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Internal insulation of historic buildings with earth building materials

When renovating and converting historical buildings, it is important to reduce energy consumption as far as is reasonably possible, especially in northern European climates. Part of this involves determining to what extent external walls should be insulated to achieve additional energy savings, over and above the insulation of the roof and basement, and the modernisation of the heating and ventilation systems. Depending on a building's geometry, the building envelope accounts for only 30-40% of heat loss, with about 33% resulting through doors and windows. Insulating the facade is about twice as expensive as insulating the roof and basement. In addition, depending on the nature of the external walls, one needs to decide whether to insulate the outer or inner face of the external walls. In many cases, insulation cannot be applied to the exterior of a building as it would obscure important historical details. That leaves insulation of the internal wall face of external walls as the only option, although this is challenging from a building physics point of view. Earth building materials are ideally suited for this complex situation.

External insulation vs. internal insulation

Both external and internal insulation have advantages and disadvantages, which need to be individually assessed for each project.

The pros (⊕) and cons (⊖) of both external and internal installation are outlined below:

External insulation

- ⊕ unproblematic physically and technically with respect to moisture in the construction
- ⊕ more effective than internal insulation for the same thickness of insulation material
- ⊖ can often obscure the visual appearance and design of a building
- ⊖ surface condensation and formation of algae cannot be excluded by the majority of insulating materials
- ⊖ scaffolding costs
- ⊖ alterations need to be made to roof drainage, window sills etc.
- ⊖ can project beyond the site boundaries

Internal insulation

- ⊕ apartments can be insulated independently
- ⊕ no scaffolding costs
- ⊕ interiors heat up more rapidly
- ⊖ building physics design and analysis is necessary to avoid potentially serious moisture problems
- ⊖ is less able to buffer moisture from driving rain
- ⊖ insulation weakspots where building elements penetrate the insulation layer (e.g. ceilings or crosswalls)
- ⊖ slight reduction of interior (living) space
- ⊖ installations and details need to be adapted
- ⊖ partial loss of thermal inertia (less able to protect against heat gain in summer)

As mentioned above, external insulation is out of the questions when a historical facade is decorative or historically important. In such cases, internal insulation of the external walls is the only viable option.

Germany's Energy Saving Ordinance 2014 (EnEV) does not specify a general obligation to insulate the external walls of existing buildings. External walls must only be insulated if outside work on the building envelope is undertaken, for example in the event of the complete replacement of a wall, cladding of the wall or renewal of the external render.

The EnEV does not stipulate a minimum thermal insulation effect for internal insulation. Internal insula-

Fig. 1 The external insulation of many historic buildings is often impossible as it would rob them of their identity

tion should ideally be as thick as possible "as far as is technically viable and safe for the wall". As such, the EnEV avoids stipulating excessively thick insulation layers that could lead to building damage, recommending instead a "reasonable" level of insulation as per the state of the art. In all cases, however, a minimum thermal insulation in accordance with DIN 4108-2 of > 1,2 m^2 K/W (equivalent to a U-value < 0.83 W/m^2K) must be observed.

Light earth internal insulation vs. insulation panels bedded in earth mortar

In general, one can distinguish between internal insulation made of thermally-insulating earthen materials (λ = 0.1 ... 0.2 W/mK) and internal insulation using more performant capillary-conductive insulation materials (λ <0.1 W/mK) bedded in earth mortar and coated with clay plaster. Both techniques are suitable for the renovation of half-timbered walls as well as for solid earth buildings, brick and natural stone buildings [1].

The use of light earth internal insulation has become established practice over the past three decades, whereas the practice of bedding insulation board in earth mortar has only become more common over the last ten years. Both approaches are based on the principle of capillary action, i.e. the ability of the

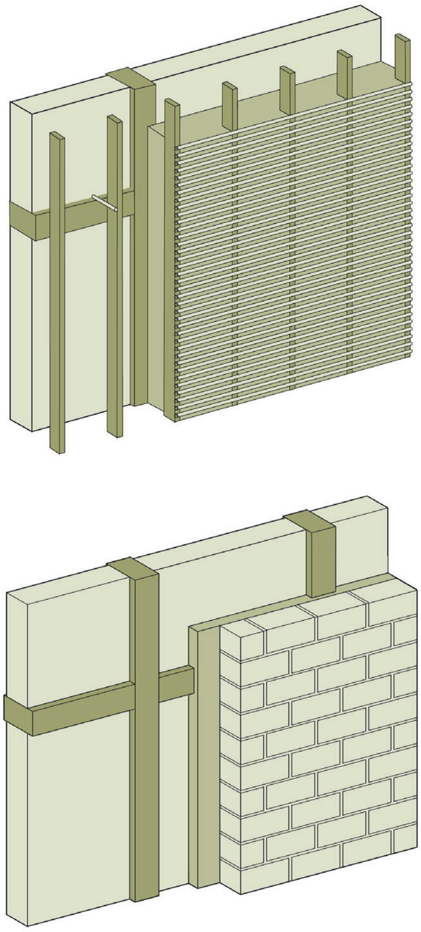

Fig. 2 Light earth internal wall lining methods. a) as a moist malleable mass, and b) as internal masonry layer

material(s) to transport and dissipate moisture and condensation. These systems are therefore tolerant to moisture in the building structure, for example as a result of driving rain or structural damage. Instead of moisture being trapped within the structural layers (interstitial moisture) by vapour barriers or vapour-retardant layers, they can transport moisture through and out of the wall.

With light earth internal insulation systems, moisture within the wall can, however, become critical during the construction phase. Intensive drying measures must be undertaken to ensure the light earth material can dry out quickly and effectively. Furthermore, to avoid producing excessive moisture, internal insulation layers should not be over-dimensioned. Insulation thicknesses of 6 to 8 cm have proven to offer a suitable and mathematically verifiable level of insulation.

For insulation boards, softwood fibreboard and mineral foam panels can be recommended as estab-

Fig. 3 Internal insulation with a) softwood fibreboard and b) mineral foam panels bedded in earth mortar

lished materials for internal insulation. The initially commonly-used reed matting panels offer no significant calculable effect unless used at thickness upwards of 4 cm. Softwood fibreboard panels are similarly flexible and therefore a good alternative for the internal insulation of timber-framed buildings. Mineral foam boards are more commonly used for the internal insulation of solid wall constructions, e.g. stone or masonry.

Light earth internal insulation has the following pros (⊕) and cons (⊖):

- ⊕ unproblematic structurally and physically if not too lightweight
- ⊕ high thermal retention capacity combined with a moderate thermal insulation capacity
- ⊕ can accommodate irregular wall thicknesses without the need for additional layers when using light earth mortar
- ⊖ moderate insulation effect
- ⊖ reduction of (living) space due to thick layers
- ⊖ higher load: thick layers in multi-storey buildings may require additional loadbearing measures
- ⊖ long drying time when used as moist levelling course or when embedded behind masonry.

This last aspect is particularly problematic and can be the cause of significant damages (Fig. 4) when drying measures are ineffective. This is not adequately discussed in the literature on light earth internal insulation [2], [3].

By comparison, internal insulation using thermal insulation boards bedded in earth mortar and coated with clay plaster have the following (⊕) advantages and (⊖) disadvantages:

- ⊕ low heat loss
- ⊕ light loads
- ⊕ short drying times if no thicker mortar layers are required to level surface irregularities
- ⊕ rooms heat up comparatively quickly
- ⊖ low thermal retention capacity
- ⊖ careful structural-physical analysis is necessary

In historical half-timbered and solid structures, structural elements, such as cross walls and ceilings, that intersect with the external wall are largely unproblematic in terms of thermal bridging. It is, nevertheless, imperative to undertake a building physics analysis of the ceiling joist supports, at least in historical brick buildings.

The structural-physical properties of earthern internal insulation materials can be determined using specialised computer software that takes the capillary conductive properties of existing and new insulation materials into account, e.g. COND, WUFI or DELPHIN. The last two programs also consider exposure to driving rain at specific geographic locations. Such analyses show that moisture caused by exposure to rain can drastically increase the resulting overall level of moisture in the wall.

Fig. 4 a + b Mould and fungus formation due to too slow drying of the light earth internal insulation layer. Mill, Germany

Examples of bad practice

Light earth internal insulation of a historic mill

The historic mill was converted for residential purposes. The damaged oak half-timbering was repaired and given new masonry infill. A light earth internal insulation system was chosen and calculated as being suitable. However, the insulation was only able to dry out slowly after installation, and despite additional efforts to improve drying (heating and greater air exchange rate), extensive mould and fungal growth formed during installation in the transitional zone between the light earth shell and existing wall.

The slow drying can be attributed to a variety of reasons that although each only partially responsible were in combination catastrophic:

- excessively thick light earth lining (~18 cm)
- permanent formwork insufficiently permeable (solid fraction ~2/3)
- very light density of light earth mixture (300 kg/m^3)
- aggregates in the mix not capillary conductive.

This led to further damages to the timber frame and the entire internal insulating layer had to be removed and replaced with wood fibre insulation panels bedded in earth mortar.

Wood fibreboard internal insulation of a historic stone and half-timbered house

The building from the 15th century had been renovated in line with historical guidelines and lined with a wood fibreboard internal insulation system. The internal insulation was bedded in a cement-based polymer-modified adhesive mortar, which was not as agreed between the client and contractor. Moreover, instead of applying adhesive to the entire surface area, only mortar dabs were applied to fix the panels, which is unacceptable for internal insulation.

In addition, the water and heating pipes were not relocated and so remained between the existing wall and internal insulation leading in winter to potentially fatal consequences for the pipes and the insulation.

Fig. 5 a + b The improper bonding of the internal insulation panels could be detected by knocking and is plainly visible at open junctions such as the window sill. After opening a section of the wall, the full extent of the inappropriate bonding method was revealed.

Fig. 6 a + b Light earth internal insulation with hemp. Former livestock barn in Ribbeck, Germany

Examples of good practice

Limestone-pisé barn in Ribbeck near Berlin

This former livestock barn for sheep was built in the mid-19th century as a lime-pisé construction. To begin with, comprehensive drying, desalination and crack repair works were undertaken. Once complete, a 15 cm thick internal insulation layer of light earth with hemp aggregate was installed. The irregular internal face of the existing wall was deemed sufficiently robust to stand without further strengthening measures and the light earth insulation lining serves to even out surface irregularities and provide a level wall face. The insulating measures improved the U-value of the wall from 1.2 to 0.59 W/m^{2}K.

Granary in Freiberg

The historic granary with three full and three attic storeys was converted into a library. The historic stone walls are made of very dense and thus highly thermally conductive gneiss stone. Before applying the internal insulation system, the wall foundations were drained, and a so-called sacrificial plaster applied to draw out soluble salts from the underlying wall. A building physics analysis of the walls revealed that the stone was so impervious to vapour transport that the only viable internal insulation method was to use mineral foam board. The panels are bedded in earth mortar and coated with a clay plaster. The addition of 6 cm of mineral foam board improved the U-value of the wall from 1.3 to approximately 0.50 W/m^{2}K.

Fig. 7 a + b Internal insulation of a granary in Freiberg/Saxony (Germany) with mineral foam insulation board bedded in earth mortar with additional wall heating and clay facing plaster

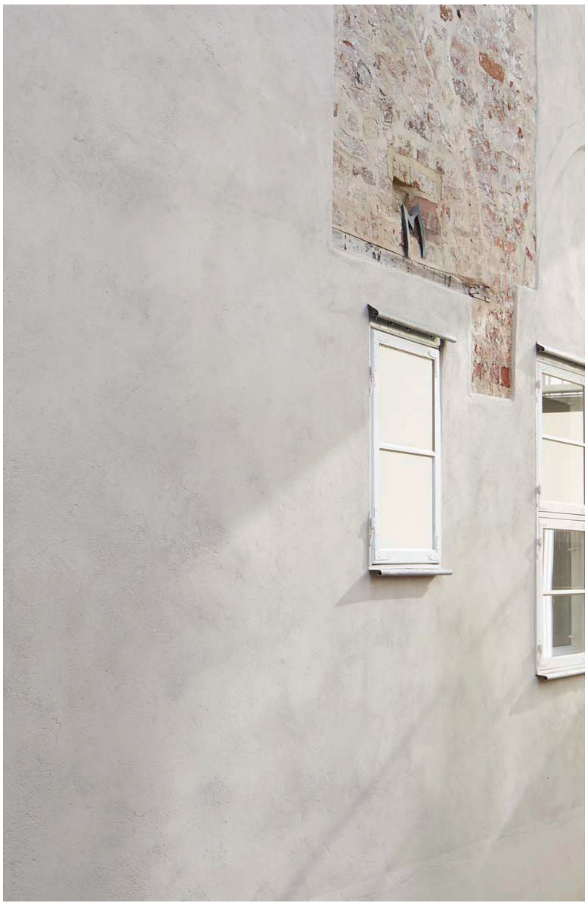

Fig. 8 a + b Internally insulated historic facade of a burgher's house in Wismar, Germany

Late Gothic burgher's house in Wismar

The burgher's house, originally from the Late Gothic period, with later alterations in the Baroque and "Gründerzeit" perods, is located in the historic centre of the town of Wismar and is protected by the UNESCO World Heritage status. The internal walls of the gable-fronted building, built with so-called "monastery format" bricks, are half-timbered wall constructions with brick infill. The rooms of the entire building were faced with historical clay plaster, the staircase with lime plaster. Foundation settlement and significant moisture and salt damage made it necessary to comprehensively renovate the building. The energy-efficient renovation concept included, alongside the internal insulation of the external walls, additional insulation of the bottom floor and uppermost ceiling as well as energy and heat generation using a micro-

CHP plant. Through these measures, the building was able to attain KfW Efficiency House level KfW85.

A horizontal damp course was installed, in parts where the geometry did not allow otherwise, using a chemical moisture barrier against rising damp. The walls were desalinated to an acceptable level by repeated application of sacrificial earth plaster. Mineral foam boards were used for the internal insulation of the up to 80 cm thick walls due to residual moisture and salt content within the walls. Wood fibreboard was used on the upper floors. Both types of internal insulation were coated with a clay plaster.

Conclusion

For design and historic preservation reasons, external insulation is often not viable for historic buildings. In such cases, internal insulation can be considered if the external walls need to be insulated. Earth building materials are increasingly being used for the renovation of half-timbered buildings, and not only for those with earth infill but also solid constructions and brick and natural stone buildings. The capillary conduction of earth insulation systems means that they obviate the need for vapour barriers or retarding membranes. Furthermore, earth internal insulation systems are fault-tolerant systems. They help to substantially reduce the thermal conductivity of existing wall structures without lowering them to the levels of new buildings, which are not always compatible with historical buildings and materials.

However, to function correctly, internal insulation must be installed properly. As described, improper insulation may not only render insulation measures ineffectual but can also cause serious building damage. As a consequence, installation works need to be carefully planned, executed and also supervised.

In addition, further research is required into the drying behaviour of wet light earth mass in the building phase. In the use phase, all of the systems presented in this paper are durable and unproblematic.

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