THERMAL AND MECHANICAL OPTIMIZATION OF THE WALL-FLOOR-JUNCTION OF EXTERNAL WALLS BASED ON PASSIVE HOUSE STANDARDS

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ABSTRACT

In the context of the increasing requirements for thermal protection and energy efficiency, particular attention has to be paid to the connection of the slab to the monolithic wall. Usual constructions (bearing length corresponds to half wall thickness) do not meet the risen (and still rising) energy and heat insulation demands. Therefore, a thermal optimization of the wall-slab-connection is required, which is carried out by means of a significant reduction of the bearing length of the slab.

Recently, an investigation on the consequences of such a reduction is carried out at the Chair of Structural Design at TU Dresden. In the framework of the project, the effects of the reduction of the bearing length on the stability and usability of a system and the failure of partially supported slabs in the ultimate limit state are to be investigated. Furthermore, the contribution of the facing unit to the load transfer is to be analyzed. Based on an evaluation of different geometry and material combinations of the joint between the wall and the floor, the structural-physical requirements on the materials were specified. In addition, the boundary conditions and the general objectives for the structural analysis were defined.

Using experimental tests and numerical simulations, the process of fracture of the wall-slab-connection in case of failure is to be analyzed subsequently. Based on the real material and structural behaviour, a suitable model for the structural analysis of partially supported slabs will be developed, which allows for the reliable structural design of various bearing lengths.

KEYWORDS: masonry, passive house, partially supported slabs, thermal bridges

INTRODUCTION

In recent years, the requirements for the thermal protection and the energy efficiency have increased steadily. As a result, the relevance of thermal bridges at connection-details increases. For the certification as a "Passive House suitable Component" according to the criteria of PHI Darmstadt [1], the linear thermal bridge coefficient ψ should be smaller than or equal to 0.01 W/(mK). Keeping this limit value, the component is considered to be free of thermal bridges.

In this context, particular attention has to be paid to the connection of the slab to the monolithic wall. Usual constructions, where the support length *(a)* of the reinforced concrete slab *(2)* (denotations according to Figure 1) is equal to or greater than half the wall thickness t do not meet the risen (and still rising) energy and heat insulation requirements (note, that in general, wall thickness t do not consider the thickness of the plaster layer). Therefore a thermal optimization of the wall slab connection is required, which is carried out by means of a significant reduction of the bearing length, see Figure 1.

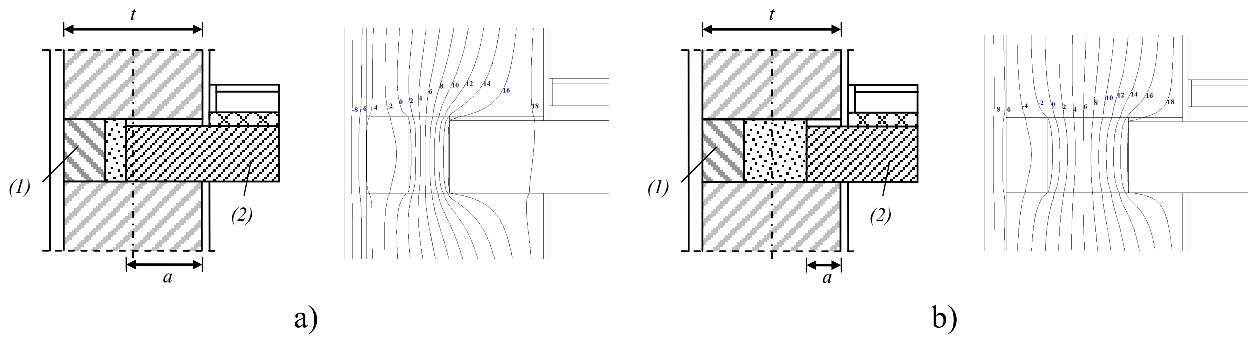


Figure 1: Thermal optimization of the wall slab connection (arrangement and isotherms): a) Usual constructions with bearing length ≥ $t/2$; b) Reduced bearing length < $t/2$

While the assessment of the thermal bridge effect is sufficiently scientifically studied [2], the failure behaviour of partially supported slabs requires in-depth investigations. In addition to the influence on the structural behaviour, the reduction of the support length results in falling below the limits of the applicable regulations in Germany ($a \geq t/2$). The reduction of the support length leads to load concentrations in the range of the support of the slab and the facing unit *(1)*, which demands a new model for design and structural analysis.

The hitherto approach is not suitable for these cases, since, for example, the facing unit, which is significantly involved in the load transfer due to a reduction of support length, is not considered. As a result, the predicted load bearing capacities of suchlike constructions considerably decrease and, thus, they can hardly be verified at present.

The research project aims at the clarification of the above mentioned fundamental problem, which is caused by the increase of the thermal requirements for single-leaf walls. The monolithic design is to be adapted to the new demands of energy conservation, to maintain the competitiveness of this traditional and still widespread construction method.

THERMAL REQUIREMENTS

Based on the criteria for Passive House Component certification [1], the requirements for the wall construction material and the support of the slab (necessary reduction of bearing length) were worked out. Thus, the thermal transmission coefficient (U-value) has to be less or equal to 0.15 W/ (m²K).

The support of the slab on the external wall usually represents a structural thermal bridge with increased heat transfer (additional heat loss). At this, the heat transfer at the connection detail is characterized by means of the thermal bridge coefficient ψ. Regarding to the criteria for "Passive House suitable Components" ψ has to be less or equal to 0.01 W/(mK). In this case, the additional heat losses resulting from the thermal bridge do not need to be taken into account for the set up of the energy balance. The linear thermal bridge coefficient is calculated according to DIN EN ISO 10211 [2]. In general, the calculation is performed using common FE software.

REQUIREMENTS FOR THE SUPPORT OF THE SLAB

The German standards [3, 4] do not provide any regulation concerning the minimum bearing length of a slab. However, according to the building authorities, the bearing length has to be greater than or equal to half of the wall thickness and the facing unit must not be taken into account for the structural design. The limit value of $a \geq t/2$ can be derived from the restriction of gaping joints to the half wall thickness.

In EC6 [5] there is also no provision for a minimum bearing length. According to the National Annex [6] the bearing length a has to satisfy Equation 1.

$$a \geq \max\left(100mm; \frac{t}{3} + 40mm\right) \tag{1}$$

The simplified calculation method in EC6-3 [7] and the corresponding National Annex [8] provide various regulations regarding the bearing length of the slab. A summary is given in Table 1.

Table 1: Minimum bearing length depending on wall thickness *t*

t	Minimum bearing length in (mm)				
	t/2	EC6	EC6-3		
(mm)	(mm)	National Annex	Chapter 4.2.1	Appendix A	National Annex
300	150	140	120	200	150
365	180	161.67	146	243.3	164.25
490	245	203.3	196	326. 7	220.5

THERMAL ANAYLSIS

By means of a parameter study it was checked, under which conditions the thermal transmission coefficient U of a monolithic wall construction (consisting of external plaster, masonry, internal plaster) will be less than 0.15 W/(mK). Table 2 shows the range of the parameters used in this study, which correspond to the current state of the art.

Table 2: Range of parameters for calculation of *U*-values

Parameter	Range
Thickness of masonry unit t_{unit} (m)	0.365 / 0.400 / 0.425 / 0.48 / 0.49
Thermal conductivity masonry units λ_u (W/(mK))	0.065 / 0.080 / 0.100
Thickness of external plaster $t_{p,e}$ (m)	0.02 / 0.04 / 0.06 / 0.08
Thermal conductivity of external plaster $\lambda_{p,e}$ (W/(mK))	0.07 / 0.15 / 0.25 / 0.35
Thickness of internal plaster $t_{p,i}$ (m)	0.015
Thermal conductivity of internal plaster $\lambda_{p,i}$ (W/(mK))	0.25 / 0.35 / 0.50

As result of the parameter study, the U-value is plotted as a function of the thickness of the masonry unit, see Figure 2. The three additional lines shown in the diagram connect the points of one combination for which only the thickness of the unit is changed while thickness and thermal conductivity of plaster and thermal conductivity of the unit are constant.

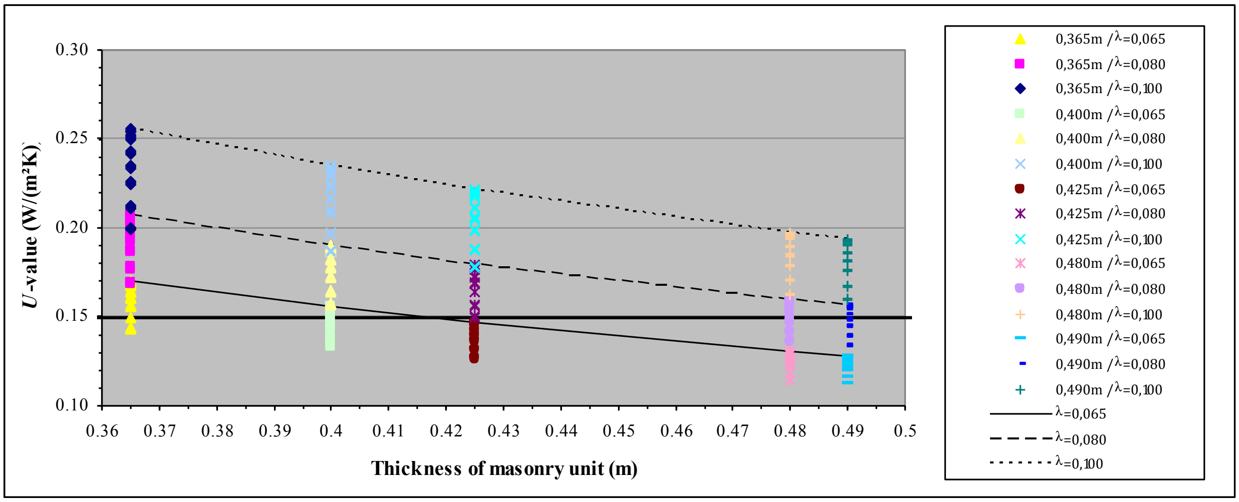
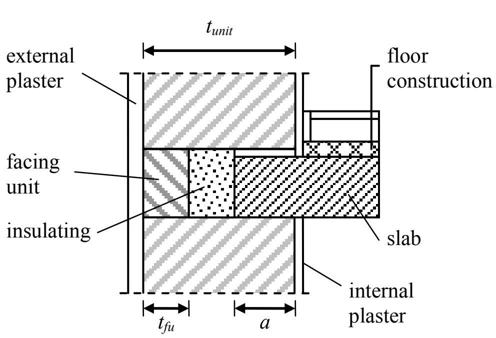


Figure 2: *U*-value depending on the thickness of the masonry unit for different combinations

From the results of the parameter study it can be seen, that it is difficult to reach the boundary value of 0.15 W/(mK) with a wall thickness of 36.5 cm (without plaster). Even with a wall thickness of 42.5 cm (without plaster) the required *U*-Value can be reached only by using a masonry unit with a very low thermal conductivity ($\lambda_u \leq 0.08$ W/(mK)) and a corresponding external insulating plaster ($\lambda_p = 0.07$ W/(mK)).
Moreover, it was checked in the project, how different geometries of the wall slab connection and the use of different building materials (variation of thermal conductivity) affect the thermal bridge. In order to gain general information on the influence of the bearing length on the thermal bridge, another parameter study was conducted. The study is based on the structure shown in Figure 3, wherein the thickness of the unit t_{unit} was varied between 365 and 490 mm and the bearing length a was varied between 50 and 300 mm. Figure 3 also contains the investigated parameter range.



Parameter	unit	Range
t_{unit}	mm	365 - 490
λ_{unit}	W/(mK)	0.06 - 0.10
$\lambda_{face,unit}$	W/(mK)	0.14 - 0.24
$t_{p,e}$	mm	20 - 80
$\lambda_{p,e}$	W/(mK)	0.07 - 0.25
$t_{p,i}$	mm	15
$\lambda_{p,i}$	W/(mK)	0.25 - 0.5

Figure 3: Detail of wall slab connection for parameter study and range of parameters concerning the influence of the bearing depth on the thermal bridge

Figure 4 shows the calculated thermal bridge coefficient depending on the ratio of bearing length and wall thickness for a selection of the analyzed combinations.

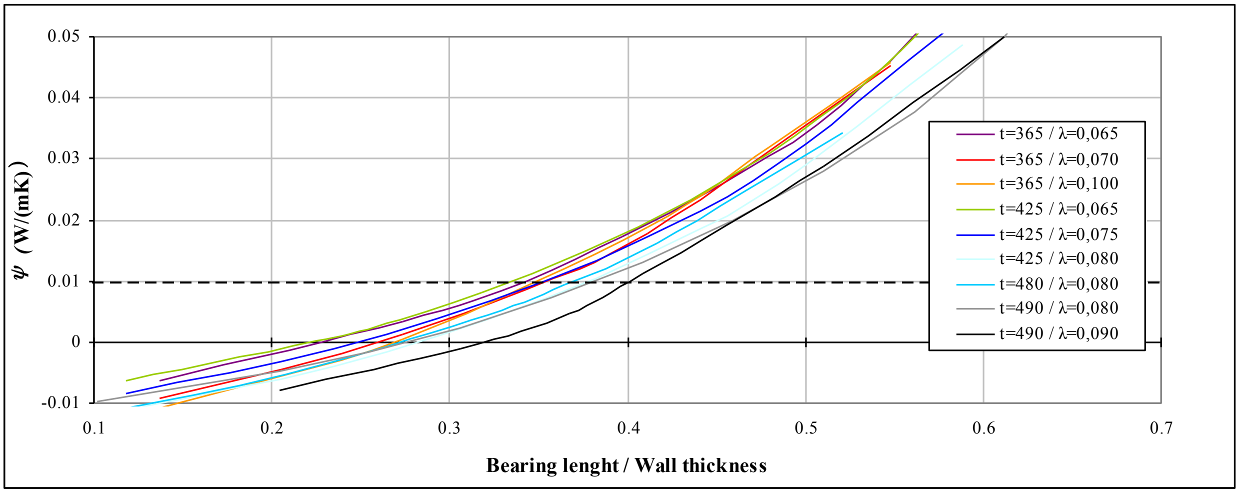


Figure 4: Thermal bridge coefficient depending on the ratio of bearing length to wall thickness (selection of analyzed combinations)

From the diagram in Figure 4 it can be seen that the limit value of $\psi < 0.01$ W/(mK) is generally achieved when the ratio of bearing length and wall thickness lies between 0.3 and 0.4. That means that the normative required minimum bearing length is not sufficient to design a wall slab connection free of thermal bridges within the meaning of the certification of “Passive House suitable Components” [1].

NUMERICAL MECHANICAL ANAYLSIS

The numerical investigations aim at various objectives. Besides the preparation of the experimental studies (specification of load regime, development of test set up), the analysis will support the identification of the critical areas of the constructions. Finally, an analytic model for the structural analysis of partially supported slabs will be generated based on an extensive parameter study.

The two-dimensional numerical analyses for the systematic study of the structural behaviour of the wall slab connection are carried out by means of a specific structural member. The model consists of one floor in the intermediate story (external wall) and, to consider the effect of adjacent walls, a half floor below and above, see Figure 5.

For the preliminary simulations, a wall thickness of 0.49 m and a wall height of 3.0 m were chosen. According to the results of the thermal analysis, the ratio between bearing length and wall thickness was assumed to amount to 0.3.

As first results show, the masonry units at the top and the bottom of the wall (first layer) are exposed to a high horizontal stress, see Figure 5. Therefore, the cracking of the unit layer above and under the slab due to horizontal stresses as well as the propagation and the formation of cracks will be analysed qualitatively in the scope of the experimental investigations.

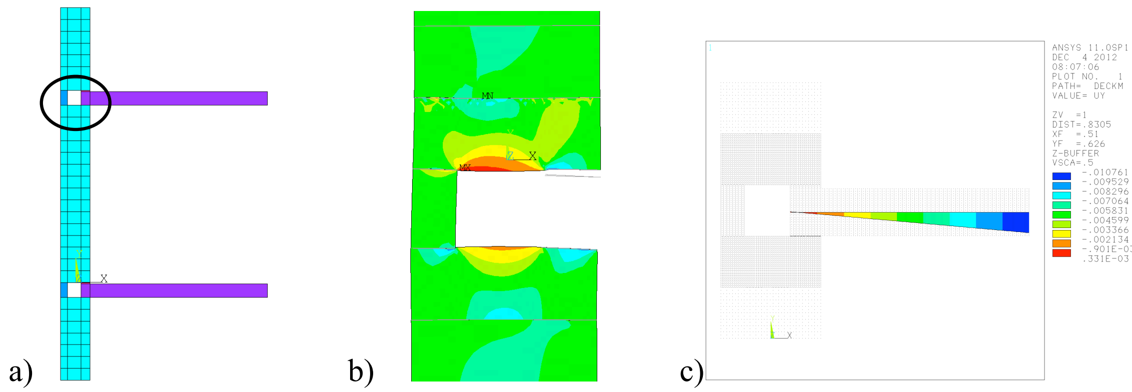


Figure 5: a) 2D FE-Model; b) FE-Simulation with transversal tensile stresses at the upper wall slab connection; c) Deformation of the slab under uniformly distributed load

To determine the relationship between applied loadings and rotation of the slab, which is important for the experimental investigations, a numerical parameter study was carried out. Since for the investigations the largest deformations / rotations of the slab are of interest, the analyses were performed using a slab of 6 m length, which was assumed to be cracked with a modulus of elasticity of 12.000 MPa. In the calculations, the load on top of the system and the loads of the slab were varied. Figure 6 shows the calculated angle of inclination (Φ) of the slab in the area of the support depending on the loading of the upper wall N_u and different load cases p_{slab} on the slab (uniformly distributed load).

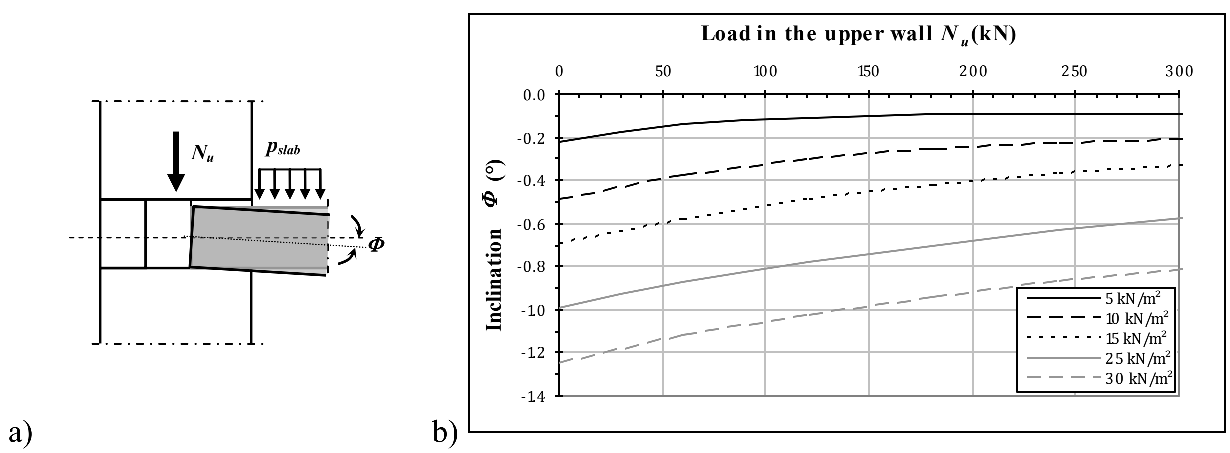


Figure 6: a) Loadings and angle of inclination Φ for wall slab connection; b) Angle of inclination Φ of the slab in the area of the support depending on the load in the upper wall and different loads on the slab

From Figure 6 it can bee seen, that, as expected, for the same floor load the angle of inclination decreases with increasing loading of the wall. This can be attributed to the increase of the restraint of the slab when the load on top is increasing.
In addition to the deformation of the slab, the deformations of the walls have been determined in the scope of the numerical calculation. However, the rotation angles of the walls were found to be very small due to the short bearing length (up to 10% of slab rotation).

EXPERIMENTAL INVESTIGATIONS

In the framework of the experimental investigations, approximate tests for the qualitative analysis of the failure behaviour and the estimation of the load bearing capacity of the optimized wall slab connection are carried out. The material parameters of the particular building materials are determined in accompanying material tests.

Out of the variety of available masonry materials, lightweight concrete blocks, autoclaved aerated concrete masonry units and vertically perforated bricks were selected for the tests. The first series of experiments on vertically perforated bricks has been completed. In Table 3, information on the properties of the used materials can be found, whereas f_b, f_m and f denote the particular compressive strength, f_{bq} is the splitting tensile and f_{bt} is the bending tensile strength.

Table 3: Properties of used materials

Shape	Masonry Unit	Mortar	Masonry
	size = 200 / 490 / 249 mm f_b = 10.63 MPa	f_m = 13.54 MPa f_{bt} = 2.16 MPa f_{bq} = 1.63 MPa	f = 5.44 MPa

For the experimental investigations, two sections (specimens W1 and W2) of the wall slab connection were bricked up with the dimension $l/t/h$ = 0.60/0.49/1.25 m. The specimen consists of a reduced reinforced concrete slab (0.60/1.20/0.23 m) and facing unit as well as two layers of masonry units below and above the slab. According to the results of the thermal investigations, the bearing length of the slab was determined to 15 cm (a/t=15/49=0.3). Figure 7 shows the schematic experimental test set-up. The load F_1 on top of the wall simulates vertical loads resulting from additional floors (N_u in Figure 6). With the help of F_2, loads applied by the slab (N_{slab}) are reproduced.

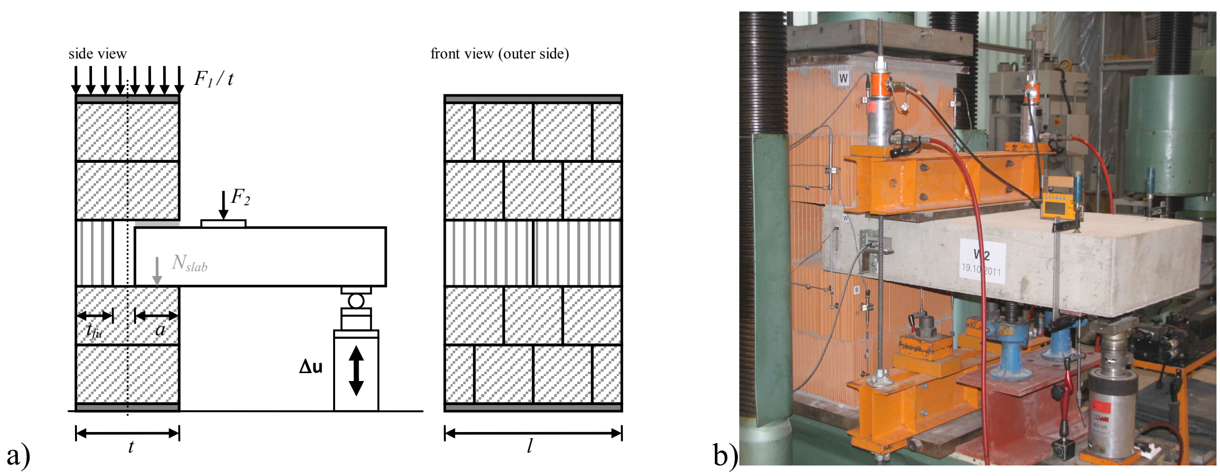


Figure 7: a) Schematic test set-up with applied loads; b) Specimen W2 in test machine

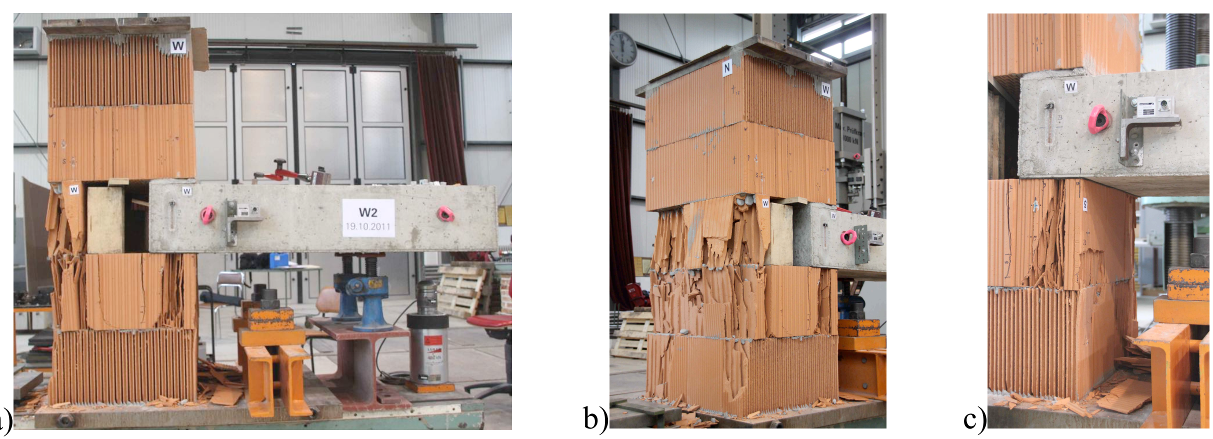
Due to the use of a reduced slab, the inclination can not result from the "natural" deflection. Therefore, the slab has to be inclined by the angle Φ depending on the load regime and

corresponding to the numerical calculation (cf. Figure 6). The bearing point at the free end of the slab has been designed as vertically displaceable.
In contrast to the FE-simulation, applying the experimental load on top and bottom of the wall to the entire cross section leads to the prevention of the wall deformation. The inclination obtained from the FE-analysis would therefore have to be reduced by the wall deformation. Since these values were found to be very small and, moreover, their inclusion positively affects the load application, they are neglected in the tests.
The time of failure of a specimen is defined as the point of time, at which the specimen is collapsing. The failure load results from the sum of load F_1, the reaction force applied by the floor (caused by F_2) and the net weight of the upper wall structure. Table 4 contains the loads for specimens W1 and W2 at the time of failure and the resulting compressive strengths. Here, f_{tot} is related to the complete cross section, while f_{net} is related to the net cross section (load-carrying section = bearing length and thickness of facing unit). The compressive strength from the technical approval converted to the mean value (for comparing with the test results) is denoted as f_{ma}, and AM is the arithmetic mean value.

Table 4: Test results

	Unit	W1	W2	AM
N_o	kN	714	749	731.5
f_{tot} (t)	MPa	2.43	2.55	2.49
f_{net} $(a+t_{fu})$	MPa	4.49	4.71	4.60
f_{ma} [1]	MPa		2.28	
[1] f_{ma} = approval value · 1,2 = (1.9 MPa ·1,2)				

As can be seen in Table 4, the experimentally determined compressive strength exceeds the theoretical mean value of masonry compressive strength. The observed mode of failure was similar for both specimens. The ultimate failure was caused by exceeding the transversal tensile strength perpendicular to the direction of load application within the area of the facing unit. On the eve of failure, the outer shells of the facing unit buckled, the specimen was compressed and further shells were blown of. Figure 8 shows specimen W2 after the test. The damage in the range of the facing unit and below the slab is clearly visible.



a) b) c)

Figure 8: Specimen W2 after test (with temporary supporting system between slab and facing unit); a) Side view; b) Outer face of specimen; c) Damage below slab

The outer face of the specimen remained free of cracks during the test. At the half of the failure load, the first clearly visible cracks occurred at the inner face of the specimen below the slab (vertical cracks in conjunction with the spalling of some outer shells). In contrast, on the longitudinal side of the specimen first vertical cracks occurred in the lower load range in the middle of the masonry units in the first layer above and below the slab, as was predicted in the numerical simulation (cf. Figure 5). However, the cracks did not propagate across the entire height of the specimen and were not directly involved into failure.
During the further project work, ways and means to prevent such cracking will be identified (e.g. a bed joint reinforcement from carbon fibre).
Strain gauges were applied at the facing unit and at the slab (cf. Figure 8 c) in the area of the support to determine the load spread between facing unit and slab support based on the measured deformation and the previously determined modulus of elasticity of facing unit and slab. Figure 9 shows the load spread between facing unit and slab support for specimen W2.

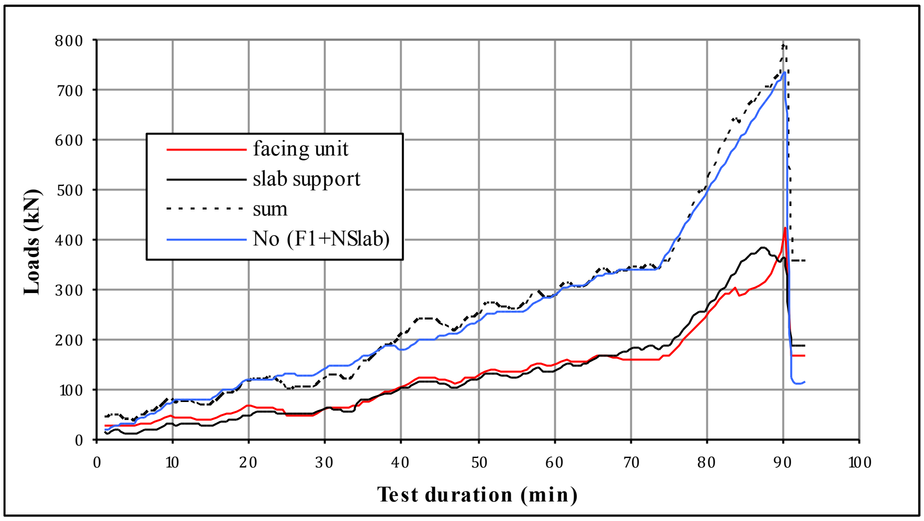


Figure 9: Load spread between slab support and facing unit, sum of both load parts and comparison with the applied loads depending on the test duration

As can be seen from Figure 9, the facing unit and the support of the slab transfer nearly the same load during a long period time. Below, respectively above the facing unit, the available area for load transfer is 25% less than the area below the slab. Assuming an equal load spread leads to higher compressive stresses and finally to the failure in the range of the facing unit.

SUMMARY AND PERSPECTIVE

The research project deals with the thermal optimization of slabs connected to external monolithic walls and the analysis of the resulting impact on the load bearing behaviour of the structure.
With increasing demand on the reduction of transmission losses, thermal bridges in the area of the wall slab connection gain more importance. Therefore, an optimization with respect to both, thermal properties and mechanical load bearing behaviour, is required and should be carried out by means of a significant reduction of the bearing length of the slab. Based on the criteria for

"Passive House suitable Components", the necessary reduction was specified. It was shown, that a reduction of the bearing length leads to a minimization of the thermal bridge problem. Resulting from the evaluation of different wall constructions and parameter studies, the limit value for the thermal bridge coefficient ψ can be met in general by reducing the bearing length a to a ratio of 0.3-0.4 times the wall thickness t.

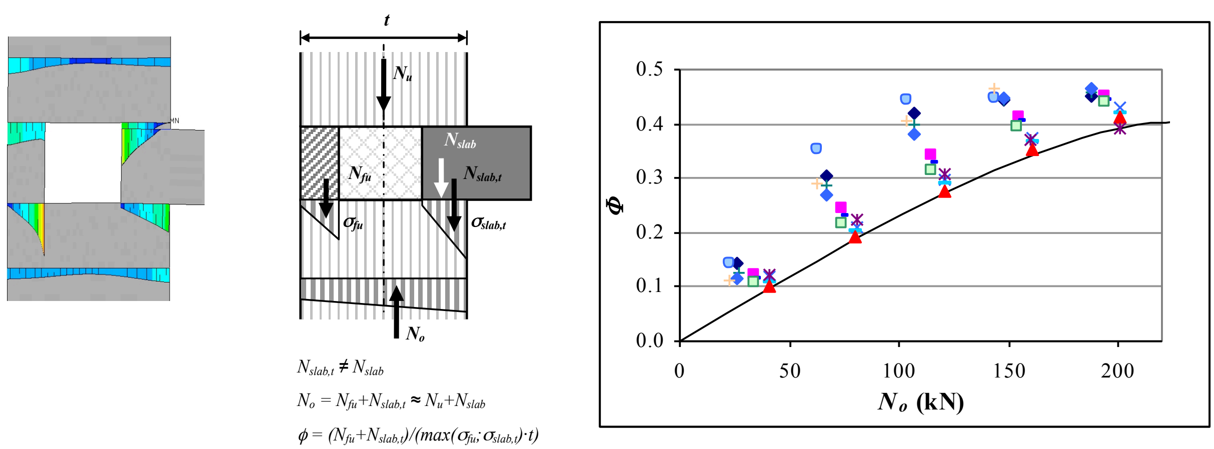
Therefore, the minimum bearing length according to the standards has to be reduced up to 20%.

As experimental results show, the facing unit plays a major role concerning the load transfer and should not be neglected in the scope of the design. Furthermore, it became apparent that the failure of partially supported slabs with reduced bearing length occurs in the range of the facing unit instead of under the partially supported slab.

Next, the experimental investigations of autoclaved aerated concrete and lightweight concrete blocks will be carried out. If necessary, the test set up will be slightly modified. 18 additional tests are planned. In the framework of the tests, the direct effect of the shortening of the slab on the load bearing capacity of the wall slab connection will also be investigated by comparing test results with different bearing lengths.

Finally, the numerical model will be adjusted according to the experimental data. Based on an extensive numerical parameter study and the experimental results, a model for the structural analysis of partially supported slabs will be developed, which allows the reliable structural design for various bearing lengths.

According to the German standard, the vertical resistance of a single leaf wall is usually calculated by means of a capacity factor ϕ. This is the ratio of the load bearing capacity of a cross section, allowing for capacity reducing effects, and the capacity of an ideal centrically loaded wall. In this context, a first approach for a new model suggests a determination of the reduction factor depending on the actual load situation. The loads transmitted by the facing unit (N_{fu}) and the slab ($N_{slab,t}$) will, at this, be calculated numerically. Subsequently, they will be compared to the load bearing capacity of the complete cross section, resulting from the product of relevant compressive strength (maximum of σ_{fu} and $\sigma_{slab,t}$) and wall thickness (assuming a rectangular stress block). Figure 10 shows the numerical calculated capacity factors.



a) b) c)

Figure 10: a) Stress distribution in FE-Simulation; b) Forces and load components; c) Numerical calculated capacity factors depending on total load

Further project processing will show whether the coverage of all parameters and influences in one capacity reduction factor is possible and constructive, or whether several structural analyses must be carried out for the design (e.g. separate structural analyses under the facing unit and under the support of the slab).
In addition, investigations on the influence of horizontal chases near the partially supported slab are planned.

ACKNOWLEDGEMENTS

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