OPTIMISATION OF VERTICALLY PERFORATED CLAY UNITS FOR CENTRAL EUROPEAN SEISMIC AREAS

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SUMMARY

Increased requirements resulting from the load codes were the starting point of investigations into the loadbearing behaviour of masonry walls under in plane shear loads. One among many other aspects is the optimisation of the product properties of vertically perforated clay units in shear walls. The optimisation process, carried out within the EU-sponsored research project ESECMaSE, comprised an optimisation of the material composition as well as an optimisation of the perforation pattern. Prototype units were produced and tested. The relevant material properties of the units were significantly improved, but the optimisation didn’t result in a significantly improved resistance of the shear walls to horizontal loads under practical conditions. The results are discussed.

INVESTIGATIONS INTO THE MATERIAL COMPOSITION

Investigations carried out at the Institut für Ziegelforschung (Roßbach and Hauck, 2004) aimed at the determination of the influence of material composition and firing temperature on the relevant material parameters for masonry units in shear, i.e. the tensile strength and the modulus of elasticity.

As shown in many previous investigations, the firing temperature has some influence on these parameters. Unfortunately, the results are only valid for the tested type of material and can not be generalized. Raw materials from three participating clay unit producers in Austria, Germany and Italy were included in the tests in (Roßbach and Hauck, 2004).

Figure 1 shows the test set-up for the determination of the tensile strength of shells, developed by ibac Aachen (Metzemacher et al. 1990). The tests are carried out with specimens of dimensions 160 mm x 40 mm x thickness of the shell with a load application through a gripper that increases horizontal forces with increasing tensile forces in the specimens. The determined tensile strengths (mean values of a series of 6 specimens) for different firing temperatures for the three basic materials AO trough CO and one material modification A1 (replacement of 5% by mass with loam) are given in figure 2. The firing temperatures were chosen according to the situation in the relevant factory. Table 1 gives the mean values and corresponding standard deviations from figure 2.

The investigations showed a significant influence of the firing temperature on the firing shrinkage of the materials, see figure 3. For materials AO and CO, the firing shrinkage increased significantly with higher firing temperatures. The mass modification A1 decreased the firing shrinkage of mass AO by 40 % to 75 % for the tested temperatures.

Table 1: Tensile strength (mean values f_t and standard deviation sd) of clay shells and firing temperature (Roßbach and Hauck, 2004)

Material	Firing temperature							
	870°C		900°C		930°C		960°C	
	f_t	sd	f_t	sd	f_t	sd	f_t	sd
	N/mm²							
A0	nd	nd	5,43	0,485	5,49	0,411	5,05	0,995
A1	nd	nd	6,47	0,841	6,23	0,803	8,45	0,402
B0	3,01	0,353	2,74	0,164	3,51	0,451	nd	nd
C0	2,12	0,261	2,20	0,082	2,51	0,263	nd	nd

nd: not determined

Figure 1: Test set-up (Metzemacher et al. 1990)

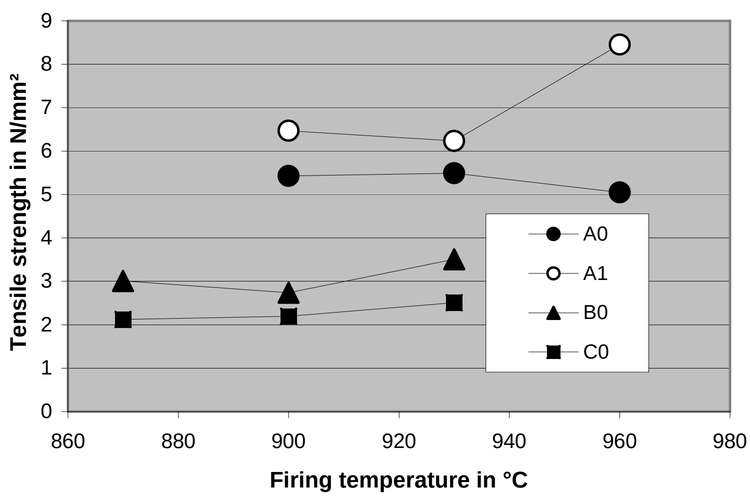


Figure 2: Tensile strength of shells and firing temperature (Roßbach and Hauck, 2004)

Material AO showed the highest tensile strength of the basic materials. This material was therefore chosen for further mass modifications and the production of prototypes.

The firing temperature did not influence the tensile strength significantly, i.e. to a magnitude exceeding the coefficient of variation, except for modification A1 and 960°C where an increase of more than 67% of the tensile strength was obtained.

The coefficient of variation of the tensile strength of the specimens was within 4 to 19 % (standard deviations between 0,08 and 1,00 N/mm²), a typical range for mineral building materials.

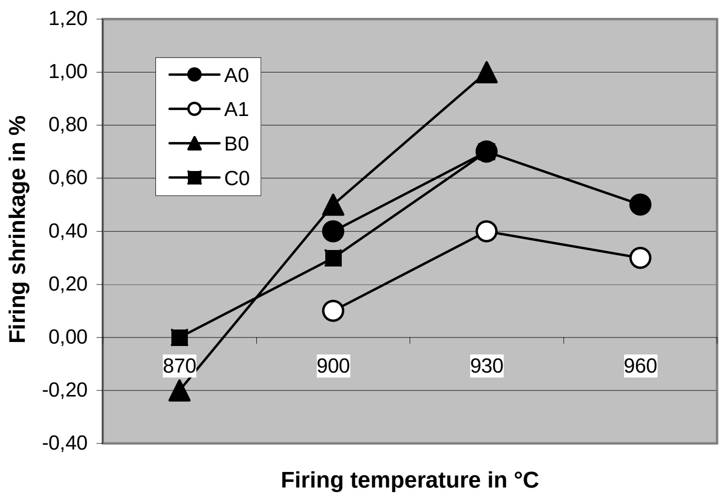


Figure 3: Linear firing shrinkage and firing temperature (Roßbach and Hauck, 2004)

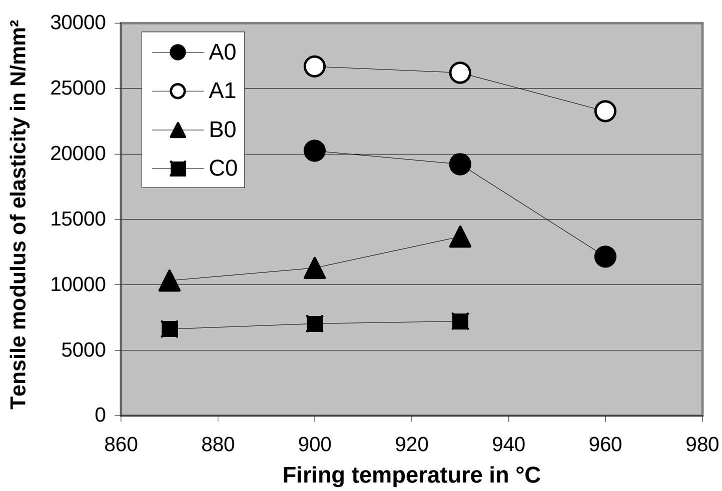


Figure 4: Tensile modulus of elasticity of clay unit shells and firing temperature (Roßbach and Hauck, 2004)

Figure 4 shows the modulus of elasticity for the different materials and firing conditions. For materials AO and A1, an increase of the firing temperature decreased the modulus of elasticity.

The ultimate tensile strains are given in figure 5. The highest value was determined for the firing temperature 960°C and mass A0.

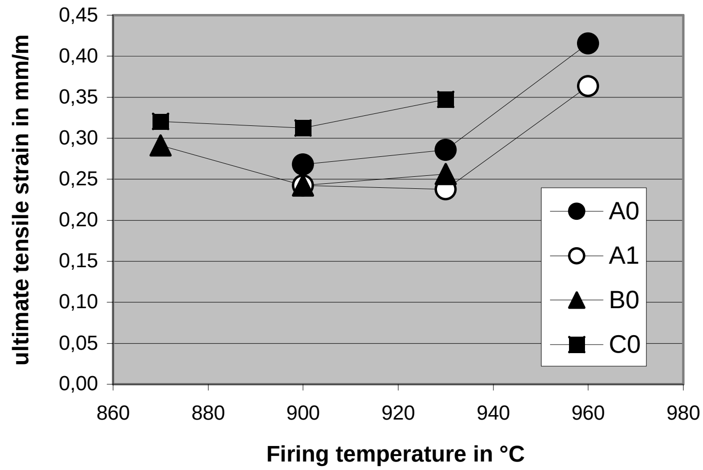


Figure 5:Ultimate tensile strain of clay unit shells and firing temperature (Roßbach and Hauck, 2004)

NUMERICAL INVESTIGATIONS INTO THE INFLUENCE OF THE PERFORATION PATTERN

Vertically perforated bricks for loadbearing inner walls in Central Europe are typically 140 to 240 mm wide and have a perforation pattern shown in figure 6 for a 175 mm wide unit. These units are optimised for sound insulation and productivity reasons with straight webs perpendicular to the outer face of the wall. In the case of in plane loads, there are normally just the two outer shells capable to resist the forces, see figure 6.

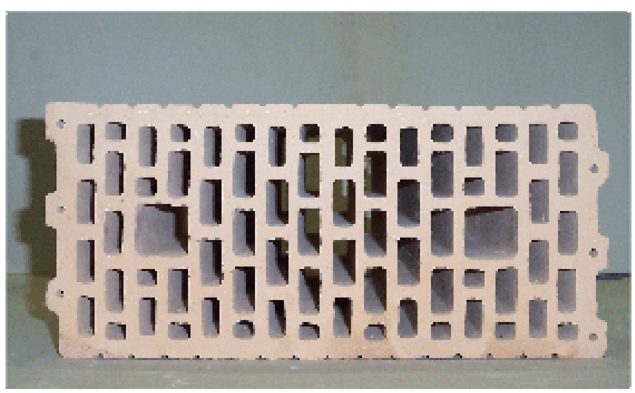
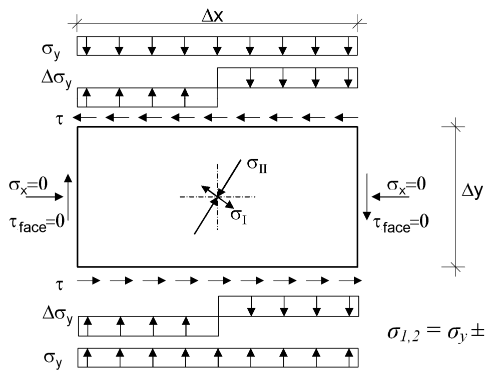


Figure 6: Typical clay unit for loadbearing walls in central Europe (HLzB)

This typical perforation pattern was the starting point for a series of optimisation steps based on finite element calculations described in detail in (Schermer 2005).

The numerical investigations started with a spatial shell model using the finite element method where the shear- and normal stresses were applied consistent with the boundary conditions in shear walls (see figure 7).



$$\sigma_{1,2} = \sigma_y \pm \Delta\sigma_y = \sigma_y \pm |\tau| \cdot 2 \cdot \Delta y/\Delta x$$

Figure 7: Stress assumptions for a single unit under combined normal- and shear-stresses (Mann and Müller 1982)

The analysis of the results with the localisation of the relevant maximum tensile stresses and the corresponding initial crack orientation couldn't be carried out in a satisfactory way, using the linear-elastic assumption in the applied model. The application of non-linear material behaviour was not possible, as no suitable models for the brittle behaviour are available so far. It wasn't possible to consider the spatial effects, e.g. numerically caused stress peaks in the corners, or the effects of firing cracks in the brittle material.

As a consequence, the investigations were simplified in the next step to a plane 2 D-model with constant tensile stresses in the longitudinal direction. It was assumed, that under combined action on the units, the stresses in the longitudinal direction are decisive and representative for the behaviour and the failure of the units. The calculations were analysed on one hand based on the maximum tensile stresses occurring in the critical section. On the other hand on a design process consistent with the general design procedure of concrete shells in form of the integration of the required reinforcement was used. In addition, the sum of the cross section area in the relevant section was taken in account.

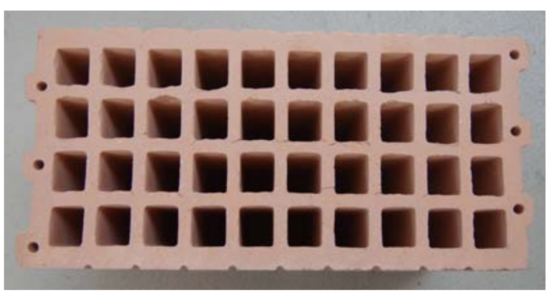


Figure 8: Perforation pattern of the prototype clay unit Nr. 1

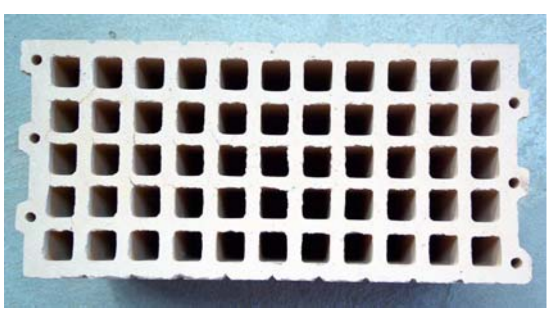


Figure 9: Perforation pattern of the prototype clay unit Nr. 2

The calculations at the Technical University of Munich (Schermer 2005) showed the positive influences of additional webs parallel to the face of the unit as well as of uniformly distributed webs parallel and perpendicular to the shells. For the perforation pattern with three straight internal webs (see figure 8) an increase of the tensile strength in the range of 50% was predicted.

DEVELOPMENT OF AN EXTRUSION DIE

Based on the results of (Roßbach and Hauck, 2004) and (Schermer 2005), an extrusion die was developed at Ziegelwerk Bellenberg in cooperation with Arbeitsgemeinschaft Mauerziegel and Ziegelmundstücksbau Braun.

The results of the calculations in Munich as well as requirements from the building site were taken into account and resulted in the perforation pattern chosen for the extrusion die shown in figure 8. This pattern takes into account the possibility of the typical construction method for general purpose mortar putting two thumbs in diagonal holes as well as the bricklaying with special devices for masonry with thin layer mortar.

UNIT PROPERTIES OF THE OPTIMISED LAYOUTS

Prototype units with the extrusion die Nr. 1 were produced at Bellenberg and tested at the Munich University (Grabowski 2006). The production did not take benefit of the results concerning the material optimisation in (Roßbach and Hauck, 2004), as the density of the optimised units was expected to be too low for that type of clay unit to be accepted in the market. The production costs for firing temperatures of 960°C also exceeded the limits of economic efficiency taking the exploding energy costs into account. Table 2 shows the most important material properties of the prototypes Nr. 1 and 2 in comparison with the typical perforation pattern HLzB.

Table 2: Type of unit, Compressive strength perpendicular to the bed joint f_b, Compressive strength parallel to the bed joint f_{bl}, splitting tensile strength $f_{t,sp}$

Type of unit	Dry density kg/m³	percentage of voids	f_b	f_{bl}	$f_{t,sp}$
			N/mm²		
HLzB (see figure 6)	810	40,7	19,3	2,5	0,61
Prototype No. 1 (see figure 8)	780	44,7	14,1	4,9	0,38
Prototype No. 2 (see figure 9)	850	43	16,9	4,8	0,83

The compressive strength f_b of the optimised units perpendicular to the bed joints was significantly lower than for the conventional units. The compressive strength parallel to the bed joints f_{bl} was, on the other hand, almost doubled.

This strength is regarded as a decisive parameter for the suitability of masonry units in earthquake regions in most of the national codes in Europe. The requirements for f_{bl} range from 1,5 N/mm² in the Italian National Standard [6] to 2,0 N/mm² in Eurocode 8 – EN 1998-1 [7].

The splitting tensile strength $f_{t,sp}$, which is proposed as an alternative method for the determination of the relevant tensile strength for anisotropic masonry units in (Grabowski 2005), was not improved at all. It was nevertheless expected to achieve a significantly improved shear resistance of masonry walls with Prototype No. 1 units. As this was not the case, prototype Nr. 2 was produced and tested in additional shear tests.

STATIC-CYCLIC TESTS ON FULL SCALE SHEAR WALLS

A series of static-cyclic shear tests with conventional and optimised units (Prototypes No. 1 and 2) was carried out at the Kassel University, the detailed results will be presented elsewhere in these proceedings (Fehling and Stürz 2008). The test set-up is shown in figure 10.

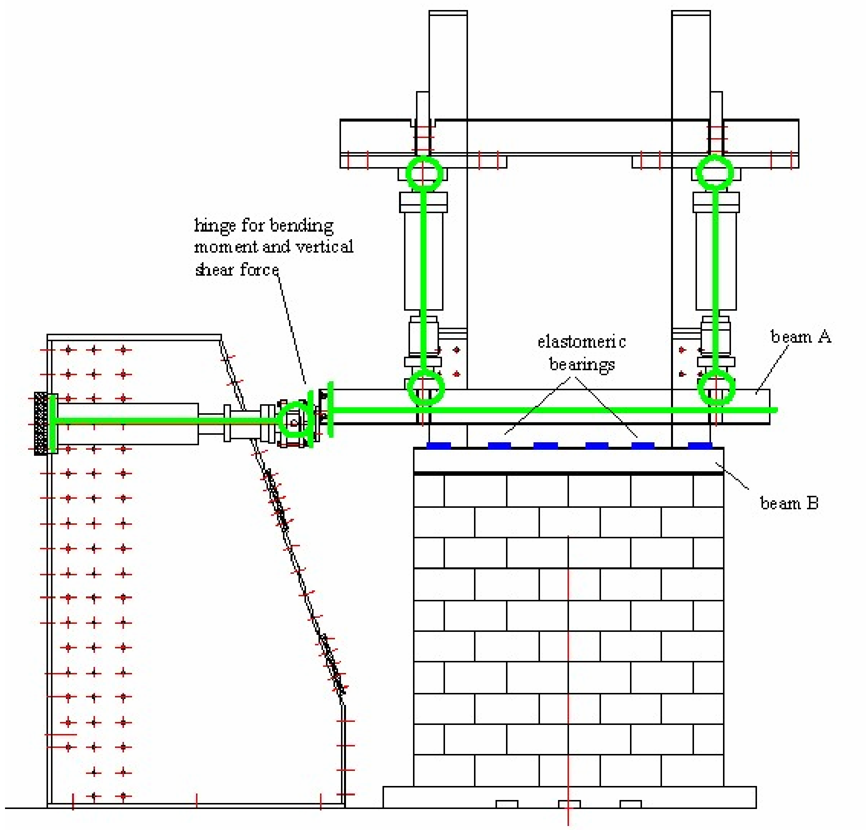


Figure 10: Test set-up for static-cyclic shear tests on masonry panels (Fehling and Stürz 2008)

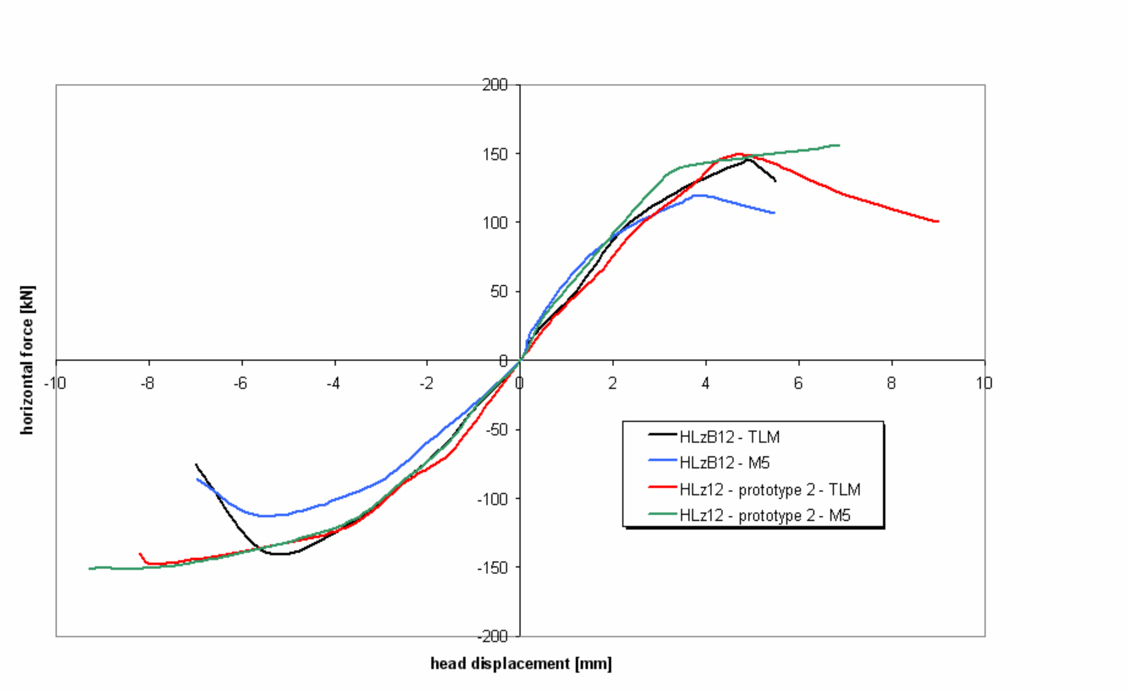


Figure 11: Load-displacement characteristics of clay unit masonry under in plane shear (Fehling and Stürz 2008). vertical stress = 1,0 N/mm² (TLM: thin layer mortar)

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Figure 11 shows a comparison of the load-displacement characteristics of four specimens with conventional and optimised units with thin layer mortar and general purpose mortar M5. The load situation on these walls was designed to produce unit tensile failure. The applied vertical stresses were equivalent to approx. 1 N/mm². The specimens with optimised units showed a slight tendency for a more "ductile" behaviour, reaching the ultimate load at higher head displacements compared to the conventional specimens. Cracks were formed mainly in the units, so that a significant increase in the shear strength of the walls with optimised units could be expected, due to the significantly increased tensile strength of the optimised units.

Nevertheless, the ultimate shear resistance of the walls with Prototype No. 2 units was only slightly higher than for the walls with conventional units. This is supposed to be caused mainly by the lower compressive strength of the optimised units.

The almost doubled compressive strength parallel to the bed joints had on the other hand obviously only a slight influence on the shear resistance.

CONCLUSIONS

It seems to be evident that the compressive strength perpendicular to the bed joints is the decisive parameter for the loadbearing capacity of clay masonry walls under horizontal loads even in situations where shear failure is the relevant failure mode. On the other hand, the compressive strength parallel to the bed joints does not contribute as much as is was expected so far. Future optimisation steps should take these findings into account.

The investigations of the ESECMaSE project proved that for most practical applications, i.e. rather short walls with moderate vertical loads, the governing failure mechanism is a compressive failure of the units in the corner of the shear wall. A corresponding design model will be presented elsewhere in these Proceedings (Graubner and Kranzler 2008).

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