BOND BEHAVIOR AT THE BOTTOM OF A LIGHTWEIGHT MASONRY BASEMENT WALL UNDER LATERAL LOAD

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ABSTRACT

Out-of-plane loading on masonry walls under sufficient vertical load can be effortlessly verified by simplified calculation methods according to the European masonry standards. Difficulties, however, may arise with regards to the cost-effectiveness of certain designs. This occurs especially in the design of light vertically loaded exterior basement walls under horizontal earth pressure load. E. g. large wall openings on the ground floor of a building may be responsible for this type of issue.

The development of a realistic analysis approach for out-of-plane loaded clay masonry basement walls under light vertical loads is underway. This approach falls within the scope of a research project currently carried out at the Institute of Building Materials Research, Aachen University, in cooperation with the Brick and Tile Research Institute Essen. This new calculation method should accurately describe the stress and deformation behavior of basement walls. This process will take into account adjacent concrete construction components such as ceilings and basement slabs, as well as include diverse damp-proof courses which are necessary to protect the masonry wall against rising capillary water.

A new test procedure has been developed to determine the shear strength and frictional behavior of masonry and mortar between each other as well as with adjacent concrete construction components. Experiments on small test specimens with this test procedure provide also information on the impact of various damp-proof courses with respect to the bond behavior at the bottom of the wall. Moreover, tests on walls will be conducted to determine their actual boundary conditions as well as their load-bearing and deformation behavior. Finally, theoretical investigations will be conducted in order to recalculate, by means of the finite-element-method, the experimental test results. These will also serve to determine normal and shear stress distributions in the respective cross-sections at the upper and lower ends of basement walls.

KEYWORDS: basement wall, bond behavior, out-of-plane loading, masonry design

PREVIOUS INVESTIGATIONS

Masonry walls that experience an out-of plane load are subjected to bending and shear forces. This loading case can be considered as non critical, if the simultaneously acting vertical load is sufficiently high and the eccentricity (lever arm) of the vertical load large enough to counteract the resulting flexural moment due to earth pressure. Thereby, the bed joints should not gape further than the middle of the thickness of the cross section of the wall. This condition restricted also the eccentricity of the vertical load ($e \leq 0.33 \cdot d$). Figure 1 illustrates this approach of a vertically, tensed arch (red line). The design of basement walls in Germany and Europe is based on this approach, which was developed in 1984 by Mann, Bernhardt [2] and corresponds to the wall structures of that time. Out-of-plane loading on masonry walls under sufficient vertical load can be so effortlessly verified by simplified calculation methods according to the German masonry standards [3].

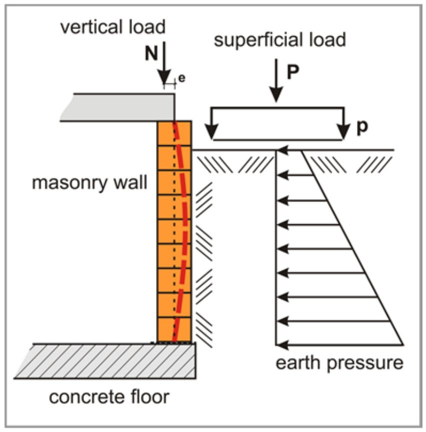


Figure 1: Out-of-plane Loaded Clay Masonry Basement Wall under Vertical Load

The vertical load on masonry basement walls has been, however, considerably reduced over the last years. This is for instance caused by the facts, that the mass of the current masonry units has been reduced, because of the increased demands on the thermal insulation. On the other hand, the floor plan designs for new buildings, where e. g. reinforced concrete ceilings over large areas are spanned uniaxially have been changed. Often, any vertical load acts on some basement wall sections due to large windows and terrace doors on the floor above the basement wall. As a result, the out-of-plane load-bearing capacity of the basement wall is reduced. The required minimum vertical loads according to the German standards [3] can difficultly be achieved by the design of light vertically loaded exterior basement walls under earth pressure load in new buildings.

On the resistance side for the design of masonry walls of this kind, the flexural strength (perpendicular and parallel to the bed joint) and the shear strength of the masonry are prevailing. These design values are additionally influenced by the bond properties between masonry unit and mortar (adhesive shear strength) and a load dependent frictional component. Besides the bending load-bearing capacity, it must be ensured that the horizontal reaction forces at the base and on the top of the wall are being conducted in the ceiling and the basement slab by shear stresses. In this case, a sufficient load bearing capacity and stability of the wall is ensured only by the bond behavior of masonry units and mortar between each other and their bond to the adjacent components (concrete basement slab and ceiling). The transmissible bond stresses above the basement slab of the wall are also influenced by damp-poof courses. These are necessary to protect the masonry walls against rising capillary water uptake. Damp-proof course layers can disrupt the adhesion between the masonry wall and concrete basement slab and significantly reduce the coefficient of friction. For this reason, DIN EN 1996-2/NA [4] limits the available moisture barrier layers to those made of bituminous sheeting (R 500), mineral sealing slurries or a material with similar friction behavior. For the proof of the lateral forces for the designing of basement walls according to the German standards [3], the coefficient of friction at the base of the wall is to be set equal to the coefficient of friction between masonry unit and mortar ($\mu = 0.6$) without taking into account the use of a moisture barrier layer. But as long as the influence of the damp-proof course layer on the bond behavior is not taken into account by the German standards, this could lead to shear failure at the top and the basement slab of the wall.

For an adequate estimation of the load-bearing behavior of out-of-plane loaded masonry components there is a lack of essential knowledge. This applies on the one hand to the knowledge of the actually resulting normal and shear stress distributions in the corresponding cross-sections at the top and bottom of the wall for its design. On the other hand, there is a lack of sufficient knowledge about the bond strength and the deformation behavior between masonry and adjacent components with and without moisture barrier layers in the bed joint. In the literature, there are very few reports which consider the impact of moisture barrier layers with respect to the bond behavior in the bed joint. One of the unique reports found concerning the investigation about the bond behavior between masonry components and concrete slabs is described in [5]. But these investigations are limited to an in-plane shear load case. Especially for out-of-plane-loaded masonry walls, there is a still need to investigate the bond behavior at their base.

To get some fundamental knowledge about these gaps, extensive experimental investigations about the load-bearing behavior of out-of-plane clay masonry walls have been conducted. In doing so the bond properties between clay masonry units and adjacent building materials are being determined considering the influence of moisture barrier layers. This investigations are part of a research project [1] currently carried out at the Institute of Building Materials Research, Aachen University, in cooperation with the Brick and Tile Research Institute Essen. Finally, on the basis of these studies, an approach for the design of basement walls comprising more realistic bond material laws should be derived. Especially for the clay masonry walls, economic and from a technical perspective desirable wall structures can be achieved by the new approach resulting from this research project, despite the modern floor plans for new buildings and lighter masonry units. By knowing the actual load-bearing and deformation behavior of basement walls, structural damage can also be actively counteracted, at least in the planning stage.

SELECTED APPROACH

To be able to describe exactly the state of stress and deformation of a wall being subjected to out-of-plane forces, the fundamental material characteristics are to be determined by appropriate material laws in the bed joints considering the shear and axial forces. The deformation-dependent adhesion and friction properties of the masonry itself, i. e. between masonry unit and mortar, as well as the bond between masonry and adjacent components including the moisture barrier layers are basic material laws as input for design.

In the first step, experimental investigations of the bond properties between masonry unit and mortar were performed. Based upon this research, representative masonry unit-mortar combinations were selected, on which the bond behavior between masonry and concrete basement slab on small test specimens are determined. These specimens represent a section of the out-of-plane loaded basement wall at their base. The influence of various in the bed joint embedded moisture barrier layers on the adhesion and friction behavior is investigated. For the investigations a test method was developed, because no suitable test method exists until now. In the current paper, the development of this novel test method is described and our latest results obtained by this method are shown.

To determine the actual material laws in the bed joint of an out-of-plane loaded wall, the shear tests on small specimens should be simulated applying the finite-element-method. By doing so, the load-displacement curves obtained from the simulation should be adjusted in the best possible way to the experimental test results. In addition, a two-dimensional finite element model of storey-high walls with different dimensions and loads should be generated. The calculated material laws of the test specimens will be applied at the bottom of the walls in the numerical simulation. The FE-models of the walls should be calibrated with respect to tests on storey-high wall specimens. Based on the analysis of normal and shear stress distributions in the relevant cross-sections at the top and bottom of the wall for the design, analytical relationships are to be derived. Depending on the various geometric, material and load-dependent parameters, the analysis approaches for the design of masonry basement walls are also to be derived. The last mentioned steps are still being proceeded.

APPLIED MATERIALS AND MATERIAL CHARACTERISTIC VALUES

For the experimental investigations, many different hollow clay units were used, because their different suction and surface characteristics may have an influence on the development of mortar strength and the bond properties in the bed joint (see table 1).

A general purpose mortar M5 with low mortar strength was selected for the bed joint at the bottom of the wall to cover the worst case for the bond behavior in that bed joint. For the other bed joints of the storey-high wall specimens a thin-bed mortar as well as a general purpose mortar are going to be used.

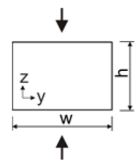
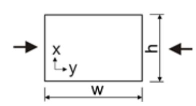
For the determination of the bond behavior at the base of a basement wall a traditional sand-surfaced, bituminous sheet and a fine sand-surfaced, bituminous layer are used (see table 1). As reference composite specimens without moisture barrier layer are used. Furthermore a standard plastic waterproofing membrane and a mineral sealing slurrie will be examined.

Table 1: Applied Materials

Clay Units			Damp-Proof Courses	
				
Type M	Type N	Type Z	Bituminous Layer, sand-surfaced (B)	Bituminous Sheet, sand-surfaced (R)

The standard characteristics of the selected masonry units (size, volume of holes, dry bulk density and compressive strength in z-direction) were determined. In addition, the compressive strength of the masonry units in y-direction was determined. This is a relevant parameter for out-of-plane loading on masonry walls. The material properties of the masonry units are shown in table 2. For the given mean values, six tests for each type of unit were performed. For the mortar used, the fresh and hardened mortar characteristics were determined. Moreover, the bond shear strength and friction coefficients between the masonry units and mortar should be determined according to DIN EN 1052-3 [6].

Table 2: Test Results of the applied Clay Units (mean values)

Results / Clay Units	Measure			Volume of all Holes	Compressive strength		Oven-Dry Density	Absorption of Water
	Length l	Width W	Height h					
	mm			%	N/mm²		kg/dm³	kg/(m^2·min)
Type M	246	365	249	47	9.2	0.7	0.8	3.1
Type N	245	365	248	49	7.3	0.6	0.7	2.1
Type Z	235	172	113	< 15	36.6	12.7	1.8	2.1

DEVELOPMENT OF A NEW TESTING METHOD

On the search for a testing method to determine the shear strength of composite specimens, which considers the load case of basement walls, the-state-of-the-art test methods found in the literature have been put together. The test set-up according to DIN EN 1052-4 [7] is not suitable for an out-of-plane loading. With the objective to examine the bond between masonry and adjacent components, the use of this method is not recommendable due to the specimen geometry and the arrangement of vertical joints in the test specimen. In addition, the eccentricity of the normal force has not been considered in [7]. Own previous experience has also shown that for the determination of material laws using finite-elements simulations it is appropriate to check only one failing joint. For this reason, the method in accordance to DIN EN 1052-3 is also not convenient for the tests. There is, however, no simple appropriate test method for determining the shear stress-displacement curves of the joints, with the exception of the torsion test method on hollow cylinders developed at ibac [8]. This method is, however, not applicable for hollow clay units.

Based on the findings from the literature, summarized in [1], and extensive own experimentation, an appropriate test method for determining the shear strength at the base of a basement wall has been developed and improved at ibac. This new test procedure is shown in Figure 2. With our test set-up the applied normal and shear forces on the specimen are similar to the vertical and earth pressure loads found in the real situation. Thus, it is not necessary to rotate the specimen for testing. This is an advantage, because by rotating the specimen the bond in the joint could be debilitated or damaged. Furthermore, the interaction of the masonry unit with the adjacent concrete slab on the bond behavior can be taken into account due to the dedicated set-up configuration. Another advantage is that this new test method takes also into account the influence of the eccentricity of the vertical load. During the development of the procedure, one had particularly to take into account the interaction of the resulting shear and normal forces in the joint.

In addition to the determination of the initial shear strength and friction coefficients, the test method is appropriate for determining the shear load-displacement curves in the joint. These curves should be recalculated by simulating the shear tests with the finite-element-method. This has the objective to determine the actual material laws (i. e. the complete shear stress-displacement curves as a function of load at constant shear and normal stress distribution) in an inverse manner. An analogous inverse determination was implemented for instance in [9]. The actual material laws have to be determined, because irregular shear and axial stress distributions may occur in the joint, due to the loading conditions of the test specimen. Afterwards, in the numerical simulation of the storey-high walls, the actual material laws determined in this way will be applied.

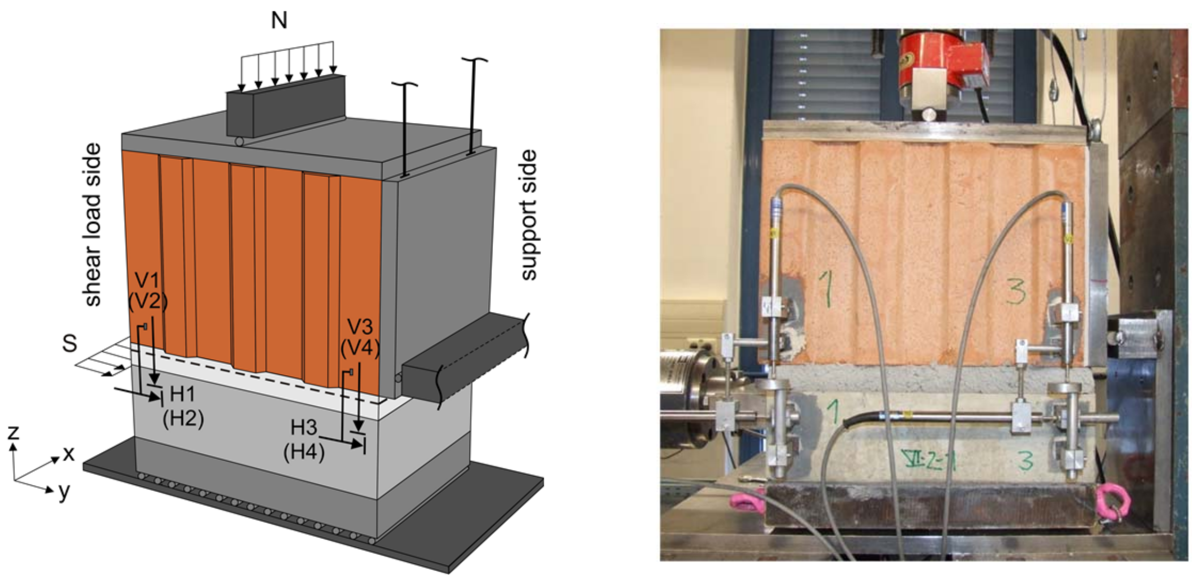


Figure 2: Test Set-up to determine the Shear Strength and Frictional Behavior

EXPERIMENTAL INVESTIGATIONS OF THE BOND PROPERTIES AT THE BOTTOM OF A BASEMENT WALL

With the aim of determining the bond properties between masonry basement walls and adjacent concrete floor slabs using the developed test set-up, several experimental investigations are being conducted.

At the beginning of the investigations, hollow clay units with extremely filigree structure were chosen to determine the bond properties at the bottom of a basement wall. These kind of hollow clay units are commonly used for the construction of basement walls. Differently as intended, the filigree structure of the masonry units caused the masonry unit to break down, before the bond could fail. Thus, the bond properties in the joint could not been determined. For the determination of the bond properties, hollow masonry units with sufficiently compressive strength and continuously stiffening webs in y-direction were selected (see tables 1 and 2).

Due to the large number of possible parameter variations, only dedicated combinations of parameters are examined. The test series planned so far are given in table 3. Each series consist of three test specimens for each applied vertical load. Only two of the three selected vertical loads (0.1 and 0.3 N/mm²) of the series III – VII have been tested until now.

Table 3: Test Series

Parameters / Test Number	Clay Units	Damp-Proof Courses	Mortar	Concrete	Vertical Load	
					Value	Eccentricity
I	Type Z	none (O)	General Purpose Mortar M5	C 20/25	0.1, 0.2 and 0.3 N/mm²	e = 0
II		Bituminous Sheet (R)				
III	Type M	none (O)				
IV		Bituminous Layer (B)				
V		Bituminous Sheet (R)				
VI	Type N	none (O)				
VII		Bituminous Layer (B)				
VIII	Type Z	none (O)				e = 0.33·d
IX		Bituminous Sheet (R)				
X	Type N	none (O)				
XI		Bituminous Layer (B)				
XII	Type M	none (O)				
XIII		Bituminous Layer (B)				

The test specimens correspond to the build-up at the bottom of a basement wall. They consist of a concrete body (the concrete basement slab), a masonry unit and mortar with and without damp-proof course layer embedded in the bed joint. Figure 3 shows the production of the composite specimens.

Figure 3: Production of Test Specimens with in Mortar embedded Damp-Proof Course

The load is carried out by a shear force, which is brought closely to the bed joint, and an acting normal force perpendicular to the shear force (see figure 2). The selected normal loads (0.10, 0.20, 0.30 N/mm ²) correspond to minimum vertical loads from the upper floors assuming the dead load of 1, 3 or 5 stories on the top of the wall. The normal force can be applied in a centric (e = 0) or eccentric way (e = 0.33·d), so that the influence of the eccentricity of the vertical load by the determination of the bond properties could be taken into account. To measure the horizontal displacements in the composite joint, inductive displacement transducers are attached on the front and back side of the sample, on the load application side and on the support side (see Figure 2). By means of four vertical inductive displacement transducers, a rotation of the masonry unit during the test can be determined additionally. This especially occurs if the vertical load is applied in an eccentric way.

Figure 4 shows the measured shear load-displacement curves of two experimental test series and three specimens for each series and for the two different applied vertical loads. The difference between these series is the used damp-proof course. The horizontal displacements measured at the front and back side of the specimen were meaned for the shear load application and the support side. The maximum measured value of the shear load for the lightest vertical load (0.1 N/mm²) was always less than for the higher vertical load (0.3 N/mm²). The results of both series are similar. The failure in the joint occurs between the damp-proof course and the mortar. The upper part of the specimen (masonry unit and mortar) slides above the damp-proof course. Only within the series with the traditional damp-proof course (R) and a vertical load of 0.1 N/mm², the failure occurs between concrete and mortar. That´s why the shear-displacement curves show a peak.

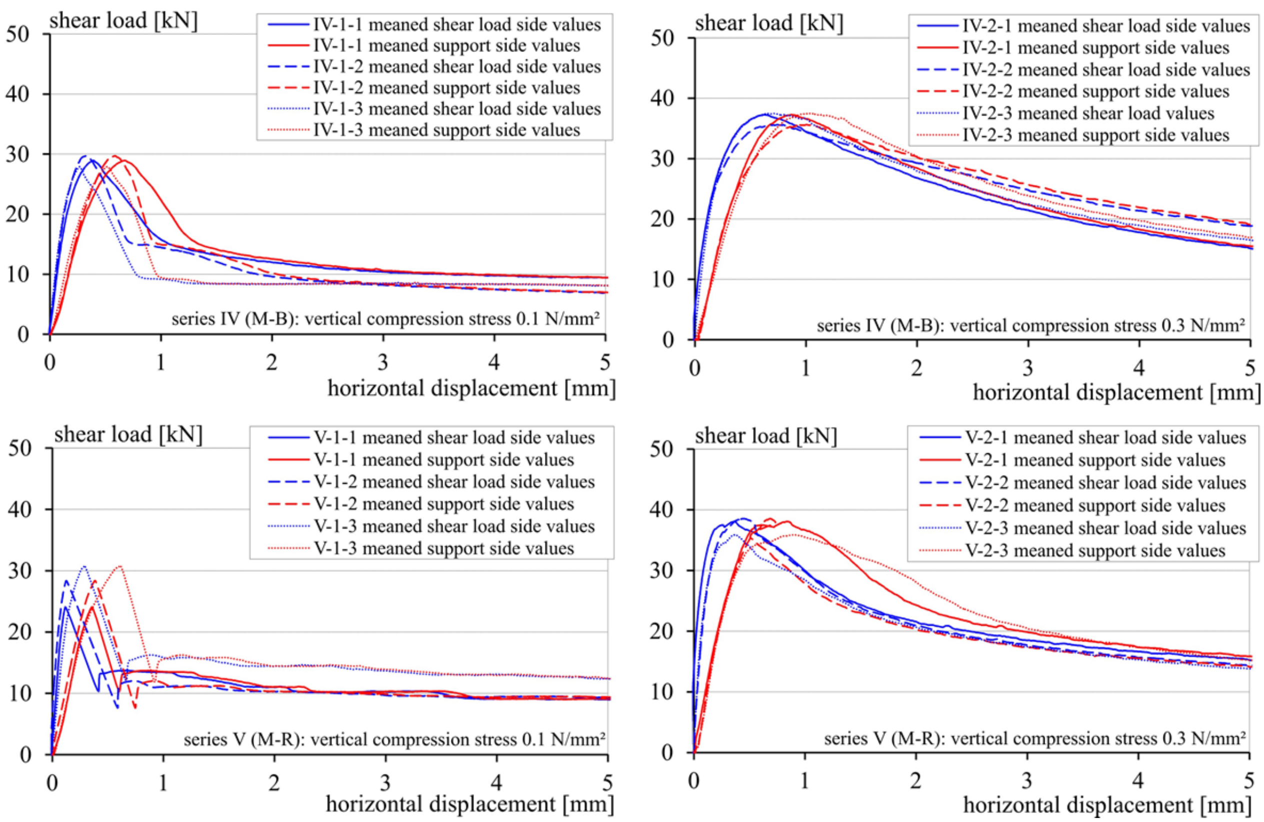


Figure 4: Load-Displacement-Curves

Figure 5 shows the typical failure cases of the bond. In the test of specimens with moisture barrier layers, bond failure occurred mostly between mortar and damp-proof course, above or underneath the damp-proof course. In some cases the traditionally used bituminous sheet (R) has cracked, while the other bituminous layer (B) deformed elastically. Generally, the bituminous sheet (R) has a better friction behavior than the other one (B). In the composites without a moisture barrier layer, the failure either occurs between mortar and concrete or between hollow clay unit and mortar. Sometimes a mixed failure occurs also.

Figure 5: Typical Failure Cases of the Bond in the Bed-Joint:
a) Sliding underneath the Damp-Proof Course; b) Sliding above the Damp-Proof Course;
c) Cracking of the Damp-Proof Course (R)
d) Failure between Mortar and Concrete; e) Failure between Mortar and Clay Unit;
f) Mixed Failure between Mortar and Concrete or Mortar and Clay Unit

In Figure 6, the series in dependence of the masonry unit or the damp-proof course used were put together in diagrams. These diagrams show the maximal shear stresses determined from the maximal measured loads (single values) plotted against the applied vertical compression stresses for each series. The specific type of failure of the bond is given in the diagrams for each single value. Furthermore, the linear equations obtained from the regression calculations based on the Mohr-Coulomb Failure Criterion for each series are showed in the diagrams. Differently as described for instance in [6], the regression equations were determined from the values of only two of the three selected levels of vertical compression (0.1 and 0.3 N/mm²). These regression calculations were performed for determining the initial shear strength and the static friction coefficient in the bed joint. In the regression calculations, the bond failure in the bed joint was considered as a system failure, without differentiating the type of failure of the bond of each test specimen included in the evaluation.

Basically, higher adhesive shear strength and friction coefficients were obtained with the hollow clay unit type (M) compared to other type (N). As a result of the non-filled holes of the hollow clay unit type (M), mortar pins get generated. These mortar pins enable a better grip in the joint and have a favorable impact on the bond.

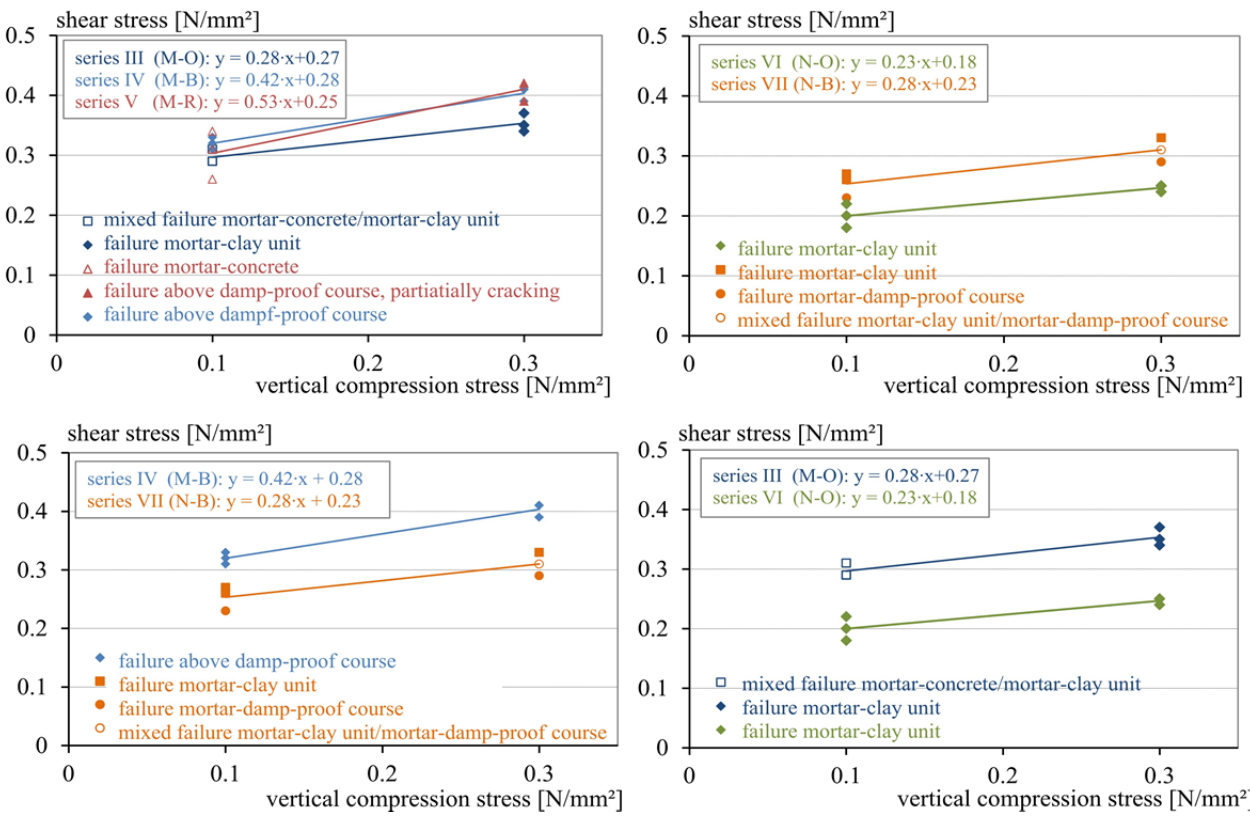


Figure 6: Bond Relevant Parameters at the Base of a Masonry Wall:
a) Clay Unit M; b) Clay Unit N
c) Bed Joint with Bituminous Layer B; d) Bed-Joint without Damp-Proof Course

The values of the determined friction coefficients are considerably lower than 0.6 over the totality of the performed tests (see figure 6 and table 4). In contradiction to what was expected, the values of the friction coefficients of the specimens without moisture barrier layers were lower than the ones with in mortar embedded damp-proof courses. One of the reasons, why this occurred could be explained by the observed local failure of the hollow clay units. A local failure of the hollow clay units occurs more often at the specimens without moisture barrier layers than rather by the ones with moisture barrier layer. On the other hand, the thickness of the bed-joint (30 mm) of the tested specimens could have an influence on the bond properties, in comparison to the usual thickness of the bed joints (12 mm) of other specimens used by determining bond properties according to the standards. Another reason that could explain the lower values found can be reattributed to the different loading situation. In this case an out-of-plane and a light vertical loading were applied differently than according to DIN EN 1052-3. These results show that the assumption made by the German and European standards [3] about the frictional coefficient $\mu = 0.6$ is not safe enough for the design of basement walls, at least for light vertically loaded basement walls. This fact clearly demonstrates that more studies about the bond properties should be conducted to propose safe values for the design of basement walls.

Parallel to the shear tests, the in-situ compressive strength in the bed joint was determined, also above and below the damp-proof course. The compressive strength of the mortar in the bed joint above the damp-proof course was always lower than the one measured below (see table 4). This could be explained by the different water suction characteristics of the masonry unit and concrete. Another reason could be explained in the difference of the thickness of the bed joint above (10 mm) and below (20 mm) of the damp-proof course and the associated higher drying surface during the hardening of the mortar. In consequence this should be further investigated.

Table 4: Test Results (mean values)

Results / Test Number	Clay Units	Damp-Proof Courses	Mortar Compression Strength				Initial Shear Strength	Coefficient of Static Friction
			Prisms	in the Bed Joint				
				above	below	without		
				Damp-Proof Course				
			(N/mm^2)				(N/mm^2)	–
III	Type M	none (O)	8.8	-	-	13.3	0.27	0.28
IV		Bituminous Layer (B)	8.4	8.6	11.4	-	0.28	0.42
V		Bituminous Sheet (R)	8.1	7.0	13.6	-	0.25	0.53
VI	Type N	none (O)	8.8	-	-	12.1	0.18	0.23
VII		Bituminous Layer (B)	7.6	10.1	12.7	-	0.23	0.28

SUMMARY AND OUTLOOK

A realistic description of the stress and deformation behavior of light vertically loaded clay masonry basement walls under earth pressure should lead to the development of a design approach. This design method has to take into account the actual bond behavior between masonry and adjacent components. With this aim, extensive theoretical and experimental investigations are carried out at the Institute for Building Research, Aachen University.

In this paper, the studies on small test specimens were performed for the determination of the shear behavior at the bottom of a basement wall by means of a special developed test method. These experiments provide information about the influence of different damp-proof courses on the shear and friction behavior in the bed joint. Additionally they demonstrate the importance of the determination of realistic friction coefficients at the lower end of a basement wall. Based on these investigations, the actual material laws of the bed joint should be determined with the help of finite-element simulations. A realistic modeling of the deformation behavior of out-of-plane loaded basement walls should be based on these material laws. This finite-element-model is to be calibrated on the basis of large wall specimen tests.

In further research, the influence of other masonry units should be systematically investigated. So that, the new derived approach can be extended to other lightweight building materials.

ACKKNOWLEDGEMENT

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REFERENCES

1. Brameshuber, W., Saenger, D. (in process) „Standsicherheit horizontal belasteter Mauerwerkwände unter geringer Auflast“ Institut für Bauforschung, Aachen. - (in German)
2. Mann, W., Bernhardt, G. (1984) „Rechnerischer Nachweis von ein- und zweiachsig gespannten gemauerten Wänden, insbesondere von Kellerwänden auf Erddruck“ Berlin : Ernst & Sohn. - In: Mauerwerk-Kalender 9, S. 69-84 - (in German)
3. DIN EN 1996-3/NA:2012-01 (2012) „ National Annex - Nationally determined parameters - Eurocode 6: Design of masonry structures - Part 3: Simplified calculation methods for unreinforced masonry structures“ NABau im DIN, Berlin.
4. DIN EN 1996-2/NA (2012) “National Annex - Nationally determined parameters - Eurocode 6: Design of masonry structures - Part 2: Design considerations, selection of materials and execution of masonry” NABau im DIN, Berlin.
5. Mojsilovic, N.; Krucker, M. (2012) “Shear Tests on Masonry Elements with Damp-Proof course Membrane. Florianopolis” Proceedings of the 15th Brick/Block Masonry Conference, Florianopolis, Brazil, June 03rd to 06th, Universidade Federal de Santa Catarina.
6. DIN EN 1052-3:2007-06 (2007) „Methods of test for masonry - Part 3: Determination of initial shear strength” NABau im DIN, Berlin.
7. DIN EN 1052-4:2000-09 (2000) „Methods of test for masonry – Part 4: Determination of shear strength including damp proof course“ NABau im DIN, Berlin.
8. Schmidt, U., Hannawald, J., Brameshuber, W. (2008) “Theoretical and Practical Research on the Flexural Strength of Masonry” Proceedings of the 14th International Brick and Block Masonry Conference, Sydney, 17-20 February 2008, Callaghan: University of Newcastle (Masio, M.; Totoev, Y.; Page, A.; Sugo, H. (Eds.))
9. Schmidt, U., Beer, I., Brameshuber, W. (2005) “Tests on the Load Bearing Behavior of Masonry Shear Walls” Proceedings of the 10th Canadian Masonry Symposium, Banff, Alberta, Canada, June 8-12, 2005, S. 704-713, University of Calgary: Department of Civil Engineering.