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The Effect of Material Type and Joint Thickness on Wall Behavior in Conventional Masonry Walls

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Abstract
Masonry walls are systems that are typically preferred in conventional structures. The complex structure of masonry walls makes it harder to determine wall behavior. However, wall behavior is affected by the types of material used in conventional walls and the way joints inter-act with masonry units. This study aims at investigating the effect of joint thickness and materials factor on wall performance. Materials used in historical and conventional structures are preferred to accomplish this. The study involved hollow bricks, clay bricks, NHL 3.5 and CEM 32.5. Three different joint thicknesses were used to set up 12 different combinations. Damage estimation of the wall was carried out through moving live load under constant vertical load. Different mate-rials of different joint thicknesses and mechanical properties were studied for their effects on the wall. The results indicated that a joint thickness of 20 mm preferred in wall production was more convenient. The strength of walls produced from durable material was found to be higher.

Keywords
Conventional wall, joint thickness, mortar, masonry unit, lateral and vertical load.
1. INTRODUCTION

Conventional walls serve as carrier or divider in structures. These walls are designed to bear the vertical load inside the structure (Venkatesh 2010). Masonry walls are composite members made up of joints and units. Performance of elements consisting of members of different properties is a complex system. The effect of the characteristic properties of the material used in walls on wall performance was investigated through literature review. It was pointed out that joints affect the load-bearing capacity and strength of the wall depending on their relation to the masonry unit (Stawiski and Kania 2013; Akhaveissy 2012 and Shevaldykin 2003). In-plane forces moving in parallel with the wall plane inside the structure resist the bond between the bricks and mortar. This is how the damage on mortar beds and connection points is detected (Mojsilovic and Stewart 2015).

Since the materials used in the construction of the walls will affect wall behavior, properties of the materials used are determined by mechanical experiments (Ravula and Subramaniam, 2017; Gesualdo and Monaco 2015). Special mortars are prepared for the joints in masonry walls. The strength of mortars, on the other hand, depends on the granulometry, workmanship of the material used and on the water/cement ratio. In walls made of brittle materials, sudden collapses take place under the load effect and sudden cracks and breaks occur as soon as they exceed the bearing limit. In an experimental study in 2017 Slivinskasa et al. experimented on mortar samples in order to investigate the effects of compressive strength of mortar to that of the wall. Other studies aiming to find out the mechanical properties of the mortar emphasized that it was necessary to perform compressive strength, elasticity modulus and tensile tests (Slivinskasa et al. 2016). It was observed that the increase or decrease in the compressive strengths of masonry walls caused changes to the strengths of masonry wall. The mortar acts homogeneously in masonry prisms constructed with strong mortar and damage attributable to strain occurs along the joint (Mohammad et al. 2017). Characteristic properties of the mortar especially in the bed joints affect the deformability of the wall (Vasconcelos and Lourenco 2009). The elasticity modulus is to be calculated in order to assess the properties of deformation in the bed joint. On the contact area of the mortar, the elasticity modulus of the mortar is dependent on the unit height of the wall and on the joint thickness (Zavalis et al. 2014). Selecting joints with different thicknesses and whether the brick size is greater or less than the joint thickness affect the strength of the brick wall. Changes in the surface area lead to changes in bonding strength. The adherence between the masonry unit and the mortar used in wall production affect wall behavior. The bond strength between the brick and the mortar is affected by several factors including the types of mortar, surface properties, its form and size, water absorption capacity of the brick, the cure method and workmanship (Thamboo 2013; Reddy and
Vyas 2008; Pavia and Hanley 2010). In a 2017 study Singh and Munjal used a concrete and clay bricks with different surface types. As the concrete brick had excessively porous surface and the surface area was filled, the strength was lower.

Gumaste et al. 2007 examined the elasticity modulus and compressive strengths of the masonry walls under compression load. They found that the masonry compressive strength can be 25% to 50% of the brick compressive strength. They also stated that another reason of collapse in masonry walls with low-strength mortars is the weakening that takes place on the brick/mortar surfaces. The uncertainty between brick/mortar surfaces also cause uncertainty in the masonry. If shifting/shearing yield occurs due to the loss of adherence between brick and mortar, the lateral compression value in the bricks drops and tensile rupture will occur. If even one of the bricks in the wall is weak, this brick can be crushed due to the tensile rupture in other bricks. In the walls made with a mortar having high compressive strength, however, the strain occurring in vertical mortar joints can lead to shear yields in the brick below. Masonry walls usually reach force depletion under out-of-plane effects, seismic movements and shear effects. Walls with big cross sections are unlikely to exhibit damage types attributable to normal strains. In general, masonry walls bear normal strain at a very little proportion of their capacities. Normal strain on the walls may not exceed 10-15% of the existing capacity. The binding mortar reaching force depletion or the adherence between the masonry unit and the binder becomes zero will lead to a shear mechanism. In some of these mechanisms, the masonry unit reaches force depletion earlier than the joint does. Moreover, different failure modes occur depending on the magnitude and direction of the shear and normal strain applied on the wall (Schueremans, L. 2001; Yanez et al. 2004 a; Ahmad 2017).

The study aimed at investigating the effects of masonry units and joints used for the bonding of conventional walls on any potential damage on the wall. For that purpose, an experimental study was carried out using prototype walls produced in the laboratory. The damage was analyzed and interpreted.

2 EXPERIMENTAL STUDY

2.1 Materials Used in Experimental Study

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 clay have dimensions of (length x width x height) 290 x 190 x 135 mm and hollow bricks 190 x 90x 50 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

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). The mixture proportions of the mortar is given in Table 2.

**Table 2.** Mixture Proportions

Mechanical tests were performed on mortar samples and masonry units. Sample sizes for the tests to be performed on mortar samples φ100x200 mm cylinder and a 40x40x160 mm prism. Mechanical tests were performed after the produced samples were strengthened for 28 days. Visuals of the test are given in Figure 1

**Figure 1.** Mechanical Test

Test analysis results are given in Table 3. Strengths of hollow bricks and clay bricks are much closer to one another (6.38-6.05 MPa). However, the elasticity modulus of hollow bricks is 288% higher than that of the clay bricks. Also, the elasticity of the CEM 32.5 mortar is 300% higher than NHL 3.5 lime mortar. Flexural strengths of mortars are also close to one another (2.12-2.59 MPa). Flexural strength of hollow bricks is 0.3 MPa while it is 0.8 MPa for clay bricks.

**Table 3.** Mechanical test results for the materials used in the wall

### 2.2. Masonry Wall Testing System

The walls in this study were subjected to repulsion analysis in the laboratories of Yıldız Technical University. The test system used in the study is given in Figure 2. 4 LVDTs were placed on the device to measure the displacements in different parts of the wall. The LVDT was prevented from reaching the top and bottom of the wall when placing it. It was possible to install 4 LVDTs in the assembly. The distance between LVDTs is 150 mm. In different wall systems, it corresponds to both grout and brick. Wall performance is assessed through the graphs showing the strain and displacement of the damage caused by the mechanical impact (Bennett et al. 1997 and Barbosa 2010). The displacements on these walls are to be characterized (Furtado et al. 2015).

**Figure 2.** Testing Apparatus
Twelve different types of wall models were produced for the experimental study. CEM 32.5 cement mortar and NHL 3.5 lime mortar along with hollow and clay bricks were used in the production of the walls. When producing walls, the horizontal joint thicknesses were set as 10, 20, 30 mm and vertical joint thicknesses as half that of the horizontal joint (10, 10, 15 mm). N1Y and C1Y symbolic N: Lime, C: Cement; 1, 2, 3: Horizontal joint thickness; Y: Hollow Bricks, H; Clay Bricks. Forms of joints and wall classifications are given in Table 4. Lining was performed on the wall surfaces to which horizontal and vertical load will be applied. A vertical load of 45 kN was applied to the walls constructed with cement mortars, whereas a vertical load of 25 kN was applied to the walls constructed with lime mortars with lower compressive strength. Horizontal load value was primarily applied as 5 kN and then gradually increased (ΔP=5 kN). Test times ranged between 15-25 minutes.

2.4. Wall Test Analyses

2.4.1. Walls Produced with Hollow Bricks

Walls were produced in laboratories in single rows in a similar way to conventional masonry walls. After the loads were applied to the walls, displacements were recorded in 4 different areas with the help of the LVDT. Based on these readings, load-displacement graphs were created. Post-test status and displacement graphs are given in Figure 3, Figure 4 and Figure 5.

Figure 3. CY-NY Wall Damage

Due to the porous nature of hollow bricks, pores were filled with mortar. Additional load was applied to the weight of the wall. And this enabled the wall to have a more rigid performance. Overall, damage occurred on masonry unit surfaces along with the damage on the joints and in some areas, bursting was observed on masonry unit surfaces. The strength of CEM IV 32.5 R mortar used in the joints of CY walls was 12.5 MPa whereas the compressive strength of the hollow bricks was 6.38 MPa. As the strength of the mortar produced with CEM cement was higher, the CEM-standard wall was stronger. As the mortar strength was higher than the brick strength, the initial damage occurred in the brick and this was then followed by the damage in the joints. Substantial damage was observed in the bricks at the end of loading (Figure 4.).

Figure 4. CY Load-Displacement Graph

Flaking was observed in the brick gaps and surfaces where there was lateral repulsion. Cracking was observed in the form of sharp breaks. In the overall view, there was diagonal damage along with some additional damage. While the compressive strength of NHL 3.5 was 4.59 MPa, it was 6.38 MPa for the hollow bricks. The proximity of these strengths allowed the wall and the joint to work together. And the damage was generally diagonal.
However, additional damage was observed in areas with lateral loading. As shown in Figure 5, chipping generally occurred in the joints.

**Figure 5. NY Load-Displacement Graph**

More noticeable damage occurred in walls with joint thicknesses of 10mm both on masonry units and the joints. As the joint were thin, the walls failed to perform as a whole. The displacement graph showed that the damage moved to the elasto-plastic area. While 20 mm walls had higher strength, it was found that the 30mm walls remained between 10mm and 20mm walls. LVDTs were placed in 4 different parts of the walls. The highest level of displacement was found on the same level as the lateral load. Apart from lateral loading, crushing failures occurred due to the vertical load.

As the joint thickness increased, the shortenings on the surface sharpened and when the joint thickness was lower, more surface damage was observed. Prior to the test, 4 LVDTs were placed at regular intervals from the bottom to the top of the samples in order to determine the displacements and based on these displacements, load-displacement curves were drawn.

Strengths varied less in the samples of the NY group. However, the highest strength was observed in N2Y and, as shown indicated by the displacement curves, the shortenings were brittle.

**2.4.2. Walls Produced with Clay Bricks**

Clay bricks are commonly used in conventional and historical structures. Therefore, twelve different types of wall model was produced with clay bricks similar to the walls produced with hollow bricks. The damage and load-displacement graphs are given in Figure 6, Figure 7 and Figure 8.

**Figure 6. CY-NY Wall Damages**

While the strengths of the clay bricks is close to that of the hollow bricks, their elasticity modulus were too low. Due to the strength of the mortar being high and the wall being weak, we observed diagonal damage on the walls along with other damage in parallel to the diagonal damage line. The walls were pulled down after the test load was removed. The thick joints in the samples performed as brick walls. Cracks occurred in the bricks. The load-displacement values of all the samples are close to each other. After having been removed from the testing apparatus, the walls were completely pulled down. Substantial damage occurred due to single-row bonding and low adherence between the masonry unit and the joint in the wall.

**Figure 7. CH Load-Displacement Graph**

**Figure 8. NH Load-Displacement Graph**
The bricks also had full cracks in some parts. After the production of the C1H wall was completed, the wall could not remain in balance. After the experiment, the wall and the mortar were completely separated from the test system. The wall was completely destroyed. The strength of NHL 3.5 cement mortar was closer to the strength of the clay brick. The strength of these walls were even lower. Cracks occurred on the clay bricks in the lower part of the wall. The wall with joint thicknesses of 20 mm were found to be stronger when compared with the other two samples. No significant difference was observed between the strengths of group NH walls. N2H walls with 20 mm joints had the highest strength rate with 14.41 kN which implies that the strengths did not very much. Also, the load-displacement rates of the samples were close to one another.

2.5. Analysis and Comparison of Test Results

Materials were initially tested as part of the study. Primarily, different mortar types were used in the walls bonded with hollow and clay bricks. The difference between the strengths were examined in order to determine the strength by mortar type and there was an almost 50% difference in wall strength. This difference is shown in the graphs by an intermediary line in Figure 9.

Figure 9. Compared Load and displacement

The fact that the hollow bricks had higher mechanical strength than clay bricks led to the higher strength in the composite panels with the CEM-standard cement. The examination of displacements indicated that the displacement went above 50 mm in CY-NY coalition.

Wall strengths by joint thickness are shown in Table 4. When deciding on the joint thickness in the walls, the dimensions commonly preferred in conventional walls were selected. As these walls are bonded irregularly, they generally do not have a single type of wall.

Table 4. Horizontal Load-Displacement by Joint

Examination of joint thicknesses indicate that the strengths were up to 107.16 kN in 20 mm walls. The strengths of 10 mm and 30 mm walls were found to be close to one another. The CY wall strength was the lowest with 92.53 kN and the lowest rate in KH walls was 12.08 kN (Figure 10).

Figure 10. Horizontal Load by Joint Thickness

3. CONCLUSIONS

This study aimed at investigating the effects of joint thickness and materials used in conventional walls. For this purpose, the walls were bonded with hollow and clay bricks using CEM-standard 32.5/NHL 3.5 mortar. However,
another parameter, that is the joint thickness, was altered. The materials were put to mechanical tests. Tests were applied on the walls using horizontal and vertical loads. Damage estimation was carried out under dynamic loads. Load-displacement graph was also recorded. These examinations indicated that:

- Although the strengths of the masonry units were close, the elasticity modulus was found to be approximately three times higher in hollow bricks. The strength and elasticity modulus of CEM-standard 32.5 mortar used in the joint was higher than that of NHL 3.5 The mechanical strength of the materials was found to have an impact on wall strength.

- The strength of the walls produced with CEM-standard 32.5 cement was approximately twice the average strength of the walls produced with NHL 3.5 lime mortar (66.85kN/28.83 kN). While the strength of the cement was three times higher than that of the lime mortar, this was twice higher in the walls. This pointed to the effects of the brick strength and the co-performance of bricks and joints.

- The manner in which the walls were bonded affected the wall strength. It was found that since the width of the clay bricks were lower and they were bonded in a single row, some damage occurred.

- The average of the walls with the lowest strength was found in the walls produced with clay bricks (23.53kN). This was because clay bricks had low elasticity modulus. Furthermore, clay bricks did not work especially in the walls with thin (10mm) and thick (30 mm) joints.

- The increase and decrease in the joint thickness affected the occurrence of damage. While we had similar results in 10 mm and 30 mm joints, higher strength was achieved in 20 mm joints.

- The width, smoothness of the surface of masonry unit and its bond with the joint affect its strength and friction. The narrow space in clay bricks and the joint thickness which was close to the norm of the clay brick reduced the bond in between. While the use of strong mortar improved wall strength, it caused the brick to disintegrate before the joint under shearing force.

Loss of adherence was observed in joint surfaces due to shear. There was also chipping in connection points. The strength of the material used in conventional walls affected the wall. The strengths of the joint and the masonry unit being close to one another also affects the overall performance of the wall. The joint thickness also had an impact on the wall balance. It also revealed the shear and friction effect between the masonry unit and the joints.

**Acknowledgments**

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References


Venkatesh S.V. 2010. Strenght characteristics of brick masonry wall before and after encasing with ferro cement. 8-th International Masonry Conference 2010 in Dresden.


Figure 1. Mechanical Test

Figure 2. Testing Apparatus

Figure 3. CY-NY Wall Damages

Figure 4. CY Load-Displacement Graph

Figure 5. NY Load-Displacement Graph

Figure 6. CH-NH Wall Damages

Figure 7. CH Load-Displacement Graph

Figure 8. NH Load-Displacement Graph

Figure 9. Compared Load and displacement

Figure 10. Horizontal Load by Joint
Table 1. Chemical composition, physical and mechanical properties of the binder materials

<table>
<thead>
<tr>
<th>Components (weight %)</th>
<th>CEM IV/B (P) 32.5 R Cement</th>
<th>NHL 3.5 Natural Hydraulic Lime</th>
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<tr>
<td>SiO2</td>
<td>35.9</td>
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<td>Al2O3</td>
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<td>Fe2O3</td>
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<td>MgO</td>
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<td>(SO3)2-</td>
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<td>Cl-</td>
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<td>Minor Additional Constituents</td>
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<td>Specific Gravity</td>
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<td>Standard (28-day) Compressive Strength (MPa)</td>
<td>36.4</td>
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Table 2. Mixture Proportions

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<th>S:C:W</th>
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<td>NHL 3.5 Natural Hydraulic Lime</td>
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Table 3. Mechanical test results for the materials used in the wall

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<th>Flexural Strength (MPa)</th>
<th>Elasticity Modulus (MPa)</th>
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<td>Hollow Bricks (Y)</td>
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<td>Clay Bricks (H)</td>
<td>6.05</td>
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<tr>
<td>CEM 32.5 (C)</td>
<td>12.5</td>
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<td>NHL 3.5 (N)</td>
<td>4.59</td>
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Table 4. Horizontal Load-Displacement by Joint

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<th>Ultimate Horizontal Load (kN)</th>
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<td>C10</td>
<td>34.12</td>
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<td>C20</td>
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<td>C30</td>
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<tr>
<td>Navg</td>
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<td>12.97</td>
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<td>Cem W. Averga</td>
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<tr>
<td>Lime Wall Averga</td>
<td>32.29</td>
<td>28.83</td>
</tr>
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</table>
**Figure 1.** Mechanical Test

**Figure 2.** Testing Apparatus

**Figure 3.** CY-NY Wall Damages

C1Y  
C2Y  
C3Y
Figure 4. CY Load-Displacement Graph

Figure 5. NY Load-Displacement Graph
Figure 6. CH-NH Wall Damages

Figure 7. CH Load-Displacement Graph

- a. C1H- Load Displacement
- b. C2H- Load Displacement
- c. C3H- Load Displacement

Figure 8. NH Load-Displacement Graph

- a. N1H- Load Displacement
- b. N2H- Load Displacement
- c. N3H- Load Displacement
Figure 9. Compared Load and displacement

a. CY-NY
b. CH-NH

Figure 10. Horizontal Load by Joint