

Detalles minimalistas frente a los requisitos de protección térmica con hormigón ligero

Minimalistic details facing thermal protection requirements with lightweight concrete

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Resumen: En la década de 1970 los gobiernos del centro y norte de Europa establecieron requisitos de protección térmica conducentes a la reducción de la transferencia de calor a través de la envolvente del edificio. Consecuentemente, se emplearon dos tipos de estrategias diferentes para reducir la pérdida de calor de las paredes exteriores: la primera se basaba en el uso de materiales de construcción, nuevos o modificados, que poseían una conductividad térmica reducida respecto a los materiales utilizados anteriormente; la segunda proporcionaba una capa de aislamiento especial. En relación al detalle del diseño, las construcciones con capas especializadas siguen pudiendo parecer simples, pero en el ámbito de la construcción resultan complejas y frágiles. Esto lleva a la pregunta: ¿Es posible diseñar detalles simples, tanto en apariencia como en su construcción? En este artículo se analizan las ventajas y las limitaciones de las diferentes tipologías de paredes exteriores dentro de las restricciones legales actuales en Europa Central. Después la temática se centra en el material de hormigón ligero y, resultando una cuestión clave, se presenta el análisis de las diferentes posiciones de las ventanas dentro de la pared (al ras de la parte interior / exterior de la pared o en el centro). Atendiendo a una fuente de la investigación con raíces arquitectónicas, las capacidades constructivas y limitaciones del diseño también son consideradas. En la conclusión, se apuntan las perspectivas futuras de desarrollo material y las consecuencias para el diseño de detalles.

Palabras clave: Envolvente de edificio de una sola capa, construcción de edificios, hormigón ligero, detalle de ventana, puente térmico

Abstract: *In the 1970s governments in Central and Northern Europe established thermal protection requirements, leading to the reduction of heat transfer through the building envelope. Subsequently, two different strategies were employed to reduce the heat loss of exterior walls: the first relied on new or modified building materials that possessed decreased thermal conductivity than previously used materials; the second provided a special insulating layer. Concerning detail design, constructions with specialized layers still might appear to be simple but on a construction level they are complex and fragile. This leads to the question: Is it possible to design simple details, which concern both appearance and construction? In this article we begin with the advantages and constraints of different exterior wall typologies within today's legal restrictions in Central Europe. After that we focus on the material of lightweight concrete. As a key issue the analysis of different window positions within the wall (flush to the inside/outside wall or in the middle) is presented. Since the source of the investigation has architectural roots, constructive capabilities and design constraints are also regarded. In the conclusion, future prospects of material development and the consequences for the detail design is given.*

Keywords: *Single layer building envelope, building construction, lightweight concrete, window detail, thermal bridge*

INTRODUCTION

For the construction of the first huts, humans took materials from their environment and assembled it in such a way that it provided weather protection. As soon as human civilization reached a higher level, aesthetic aspects such as proportions of buildings and artwork become relevant beside the pure functional abilities. Therefore when adapting new materials for building constructions before industrialization, often construction methods slowly changed as architects, engineers and clients were attached to viewing habits and not to the logic of construction independently of the material. But eventually materials were used in appropriate ways, which lead to changes in the architectural style.

Since industrialization, changes in building constructions occur on multiple layers. Instead of developing suitable construction methods for a material, its characteristics might be changed. Hence the idea of a construction and its details is no longer limited by constraints of a material but by the material's potential to be altered. According to the final properties of the material, the details can be extremely simplified.

While in history new construction techniques lead to new trends in architectural style, today's changes emerge mostly from legal restrictions being amended. One example of this is the 1970s energy crisis. As a consequence, governments in Central and Northern Europe established thermal protection requirements that intended to reduce the energy amount for heating by diminishing the heat transfer through the building envelope.

EXTERIOR WALL TYPOLOGIES

Two different strategies were employed to reduced the heat loss: the first relied on new or modified

building materials that possessed decreased thermal conductivity than previously used materials; the second provided for the inclusion of a special insulating layer. Due to multiple reasons constructions using specialized layers were soon found to be at an advantage. The most popular contemporary façade system in Central Europe e.g. is the ETIC-system, which is insulation glued and mechanically fixed onto a massive wall with plaster on the interior and exterior sides (Figure 1). One purpose for the success of such systems was the calculation method, which was adopted to compare the efficiency of building components related to the heat transfer (U-value). The method only regarded the transmission of heat through the component concerning conductivity. Solar gains, mass being able to store heat and the heating system did not influence the calculation results although in reality they affect the consumption.¹ Due to this simplification, the ETIC-system seemed to be very efficient and compared to others the building costs were -and still are- very low.

Examples of other multi-layer systems are external wall claddings with an insulation layer, interior-insulated walls or core-insulated walls. Each system provides different advantages but they all benefit from the calculation method. In addition to the ETIC-system we want to have a closer look at core-insulated walls (Figure 1). They look like traditional massive walls as their interior and exterior layer is made out of a massive material e.g. normal concrete. Putting them up them is more complex and time consuming. Their benefit concerning saving solar gains compared to an ETIC-system is very little. On the one hand their exterior layer has a much higher heat storage capacity than the insulation layer but on the other the thermal conductivity is also very high. Therefore core-insulated walls can be "charged" by the sunlight with a high amount of thermal energy within a short period but they will also lose it very quickly. Materials like wood or lightweight concrete have a much better relation between the thermal conductivity and heat storage

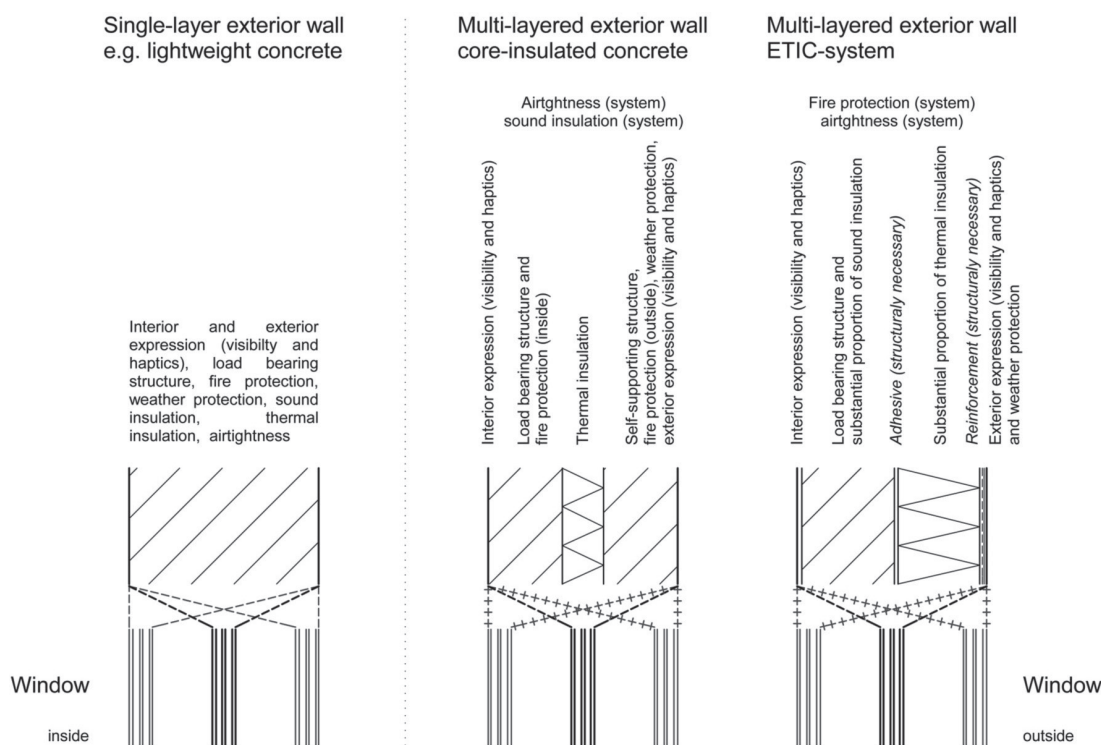


Figure 1. Comparison of function(s) of each layer in a single-layer exterior wall and in multi-layered exterior walls and the ability of different window positions.

capacity to benefit from the daily peak-to-peak-value of the temperature.² The quality of this relationship can be quantified by calculating the "dynamic U-value" which includes changing temperatures throughout the day, the thermal conductivity and the heat storage capacity.³ This calculation method is hardly used today, as it is not part of legal requirements.

Because of the reduction onto the heat transfer when introducing thermal protection requirements in the 1970s, the structure of building components has changed immediately while the appearance of buildings and the layout of ground floors or the

composition of space stayed almost the same, even though this also has an impact on the energy heating demand. And again, architects, engineers and clients just followed the rules and perpetuated on the existing building structures instead of thinking about the logic of building systems for decreasing the energy demand in a holistic way. Meanwhile the calculation methods got enhanced but they still focus on selected topics of the energy demand.

In the last decade the next driver for change arose with the discussion about sustainability. Considering this discussion the sustainable use of natural resources

has been introduced as a basic requirement for construction works in the amended Construction Products Regulation of the European Union in 2011. As a first step, legal restrictions are going to reduce sustainability to life cycle assessments of materials, which is already a big challenge for the building industry. Building certificates for sustainability such as the German DGNB go even further as they assess additional factors and therefore offer a more holistic approach. The next (slow) change has been initiated.

Potential of altering the constraints of a material

Concerning sustainability, single-layer constructions have several advantages. One is that life cycle assessments embrace the recycling of materials. It seems to be obvious that constructions being made out of a single layer should be easier to recycle than a multi-layered component. In reality it might not be that simple as single-layer exterior walls can also be based on a composite material. But at least there do already exist technologies that enable the splitting of such a composite into its primary materials. Although some positive effects of a single layer exterior wall concerning the heat energy demand have not been considered yet and as mentioned before, it can be used because of its positive behavior concerning its life cycle anyway.

In comparison, the recycling of an ETIC-system is very poor. Completely different materials are mixed and – in the worst case scenario – they are even glued together. In addition, anchors are necessary as a mechanical backup for the adhesive. Therefore it is hardly possible to divide the system into the raw materials at its expiry date. Today such exterior walls are treated as special waste. Due to the “Directive [2008/98/EC] of the European Parliament and of the Council on waste” and the “Regulation (EU) No 305/2011 of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products”,

and in a couple years, this will be prohibited. . A core-insulated concrete exterior wall is much easier to divide into its individual materials than an ETIC-system and only a little more complicated than recycling a lightweight concrete.

Apart from the legal restrictions, it is very interesting to use modified materials for single-layer constructions thanks to its characteristics in detailing. Let's quickly compare a single-layer exterior wall made out of lightweight concrete to a multi-layered exterior wall using the ETIC-system or having a core-insulation. (Figure 1) The lightweight concrete has to perform as the load bearing structure. Furthermore it has to ensure the sound insulation, the heat insulation and the airtightness. It must resist weather and fire. Finally, the material provides the visible and haptic expression of the wall. Although lightweight concrete is not the optimal material for fulfilling each individual requirement, it complies with the necessary needs. In contrast to that, every layer of the ETIC-system is specialized in achieving one or a maximum of two specifications. Only for the purposes of fire protection and being airtight the component has to perform as one system. Two extra layers are necessary. They are not obligatory to fulfill a requirement but to provide the whole system. Core-insulated exterior walls usually consist out of a load-bearing wall on the inside and a self-supporting wall on the outside. The inner and the outer layer do also characterize the visual expression of the wall and guarantee the fire protection. Both layers are important for the sound insulation and the airtightness, combining them with the thermal insulation improves the capabilities of the whole system. Apart from the influence towards sound reduction and airtightness the insulation layer reduces the thermal conductivity of the system.

The standard assembly is no problem with all systems, but what happens at its boundaries e.g. at an opening with a window? In the ETIC-system there

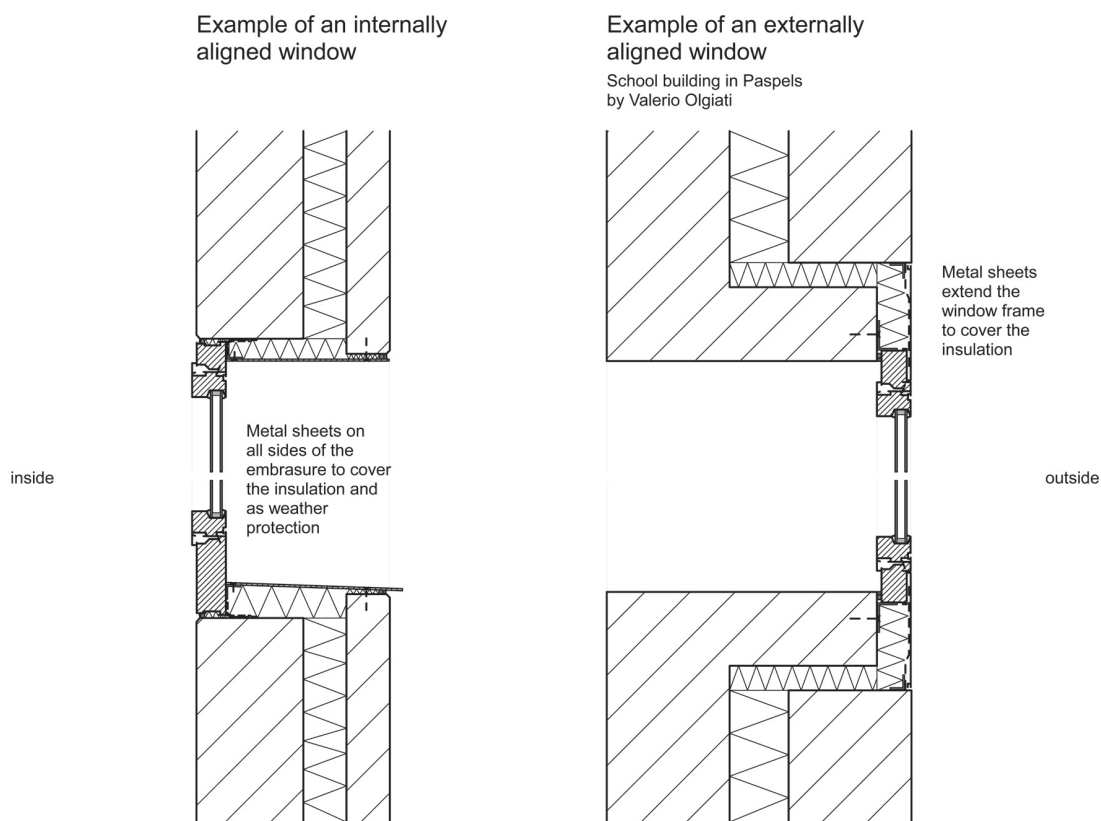


Figure 2. Example of an internally and externally aligned window in a core-insulated concrete wall.

are separate layers for the loads and for the thermal insulation. On the one hand, a window causes loads (wind, self-weight). Therefore it has to be fixed on the load bearing structure. On the other, it is part of the thermal shell. Thus, it has to be in contact with the thermal insulation. This leads to an optimal window position at the border between the load bearing layer and the insulation layer. This is the same regarding core-insulated concrete walls which have the advantage that the window frame can be fixed on the interior or the exterior concrete layer.

However extreme window positions, such as internally or externally aligned, are possible but leading to complex constructions as the gap between the window frame and the specialized layer has to be closed. This leads to additional elements or a complex detail development and difficult construction in the building process. (Figure 2) The architects of the example of an internally aligned window use a metal sheet on all sides of the embayment to cover the insulation. This solution enables a small window frame while indicating that there is something to cover between the concrete.⁴ In

Paspels, Valerio Olgiati wanted to have concrete in the embrasure also. Therefore the standard assembly with its core insulation had to be covered by concrete. As a result of the thickness of the concrete and the insulation, the window frame needed to be extended by nearly 20 cm.⁵ When building with lightweight concrete the position of a window theoretically speaking does not matter, as the material is the load bearing structure and the isolation. From the geometrical point of view heat bridges will be avoided in a central position in the wall,⁶ but the freedom in practical detail design depends on the heat conductivity of the building material. We will focus on that later.

When changing the properties of a material, a deep knowledge about the material is required. The goal of the modification should be defined clearly. In addition, important limits must be set as changing one of the parameters of a material usually affects other characteristics, too. The complexity of modifying materials leads to long and therefore generally expensive processes, but the final result is often worth it.

LIGHTWEIGHT CONCRETE

Concrete is a composite material basing on the mixture of cement, aggregates and water. Varying mass, size or type of ingredients leads to different properties of the final concrete. Beyond that additives and admixtures can also be used for changing properties. Therefore concrete is suited well for modification. .

Since normal concrete has a high thermal conductivity, it is not possible to use it for a single-layer exterior wall under the contemporary conditions in Central Europe. By using light concrete aggregates like foam glass or foamed clay instead of e.g. gravel the thermal conductivity can be lowered. (Figure 3) Thus this also reduces the load-bearing capacity. For small projects

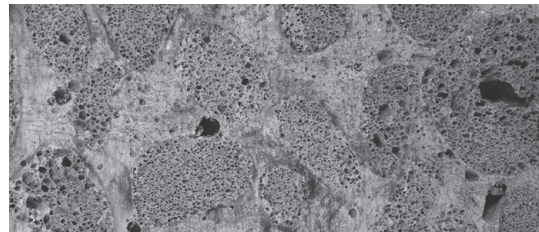


Figure 3. A section of lightweight concrete (Technolith) in scale 1:1 with foam glass and light sand as porous aggregates.

a concrete of the provided strength class LC 8/9⁷ is suitable. With foam glass as an aggregate one is able to perform a concrete of this strength class with a lambda of 0.22 W/m²K (heat conductivity), while with foamed clay the lambda is approximately 50% higher.⁸ The problem of using foam glass as an aggregate is that it may initiate an alkali silica reaction, which leads to cracks in the concrete, a reduction of the load-bearing capacity and a reduced durability. In Austria, Germany and Switzerland, the company Technopor exclusively offers a modified foam glass, which does not react with the alkaline components and therefore can be used as an aggregate in concrete.

Finally, Prof. Mike Schlaich and his research team of the TU Berlin worked out a concrete recipe basing it on foamed clay and an air-entraining agent, which has a lambda of 0.19 W/m²K while belonging to the strength class LC 8/9.⁹ The team of TU Berlin is still working on improving the properties of the mixture. These two concrete recipes – one belonging to Technopor and the other to Prof. Schlaich- can both be used for an economic and ecological solution of a building envelope in the moderate climate of Central Europe.

Simple construction details due to material properties

The properties of lightweight concrete differ from normal concrete but the fundamental characteristics



Figure 4. House Meuli in Fläsch (Switzerland) designed by Bearth & Deplazes with windows flushed to the inside wall.

are the same. As described lightweight concrete is less load-bearing. It has a ten times lower heat conductivity than normal concrete but it is still five times worse than a common insulation material like Polystyrene. Because of the contemporary legal requirements in Austria, this leads to exterior walls with a thickness of at least 50 cm. Due to its mass it is able to provide sound insulation. It does not burn and is airtight. The weather resistance is still given but due to the higher porosity lightweight concrete has a tendency to absorb water. Moisture raises the heat conductivity hence it makes sense to cover the exterior surface with hydrophobizing, which also closes little gaps and therefore extends the durability of the concrete. It seems easy to design details with such a material. What is it like in reality?

The first published project using lightweight concrete since establishing thermal protection requirements was the single-family house Meuli in the Swiss village Fläsch in 2001 (Figure 4). Its exterior walls are 50 cm thick and

made of lightweight concrete with a lambda of 0.33 W/mK. The raw appearance of the façade is a modern interpretation of traditional houses. As the windows are flushed to the inside wall, the deep embrasure underlines the openings in the wall on the outside. Inside the house windows give the impression of a picture. From the constructional point of view, there is no problem in fixing the frame. For sound protection, airtightness and even for fire protection the position of the windows is not relevant. The embrasure's water resistance is enhanced due to hydrophobizing. Even the "sill" is just concrete. In this area the concrete forms a channel with a gentle incline towards a drain, which leads to a rainspout. This elegant solution prevents sediments below the sill. Due to building physics, an offset in the concrete was necessary for the wooden frame to avoid condensate because of low temperatures in winter. This was the only restriction in the detail design: condensate.



Figure 5. Tenerife Espacio de las Artes (TEA) designed by Herzog & de Meuron.

Taking a closer look at window details of other buildings with external walls made of lightweight concrete, it becomes obvious that the thermal separation between inside and outside is often close to the inner surface of the wall. The only alternative seems to be a covering of the embrasure with insulating material. Before analyzing the problem, let's have a look at a smart detail solution.

The Tenerife Espacio de las Artes (TEA) is a multifunctional center for art and culture completed in 2008 in Santa Cruz de Tenerife. It was planned by the architectural office of Herzog & de Meuron and seems to be an excellent reference for a simple

construction detail. The exterior walls are made of 60 cm of "normal" concrete. This leads to an U-value of 2.44 W/m²K. Concerning the legal restrictions in 2006, the exterior wall had to meet an U-value of 1.22 W/m²K on Tenerife,¹⁰ which is less than the value of the contemporary assembly. Therefore the architects must have followed an alternative way to meet the legal restrictions concerning the energy demand. To underline the monolithic appearance of the building, the windows are externally aligned. (Figure 5) The detail is very minimalistic as windows do not have to be operable. The formwork was executed with a projection of 2 cm to the inside for the glazing. Finally, the window pane was fixed on the concrete with an adhesive and

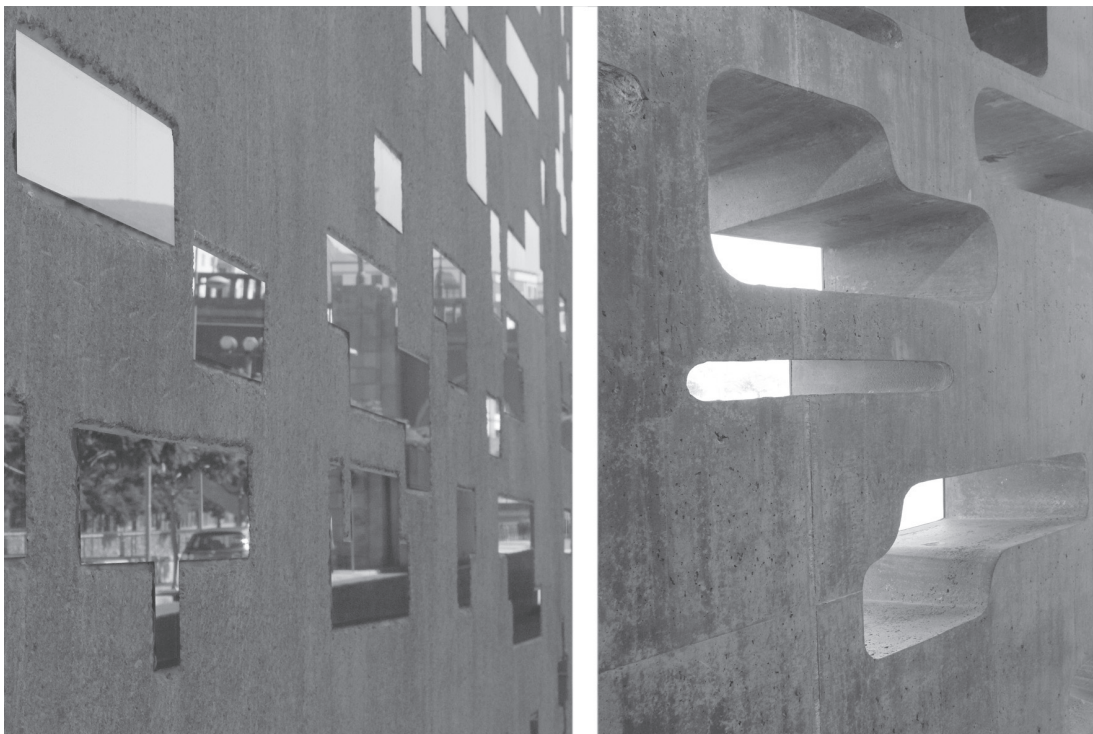


Figure 6. Externally aligned window panes without any frame at the TEA.

a silicone strip. An in-situ silicone joint closes the gap around the glazing. (Figure 6) Due to the warm climate, this is not a problem from a building physics view. Is it possible to translate this simple construction for a moderate climate?

Constraints by building physics

What's the problem of the window position due to condensation? It is very simple of course: as the calculation method of the norm for the winter case does not consider solar gains and outdoor temperature changes, the temperature inside the wall raises linearly from the outer surface to the inner surface. When a

window is on the inner side, the element is located in the warmer area of the wall. This leads to warmer surfaces of the window frame in the boundary area towards the wall. When moving the window position further to the outside, the frame gets closer to the colder area of the wall. This leads to a lower temperature on the window frame compared to the frame position closer to the inside. (Figure 7) Another factor which is important for the temperature gradient inside the wall is the thickness of the material. Raising the depth of the wall leads to a smaller temperature change per centimeter.¹¹ Although this is only true for the simplified assumption of interior and exterior static temperatures, it is still similar for the existing dynamic reality. Today's standard simulation

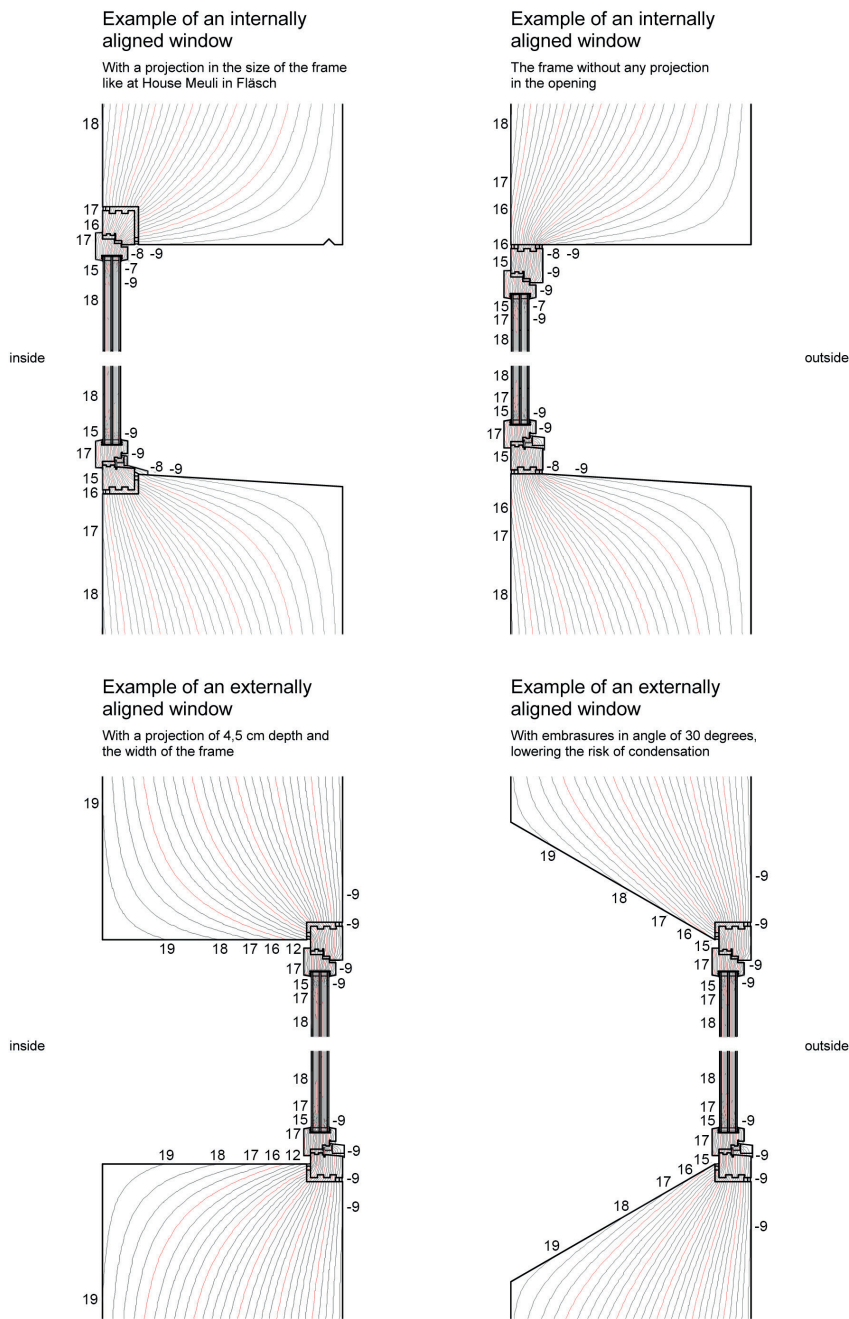


Figure 7. Internally and externally aligned windows in a lightweight concrete wall (U-value of the wall: 0.35 W/m²K, thickness: 60 cm) analysis with the thermal bridge software *flixo*.

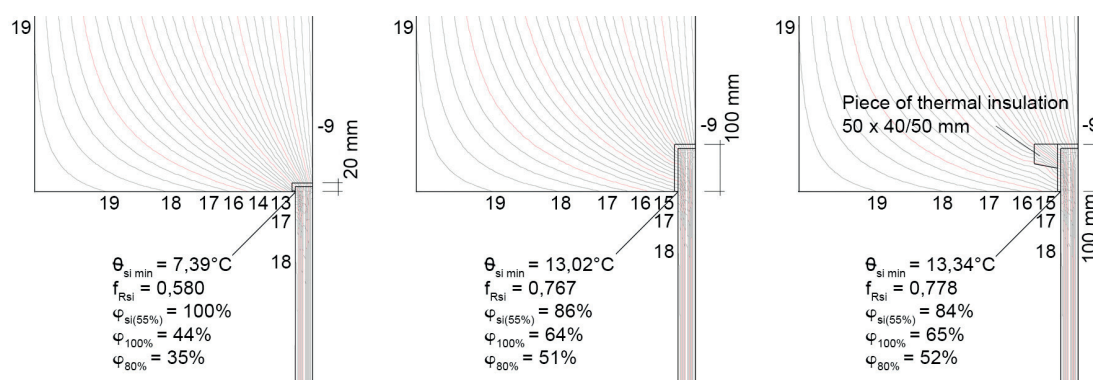


Figure 8. Openings in lightweight concrete with window panes flushed to the outside surface. Left: 2 cm overlapping, middle 10 cm overlapping and right 10 cm overlapping plus additional insulation. Thermal bridge analyzed with the software flixo pro.

programs for thermal bridges, which visualize the temperature profile inside building constructions e.g. the software flixo, use the static temperature assumption as this perfectly matches the popular assemblies. The simulation results for massive building envelopes indicate problems of a detail design, but they definitely need further interpretation.

What is important to know for interpreting the simulation output? Condensation needs a humidity of 100%, for mold growth 80% is enough. The air temperature on the inside is always 20°C due to the norm. The assumed room humidity differs in the simulation. It depends on the consideration of mold growth or condensation, and on the region where the building is going to be situated. For the region of Graz the minimal temperature in winter is -10°C according to the norm. This leads to an assumed air humidity of 55% for the simulation of condensation and 45% for the simulation of mold growth – both at an inside air temperature of 20°C. In the following details three different phi-values of the worst part of the construction are always given. The first one " $\varphi_{si(55\%)}$ " displays the humidity in that area, when the air humidity in the room is 55%. The second one " $\varphi_{100\%}$ "

is the limit, how high the humidity must be at an air temperature of 20°C to have condensation at this part of the construction. The last one " $\varphi_{80\%}$ " is the critical value for humidity, when mold growth will begin.

The contemporary thermal regulations in Austria cause a minimum wall thickness of 60 cm when using the receipt of Technopor.¹² For simulations with the analyzing software flixo a triple glazing with a u-value of 0.5 W/m²K and a width of 36 mm is chosen. What would a window detail similar to the TEA look like for a building in Central Europe? First of all, improving the lambda of the lightweight concrete will reduce the problem of the low surface temperature. Therefore it is easier to design a detail with the Technopor recipe (lambda: 0.22 W/mK) than with the lightweight concrete, which was used for the house Meuli (lambda: 0.33 W/mK).

If the opening was built with a projection of 2 cm – as it is at the TEA – it would cause condensation and mold growth as the temperature would be less than 8°C. By extending the projection, the temperature in the corner increases. A projection of 10 cm seems to be enough to avoid condensation or mold growth. (Figure 8)

When lower outside temperatures have to be considered, it would be an alternative to implement a piece of thermal insulation behind the glass instead of extending the projection. Using this solution needs a minimal projection of approximately 10 cm as it must be guaranteed, that the concrete will still flow into the corner of the formwork below the insulation.

The next possibility to raise the temperature in the corner is to slope the embrasure. It has a similar effect like a thinner wall, which is not possible due to the necessary minimal U-value. The slope increases the heat transfer through the wall and therefore leads to a (slightly) higher energy demand.¹³ Apart from that it has some benefits. Firstly, it has advantages for the casting process as it simplifies the stripping of the formwork. Secondly, the light quantity getting into the room is reduced due to the wall thickness. Beveling the embrasure leads to a higher light quantity without changing the size of the opening itself. Thirdly, it improves the airflow in the window recess. This complex problem needs some background information: actually, it depends on a couple of parameters like the size and depth of the window recess, the temperature of the surfaces and the air, the air humidity and even on the heating system. When convection heating such as a radiator or floor heating is used, the lower part of the window might be significantly cooler than its top part as a kind of shadow zone arises when the distance between the edge of the inner sill and the window is too big. Independently of the air temperature and humidity, condensation might appear although a thermal bridge analyzing software does not indicate this problem.

Another possibility to avoid condensation is by integrating a heat pipe in the embrasure. Inserting pipes in the concrete is simply done in the building process but the disadvantage is that such components have a significant shorter life span in comparison to lightweight concrete. Exchanging those pipes is

inordinately more difficult and they also impair the recycling behavior of the concrete.¹⁴

Heating the embrasure somehow completes the circle: when the façade with the window is facing the sun at some point of the day, the solar gains by the window and the lightweight concrete will establish higher temperatures in reality than assumed in the simulation with static boundaries.

CONCLUSION

The implementation of restrictions concerning building energy consumption introduced a change in the construction of building envelopes towards working with specialized layers. This seems to be more efficient concerning energy loads for heating but it leads to complicating detail designs as these constructions get more and more fragile concerning building physics. The extension of legal requirements by introducing sustainability as a further aspect initiates the next change in construction technologies, as parameters like recyclability have to be considered in future. This is a big disadvantage for multi-layered exterior walls as they are made of different materials, which have to be separated for recycling. Single-layer building envelopes using modified materials e.g. lightweight concrete are also able to meet today's requirements concerning recyclability and building energy loads. The research indicates that building physics simulations using static boundaries do not correctly reproduce the reality. These simulations for example do not consider the heat storage capability of the lightweight concrete. Therefore dynamic simulations are necessary to develop the optimal solution for a detail as in reality the temperature gradient will be different (less critical) compared to the result of a static simulation. Apart from the ecological advantages, these materials enable architects to develop minimal details with little constraints.

Notes and References

- ¹ See: MEIER, C. *Mythos Bauphysik. Irrtüemer, Fehldeutungen, Wegweisungen*. Renningen: expert verlag, 2007, p. 57-58.
- ² See: KELLER, B. *Bautechnologie III. Bauphysik. Teil 2: Die Energetik des Gebäudes*. Zurich: Lecture notes ETH, 1999, p. 82-87.
- ³ See: KELLER, B. und RUTZ, S. *PINPOINT. Fakten der Bauphysik*. Zurich: vdf Hochschulverlag, 2007, p. 59.
- ⁴ See: BAUS, U. *Sichtbeton. Architektur, Konstruktion, Detail*. Munich: Deutsche Verlags-Anstalt, 2007, p. 162.
- ⁵ See: DEPLAZES, A., Editor. *Constructing Architecture. Materials Processes Structures. A Handbook*. Basel: Birkhäuser, 2008, p. 367.
- ⁶ See: KNAACK, U. et al. *Façades. Principles of Constructions*. Basel: Birkhäuser, 2007, p. 54-55.
- ⁷ Classification according to EN 206-1 Concrete - Part 1: Specification, performance, production and conformity.
- ⁸ See: FILIPAJ, P. *Architektonisches Potential von Dämmbeton*. Zurich: vdf Hochschulverlag, 2010, p. 23-25.
- ⁹ See: SCHLAICH, M. and HÜCKLER, A. *Infraleichtbeton 2.0*. In: *Beton- und Stahlbetonbau*, 107, Heft 11. Berlin: Ernst & Sohn, 2012, p. 762.
- ¹⁰ See: *Technical building code DB HE : saving energy table 2.1. maximum thermal transmittance of closures and interior partitions of thermal enveloping* U en W/m²K.
- ¹¹ Increasing the walls width reduces the risk of condensation when the window position is closer to the inside surface and increases the risk of condensation when the window position is more on the outside. The reason is that the temperature changes less per centimeter inside the wall when the wall is thicker. Therefore, measuring in the same distance from the surface, the wall is colder or warmer
- ¹² Due to the OIB Richtlinie 6 (Austrian guideline for the energy demand of buildings) the maximum U-value for exterior walls is 0.35 W/m²K.
- ¹³ Concerning building physics it makes sense to slope the embrasure only when the window is flush to the outside as in this case a thinner exterior wall reduces the risk of condensation. If the window is flush to the inside, the risk of condensation will increase.
- ¹⁴ See: LUEKING, T. *Keep It Simple! On the Qualities of Single-Layer Exterior Walls of Lightweight Concrete*. In: *Graz Architecture Magazine – GAM.09. Walls: Spatial Sequences*. Vienna: Springer, 2013, p. 171-172

BIBLIOGRAPHY

- BAUS, U. *Sichtbeton. Architektur, Konstruktion, Detail*. Munich: Deutsche Verlags-Anstalt, 2007
- DEPLAZES, A. Editor. *Constructing Architecture. Materials Processes Structures. A Handbook*. Basel: Birkhäuser, 2008
- FILIPAJ, P. *Architektonisches Potential von Dämmbeton*. Zurich: vdf Hochschulverlag, 2010.
- KELLER, B. *Bautechnologie III. Bauphysik. Teil 2: Die Energetik des Gebäudes*. Zurich: Lecture notes ETH, 1999.
- KELLER, B., RUTZ, S. *PINPOINT. Fakten der Bauphysik*. Zurich: vdf Hochschulverlag, 2007.
- KNAACK, U., KLEIN, T., BILOW, M., AUER, T. *Façades. Principles of Constructions*. Basel: Birkhäuser, 2007.
- LUEKING, T. *Keep It Simple! On the Qualities of Single-Layer Exterior Walls of Lightweight Concrete*. In: *Graz Architecture Magazine – GAM.09. Walls: Spatial Sequences*. Vienna: Springer, 2013, p. 166-179.
- MEIER, C. *Mythos Bauphysik. Irrtüemer, Fehldeutungen, Wegweisungen*. Renningen: expert verlag, 2007.
- MEIJS, M., KNAACK, U. *Components and Connections in Architecture. Principles of Construction*. Birkhäuser Basel-Boston-Berlin 2009.
- SCHLAICH, M., HÜCKLER, A. *Infraleichtbeton 2.0*. In: *Beton- und Stahlbetonbau*, 107, Heft 11. Berlin: Ernst & Sohn, 2012, p. 757-766.

IMAGES SOURCES

1. Author, 2013. 2. Author, 2013. Sections basing on drawings in Baus, U. *Sichtbeton. Architektur, Konstruktion, Detail*. Munich: Deutsche Verlags-Anstalt, 2007, p. 162 (left) and Deplazes, A., Editor. *Constructing Architecture. Materials Processes Structures. A Handbook*. Basel: Birkhäuser, 2008, p. 367 3. Author, 2013. Lightweight concrete sample made by Technolith. 4. Tobias Münch, Hamburg, D, 2009, right picture published in *GAM 09. Walls: Spatial Sequences*, Vienna: Springer, 2013, p. 173. 5. Johannes Würzler, Graz, AT, 2012, detail published in *GAM 09. Walls: Spatial Sequences*, Vienna: Springer, 2013, p. 166. 6. Johannes Würzler, Graz, AT, 2012. 7. Author, 2013. Analyzed with thermal bridge software flexo pro. 8. Author, 2013. Analyzed with thermal bridge software flexo pro.