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Scaling unreinforced masonry structures with hollow-core clay bricks for laboratory testing

S. Petry[1], K. Beyer[1]

[1] Earthquake Engineering and Structural Dynamics Laboratory (EESD), School of Architecture, Civil and Environmental Engineering (ENAC), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Abstract. For a shake table test on a four-storey structure with both unreinforced hollow-core brick masonry (URM) walls and reinforced concrete (RC) walls, the test unit had to be constructed at half-scale. While past experience showed that testing RC structural elements at reduced scale leads to similar results as full-scale tests, a literature review on tests of scaled masonry revealed that scaling of masonry was more challenging. For instance, several researchers reported that the scaled masonry was stronger but less stiff than the full-scale masonry. However, previous work concentrated on the scaling of solid clay material and not all conclusions can be translated directly to masonry with modern hollow-core clay bricks. As a preparation to the shake table test, an extensive test program on full- and half-scale hollow-core brick masonry was conducted. This paper presents results of material tests that were conducted to develop a half-scale masonry that matched the full-scale masonry best. Our results are compared to previous investigations and the differences between scaling of masonry with solid and hollow-core bricks are discussed.

Keywords: Seismic testing; Scaling effects; Hollow-core clay bricks; Masonry properties;

1 INTRODUCTION

Scaling of solid brick masonry has been the subject of several past research projects, e.g. (Hendry & Murthy, 1965; Egermann, et al., 1991; Tomaževič , et al., 1990; Tomaževič & Velechovsky, 1992; Mohammed, 2006; Mohammed & Hughes, 2010). However, owing to their good insulation properties and the reduced clay consumption, hollow-core clay bricks instead of solid clay bricks are nowadays used for masonry construction in Europe. Although some recommendations for the scaling of solid clay bricks are available, not all conclusions can be directly applied to hollow-core masonry. For instance, several researchers reported the strength of solid bricks to increase when they were cut before the burning, e.g. (Egermann, et al., 1991). For hollow-core bricks we found, however, that this phenomenon can be eliminated by scaling the number of web and shells while keeping their thickness constant. The aim of this article is therefore to give an overview on the effects of scaling when dealing with modern hollow-core clay brick masonry with fully mortared bed and head joints. The paper starts with a brief state of the art review on the scaling of masonry. As outlined above, the majority of existing works addressed the scaling of solid brick masonry. For this reason, the literature review includes also a discussion on the differences between solid and hollow-core clay brick masonry. In the second part, a comparison of test series on hollow-core clay brick masonry at full- and half-scale is presented. The test results are discussed with respect to the scaling but also with respect to existing experiments on full- and small-scale solid brick masonry. The paper concludes with recommendations on the scaling of hollow-core clay brick masonry.

2 LITERATURE REVIEW ON THE SCALING OF MASONRY

2.1 Scaling effects in solid clay brick masonry

Scaling of masonry has been the subject of several research projects. The most recent detailed experimental study is presented in (Mohammed, 2006; Mohammed & Hughes, 2010) which comprises different standardised material tests on solid clay brick masonry at different scales (1/6-, 1/4-, 1/2- and full-scale). When comparing the results of compression tests, similar failure patterns was observed for the specimens at all scales. Despite this, the compressive strength was significantly higher for the masonry panels tested at 1/6- and 1/4-scale than the compressive strength of the full-scale masonry (Mohammed & Hughes, 2010). The 1/2-scale masonry developed a compressive strength similar to the full-scale masonry. Hendry and Murthy (1965) had also observed that the compressive strength increased for small scale masonry. However, the increase in strength was attributed to the following two phenomena: (1) the burning of a reduced-scale brick can increase the strength of the brick (Egermann, et al., 1991) and (2) the scaling of the mortar joint affects the percentage of water sucked from the mortar by the brick during the curing of the mortar and thus the strength of the mortar joint, e.g. (Drysdale & Hamid, 2008; Mohammed & Hughes, 2010). Mohammed (2006) reported that the brick unit at 1/6- and 1/4-scale was indeed slightly stronger in compression. Nevertheless, the compressive strength between the bricks at different scales varied less than the strength of the masonry assemblage and it was therefore concluded that both phenomena contribute to the difference in strength between full-scale and small-scale masonry. Other researchers reported the scaling to affect the elastic stiffness due to the different overburden stress during construction e.g. (Hendry & Murthy, 1965; Egermann, et al., 1991). To avoid this effect, Mohammed and Hughes (2010) built their specimens horizontally and obtained from compression tests as a result similar stiffnesses in the elastic range. While such a construction practice is feasible when conducting material tests on small specimens, it is impossible to construct entire buildings in a horizontal position. Such an approach is therefore valid for investigating the effect of different parameters on the scaling but cannot be part of recommendations for the construction of scaled test units for shake table tests. Furthermore, a slight increase of the post peak deformation capacity for reduced scale specimen when tested in compression is noticed in (Mohammed & Hughes, 2010).

When comparing the results of the shear tests performed on masonry triplets at the four different scales Mohammed and Hughes (2010) observed a large variation in initial shear strength and friction coefficient. We found from comparisons of bricks that were wire-cut before the burning with bricks that were cut with a saw after the burning significant differences in their behaviour: When the model bricks were cut after the burning, the outer faces were very smooth in comparison to the prototype brick, which was wire-cut before the burning. However, when we neglect the full-scale bricks and compare hence only the model bricks among each other, which were all cut after the burning, we can observe that the initial shear strength increases and the coefficient of friction decreases with reducing scale. The results of the diagonal tensile tests, on the contrary, revealed no clear trend with scaling factor and a similar failure pattern was observed for all test specimens (Mohammed & Hughes, 2010).

In addition, in (Mohammed, 2006; Mohammed & Hughes, 2010) flexural bending tests parallel and perpendicular to the bed joints and bond tests were presented. For most three tests no clear trends were observed or the test results were distorted by the known differences in brick surface roughness and mortar strength. Only for the flexural bending test perpendicular to the bed joints a clear trend towards a decrease of strength with smaller scales was observed.

2.2 Particularities when using hollow-core clay bricks

In addition to the general properties of scaled bricks, hollow-core clay units feature further specific properties that need also to be considered when developing a reduced-scale masonry such as for instance the anisotropic behaviour of perforated bricks. In Tomaževič et al. (1990; 1992) a significant increase in compressive strength parallel to the perforation is observed. In general the vertical compressive strength is mainly influenced by the net area of the bricks and not by the shape of the perforation, e.g. (Ganz, 1985). Tomaževič et al. (1990; 1992) does not indicate the void ratio of model and prototype brick and therefore does not allow to draw conclusions on the effect of the scaling on the hollow-core brick strength.

In case of seismic loading, masonry elements are subjected to loading in the horizontal direction and hence, also the horizontal in-plane properties, such as the horizontal compressive strength of the bricks should match between prototype and model brick. While the shape of the perforation is not decisive for the vertical stiffness and strength of the brick, it has a significant influence on the horizontal strength and stiffness. Lourenço et al. (2010) found that bricks with continuous and straight webs and shells in the in-plane direction (mostly the case for a rectangular perforation) were significantly stronger when subjected to horizontal in-plane compression than bricks with rice-shaped holes. For this reason, we concluded that the shape of the holes should be maintained when scaling the bricks. In (Petry & Beyer, 2012), we further showed that – if web and shell thickness are approximately equal in prototype and model brick and if both bricks are fabricated using the same burning procedure – the strength of prototype and model brick are similar.

In addition to the brick itself, the perforation affects also the brick mortar interface. Especially when subjected to shear, the load transfer mechanism at the mortar-brick interface depends on the perforation since it controls the size of the mortar pillars that reach into the brick. While for solid bricks the shear strength is dominated by the cohesion and friction between mortar and brick, several researchers reported that for hollow-core clay brick masonry the shearing off of the mortar pillar is the most important shear transfer mechanism of the brick-mortar interface, e.g. (Gabor, et al., 2006).

3 INVESTIGATED MASONRY AT FULL- AND HALF-SCALE

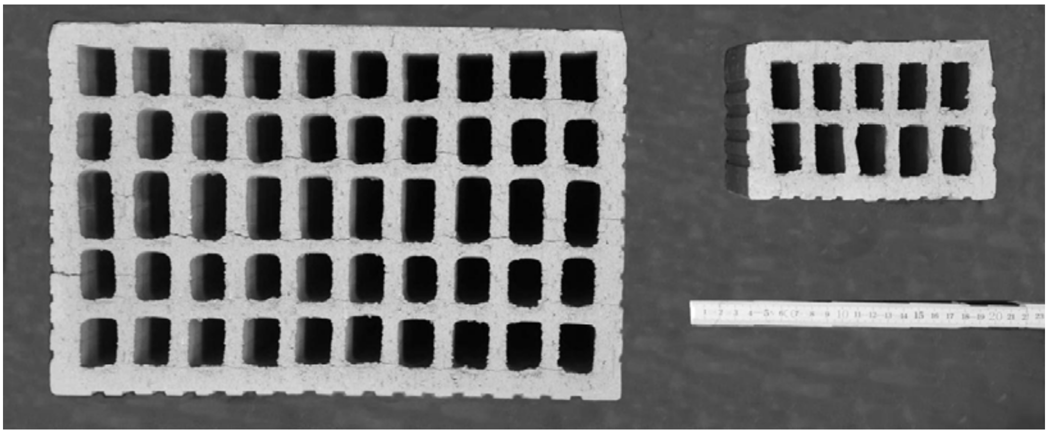

Figure 1. Final prototype and model brick: Model brick type M3, cut out from ME 10 without tongue and groove and Prototype brick P3, modified ME 20 without tongue and groove from Morandi Frères SA, Switzerland (Petry & Beyer, 2012).

The objective of this project is to develop a half-scale masonry with hollow-core bricks that has very similar properties as the corresponding full-scale masonry. Based on the recommendations found in the literature and the results of own investigations, recommendations for the scaling of hollow-core bricks were identified and summarized in (Petry & Beyer, 2012). In order to minimize the scaling effects on masonry we tried to follow all of these as much as feasible. For instance, the web and shell thicknesses were kept identical for both bricks and a similar ratio of the sum of the web and shell thicknesses to the total width of the bricks was ensured through reducing the number of webs. The chosen half- and full-scale brick are shown in Figure 1 and the mechanical properties of both bricks are summarized in Table 1. Small differences remained with regard to the void ratio and effective width, which resulted also in a slightly stronger half-scale brick perpendicular to the perforation.

The mortar joints of both masonries were fully filled using the cement-based mortar WEBER MUR MAXIT 920. Previous researcher noted that the scaling of the mortar joint thickness affects the mortar properties and thus, the masonry properties, e.g. (Drysdale & Hamid, 2008). In the literature some recommendations are given on how to clear this scaling effect, for instance, Brocken et al. (1998) recommend pre-wetting of the bricks and Green et al. (1999) recommend adding water retention products to the mortar. Nevertheless, a series of compression tests on masonry triplets built at different scales showed that prewetting the bricks or adding water retention products to the mortar for half-scale masonry resulted only in a slightly improved match of the masonry compressive strength: independent of the applied method, the triplets built at half-scale were significantly stronger than the triplets built at full-scale. Thus, it was decided to use identical mortar composition for prototype and model masonry and to scale only the size of the mortar joints (Petry & Beyer, 2012). For the full-scale specimen, the mortar joint thickness varies between 10 and 12 mm and for the half-scale specimen, respectively, between 5 and 7 mm. For both types of masonry, head and bed joints have the same thickness and are fully filled.

Table 1. Properties of the chosen bricks at half- and full-scale (Petry & Beyer, 2012).

		Full-scale brick	**Half-scale brick**	**Relative error** $\frac{MODEL-PROTOTYPE}{PROTOTYPE}$
Average dimensions of a brick				
Length	mm	297	148	-
Width	mm	194	96	-
Height	mm	189	94	-
Average mass and density of a brick				
Mass / brick	kg	9.9	1.3	-
Volumetric mass	kg/m^3	901	996	+ 10%
Void ratios and effective length / width of a brick				
Void ratio	%	49.3	39.5	- 20%
Effective length*)	%	30.6	37.8	+ 24%
Effective width*)	%	28.9	36.5	+ 26%
Average strength and deviation				
Compression, parallel to perforation	MPa	35.0 ± 7%	33.3 ± 25%	- 5%
Compression, perpendicular to perforation	MPa	9.4 ± 8%	10.8 ± 17%	+ 15%
Tensile strength, perpendicular to perforation	MPa	1.27 ± 38%	1.61 ± 41%	+ 27%

*)The effective length / width describe the percentage of filled material to voids over the gross length / width.

4 EXPRIMENTAL COMPARISON

In order to quantify the remaining differences between the full- and half-scale masonry described in Chapter 3, test specimens were constructed at full- and half-scale and subjected to three different kinds of testing: (1) a series of five uniform compression tests was performed at each scale on panels of 2 bricks x 5 layers, (2) a series of five diagonal tensile strength tests was performed at each scale on cubic masonry panels of 4 bricks x 6 layers and (3) two series with five triplets (1 brick x 3 layers) each were subjected to shear tests were performed on triplets at both scales.

4.1 Compression tests

The results from the compression tests are summarized in Table 2. During testing, the compression load was applied centrically and parallel to the perforation and the deformations of the panels were measured with four vertical and two horizontal LVDTs. The axial stiffness E_c and the Poisson's ratio ν were determined from the equivalent average deformations at 1/3 of the peak strength. In Figure 2 the vertical stress-vertical strain curves are plotted for all ten specimens and Table 2 summarises strength and stiffness values. From the mean values it can be concluded that an excellent match was obtained for the compressive strength f_u, while the axial stiffness E_c is significantly larger for the half-scale masonry than for the full-scale masonry. When looking at Figure 2 one notices that the stress-strain curves fall into two groups with respect to the initial stiffness: The first group has an approximate stiffness of E_c = 5.70 GPa while the stiffness of the second group is less stiff at the beginning (E_c = 3.41 GPa) and picks up at about 1/4 f_u. Both groups contain samples of full- and half-scale specimens but the distribution is not equal resulting hence in the different mean values. However, in order to obtain a comparison of the stiffnesses for larger stresses, the stiffness is also evaluated between 2/3 and 1/3 of the peak strength f_u (→ $E_{2/3-1/3}$), between peak strength and 2/3 of the peak strength (→ $E_{3/3-2/3}$) and as secant stiffness at the peak strength (→ $E_{3/3-0}$). The values are summarized in Table 2. It can be noticed that the stiffnesses are much more similar for larger vertical stresses. Figure 2 also shows that the post-peak deformation capacity is subjected to considerable scatter but in average the post-peak deformation capacity of the half-scale masonry is larger than for the full-scale masonry.

Mohammed and Hughes (2010) reported an increase in compressive strength for smaller scales, which they attributed partly to the scaling of the brick and partly to the scaling of the mortar thickness. In our case, the brick was scaled properly and similar strength values were obtained for both bricks (see Table 1). Hence, an increase in strength due to a stronger reduced-scale brick was avoided and also the scaling of the joint did not affect the compressive strength significantly. As a result, a good match in compressive strength was obtained.

Table 2. Results from the compression tests performed on half- and full-scale masonry wallettes.

	f_u [MPa]	$E_c = E_{1/3-0}$ [GPa]	E_c/f_u [-]	ν [-]	$E_{2/3-1/3}$ [GPa]	$E_{3/3-2/3}$ [GPa]	$E_{3/3-0}$ [GPa]
Full-scale masonry	**5.87±5%**	**3.55±9%**	**613±10%**	**0.20±19%**	**4.26±7%**	**4.28±11%**	**4.00±8%**
Half-scale masonry	**5.66±4%**	**5.46±8%**	**965±11%**	**0.20±6%**	**4.74±11%**	**4.08±16%**	**4.50±9%**

In Section 2 it was outlined that small scale solid brick masonry tends to be less stiff than its full-scale counterpart. Hendry & Murthy (1965) and Egermann et al. (1991) outlined that this difference is related to the different overburden stresses during construction and Mohammed and Hughes (2010) showed that the difference in stiffness can be reduced if the masonry is constructed horizontally.

For the hollow-core masonry we did not observe that the small-scale masonry was less stiff than the full-scale masonry. On the contrary, it tended to be stiffer but the difference reduced if the E-modulus was calculated as average E-modulus over the entire stress range rather than – as defined in codes – between 0 and 1/3f_u (Table 2). As discussed in Section 2, measures such as constructing the masonry horizontally were not investigated as the aim of this investigation was the preparation of a shake table test on a half-scale four-storey structure. In addition, the vertical construction assures a good penetration of the mortar inside the perforation of the brick, which is important for the shear transfer between mortar joint and brick. The hole sizes were equal in full- and half-scale bricks and thus the size of the penetrating mortar pillar was also similar. Accordingly, this caused also that the hollow bricks were filled with mortar over a larger ratio of the brick height at half-scale than at full-scale (see Figure 3) reducing hence the difference in vertical pressure due to the self-weight between full- and half-scale masonry. To the authors' opinion, the higher pressure during curing and the increased filling of the bricks might have both contributed to the increase of axial stiffness.

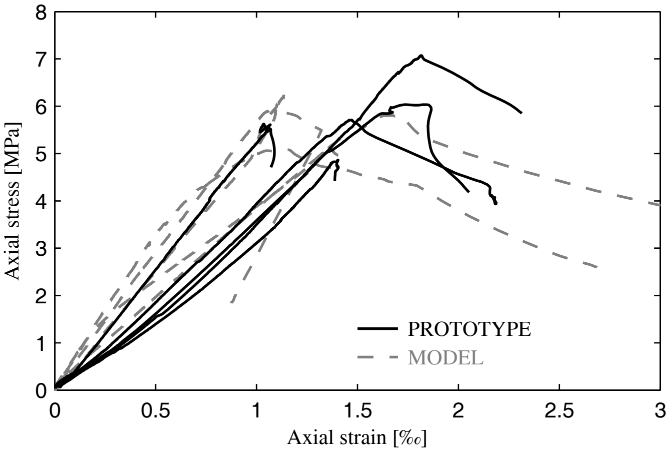

Figure 2. Stress-strain curves of the compression tests.

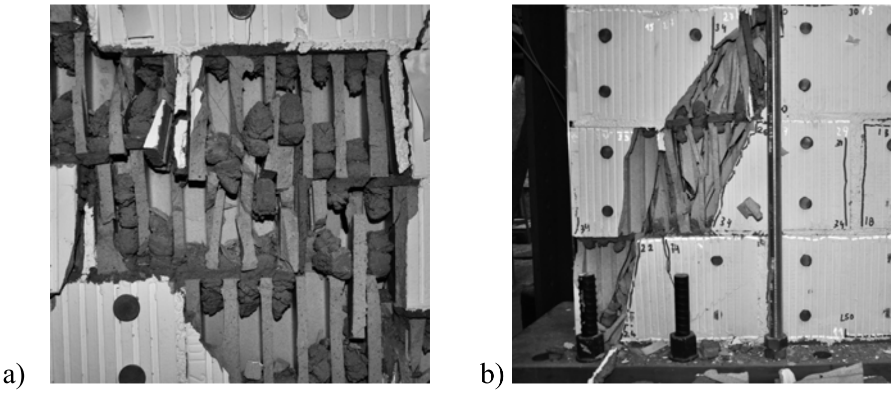

Figure 3. Photos showing the mortar penetration for an exemplary a) half-scale and b) full-scale masonry pier.

4.2 Shear tests

In Petry and Beyer (2013), five shear triplet tests were carried out at each scale (specimen TUP1-5/TUM1-5, see Table 3). It was noticed that the shear strength of the half-scale masonry was significantly lower than for the full-scale masonry. For instance, the cohesion of the half-scale masonry ($c_M = 0.20\text{MPa}$) was 25% lower than the cohesion of the full-scale masonry ($c_P = 0.27\text{MPa}$) and the friction coefficient was around 22% lower ($\mu_M = 0.69\text{MPa}$ and $\mu_P = 0.91\text{MPa}$). The cause for this distortion was attributed to the different void ratios of the bricks: In order to keep web and shell thickness equal in prototype and model brick, the hole layout of the brick was scaled by reducing the number of internal webs. Accordingly no perfect match was obtained concerning the void ratio and the effective width of the model brick (see Table 1). However, the reduced void ratio (20% less void ratio for the model brick) of the model brick decreased also the sum of the cross sectional area of mortar pillars which produce when the wet mortar penetrates in the perforation. We concluded that – assuming that the shear mechanism is dominated by shearing off of these mortar pillars – a direct relationship must exist between the void ratio of the bricks and the shear strength of the masonries. In order to confirm this assumption, another five triplets were built and tested at each scale (specimen TUP6-10/TUM6-10) and the results of all 20 specimens are plotted in Figure 4 and summarized in Table 3. The second test series confirmed the findings of the first test series.

Mohammed and Hughes (2010) observed that for the same surface roughness of the brick the cohesion increased and the coefficient of friction decreased with smaller scale. As previously stated, the shear mechanism which develops at the brick-mortar interface is different for hollow-core and solid bricks and therefore, it is not surprising that our conclusions differ from theirs.

Table 3. Results from the shear tests performed on half- and full-scale triplets.

	Triplet unit	***c*** **[MPa]**	***μ*** **[MPa]**
Full-scale masonry	TUP1-5	0.27	0.91
	TUP6-10	0.34	0.90
	Average	**0.28**	**0.91**
Half-scale masonry	TUM1-5	0.20	0.69
	TUM6-10	0.27	0.72
	Average	**0.23**	**0.70**

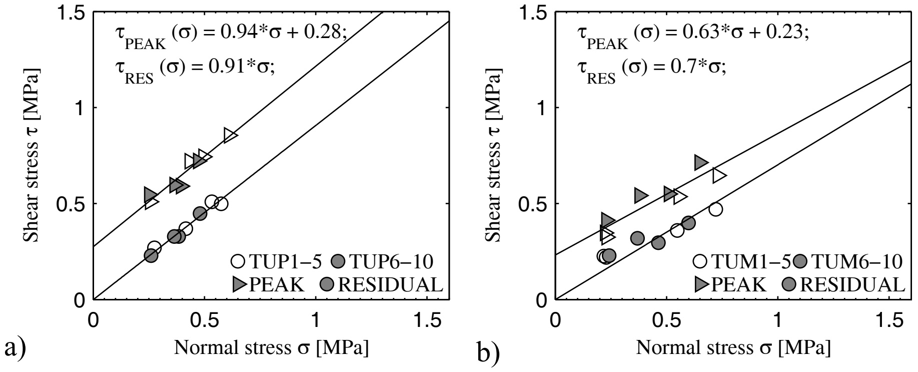

Figure 4. Results from shear tests on half- and full-scale masonry, a) full-scale masonry at peak and residual strength b) half-scale masonry at peak and residual strength.

4.3 Diagonal tensile tests

For the diagonal tensile strength, in total five specimens at each scale were tested under a local compression load at the edges as illustrated in Figure 5. Uniform load application at the corners was assured through cement layers which were put between steel support and masonry. The diagonal tensile strength is computed from the peak force F_{PEAK} in applying the following formulae:

$$f_t = \frac{F_{PEAK}}{\sqrt{2} \cdot A_N} \tag{1}$$

where A_N represents the average cross section and considers the slight differences in length L and height H:

$$A_N = \frac{(L \cdot H)}{2} \cdot t \tag{2}$$

where t is the thickness of the panel.

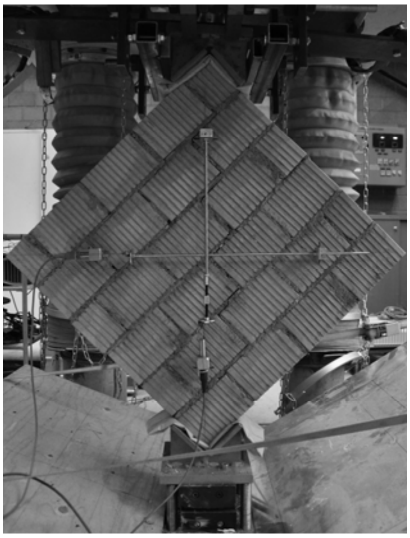

Figure 5. Diagonal tensile test on a half-scale masonry panel.

Table 4. Results from the diagonal tensile tests performed on half- and full-scale masonry panels.

	L	H	f_t	$\frac{\frac{1}{3}f_t}{\varepsilon_{ver,1/3}}$	$\frac{\frac{1}{3}f_t}{\varepsilon_{hor,1/3}}$
	[mm]	[mm]	**[MPa]**	**[GPa]**	**[GPa]**
Full-scale masonry	1230	1190	**0.496±9.7%**	**1.92±7.3%**	**19.8±73%**
Half-scale masonry	615	595	**0.336±15%**	**1.81±46%**	**39.1±115%**

During loading, vertical and horizontal strains were measured at the front and back side of the specimen with two LVDTs in each direction. In order to obtain the qualitative stiffness of the panels the strains at 1/3 of the strength were measured and divided by the corresponding tensile stress. The values are given in Table 4 and the stress-strain curves parallel to the loading application are plotted in Figure 6. While the diagonal tensile strength f_t is significantly lower for the half-scale masonry, it is more difficult to observe a general trend concerning the similitude in stiffness, due to the large variations. However, in the previous section it was demonstrated that the different void ratios of the full- and half-scale bricks reduced the effective interlock area in the half-scale brick and reduced thus the friction coefficient μ and cohesion c for the small scale masonry. In the case of the diagonal tensile tests, for all ten tests, the failure was dominated by a vertical crack which propagated stepwise through the mortar joints. Only at the end of the loading, the crack propagated for some specimens locally through the brick near the loading supports. Hence, the failure of the diagonal tensile strength specimens was provoked through failure of the mortar-brick interface and the reduced diagonal tensile strength f_t results therefore from the reduced friction coefficient μ and cohesion c for the small scale masonry.

Mohammed and Hughes (2010) had also found that the diagonal tensile strength varied for the different scales. For the solid brick masonry they tested the cracks developed likewise mostly along the mortar joints. However, the surface roughness of their prototype brick differed from that of a small scale brick which led already to large variations in the shear strength obtained from triplet tests. Although the trends observed by Mohammed and Hughes (2010) for the variation of the diagonal tensile strength with the scaling factor are similar to the trends observed by us, the reasons leading to these trends are completely different.

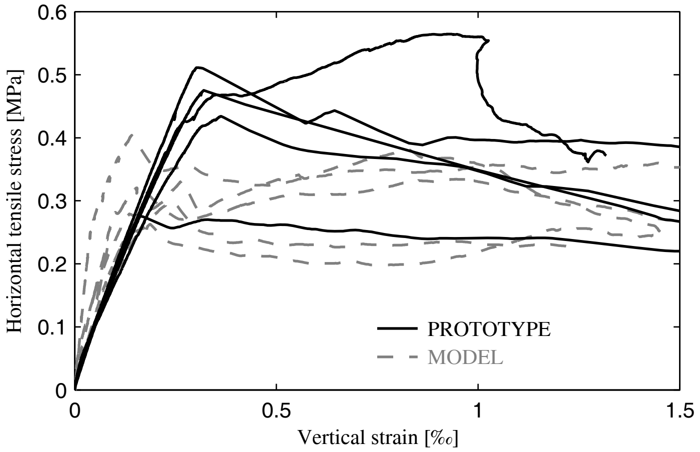

Figure 6. Stress-strain curves of the diagonal tensile tests.

5 CONCLUSIONS AND OUTLOOK

This article compares the results from our experimental campaign on scaling effects on modern hollow-core clay masonry with previously performed investigations by other researchers. Since their work was dedicated to the scaling of masonry with solid clay bricks, not all results are directly applicable to hollow-core brick masonry. Accordingly, in a first part of this article the differences between solid and hollow-core clay brick masonry were briefly discussed and the importance of the void ratio for hollow-core brick is noticed.

While for solid brick masonry past research efforts could not eliminate significant differences between prototype and small scale masonry, the research project presented in this paper showed that for hollow-core clay masonry scaling effects can be reduced to an acceptable limit. We obtained with a properly scaled brick – thus the brick at half- and full-scale had the same strength – similar compressive strength for the masonry. Hence, the scaling of the mortar joint thickness seemed to have a less important influence on the compressive strength of the hollow-core brick masonry than on the solid-brick masonry. The axial stiffness was also less affected than it is typically observed for solid-brick masonry. In particular if the mean axial stiffness between 0 and f_u is considered, full- and small-scale masonry yielded very similar results. Furthermore, the perforation modifies the shear mechanism which develops at the mortar brick interface. While for solid brick masonry the shear at the interface of mortar and brick is transferred via friction and cohesion between the two surfaces, in hollow-core masonry it is the shearing-off of the mortar pillars that penetrate into the brick which contributes most to the shear resistance. As a result, the shear strength is less dependent on the interface properties but very sensitive to the void ratio: due to the decreased void ratio of the half-scale brick, the friction coefficient, cohesion and diagonal tensile strength, which are calculated with respect to the net area of the brick, were reduced for the half-scale brick.

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