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VARIATION OF SHEAR STRENGTH OF MASONRY WITH DIFFERENT MORTAR PROPERTIES

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Abstract

The design and structure of masonry buildings are based on experiences of many centuries. Although these experiences are used worldwide, knowledge about the material behavior of masonry is still afflicted with uncertainties.

In particular, the reliability assessment of masonry buildings with respect to earthquake loadings is a complex challenge. The assessment is highly influenced by uncertainties in the material characteristics, geometrical quantities, structural details and seismic conditions. One of the key parameters regarding the resistance is the shear strength of masonry.

Therefore a series of tests on mortar prisms according to EN 1015-11 was performed, in order to obtain basic characteristics for different mortar properties, e.g. bending and compressive strength. A second test program was performed according to EN 1052-3 for the characterization of shear strength of masonry. Shear triplets were made to establish the shear strength variation due to a deliberate variation of the mortar properties. In addition for both, tests on mortar prisms and tests on shear triplets, descriptive statistical parameters were calculated and there was an attempt to describe the datasets with probabilistic distributions for further stochastic assessments.

Keywords: Old Masonry, Shear strength, Coefficient of friction

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Introduction

Masonry is used in structural engineering for load carrying elements. It is a typical construction material to withstand compression, but with low shear and bending resistance. Because of this circumstance unreinforced masonry buildings became of high interest, (a) to gather mechanical properties and their wide scatter, which is characteristic for old masonry and (b) to obtain appropriate tools for reliability assessment, analysis and retrofit methods.

General rules and design aspects are stated in specific Eurocodes (EN 1990 to EN 1998). For masonry structures, rules and design aspects are regulated in EN 1996-1-1. The documented ultimate limit states can be distinguished in (a) masonry under vertical loading, (b) masonry under shear and (c) masonry under bending. The most critical loading conditions are the shear loading and bending for unreinforced masonry. Thereby the shear and bending associated horizontal loading is mainly caused by wind loads or by seismic actions.

Regarding the material behavior under horizontal loading it could be distinguished between two types of material parameters. The first type directly affects the load side e.g. energy dissipation and behavior factor. The second type directly affects the resistance side e.g. shear resistance, tensile strength and shear modulus.

According to EN 1996-1-1 the design value of shear strength depends on initial shear strength f_{vko} and coefficient of friction μ as well as on geometrical parameters. For the characterization of these two material parameters for old masonry a testing program according to EN 1052-3 with different mortar properties was carried out. Results of this testing program as well as numerical investigations for verification are presented in this paper.

Material properties

Masonry units

The shear specimens were made with only one type of old, solid masonry bricks, see Figure 1. These types of bricks are typical for houses from the 19th century in Vienna. The mean dimensions of bricks were $L/B/H$ = 29.12/14.13/7.05 cm. The dimensions were measured according to EN 772-16.

Based on the obtained minimum dimensions in length and width, bricks were cut to provide a steady interface between bricks and mortar layer. The final dimensions of bricks were L = 25 cm and B = 12 cm. The mean value of the dry density of bricks was ρ_d = 1467 kg/m³. The compressive strength was obtained according to EN 772-1 whereby the mean value of compressive strength resulted in f_b = 19.28 MPa.

Figure 1. Old, solid bricks used for shear tests.

Mortar

For the determination of the initial and shear strength between brick and mortar a mortar mixture was chosen, which has a low strength and a simple composition. Out of three mortar mixtures a composition has been chosen so that the mortar has had almost the same characteristics as the mortar for shear tests on masonry walls to provide comparability. These tests were carried out already and they are documented in [Zimmermann 2010a]. In addition, a fourth mixture was used for additional triplet shear tests.

In a preliminary testing program, consisting of four different mixtures, mortar prisms with dimensions of 40x40x160 mm were tested to obtain compressive strength, f_m and flexural strength, $f_{m,bz}$. Table 1 show the composition of all four mortar mixtures.

	mixture I [g]	mixture II [g]	mixture III [g]	mixture IV [g]
CEM 32.5	1000	1500	2000	0
Lime	400	400	400	400
Rock flour	1200	1200	1200	0
Fine sand	4650	4650	4650	4650
Course sand 0 – 4	12445	12445	12445	12445
Water	3500	3500	3500	3250

Table 1. Investigated mortar mixtures.

The compressive strength and flexural strength were obtained according to EN 1015-11 after a curing time of 28 days. Table 2 shows the results of the preliminary testing program.

	Number of tests	mixture I [MPa]	mixture II [MPa]	mixture III [MPa]	mixture IV [MPa]
flexural strength	3	0.58	0.73	1.39	-
compressive strength	6	1.50	2.62	4.06	0.22

Table 2. Mechanical properties of mortar mixtures.

Based on these results the mortar mixture II was chosen for the first triplet shear test group because of its excellent coincidence with mortar characteristics from prior shear tests on masonry walls. The mortar mixture IV was used for the second triplet shear test group in order to obtain a possibly different behavior.

Specimens

The cut bricks became an even surface for the bearings as well as for the load application area. The height of bricks remained unchanged. The upper and lower surfaces of the specimens were confined with a cement mortar. After the specimens were built each one was pre-loaded with a compression load of about 3.0 x 10^{-3} MPa until testing. Simultaneously with building the specimens for the triplet shear tests mortar specimens of both mixtures were made for additional mortar tests.

Testing methods

In general, there is the problem of a continuously applied shear stress and normal stress along mortar joints and brick units. To avoid additional moments shear load should be applied as close as possible to the mortar joints, see [Edgell 2005]. In addition, the occurrence of tensile stresses along the joints should be prevented, because these stresses could affect the failure load [Riddington 1997]. However, some stress concentrations occur around the load introduction area and also some moment is introduced at the joint which means that it is nearly impossible to introduce a pure shear stress distribution [Van der Pluijm 1993].

The shear strength of masonry is dependent amongst other things on the shear bond properties of the mortar joints. To obtain these properties different types of specimens can be used. These test methods either consist of two, three or four bricks. A review has been published by [Jukes 1997]. Additionally experimental investigations are presented by [Abdou 2006]. Further, several test arrangements are investigated via FEM by [Stöckl 1990]. Thereby it could be shown, that in all arrangements peaks of both shear and normal stresses occur. There are also some approaches to combine the advantages of different test methods, i.e. [Popal 2010].

However, all mentioned methods have in common that they require very complex equipment and they are not a standard test method. Thus the triplet test method according to EN 1052-3 was used for the investigations presented in this paper.

Laboratory tests

Figure 2 shows the schematic test layout to determine the shear properties of old masonry. It must be mentioned that the used test set up does not fully meet the EN 1052-3 test specifications, concerning the load and reaction locations. However the test arrangement becomes more practicable because it is not necessary to ensure the right location of the roller bearings. But due to the smeared load application and smeared support situation cause a slight different reaction in those regions.

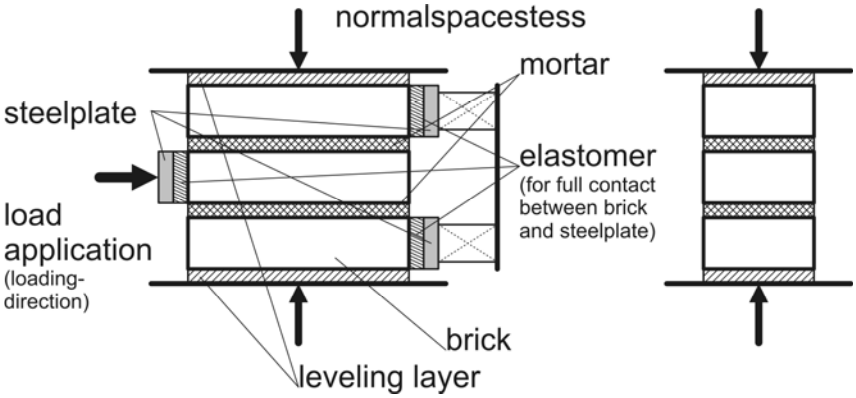

Figure 2. Schematic test layout for shear testing.

The main advantage of this testing method over previous mentioned testing methods is that bricks fully overlap. Therewith, possible influences to the shear behavior of uneven surfaces and imprints, which are typical for old bricks, are taken into account.

There are two different test procedures recommended in EN 1052-3. In the first procedure (a) specimens have to be tested at least under three different normal stress levels with at least three specimens for each level. The second procedure (b) is performed without any pre-compression with at least six specimens. In order to avoid normal tensile stresses along the mortar bed joints procedure (a) was chosen. This normal stress is undesirable since the results for the shear strength can be affected by the tensile strength of the mortar bed joints [Riddington 1997].

Two groups of specimens were tested. The testing procedure included two types of specimens with respect to the expected shear characteristics, see Table 3. Thereby the bricks are for both groups the same, but the mortar mixtures differ. In particular the mortar mixture II, which was used for group A and the mortar mixture IV, which was used for group B are shown in detail in Table 1. As documented in Table 2, the higher compressive strength of mixture II is caused from a longer curing time.

Finally, the compressive strength of masonry was determined. According to B 1996-1-1 by using compressive strength of both bricks f_b and mortar f_m, compressive strength of masonry f_k was calculated as follows:

$$f_k = K \cdot f_b^{\alpha} \cdot f_m^{\beta} \qquad \text{with } K = 0.60 \;\; \alpha = 0.65 \;\; \beta = 0.25 \qquad \textbf{[1]}$$

	compressive strength of		
	bricks MPa	mortar MPa	masonry MPa
group A	19.28	3.58	5.65
group B	19.28	0.22	2.81

Table 3. Properties of shear specimens.

Shear strength was measured by the set up shown in Figure 3 where the brick in the middle is sheared and the upper and lower bricks are supported. The horizontal shear load was applied with a hydraulic jack in the range of 15 to 115 kN. The varying pre-compression load was applied perpendicular to the shear surface.

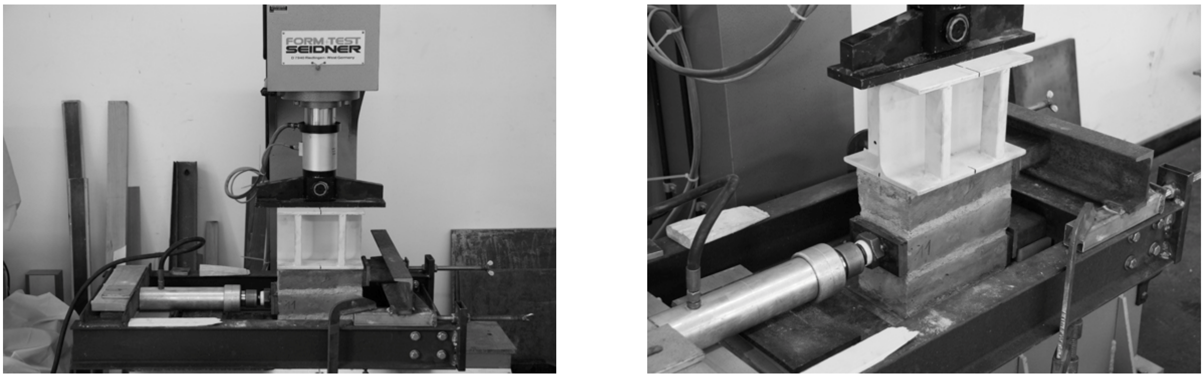

Figure 3. Triplet shear test set up.

The five vertical stress levels of 3, 7, 15, 25 and 40 % of the characteristic compressive strength f_k were applied to five specimens (in total 25 specimens) of group A. In addition, three vertical stress levels of 13, 28 and 48 % of f_k were applied to specimens of group B. In particular three tests were performed for each load level (in total 9 specimens) on this specimen group B. Those results are used for statistical assessment procedures.

Each test took about 5 minutes until shear failure occurred. There was a high fluctuation of the pre-compression load during the cracking process when pure shearing starts. The fluctuation was minimized by adjusting the pre-compression load manually. During testing the shear load and the applied pre-compression load was measured simultaneously.

Shear test results

The shear test evaluation is based on the maximum horizontal force H_{max} that has to be divided two times by the corresponding shear area = 250 x 120 mm = 30000 mm². Hence for each specimen i the shear strength $f_{v,i}$ can be calculated as follows:

$$f_{v,i} = \frac{H_{\max,i}}{2 \cdot A_i} \qquad \textbf{[2]}$$

The associated normal stress level is calculated with the applied pre-compression force N_j (j = 1...5) with respect to the corresponding shear area of the specimen i by:

$$\sigma_{d,j} = \frac{N_j}{A_i} \qquad \textbf{[3]}$$

In general, the shear strength of masonry depends on the applicable friction forces in the horizontal joints, the tensile strength of the bricks, the compressive strength of masonry and the bond strength between bricks and mortar. Furthermore it must be mentioned that the shear strength is essentially determined by the normal stress level, which is included in EN 1996-1-1 as follows:

$$f_{vk} = f_{vko} + \mu_k \cdot \sigma_d \qquad \textbf{[4]}$$

with f_{vko} = initial shear strength, without any vertical stresses, σ_d = normal stress level, perpendicular to the shear force and μ_k = coefficient of friction.

The shear test results have been evaluated according to EN 1052-3 and with a statistical approach by using 5 % fractiles of a log-normal distribution. Table 6 portrays the comparison of those evaluations.

Results from group A

The evaluation results in mean values based on Mohr-Coulomb relationship as follows:

$$f_{v,m} = 0.210 + 0.709 \cdot \sigma_d \qquad \textbf{[5]}$$

which is related with a mean value of initial shear strength f_{vo} = 0.210 MPa and a mean value of coefficient of friction μ = 0.709.

According to EN 1052-3 the characteristic value of initial shear strength f_{vko} is the minimum of either 0.8 x f_{vo} or the lowest initial shear strength of the test results. The characteristic value of coefficient of friction can be obtained in a same manner. The characteristic values result in f_{vko} = 0.17 MPa and μ_k = 0.57.

An assumption of a log-normal distribution for previous shown test results at each normal stress level allows the computation of the 5 % fractiles. Thereby the Mohr-Coulomb relationship was obtained as:

$$f_{vk,5\%} = 0.174 + 0.624 \cdot \sigma_d \qquad \textbf{[6]}$$

Figure 4 shows beside the test results the Mohr-Coulomb relationship for mean values, characteristic values according to EN 1052-3 and characteristic values based on 5 % fractiles. Further the normative relationship (indicated as “norm”) is plotted. A comprehensive analysis of the mortar properties indicated an M 2.5 – M 9 mortar class according to EN 1996-1-1. These known quantities allow the determination of the initial shear strength f_{vko} = 0.20 MPa and the coefficient of friction μ_k = 0.4.

Finally the results of this test are summarized in Table 4 by the mean values, standard deviations and 5 % fractiles.

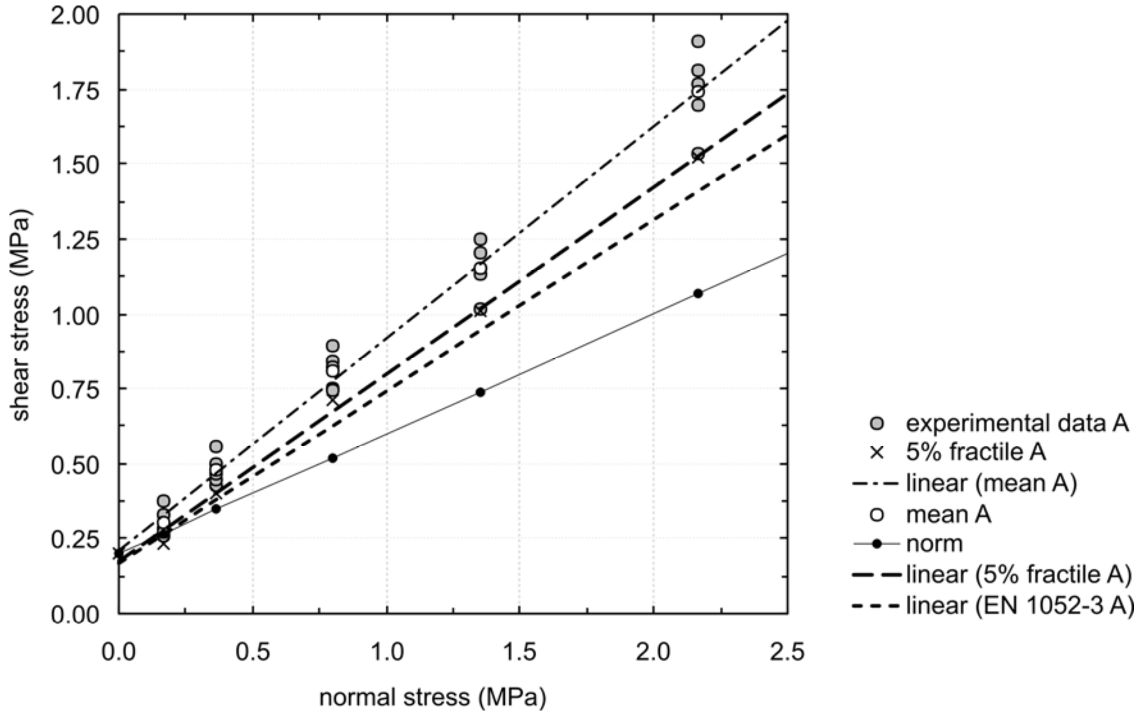

Figure 4. Shear strength with respect to normal stress, group A.

	normal force level (kN)				
	5.0	11.0	24.0	40.5	65.0
mean	0.304	0.480	0.810	1.150	1.744
standard deviation	0.0489	0.0492	0.0634	0.0890	0.1413
cov	0.1609	0.1025	0.0783	0.0774	0.0810
5 % fractile	0.2236	0.3991	0.7057	1.0036	1.5116

Table 4. Test results of shear strength (MPa) with respect to normal force level and descriptive statistical parameters.

Results from group B

The evaluation results in mean values based on Mohr-Coulomb relationship as follows:

$$f_{v,m} = 0.027 + 0.643 \cdot \sigma_d \quad \textbf{[7]}$$

which is related with a mean value of initial shear strength f_{vo} = 0.027 MPa and a mean value of coefficient of friction μ = 0.643.

According to EN 1052-3 the determination of characteristic values is the same as described above. Hence the characteristic values result in f_{vko} = 0.01 MPa (lowest value of the test results) and μ_k = 0.51.

An assumption of a log-normal distribution for previous shown test results at each normal stress level allows the computation of the 5 % fractiles. Thereby the Mohr-Coulomb relationship was obtained as:

$$f_{vk,5\%} = 0.014 + 0.623 \cdot \sigma_d \quad \textbf{[8]}$$

Again, Figure 5 shows beside the test results the Mohr-Coulomb relationship for mean values, characteristic values according to EN 1052-3 and characteristic values based on 5 % fractiles. Further the normative relationship (indicated as “norm”) is plotted. A comprehensive analysis of the mortar properties indicated an M 1 – M 2 mortar class according to EN 1996-1-1. These known quantities allow the determination of the initial shear strength f_{vko} = 0.10 MPa and the coefficient of friction μ_k = 0.4.

Finally the results of this test are summarized in Table 5 by the mean values, standard deviations and 5 % fractiles.

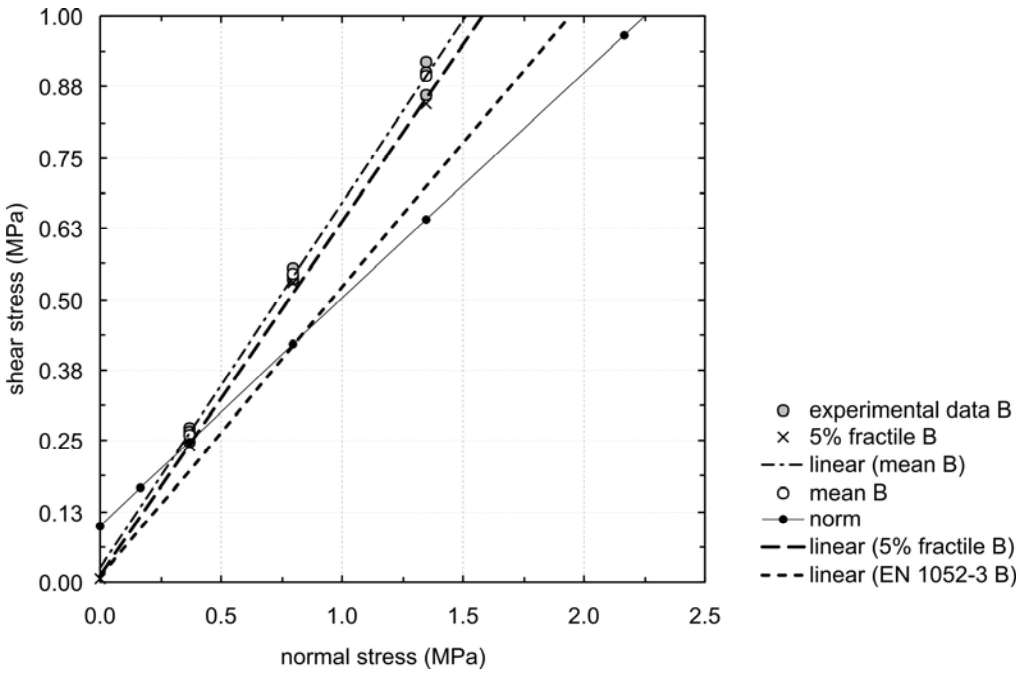

Figure 5. Shear strength with respect to normal stress, group B.

	normal force level (kN)				
	5.0	11.0	24.0	40.5	65.0
mean	-	0.261	0.544	0.893	-
standard deviation	-	0.0125	0.0092	0.0302	-
cov	-	0.0479	0.0169	0.0338	-
5 % fractile	-	0.2410	0.5291	0.8445	-

Table 5. Test results of shear strength (MPa) with respect to normal force level and descriptive statistical parameters.

	mortar group A		mortar group B	
	EN 1052-3	5 % fractiles	EN 1052-3	5 % fractiles
initial shear strength f_{vko}	0.17	0.174	0.01	0.014
coefficient of friction μ_k	0.57	0.624	0.51	0.623

Table 6. Comparison of characteristic values of initial shear strength and coefficient of friction, evaluated according to EN 1052-3 and based on 5 % fractiles.

Numerical verification

Numerical investigations were carried out, based on a calibrated material model. Detailed properties of the material model and the calibration procedure can be found in [Zimmermann 2010b]. The objective of the numerical study was to carry out the interaction between compression and shear stress for different crack widths. The crack width indicates the opening in mm of a crack in the numerical model. Thereby different widths, starting from 0.1 mm up to 0.4 mm were considered. Further these numerical investigations should serve as verification for the obtained results from shear tests.

Figure 6 shows numerical results for different stress levels and crack widths respectively. These discrete simulation results were very consistent with the Mohr-Coulomb's friction law according to Equation [4]. As it can be seen from Figure 6 the coefficient of friction is independent of the crack width whereby the investigated masonry material demonstrate a coefficient of friction of μ = 0.67. In contrast, for initial shear strength, a significant dependence on crack width was determined.

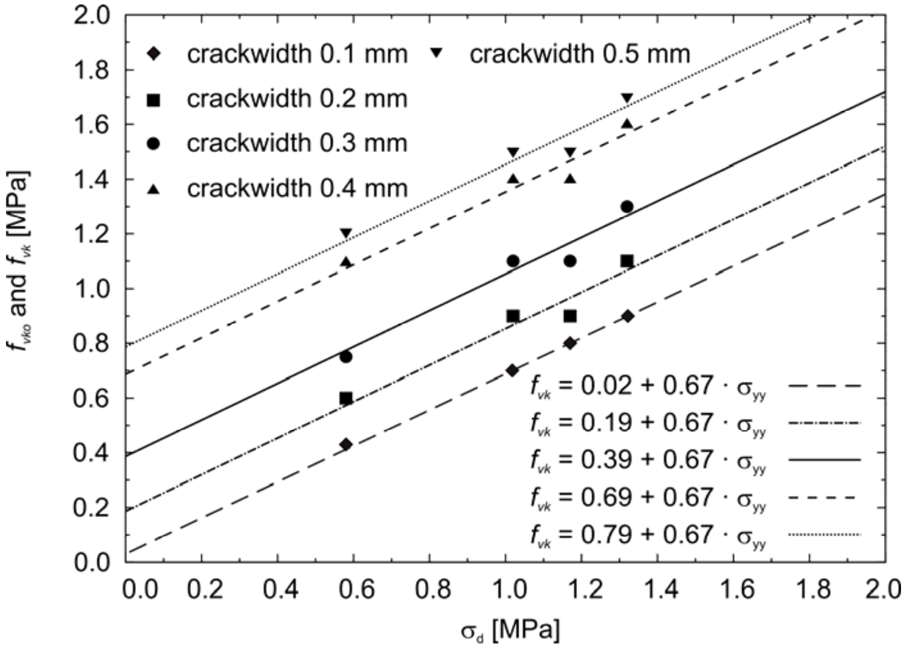

Figure 6. Interaction between compressive and shear stress.

Conclusions

As a part of the research project SEISMID, several tests on masonry were carried out. Thereby the focus was on testing the shear behavior of masonry triplets under different conditions according to EN 1052-3, but with some modifications regarding load application and support situation. Additional tests on bricks and mortar were carried out to determine the basic material properties.

To obtain possible influences on the shear behavior of masonry two different groups of shear triplets were built and tested under different normal stress levels. The two groups (A and B) differ in terms of compressive strength of mortar ($f_{m,A}$ = 3.58 MPa and $f_{m,B}$ = 0.22 MPa). The evaluation of the test results show that the shear behavior can be described by the Mohr-Coulomb friction law. Thereby characteristic initial shear strength f_{vko} and characteristic coefficient of friction μ_k have been determined according to EN 1052-3 and based on a statistical approach. Both evaluations were compared to each other and compared to the values according to EN 1996-1-1. Thereby it can be seen that there are agreements but also disagreements.

In the case of specimen group A the mean value of initial shear strength from testing (0.210 MPa) is in good accordance with the suggested normative value (0.20 MPa). In case of group B there is no agreement between the values from testing (0.027 MPa) and EN 1996-1-1 (0.10 MPa). This disagreement is mainly due to the mortar mixture, because mortar of group B has not any cement and just a small amount of lime, compare Table 1. Hence, no significant initial shear strength between mortar joints and bricks can be developed.

The evaluation of the characteristic value of initial shear strength according to EN 1052-3 results in f_{vko} = 0.17 MPa for mortar group A and f_{vko} = 0.01 MPa for mortar group B. If the evaluation is based on 5 % fractiles of a log-normal distribution the values results in f_{vko} = 0.174 MPa for mortar group A and f_{vko} = 0.014 MPa for mortar group B. As can be seen there are no significant differences of the calculated values. This indicates that both evaluation procedures are suitable to derive characteristic values from experimental test results.

The comparison of initial shear strength from experimental testing and numerical investigation is for both specimen groups in a good agreement if common crack widths of 0.1 mm and 0.2 mm are considered. The numerical determined initial shear strength is 0.02 MPa for a crack width of 0.1 mm and 0.19 MPa for a crack width of 0.2 mm.

Initial shear strength can be only assumed in an undamaged state and if the bond between bricks and mortar joints is intact. If cracking occur the initial shear strength should be omitted, because in that state the shear strength is only due to friction. When thereby the coefficient of friction is assumed to be equal before and after cracking of the specimen Equation [4] can be extended by an additional parameter κ.

$$f_{vk} = \kappa \cdot f_{vko} + \mu \cdot \sigma_d \qquad \textbf{[9]}$$

This parameter takes into account the crack condition whereby $\kappa = 1$ for the uncracked state and $\kappa = 0$ for the cracked state, see also [Vermeltfoort 2009].

The comparison of the coefficient of friction shows a big gap between test results and the value according to EN 1996-1-1. The normative value for the coefficient of friction is suggested to be 0.4. The experimental data show that the percentage of normal stress on the shear strength amounts 0.71 in case of group A and 0.64 in case of group B respectively, based on mean values.

The evaluation of the characteristic value of coefficient of friction according to EN 1052-3 results in $\mu_k = 0.57$ for mortar group A and $\mu_k = 0.51$ for mortar group B. If the evaluation is based on 5 % fractiles of a log-normal distribution the values results in $\mu_k = 0.624$ for mortar group A and $\mu_k = 0.623$ for mortar group B. As can be seen there are differences of the calculated values. This indicates that the evaluation procedure according to EN 1052-3 procedure is more conservative because mean values are multiplied by 0.8 to derive the characteristic values and any additional information of test results is neglected. These additional information are accounted by the statistical approach.

If further, the numerical results are taken into account a very good agreement can be seen. The obtained coefficient of friction from numerical investigations has been determined with $\mu = 0.67$.

Also a literature review shows that the normative value for the coefficient of friction is too low. For instance [Vermeltfoort 2010] obtained in an extensive experimental program coefficients of friction from 0.66 to 0.91. [Abdou 2006] evaluated the coefficient for solid and hollow bricks with 0.88 and 0.89 respectively. [Lourenço 2004] indicates a range between 0.7 and 1.2.

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Standards

EN 772-1: Methods of test for masonry units – Part 1: Determination of compressive strength, 2000.

EN 772-16: Methods of test for masonry units – Part 16: Determination of dimensions, 2005.

EN 1015-11: Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened masonry, 2007.

EN 1052-3: Methods of test for masonry – Part 3: Determination of initial shear strength, 2007.

EN 1996-1-1: Eurocode 6 Design of masonry structures – Part 1-1: Common rules for reinforced and unreinforced masonry structures, 2006.

B 1996-1-1: Eurocode 6 National specifications: Design of masonry structures – Part 1-1: Common rules for reinforced and unreinforced masonry structures , 2006.

Notation

L,B,H	length, width, height	$f_{v,i}$	shear strength of *i*-th test	H	horizontal force
A	area			N	normal force
f_b	compressive strength of bricks	f_{vo}	mean value of initial shear strength	K	coefficient
				α, β	coefficients
f_m	compressive strength of mortar	$f_{v,m}$	mean value of shear strength	ρ_d	dry density
				μ	mean value of coefficient of friction
$f_{m,bz}$	flexural strength of mortar	f_{vko}	initial shear strength		
		f_{vk}	shear strength	μ_k	coefficient of friction
f_k	compressive strength of masonry	$f_{vk,5\%}$	5% fractile of shear strength	σ_d	normal stress
				κ	crack parameter

Index *k* denotes characteristic value