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IN PLANE SHEAR STRENGTH OF VERTICALLY PERFORATED CLAY UNIT MASONRY – A SURVEY OF RECENT TEST RESULTS

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Abstract

The shear strength is the decisive material property for masonry subjected to in plane lateral loads such as wind and earthquake. Due to the lack of a suitable harmonised test method and suitable input parameters for a suitable design model there are still many questions open in that field. The paper gives an overview of recent tests on the in plane shear strength of vertically perforated clay unit masonry in Europe as well as an evaluation of their results.

Key Words

In plane shear strength, clay unit masonry, test methods

1 Introduction

The shear strength of masonry is the most important parameter for in plane laterally loaded masonry. Although there are some ideas about the relevant material properties, there are no harmonised test standards available which take the real stress distributions in laterally loaded walls into account.
The latest version of Eurocode 6 has already taken into account the fact, that the unit tensile strength has to be taken into account in the evaluation, but due to the small knowledge in that field and the different types of masonry structures and materials throughout Europe, values have been proposed that seem to be inappropriate for many unit/mortar combinations.
A survey of the existing German test results on clay unit masonry in 1999 has been given before (Meyer 2000). In the meantime, a significant number of additional tests with different set-ups has been carried out, unfortunately without solving the basic problems. This paper gives a summary of the current knowledge.

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2 Failure modes and test methods for in plane laterally loaded masonry walls

There are three main failure modes for in plane laterally loaded masonry walls, see fig. 1.

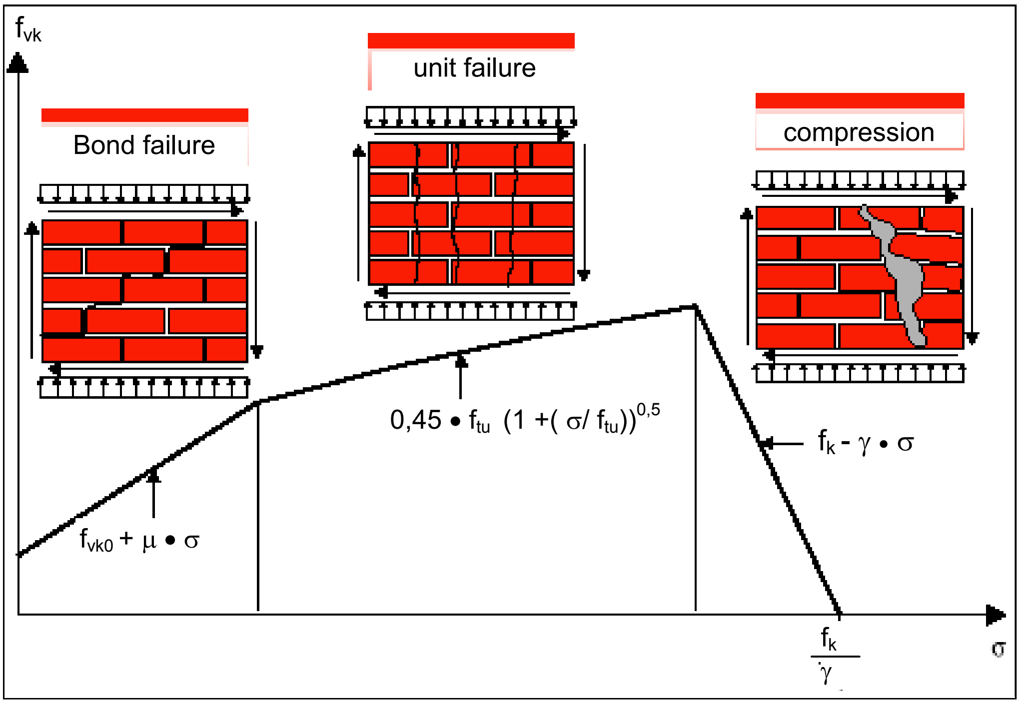

Fig. 1 Failure modes for in plane laterally loaded masonry walls (Mann/Müller 1982)

The relevant failure mode for a wall depends at least on the compressive and tensile strength of the masonry units, the bond strength between units and mortar and the amount and eccentricity of the applied vertical load. These failure criteria are different for every unit-mortar combination as the relationship between the tensile strength of the unit and the bond strength differs for these combinations. For low vertical loads, bond failure is most probable as it is for high strength units in combination with mortars with poor bond properties. Unit failure will be dominant for most types of masonry and load levels, especially for units in combination with high bond thin layer mortar. Compressive failure of units can occur in the case of high load eccentricities.

The only currently available harmonised European test method in that field, EN 1052-3, determines only the bond strength between unit and mortar. In addition, it is very questionable if the occurring stresses in the specimen are comparable to those occurring in a wall under horizontal in plane loads.

In Germany, a test method has been developed in the 1980s to apply pure shear stresses on a wall specimen.

This test combined the application of a diagonal compression applied across concrete beams fixed to the specimen with a horizontal compensation of the applied bending moment. These tests are extremely expensive and very sensitive to correct execution of the specimen, but the results can be satisfactorily reproduced in different test labs. The currently existing harmonised version does not contain the horizontal compensation of the moment any more, see fig. 2. The consequences of this modification on the test results have to be carefully checked in future research projects on that topic.

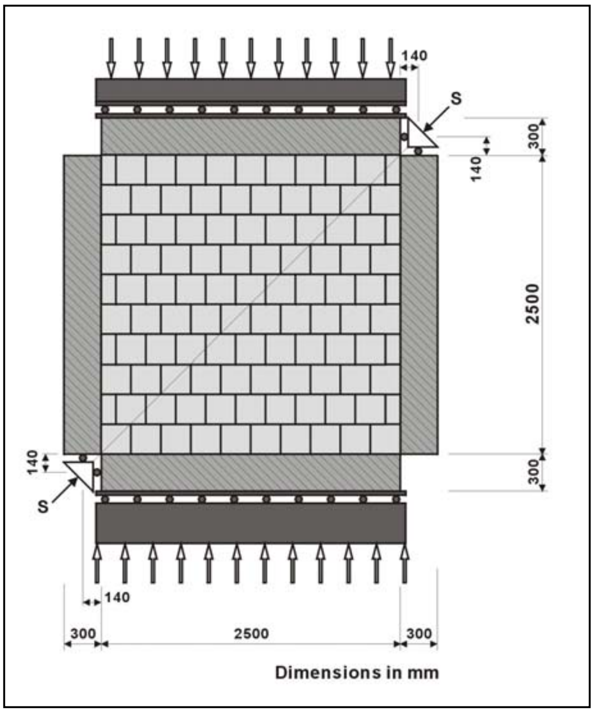

Fig. 2 Harmonised German test set-up for the determination of the shear strength of masonry walls (Roßbach, Schubert et al. 2003)

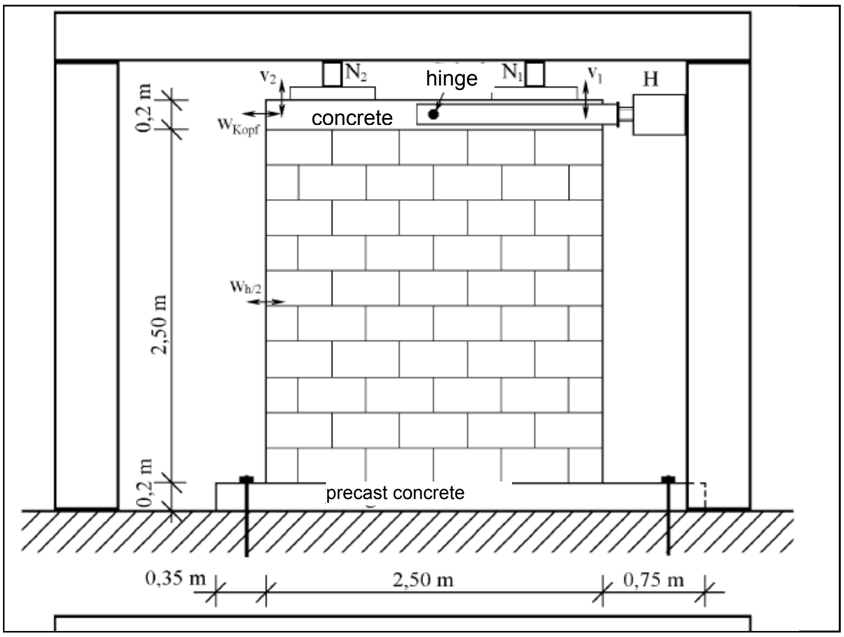

Fig. 3 Test set-up for masonry walls under in plane lateral loads (Schermer and Zilch 2004)

In recent tests on the earthquake resistance of masonry walls in Germany, a more puristic approach has been chosen, using specimens where horizontal loads were applied via a concrete cap beam with an additional compensation of the applied vertical forces, see fig. 3.

For this type of test specimen, the failure mode depends extremely on the size of the specimen and the applied vertical load. A shear failure can only be obtained for small ratios of height h vs. length l, as for higher h/l-ratios a compressive failure in the corners of the specimen will be the dominant failure mode.
An important task that will be focussed in the ESECMaSE research project (Caballero et al. 2004), sponsored by the European commission, will be the determination of one or more appropriate test method(s) for all relevant failure criteria.

3 Recent test results

3.1 Tests with diagonal compression

The available test results for vertically perforated clay unit masonry in Germany have been presented before (Meyer 2000). In the meantime, some additional test on walls made of units meeting the requirements of the German clay unit standard DIN 105 have been carried out. All relevant available values are given in fig. 4 together with the design characteristic strength curves (Mann and Müller 1982) based on the theoretical failure criteria for clay unit masonry (unit strength 15 N/mm²) and general purpose mortar M 5 or thin layer mortar as well as the limiting value for unit failure from EN 1996-1-1. All test results are significantly above the design characteristic strength determined acc. to (Mann and Müller 1982). In addition, the failure mode predicted by calculation does not correlate with the failure of the test specimens. This indicates once more, that the input parameters for calculation as well as the design formulae have to be carefully checked and improved to exploit the hidden reserves in the resistance of vertically perforated clay unit masonry walls.

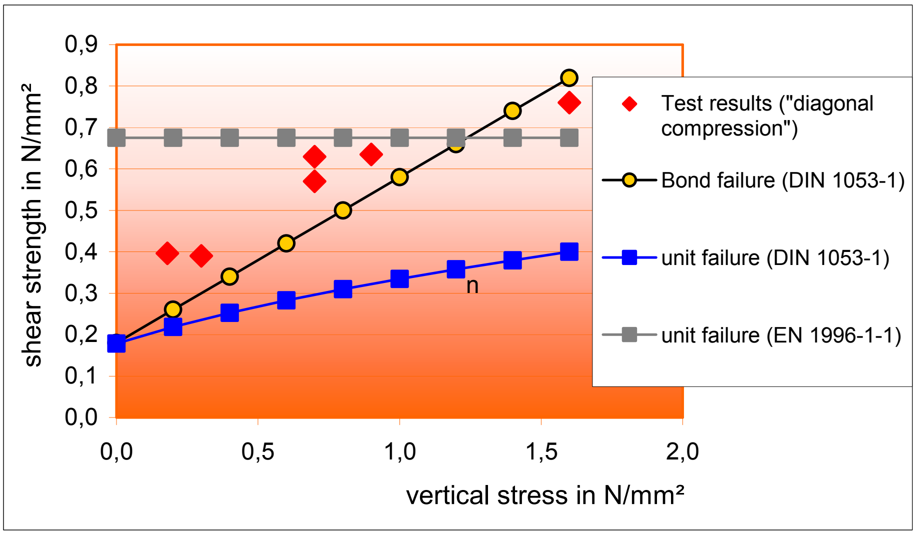

Fig. 4: Test results with specimens acc. to fig. 2

3.2 Tests with horizontal forces applied via a concrete head beam

A series of cyclic shear tests has been carried out by different researchers (Schermer 2004, Ötes 2003, Tomazevic 2004, Ötes 2004) in order to determine the behaviour of vertically perforated clay unit masonry under earthquake loads. Fig. 5 and 6 show some of the clay units used in these tests. The units used in (Ötes 2004) are designed to be filled with concrete and were used in that way in the tests. This type of construction leads to a significant improvement of the resistance of clay unit masonry, especially if the masonry is executed as confined masonry acc. to EN 1998-1. Table 1 gives some characteristic material properties of these units.

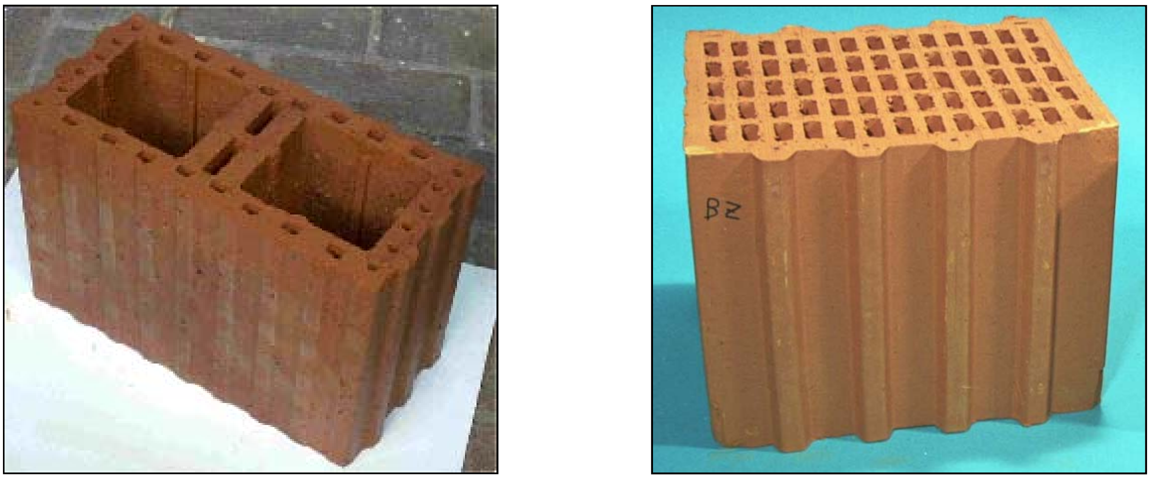

Fig. 5: units used in Ötes (2004) and Tomazevic (2004)

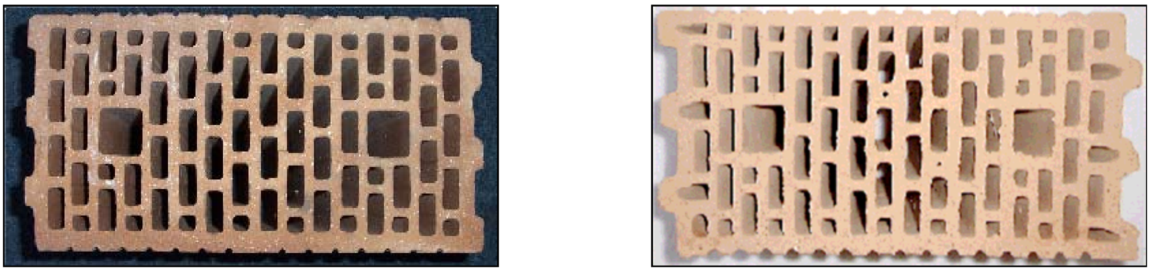

Fig.6: units used in Schermer (2004) and Roßbach (2003)

Table 1: Compressive strength of units normal and parallel to the bed joints, dry density and dimensions

Report	f_b [N/mm²]	$f_{b,\ parallel}$	Dry density [kg³]	Dimensions [mm]
Schermer 2003	16,5	2,7	900	497x175x249
Ötes 2003	14,5	2,8	770	492x172x241
Tomazevic 2004	8,6 – 15,1	4,0 – 6,2	800	245x299x(237/248)
Ötes 2004	15,4	3,6	800	374x175x249
Roßbach 2003	17,8	2,8	740	373x175x249

The specimens were tested with set-ups similar to the one shown in fig. 3, the dimensions are described in detail in table 2. The specimen used by (Tomazevic 2004) was designed as a cantilever wall and in a way that compressive failure of the units in the corners of the specimen became the governing failure mode for most of the specimens. It is therefore critical to evaluate the results in relation to shear strength, but one can at least conclude that the shear strength in the specimen is higher than the calculated value. Most other tests were carried out with an additional restraint at the top of the specimen. Table 2 gives an overview about the applied vertical stress, the maximum applied horizontal force, the displacement of the top of the specimen at that force and the calculated shear strength. The shear strength was calculated by definition as a mean value across the compressed part of the specimen in the lower third of the specimen for the cantilever walls and as the strength in mid height for the other walls. This definition has been chosen as some of the cracks observed in the tests started developing in that area. Although the compressed area of the specimen under horizontal loads is smallest on the bottom of the specimen, there seems to be a

positive restraining effect. (Tomazevic 2004) defined the relevant cross section as the mid-height of the specimen as well and therefore derived other values for the shear strength. This topic is under discussion and will hopefully be solved in the ESECMaSE project, where one work package will deal with the determination of the relevant cross-sections for design by FE-calculation.

Table 2: Tests on the cyclic horizontal load-bearing capacity of vertically perforated clay unit masonry; Test report, geometry of specimen (h x l x t), applied vertical stress, maximum horizontal force, associated displacement, calculated shear stress

test report	geometry h x l x t m	applied verti-cal stress N/mm²	maximum horizontal force kN	top displacement at maximum horizontal force mm	calculated shear stress N/mm²
Tomazevic 2004	1,50 x 1,00 x 0,30	0,69	55,0	9,44	0,304
		1,30	98,8	5,70	0,475
		0,69	56,2	9,54	0,321
		1,40	112,0	9,65	0,637
		1,38	109,4	7,18	0,600
		0,77	65,9	9,74	0,517
		1,38	101,7	9,84	0,532
		1,39	102,9	12,50	0,547
		1,32	93,8	14,96	0,444
		1,42	106,3	6,00	0,593
		1,45	110,3	7,48	0,652
		1,45	111,0	9,65	0,663
		1,37	100,4	5,31	0,517
		1,40	103,8	7,48	0,559
		1,39	102,4	5,71	0,541
		1,47	114,3	9,94	0,719
		2,10	154,9	7,48	0,815
		2,24	172,9	12,40	1,081
Ötes 2003	2,50 x 2,50 x 0,175	0,50 [1)]	140,0	4,80	0,320
		0,50	100,0	5,40	0,390
Schermer 2003	2,50 x 2,50 x 0,175	0,80 [1)]	154,9	4,50	0,576
Ötes 2004	2,50 x 1,88 x 0,175	0,50 [1)]	130,0	12,5	0,395
		0,50 [1)]	166,0	6,0	0,505

[1)] additional vertical forces applied to head beam to avoid a cantilever type performance of the wall tested

4 Comparison of test results with the design values of Eurocode 6 and DIN 1053-1

Eurocode 6-1-1 gives the design equation for in plane shear as

$f_{vk} = f_{vko} + 0{,}4\ \sigma_d \leq 0{,}065\ f_b$ or f_{vlt} (1)

for filled head joints and

$f_{vk} = f_{vko} + 0{,}4\ \sigma_d \leq 0{,}045\ f_b$ or f_{vlt} (2)

for unfilled head joints

taking into account bond failure between units and mortar as well unit failure with f_{vlt}. The limiting value for unit failure was intensively discussed. The German proposal from DIN 1053-1

$f_{vlt} = 0{,}45\ f_{tu}\ (1+ \sigma_d/f_{tu})^{0{,}5}$ (3)

derived from theoretical work by (Mann and Müller 1982) was not accepted by the majority of CEN TC 250/SC 6 but the property finally became a NDP value. Fig. 7 compares the available test results for specimens with unit failure to the recommended design limiting value for unit failure $f_{vk} = 0{,}045\ f_b$.

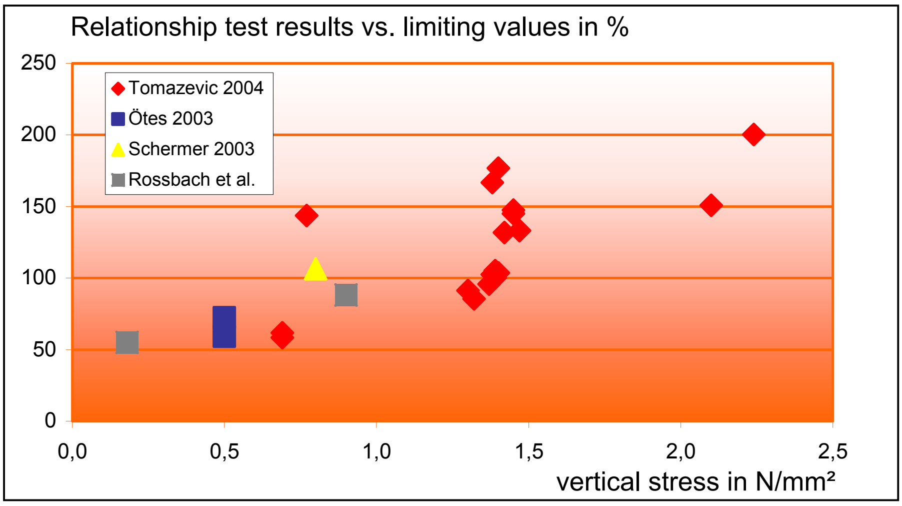

Fig. 7 Relationship between calculated shear stress from tests and limiting value of the characteristic design shear strength in EN 1996-1-1 vs. vertical stress

The figure indicates that there is a correlation of the shear stress with the applied vertical load for unit failure. Especially for vertical stresses below approximately 1,5 N/mm², the test results are below the limiting design value from Eurocode 6. This is due to the ignorance of the influence of the vertical stresses on the shear strength in case of unit failure. It is obvious that the limiting design value from EN 1996-1-1 is not suitable for the description of the shear resistance of vertically perforated clay unit masonry. Fig. 8 gives a comparison with equation (3) from DIN 1053-1.

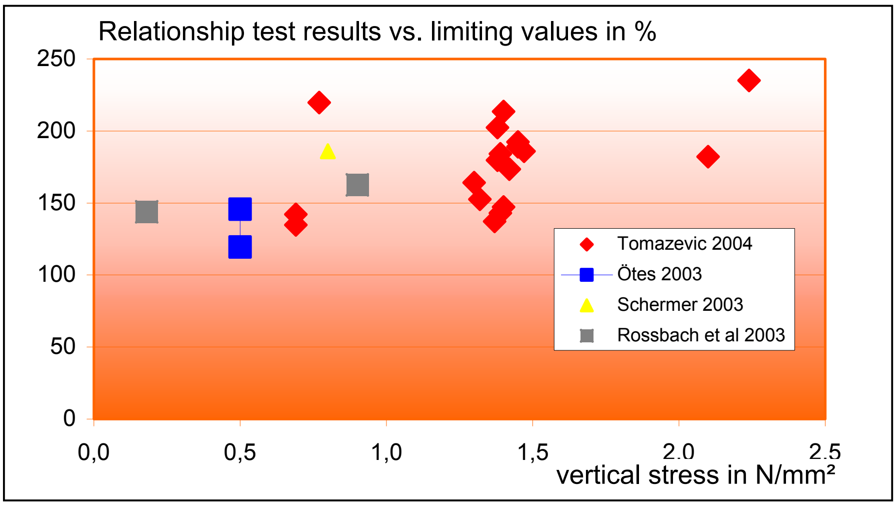

Fig. 8 Relationship between calculated shear stress from tests and design shear strength for unit failure in DIN 1053-1 vs. vertical stress

This limiting equation (3) is obviously very much on the safe side, with the test results between 20 and 135% higher than the calculated values. In addition, the influence of the vertical stresses does not seem to be adequately taken into account, as the relationships increase slightly with increasing vertical stresses. The existing reserves in vertically perforated clay unit masonry should be made available for design in the future by adaptation of appropriate design equations.

6 Conclusions

A series of shear tests on vertically perforated clay unit masonry has been carried out in the last years. A comparison shows that the proposed limiting value for unit failure from EC 6 is not appropriate. A better correlation of test results and design values was found for equation (3) from (Mann and Müller 1982) and DIN 1053-1, although there is a significant underestimation of the test results with that equation. A more appropriate description of the shear resistance of masonry walls is needed in the future to meet the requirements caused by increased horizontal loads, as given in EN 1991-1-4 for Wind and EN 1998-1 for earthquake loads and new load combinations resulting from EN 1990.

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