fe_2O_3	4.5	2.6
CaO	42.0	66.1
MgO	2.1	0.6
K_2O	0.4	0.1
Na_2O	0.1	-
$(SO_3)^{2-}$	2.0	-
Cl^-	0.02	-
Minor Additional Constituents	<0.4	1.6
Insoluble Residue	0.5	-
Loss on Ignition	2.3	17.2
Blaine Fineness (cm^2/g)	5185	2580
Specific Gravity	2.8	2.7
Standard (28-day) Compressive Strength (MPa)	36.4	3.7

Table 2 Mechanical properties of the materials

Material	Flexural Strength (MPa)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)
Brick	0.3	6.5	1425
Cement Mortar	2.1	12.5	16725
Lime Mortar	2.6	4.6	5585

In the production of mortars, the binder/aggregate ratio by weight was kept constant at 1/3 and water content was determined according to the consistency of fresh mortar. The consistency test was performed in accordance with EN 1015-3 (1999) and the required flow value of 175±10 mm in EN 1015-2 (1998) was provided for all mortar types. The standard CEN sand with a maximum aggregate size of 2 mm was used as a fine aggregate (EN 196-1). Prism specimens with dimensions of (length×width×height) 160×40×40 mm and cylinder specimens with dimensions of (diameter/height) 100/200 mm were prepared for both mortar types to determine the mechanical properties such as flexural strength and compressive strength, and also modulus of elasticity via LVDTs (linear variable differential transformer) mounted on the cylinder specimens (Fig. 2). The mortar specimens were cured, stored and tested at 28th days in accordance with corresponding standards (EN 196-1, EN 1015-11, EN 13286-43). In addition to these, the mechanical properties of the bricks were also experimentally investigated in accordance with ASTM C67 and the results of all tests are given in Table 2.



(a) Bending & compression tests on the mortar specimens (EN 196-1&1015-11)

(b) Compression test on the mortar specimen (EN 13286-43)

(c) Bending test on the brick specimen (ASTM C67)

Fig. 2 The mechanical tests

The compressive strength of the cement mortar was approximately three times greater than that of the lime mortar. However, the flexural strength of the cement mortar was lower than that of the lime mortar. The compressive strength of the brick was 92% higher than that of lime mortar, whereas 41% lower than that of the cement mortar. Examination of the deformational properties of the materials showed that the deformational capacity of the brick was the lowest in this ternary. Accordingly, combinations of the constructed masonry walls can be described as “weak mortar-strong brick” and “strong mortar-weak brick”.

3.2 Experimental setup

In this study, the test setup in Fig. 3 was established to determine the mechanical behaviour of the masonry walls under vertical and horizontal loading. Before the loading tests, the upper surface of the walls and also the lateral surface to which the horizontal load was applied had been capped with the gypsum mortar. The masonry walls were laid to a reinforced concrete footing with a height of 1.10 m. For the vertical loading, a hydraulic ram with a capacity of 2000 kN was used and uniform distribution of the load was provided via a steel plate placed under the cylinder rollers. In addition to this, there was another hydraulic ram with a capacity of 500 kN to provide horizontal loading. The masonry walls were subjected to a combination of vertical preloading and in-plane horizontal shear loading at 28th day after the production. In order to measure displacements occurred during the horizontal loading, the instrumentation including four LVDTs was fitted at different heights of the wall. The load measurements were taken by the load cells, and all load-displacement values were recorded simultaneously in a data acquisition system.

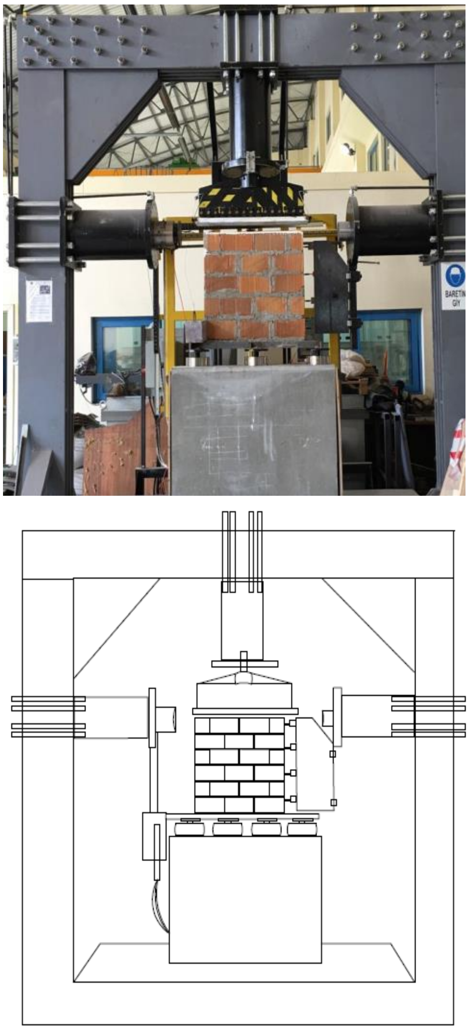


Fig. 3 Experimental setup

3.3 Walls

A total of 6 single-wythe, stretcher bond brick masonry walls were prepared; the cement mortar was used in three of them while lime mortar was used in the other three. In both ternaries, the bed joint thicknesses were 10, 20 and 30 mm whereas the head joint thicknesses were half of the bed joint thicknesses as 5, 10 and 15 mm, respectively (Table 3). The cement and lime mortar walls were labeled with the letters of (C) and (L), respectively; and the numbers after the letters also have indicated the bed joint thicknesses as 10, 20 and 30 mm.

Since the 28th-day compressive strengths of the cement and lime mortars were different, two different vertical (pre-compression) loads as 45 kN and 25 kN, respectively, were applied on the walls and these values were adapted from the results of previously carried out flat-jack tests on the original walls. Prior to the application of the lateral load, the test walls were subjected to these vertical loads in a form of uniformly distributed loading. Each increment of lateral loading was kept constant as 5 kN (ΔP=5 kN), and the load was enhanced gradually after recording the displacement values. The loading was resumed until the collapse occurred.

Table 3 Properties of the walls

No.	Wall Code	Mortar Type	Wall Dimensions (mm) Length×Width×Height	Joint Thickness (mm)	
				Bed Joint	Head Joint
1	C10	Cement	890×190×725	10	5
2	C20		890×190×755	20	10
3	C30		900×190×795	30	15
4	L10	Lime	880×190×725	10	5
5	L20		890×190×755	20	10
6	L30		900×190×795	30	15

C10

C20

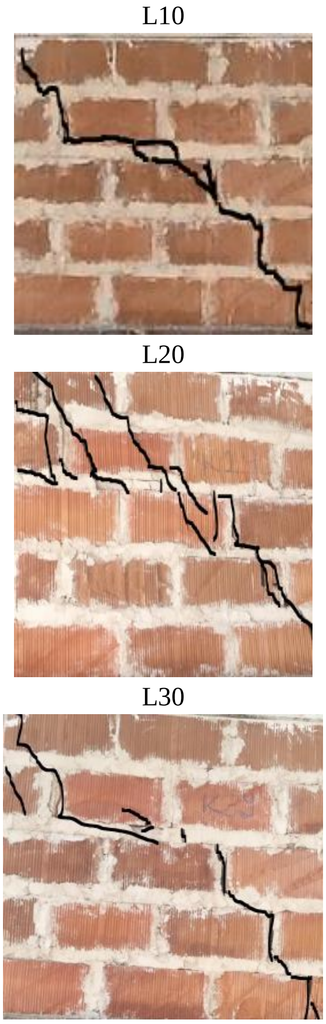
C30

Fig. 4 Damages of the cement mortar walls

4. Results and discussion

4.1 Cement mortar walls

As seen in Fig. 4, a main diagonal crack was observed extending from the top row brick, to which the lateral load was applied, to the bottom row. However, several cracks formed on the walls apart from this main crack. In general manner, the damages initiated from the brick surface and proceeded through joint surfaces in the form of capillary crack. The damages that occurred in the bricks were more obvious due to the fact that the compressive strength of the



L10

L20

L30

Fig. 5 Damages of the lime mortar walls

mortar was higher. It must be noted that spalling-type damages also occurred in the bricks of the C10 and C20 walls. The strength of the mortar used was nearly 31% more than that of the brick. The distinct disintegration was observed at the brick-mortar interfaces of the C10 wall and there were more obvious damages in the masonry units on this wall than on the other walls. Another noteworthy point was that the mortar and brick acted together in the wall of C30 and a main crack in the form of a significant line occurred during the loading. In the lower left zone (the lateral load side) of the walls, tensile stresses formed at the supporting zone.

4.2 Lime mortar walls

At the end of the loading, the main diagonal crack occurred on all three walls (Fig. 5). The tensile stresses formed at the bed joints, and under the vertical load, distinct segregations at the head joints were clearly observed. Since the strength of the mortar was close to the strength of brick, the brick acted in conjunction with the mortar under the loads. In general, at the left (the lateral load side) bottom bricks, the tensile damages occurred whereas the brick sections that adjacent to the head joints were also damaged.

Table 4 The test results

Wall Code	Δu (mm)	Δy (mm)	μ	Energy Dissipation Capacity (kNmm)	Vertical Load (kN)	Ultimate Horizontal Load (kN)
C10	34.12	28.15	1.21	2325.41	45	92.53
C20	29.81	22.85	1.30	1722.03	45	107.16
C30	32.67	17.70	1.85	1824.57	45	95.44
L10	35.96	23.61	1.52	786.72	25	42.02
L20	24.99	12.08	2.07	703.11	25	49.07
L30	52.27	30.70	1.70	1263.54	25	42.96
C_{avg}	32.20	22.90	1.45	1957.33	45	98.37
L_{avg}	37.74	22.13	1.76	917.79	25	44.68

While the damage was along a single diagonal line on the L10 wall, additional capillary damages were observed on the other two walls. The failure mechanism occur on the walls as a result of the shear forces.

4.3 Discussion of the test results

The mechanical behaviour of the walls which were subjected to the in-plane loading was investigated by the damage analyses and they were also examined for their ductility via the recorded deformations Table 4). The ductility (μ) was calculated as the ratio of the displacement at the ultimate load (Δu) to the displacement at the yield load (Δy), Eq. (1), while the yield load is accepted as the ultimate lateral load. Finally, the area under load-displacement curve of each wall was considered as the energy dissipation capacity.

$$\mu = \frac{\Delta u}{\Delta y} \tag{1}$$

According to the test data given above, the ductilities of the cement mortar walls were commonly lower than that of the lime mortar walls. The highest ductility was found for the L20 wall as 2.07, however, it was less than 2.0 for the other walls. The energy dissipation capacities of the walls varied depending on the strength of the employed mortar, and the energy capacity of the lime mortar walls was approximately half of the cement mortar walls considering the average values.

Examination of the brick masonry walls under the in-plane loads pointed to the fact that both type of mortar and joint thickness mainly affects the lateral load capacity of the walls. According to the test results, for each joint thickness, the lateral load capacity of the cement mortar walls was approximately twice that of the lime mortar walls (Fig. 6). In term of the bed joint thicknesses, the walls with the bed joint thickness of 20 mm, whether made with cement mortar or lime mortar, were found to have higher lateral load capacity, and this was followed by the walls with the bed joint thicknesses of 30 mm (Fig. 7). The highest lateral load capacity was 107.16 kN in the C20 wall while the lowest ones were observed in the L30 and L10 walls as 42.96 and 42.02 kN, respectively.

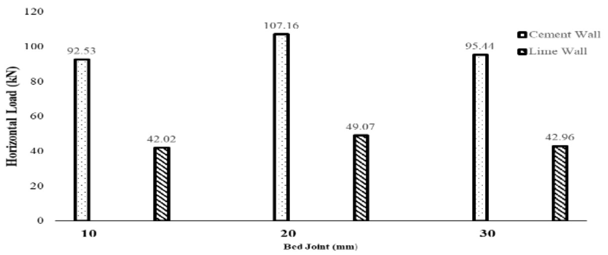


Fig. 6 Relation between the bed joint thickness and the lateral load capacity of the walls

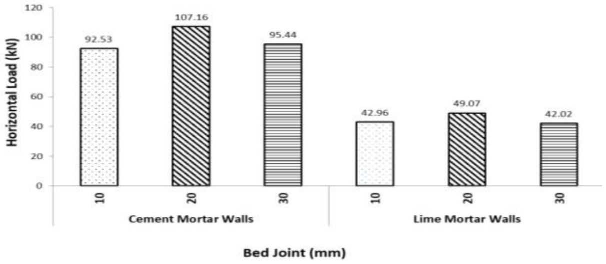


Fig. 7 Relation between the mortar type and the lateral load capacity of the walls

The displacements in the cement mortar walls were up to 32.67 mm whereas they were as high as 52.67 mm in the lime mortar walls. When the test results were evaluated with respect to the bed joint thickness, the lowest displacements were obtained in the 20 mm-walls. As seen in Fig. 8, the walls failed to conserve their energy when the ultimate load point was exceeded. Once C10 wall reached the ultimate load, no longer considerable displacement occurred.

5. Conclusions

This study was carried out to assess the effect of joint thickness and type of mortar on the performance of the brick masonry walls and following conclusions can be drawn from the results:

- The walls constructed with the cement mortar exhibited high-strength ductile behavior and kept load bearing structure subsequent to the plastic deformation. The walls constructed with the lime mortar collapsed before reaching the strength levels obtained on the cement mortar walls.
- The main diagonal crack occurred in the walls. Apart from this, the bricks had a higher amount of damage in the cement mortar walls which were comprised of “strong mortar-weak brick” combination. The capillary damages on surfaces of the bricks and ruptures at the brick-mortar interfaces were also observed in these walls. However, the damages initiated at and proceeded through the joints in the lime mortar walls.
- Since the vertically perforated bricks were employed in the construction of the walls, a quantity of the mortar leaked into the brick perforations. This case caused an increase in the weight of the walls and led them to exhibit rigid behaviour, consequently.

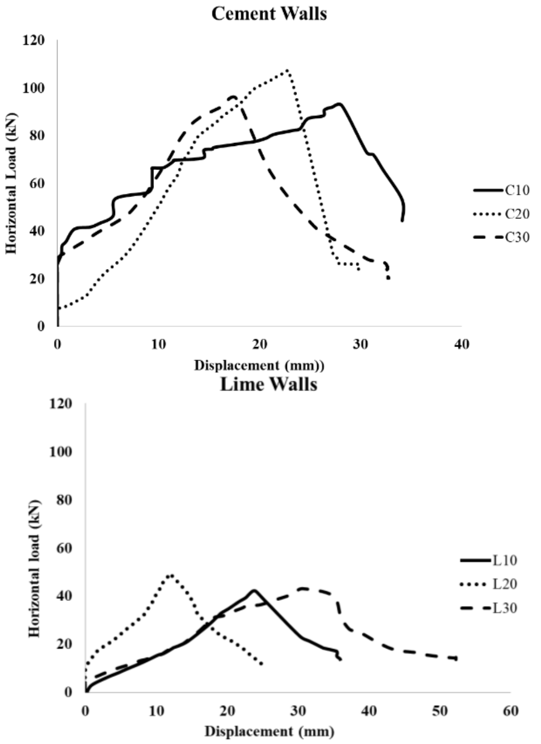


Fig. 8 Load-displacement curves of the walls

- The average lateral load capacity of the cement mortar walls was 121% higher than that of the lime mortar walls.
- As the strength of the brick was relatively lower than the cement mortar, the integrity of the mortar and unit failed and they could not be able to act together under the loading. Therefore, the spalling-type damages occurred in the bricks of the cement mortar walls.
- The ductility of the lime mortar walls was, on average 21% higher than the ductility of the cement mortar walls.
- The energy dissipation capacity in the cement mortar walls was, on average, twice which of the lime mortar walls. For each type of mortar, the energy dissipation capacity of the walls with the bed joint thickness of 20 mm was found to be lowest.
- In terms of the bed joint thickness, independently of the mortar type, the walls with a joint thickness of 20 mm had the highest lateral load capacity, although they had the lowest energy dissipation capacity. In a view of the adherence between mortar and unit, the walls with a bed joint thickness of 20 mm acted more effectively under the in-plane loading. The lateral load capacities of the walls with a joint thickness of 10 mm and 30 mm were close to each other, but a larger scale of damage was observed in the walls with a joint thickness of 10 mm.

Upon examination of the role of mortar type and joint thickness on understanding the mechanical behavior of the brick masonry walls, the effect of mortar thickness and strength of the materials on overall strength and mechanical properties of the wall have been investigate. As a result, thinner mortar thickness decrease the cohesion between mortar and masonry unit causes damages on joints. On the other hand, significant damage has occurred on masonry bricks if the mortar strength is higher.

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