Assessment of reduction of thickness of separating elements in massive clay brick buildings on the perspective of sound insulation, construction effort and sustainability

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Introduction

In Germany there is a big deficit of affordable living space like flats and appartements. On the other hand it is absolutely essential to slow down global warming among others caused by construction activities. Therefore it is necessary to discuss the potential to reduce the costs and the carbon footprint of construction of residential buildings in the context of building physics regulations – especially acoustic requirements.

In the search for solutions to reduce costs and at the same time cut CO_2 emissions in the construction industry, one of the options being discussed is to reduce the thickness of separating components between different flats. This paper discusses the required thickness of a raw concrete slab in the context of static regulations respectively fire safety requirements, sustainability and sound insulation.

Basics of planning

In Germany the static dimensioning of concrete slabs must be carried out in accordance with EN 1992-1-1:2011 [1] in combination with National Annex DIN EN 1992-1-1/NA:2013 [2]. Each load bearing component of the building structure must fulfil the criteria of "[…] serviceability, strength and stability throughout its design service life, without significant loss of utility, with anticipated maintenance but without major repair […]". If the deflection of the regarded concrete slab is in the required range, the serviceability and the utility will be fulfilled.

Example – separating ceiling in an apartment house

Figure 1 shows a typical ground plan of an apartment house with one ground floor plus four normal storeys. Each level has a floor space of approximately 30.0 m × 11.5 m with three flats. The top edge of the ceiling of the 4th floor is 11.51 m above ground level.

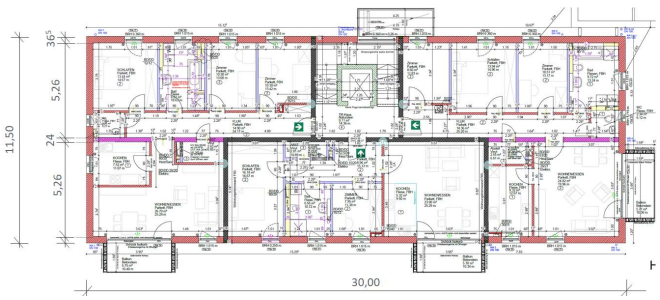

Figure 1: Ground plan of a normal floor of the regarded.

The exterior walls are made of monolithic high insulating brick masonry with a unit thickness of 365 mm (plus plaster and rendering) with a sound reduction index $R_{w,ref}$ = 50.0 dB.

The separating walls between the different flats are constructed with 240 mm formwork bricks filled with concrete. The interior walls within the flats were made either of 115 mm brick masonry or dry wall constructions.

In figure 2 the load bearing walls are highlighted in orange.

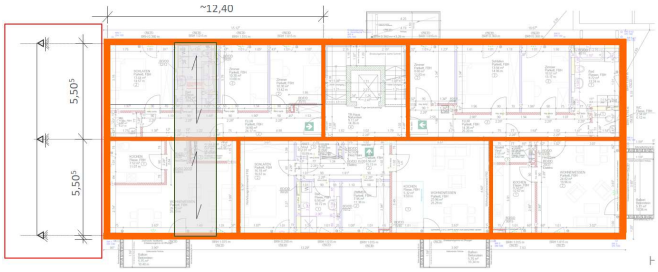

Figure 2: Load bearing walls of each floor.

To estimate the necessary thickness of the raw concrete slab it is assumed, that the concrete slab spans along the smallest distance between the parallel external walls. In figure 2 a bar of the slab is shown grey. The arrows describe the span direction. On the left side a sketch of the statical system of the continuous double-span beam is shown. In figure 3 the vertical cut of this continuous double-span beam with the load bearing external walls left and right and the load bearing interior wall in the centre is illustrated.

The concrete ceiling is supported on two third of each exterior brick masonry wall (approximately 250 mm). The statical length of the slab is measured between the midpoints of the support of the slab on the exterior wall (~125 mm) and the interior wall (120 mm). Thus the static length is:
0.125 m + 5.26 m + 0.12 m = 5.51 m.

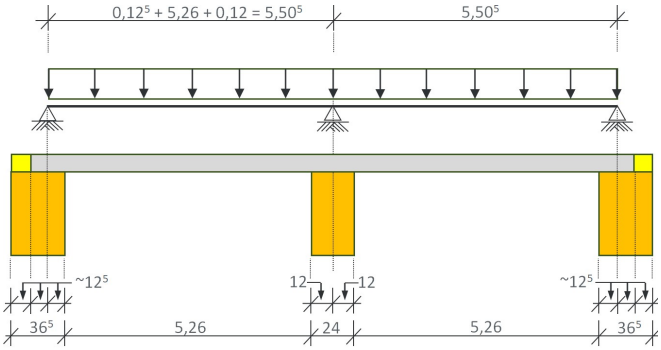

Figure 3: Sketch of the vertical cut of the concrete slab.

Dimensioning of the concrete ceiling

Fire safety requirements

The top edge of the ceiling of the 4th floor is 11.51 m above ground level. This is less than 13.0 m. The area of each flat is not more than 400 m². According to "Musterbauordnung" [9] (regulations for common living buildings in Germany) §2 "Terms" (3) Nr. 4 the building is categorised as building class 4. In combination with §31 "Ceilings" (1) Nr. 2 the ceilings of this building are required to be highly fire-retardant (according to MVV TB [10], A 2.1.3.2.3) and must fulfil the fire resistance duration of ≥ 60 min. The requirement of standard fire resistance for loadbearing separating slabs is REI 60 ([10], table 4.2.3).

In accordance with EN 1992-1-2:2010-12 [3], table 5.8 "Simply supported one-way solid reinforced concrete slabs" the minimum thickness is $h = 80$ mm and the axis distance has to be at least $a = 20$ mm. Figure 4 shows a sketch of the vertical section across the concrete slab.

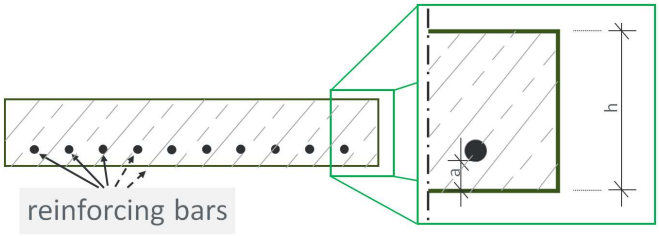

Figure 4: vertical section across the concrete slab.

The exposure resistance class of the concrete slab in an apartment house according to [1], table 4.1 is XC1 (dry environment). The nominal concrete cover c_{nom} must be calculated using the rules of [1], 4.4.1 combined with [2].

The minimum concrete cover according to [2], NDP for 4.4.1.2(5) is $c_{min} = 10$ mm caused by the maximum diameter of the reinforcement. The allowance for deviation is $\Delta c_{dev} = 10$ mm ([2], NDP for 4.4.1.3(1)P). The nominal concrete cover is

$c_{nom} = c_{min} + \Delta c_{dev} = 10$ mm + 10 mm = 20 mm.

As consequence only concrete slabs with thicknesses $h > 80$ mm with a concrete cover of 20 mm were taken into account. Thus the fire safety requirements were fulfilled.

Structural design requirements

The simplified verification of the limitation of deflection is regulated in [1], 7.4.2. The calculation depends on the span length of the slab l, the usable height of the concrete slab d, the concrete compressive strength f_{ck} and the tensile reinforcement ratio ρ. The following is an example of a proof for a concrete slab with a compressive strength $f_{ck} = 20$ N/mm² (C20/25) and $\rho = 0.2$ %. In a first step the height of the concrete slab is set to $h = 22$ cm for this sample because it is often assumed to be required.

The span length of the slab is $l = 5.51$ m (figure 3). The usable height of the slab d is the difference of real height of the concrete slab h and the distance of the surface of the concrete slab and the axis (centre) of the reinforcement. Figure 5 illustrates the distance of the surface of the concrete slab and the reinforcement $a = c_{nom} = 20$ mm. The diameter of the reinforcement is conservative determined as 10 mm.

$\Rightarrow h - d = 20$ mm + 10 mm/2 = 25 mm

The factor K respects the different structural systems. For an end span of continuous beam $K = 1.3$ [-] ([1], table 7.4N).

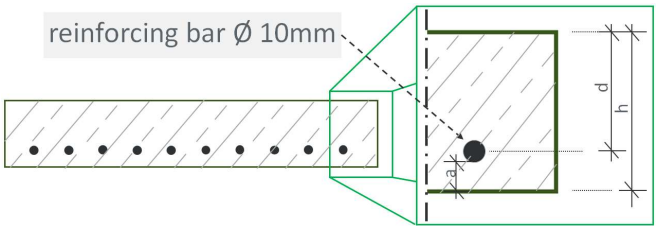

Figure 5: Description of the real height of the concrete slab h and the usable height d

The required reinforcement of the concrete slab depends on the permanent and the variable load. Table 1 shows the load assumptions of the regarded concrete slab. The dead load of the raw concrete slab of a thickness of 22 cm is $g_{k0} = 5.5$ kN/m².

Table 1: Load assumptions

Construction	Thick-ness [cm]	Weight[a] [kN/m²/cm]	Mass per area [kN/m²]
floor tiles	1	0.22	0.22
floating screed	6	0.22	1.32
raw concrete slab	22	0.25	5.5

[a] according to [5] Annex NA.A

In this sample the additional dead load caused by floating screed and floor tiles is $g_{k1} = 1.32 + 0.22$ kN/m² = 1.54 kN/m².

The specific use of the building is domestic and residential living. According to [5], table 6.1DE the category of use of the slabs is A2. That will mean that the variable load is $q_{k,1} = 1.5$ kN/m².

In case the weight per length of non-loadbearing walls is in between 3 kN/m and 5 kN/m, the surcharge of the variable load of the ceiling is 1.2 kN/m² (compare [5], 6.3.1.2, NCI for 6.3.1.2 (8)). The height of the non-loadbearing walls between the ceilings is 2.90 m and the calculation value of the density is 1200 kg/m³. With plaster on both sides the load per wall length is:

2.90 m · (0.115 m · 1200 kg/m³ + 2 · 15 kg/m²) = 4.87 kN/m.

This is in between 3 kN/m and 5 kN/m.

$\Rightarrow$ The variable load per m² ceiling shall added by $q_{k,2} = 1.2$ kN/m² $\Rightarrow q_k = 1.5$ kN/m² + 1.2 kN/m² = 2.7 kN/m².

The required reinforcement ratio according to [1] is 0.2 %. This was calculated using spreadsheet calculation of [11]. For this combination of load and resistance the construction only needs reinforcement for absorb tensile stress and no compressive reinforcement. It is required to meet higher requirements of limitation of deflection to avoid cracks in the non-loadbearing interior walls. The calculated deflection must be less than $K^2 \cdot 150 / l$.

To fulfil the simplified verification of limitation of deflection equation (1) ([1], 7.4.2, equation (7.16a)) must be applied:

$$\frac{l}{d} \leq K\left[11+1.5\sqrt{f_{ck}}\frac{\rho_0}{\rho}+3.2\sqrt{f_{ck}}\left(\frac{\rho_0}{\rho}-1\right)^{\frac{3}{2}}\right] \leq K^2 \cdot 150/l \quad (1)$$

l span length of the slab;
d usable height of the concrete slab;
f_{ck} concrete compressive strength;
ρ tensile reinforcement ratio;
ρ_0 reference tensile reinforcement ratio;
K factor to respect the different structural systems.

Inserting the values shown above, the result is as follows:
$28.3 \leq 39.6 \leq 46$
$\Rightarrow$ The simplified verification of the limitation of deflection is fulfilled for a 22 cm raw concrete slab with the shown geometry and other of qualities of components.

Variation of the height of the raw concrete slab

The proof of simplified verification of the limitation of deflection was repeated for some combinations of height of the raw concrete slab h (see table 2), concrete compressive strength f_{ck} and tensile reinforcement ratio ρ. The load parameters were not changed except the dead load of the raw concrete slab because it depends on its height. The proof for the 22 cm slab has been shown above. The other four results in table 2 were also calculated but without presenting calculating path for each variant, because it is analogue to the sample of 22 cm raw slab. The combinations marked with a dash " - " have not been calculated. This does not mean, that these variants were not still possible.

Table 2: Required tensile reinforcement ratio ρ

Strength class for concrete	Characteristic concrete cylinder compressive strength f_{ck} [MN/m²]	Reinforcement ratio [-] Height of raw concrete slab h [cm]			
		17	18	19	22
C20/25	20	-	0.3	0.25	0.2
C25/30	25	0.3	-	-	-
C30/37	30	0.3	-	-	-

For all calculated combinations summarised in table 2 the proof of simplified verification of the limitation of deflection according to [1] and [2] has been fulfilled.

For the regarded building it is possible to reduce the thickness of the raw concrete slab to less than 22 cm, down to 17 cm if the concrete compressive strength is increased.

Evaluation of sound insulation and sustainability

Table 3 illustrates that reduction of the thickness of the raw concrete slab almost means, that either the concrete compressive strength or the tensile reinforcement ratio or both must be increased to fulfil requirements of deflection. The higher the strength class of concrete respectively the reinforcement ratio, the higher the CO_2-emissions of a construction element.

The sound insulation is checked representatively for a room in one corner of the apartment house (figure 6).

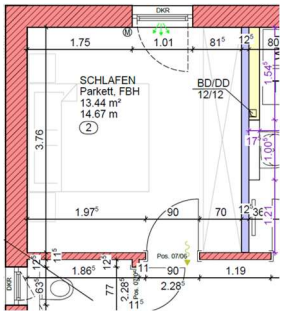

Figure 6: Ground plan of evaluated room.

The exterior walls are built of 365 mm monolithic high insulated brick masonry. The interior wall to the right is a dry wall construction and the other interior wall is made of 115 mm brick masonry. The separating surface of the overlapping rooms is S_s = 13.5 m². The applied thickness of the raw concrete slab is 22 cm. The sound reduction index (SRI) according to DIN 4109-2:2018-01 [6] is $R'_w - u_{prog}$ = 58.8 dB (note: the SRI was also measured in situ and it is about $R'_{w,situ}$ = 61 dB).

For the variants of combinations of table 2 of slab thickness, concrete compressive strength and reinforcement ratio the global warming potential (GWP) in kgCO_2-eq per m² floor area for raw slab thickness is shown in table 3. In order to take the structural steel of the upper reinforcement layer of the raw concrete slab into account, life cycle analysis according to DIN EN ISO 14040:2021-02 [7] and DIN EN ISO 14044:2021-02 [8] is calculated conservatively with the double tensile reinforcement ratio shown in table 2 with data of [12] and an observation period of 50 years related to construction element surface.
The GWP in table 3 is shown in the upper cell in each case and the calculated sound reduction index $R'_w - u_{prog}$ [dB] in each lower cell. The calculation of SRI was carried out using building acoustics software "Modul Schall 4.0" [13]. All necessary calculation values can be found in brochure "Baulicher Schallschutz nach DIN 4109 – Schallschutz mit Ziegeln" [14].

Table 3: Variation of samples (per m² floor area)

Strength class for concrete		Height of raw concrete slab h [cm]			
		17	18	19	22
C20/25	GWP	-	0.8726	0.9036	1.0261
	$R'_w - u_{prog}$		56.2	56.7	58.8
C25/30	GWP	0.8975	-	-	-
	$R'_w - u_{prog}$	55.8			
C30/37	GWP	1.0200	-	-	-
	$R'_w - u_{prog}$	55.8			

If thickness of 22 cm is defined as reference it is possible to decrease GWP about 15 % if the raw concrete slab will be reduced to 18 cm. For four floors this will be a reduction of 140 t concrete. Presumably the saving of concrete only results in a slight cost reduction, because less concrete means that more reinforcement is needed. It should be checked whether the weight saving can also lead to savings on other load-bearing components, e. g. for loadbearing walls or the foundation.

Summary/conclusions

When planning apartment houses nowadays in Germany, a thickness of separating raw concrete slab of at least 200 mm, in most cases of 220 mm is assumed. It is postulated, that these thicknesses are required in general for static and fire safety reasons. With the intention of reducing exploding building prices and saving CO_2, an optimisation of the thickness should be discussed, because the more concrete or steel is used, the higher the GWP.

In an example was shown, that depending on the span length of slabs it is possible to fulfil requirements of structural design and fire safety also with thicknesses of the slab < 200 mm.

The results shown were calculated using the simplified verification of the limitation of deflection regulated in [1]. At this point it should be pointed out, that a more precise calculation method, e. g. with FEM, enables further optimised planning with more efficient designs.

By reduction of the thickness of the raw concrete slab from 220 mm to e. g. 18 cm it is possible to decrease the GWP about 15 %. This will mean for this sample, that the calculated sound reduction index decreases about 2.6 dB and the increased requirement $R'_w \geq 57$ dB is not met. But in the urgent need to save CO_2, consideration should be given to which measures are acceptable.

Even if it is not possible to reduce the ceiling thickness for all building projects, the extent of the impact on sound insulation should be checked for reasons of sustainability, depending on the floor plan design in consultation with planners, developers and clients.

Literature

[1] EN 1992-1-1:2011-01 ”Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings”

[2] DIN EN 1992-1-1/NA:2011-01 “National Annex – Nationally determined parameters – Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings”

[3] EN 1992-1-2:2010-12 “Design of concrete structures – Part 1-2: General rules – Structural fire design”

[4] DIN EN 1992-1-2/NA:2010-12 “National Annex – Nationally determined parameters – Design of concrete structures – Part 1-2: General rules – Structural fire design”

[5] DIN EN 1991-1-1/NA:2010-12 “National Annex – Nationally determined parameters – Eurocode 1: Action on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings”

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[7] DIN EN ISO 14040:2021-02 “Environmental management - Life cycle assessment - Principles and framework”

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