Internal Insulation of Masonry Walls with Wooden Floor Beams in Northern Humid Climate

Martin Morelli

Toke R. Nielsen, PhD
Associate Member ASHRAE

Gregor A. Scheffler, PhD

Svend Svendsen, PhD

ABSTRACT

Multi-story buildings in Denmark from 1850–1950 are built with masonry walls and wooden floor beams. Large energy savings can be achieved by insulating the facades. Often interior insulation is the only possibility in order to keep the appearance of the external facade. The internal insulation reduces the drying potential of the wall, which might lead to moisture problems in the beam ends embedded in the masonry due to absorption of driving rain.

This paper describes a solution to avoid the moisture problems and still achieve large energy savings. The thermal analyses are made in thermal simulation programs for two dimensions and three dimensions. The moisture analyses are made by a two-dimensional simulation of the coupled heat, air, and moisture transport.

The results show that leaving an uninsulated part of the wall above and below the floor division could solve the moisture problem depending on the amount of wind-driven rain hitting the facade. The proposed solution would almost halve the heat loss through a typical wall section compared to the original wall structure.

INTRODUCTION

In Europe approximately 40% of the primary energy consumption is used in buildings (Tommerup and Svendsen 2006). New buildings represent only a small part of the total building stock. Hence, the energy saving potential lies in the existing buildings. In Denmark multi-story buildings from 1850–1950 are erected with massive masonry walls and wooden floor beams supported in the wall as described by Engelmark (1983) and shown in Figure 1.

Insulating the facades of multi-story buildings from 1850–1950 has a substantial energy saving potential (Tommerup and Svendsen 2006; Wittchen 2009). Old buildings often have facades worth preservation; hence, interior insulation offers the only possible solution for retrofitting these facades.

Internal insulation reduces the temperature in the existing wall and increases the risk of condensation of water vapor penetrating the new interior wall. The lower temperature in the wall also reduces the drying potential. A vapor barrier can prevent water vapor penetration from the inside. But the vapor barrier also reduces the drying potential to the inside. This might become critical for high wind-driven rain loads (Häupl et al. 2004; Scheffler 2009). As a result, water from rain may accumulate in the masonry and cause deterioration of the wooden beam ends. The critical moisture content in wood for growth of fungi is approximately 20%. The critical relative humidity for mold growth is above 80% to 90%, depending on temperature and duration of such conditions (Sedlbauer 2002; Viitanen et al. 2009).

Existing recommendations on internal insulation of masonry walls with wooden beams, e.g. Munch-Andersen (2008) and Brandt et al. (2009), state that insulation should be applied between floor and ceiling and that the exterior surface should be renovated at the same time. The heat loss through the floor division should keep the beam end warm, and the waterproof facade should limit the absorption of wind-driven rain. Scheffler (2009) has shown that the existing recommendations are not sufficient to solve the moisture problem at the beam

Martin Morelli *is a doctoral student,* ***Toke R. Nielsen*** *is an associate professor, and* ***Svend Svendsen*** *is a professor in the Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.* ***Gregor A. Scheffler*** *is a senior researcher at Xella Technologie-und Forschungsgesellschaft mbH, Emstal, Germany.*

(a)

(b)

Figure 1 *(a) The beam is supported in the pier with an air gap around the beam end. (b) A facade aesthetically worth preservation (Engelmark 2010).*

end. These studies have led to the more detailed analyses reported in this paper and to a proposed solution.

This paper consists of two parts. The first part analyzes the potential energy savings of a typical section of the outer masonry wall. The coupling coefficient analyses are made in two dimensions and three dimensions, using the heat transfer programs HEAT2 and HEAT3 (Blomberg 1996). The second part analyzes the internal insulation of masonry with a vapor barrier to avoid water accumulation at the beam end. The used method is a theoretical study using the coupled heat and moisture program DELPHIN (Nicolai et al. 2010). In the analysis, full climatic conditions including wind-driven rain and solar radiation are taken into account. The beam end detail is analyzed with regard to relative humidity and moisture content. It is the objective to study how sensitive these problems are and if they can be avoided by leaving a gap between the floor and the internal insulation of 300 mm (11.81 in.).

METHODS

Investigated Structure

The existing masonry wall has a thickness of 460 mm (18.11 in.) consisting of bricks and mortar. The bricks have the dimensions 80 mm (3.15 in.) × 220 mm (8.66 in.) separated by 20 mm (0.79 in.) lime-cement mortar. On the inside of the wall is a 30 mm (1.18 in.) lime plaster layer. The outer 220 mm (8.66 in.) of the beam end is supported in the wall on one side, and there is an air gap of 20 mm (0.79 in.) on all other sides between the beam and the masonry wall. The beams have a height of 140 mm (5.51 in.) × 140 mm (5.51 in.) with a center distance of 940 mm (37.01 in.). On top of the beam are 30 mm (1.18 in.) wooden floor boards. The internal insulation has a thickness of 200 mm (7.87 in.) with a vapor barrier between the insulation and the 15 mm (0.59 in.) gypsum board inwards. The insulation was either applied between floor and ceiling, or a 300 mm (11.81 in.) gap above and below the beam was left uninsulated. The vapour barrier was placed horizontally under the insulation in the cases where there was a gap between the floor and the insulation. Figure 2 shows a two-dimensional and three-dimensional model of the wall.

In the three-dimensional model, one quarter of the beam end was analysed. The floor division was modelled as the beam with floor boards.

The energy-saving potential of insulating the outer wall was evaluated based on a typical wall section from buildings around 1850–1950 as shown in Figure 3 (Engelmark 1983). The two windows have a size of 1.1 m (43.31 in.) × 1.65 m (64.96 in.). The height of the breast is 0.8 m (31.50 in.) which is the same as the distance between the windows. Above the windows and to the ceiling there is 0.4 m (15.75 in.). The dimensions of the floor beams are 0.14 m (5.51 in.) × 0.14 m (5.51 in.) with 0.03 m (1.18 in.) wooden flooring. The center

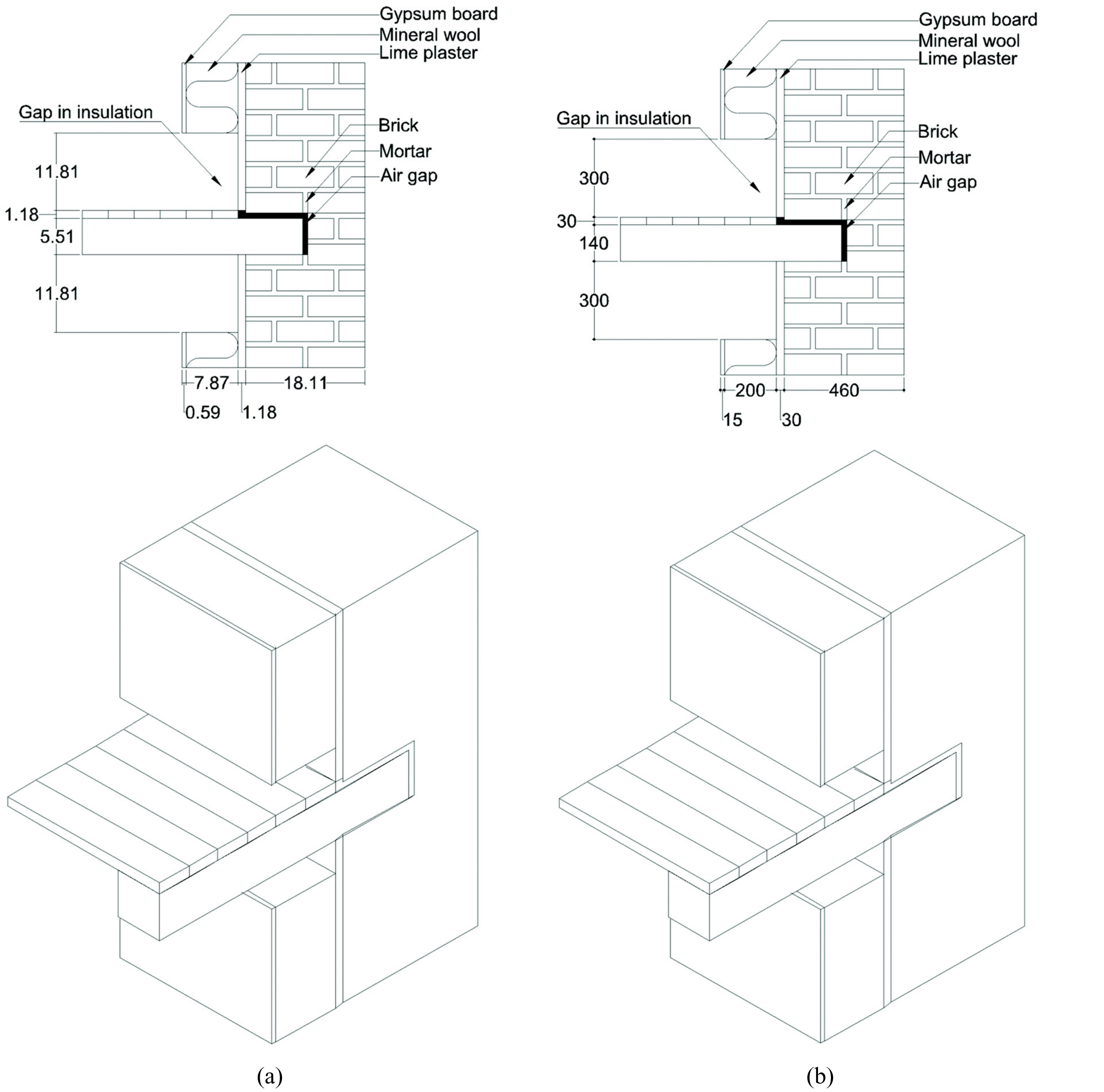


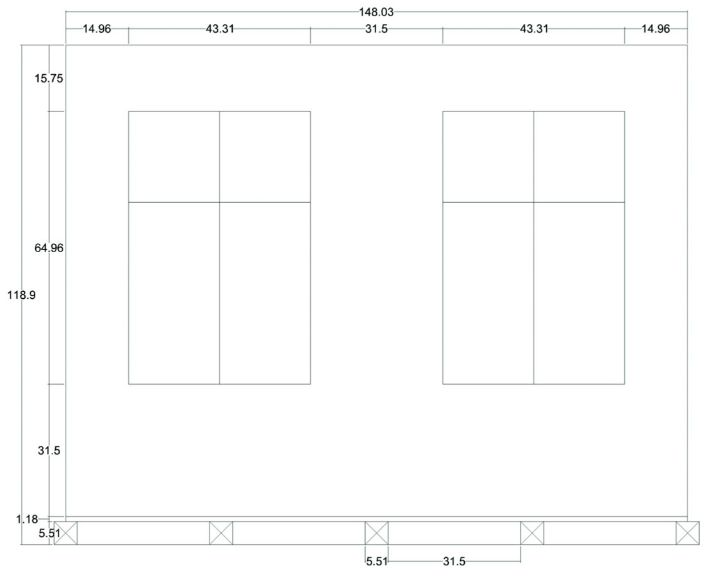
Figure 2 *Masonry wall with wooden beam end after retrofitting showing the air gap between the floor and insulation for the two-dimensional and three-dimensional model in (a) I-P units and (b) SI units.*

distance between the floor beams is 0.94 m (37.01 in.). The total width of the wall is 3.76 m (148.03 in.).

Materials and Boundary Conditions

The materials used and a list of their basic properties are given in Tables 1a and 1b. λ_{dry} is the thermal conductivity of the dry material, ρ is the density, μ is the water vapour diffusion resistance factor and A_w is the water absorption coefficient.

The interior and exterior environment was described by boundary conditions for temperature in the interior and exterior air and relative humidity. The inside air temperature was constant 20°C (68°F) and the relative humidity was 50%. The exterior climate was described by a constant outside air temperature of –5°C (23°F) in the thermal calculations. The reference year of Bremerhaven, a mild, maritime climate with a lot of rain and high humidity, was used as exterior climate in the coupled heat and moisture calculations.



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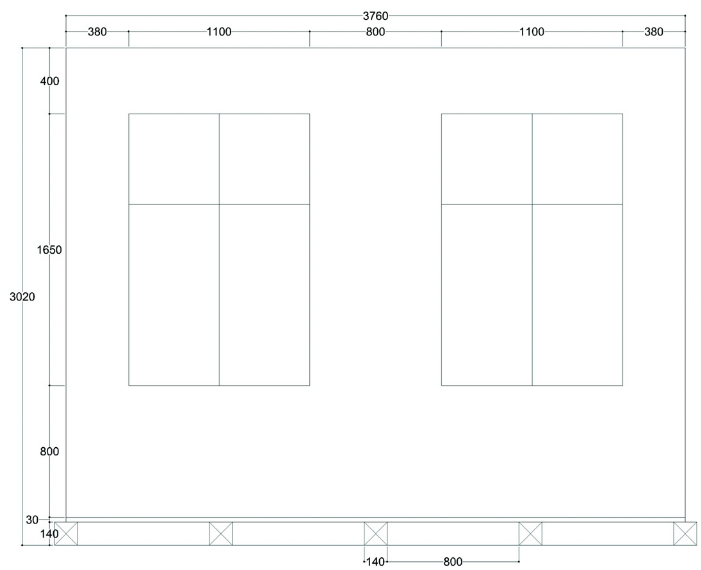


(b)

Figure 3 *Section of a typical outer wall with wooden floor beams from 1850–1950 in (a) I-P units and (b) SI units.*

The surface resistances were defined according to EN ISO 6946:2007 and as listed in Tables 2a and 2b, where the vapour diffusion resistance also is listed.

Thermal Calculations

This first study was a pure thermal investigation where the software tool HEAT2 ver. 7.1 and HEAT3 ver. 5.1 according to Blomberg (1996) was used.

The floor division was modelled as the wooden beam and flooring as shown in Figure 2. Under the flooring the temperature was set to 20°C (68°F), representing the materials in the floor division. Letting the air represent the materials in the floor division, no surface resistance was included.

In the two-dimensional calculations, the grid was analyzed by changing numbers of cells from n to $2n$. A deviation in the heat flow through the surfaces of less than 0.5% was accepted. For the three-dimensional steady-stat calculations, the grid was analyzed with regard to the heat flow through the surfaces. A deviation of 1.5% was accepted which corresponded to the maximum allowable number of cells (130 cells).

The coupling coefficient, L, was defined as the difference between the two-dimensional or three-dimensional heat loss,

Table 1a. Material Properties for Heat and Moisture Calculations (I-P)

Material Property	λ_{dry}, Btu/(ft·h·°F)	ρ, lb/ft^3	μ, —	A_W, kg/(m^2·s$^{0.5}$)
Brick Joens	0.53	112	13	0.227
Lime-cement Mortar	0.40	100	30	0.3
Lime Plaster	0.47	112	12	0.127
Spruce	0.08	33	40	0.058
Air Layer (25 mm)	0.08	0.08	0.5	–
Mineral Wool	0.02	2	1	–
Gypsum Board	0.12	53	10	0.277

Table 1b. Material Properties for Heat and Moisture Calculations (SI)

Material Property	λ_{dry}, W/(m·K)	ρ, kg/m^3	μ, —	A_W, kg/(m^2·s$^{0.5}$)
Brick Joens	0.91	1800	13	0.227
Lime-cement Mortar	0.70	1600	30	0.3
Lime Plaster	0.82	1800	12	0.127
Spruce	0.13	530	40	0.058
Air Layer (25 mm)	0.138	1.29	0.5	–
Mineral Wool	0.04	30	1	–
Gypsum Board	0.2	850	10	0.277

Table 2a. Surface Resistances for the Heat and Moisture Calculations (I-P)

Surface	Heat Flow (upwards), (ft^2·h·°F)/Btu	Heat Flow (horizontal), (ft^2·h·°F)/Btu	Heat Flow (downwards), (ft^2·h·°F)/Btu	Vapor Diffusion, s/m
Inside	0.57	0.74	0.97	$3 \cdot 10^{-8}$
Outside	0.23	0.23	0.23	$8 \cdot 10^{-8}$

Table 2b. Surface Resistances for the Heat and Moisture Calculations (SI)

Surface	Heat Flow (upwards), (m^2·K)/W	Heat Flow (horizontal), (m^2·K)/W	Heat Flow (downwards), (m^2·K)/W	Vapor Diffusion, s/m
Inside	0.10	0.13	0.17	$3 \cdot 10^{-8}$
Outside	0.04	0.04	0.04	$8 \cdot 10^{-8}$

and the one-dimensional reference heat loss through the main part of the exterior facade (wall or wall and insulation) divided with the temperature difference between the inside and outside air. This is not the same definition as in EN ISO 10211:2007.

$$L_{wall,\,2D} = (\phi_{2D} - q_{1D} \times A_{outer\ wall}) / \Delta T \tag{1}$$

where

$L_{wall,2D}$ = coupling coefficient, extra heat loss due to the non-insulated wall part and floor division

ϕ_{2D} = two-dimensional heat loss through the wall and floor division

q_{1D} = one-dimensional heat loss through wall or wall and insulation

$A_{outer\ wall}$ = outer area of the wall

ΔT = temperature difference between outside and inside

Coupled Heat and Moisture Calculations

The other study was a coupled heat and moisture investigation where the program DELPHIN ver. 5.6.5 according to Grunewald (1997) and Nicolai et al. (2010) was used.

The analyzed wall structure was facing west due to the rain and wind load in the weather data.

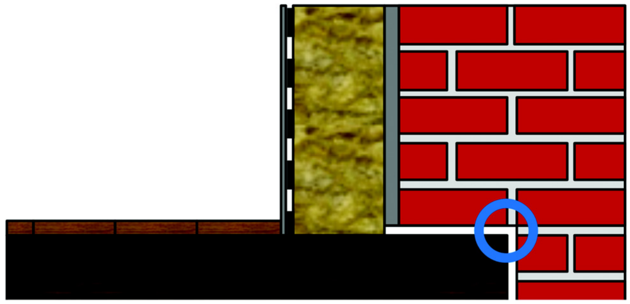


Figure 4 *Wall section analyzed by hygrothermal simulation. The blue circle indicates the point of evaluated relative humidity and moisture content.*

Table 3a. Coupling Coefficient for Difference Solutions of Internal Insulation (I-P)

Insulation, in.	Gap Size, in.	L_{2D}, Btu/(ft·h·°F)	L_{3D}, Btu/(ft·h·°F)
0	0	–0.065	0.077
7.87	0	0.018	0.412
7.87	11.81	0.555	0.651

Table 3b. Coupling Coefficient for Difference Solutions of Internal Insulation (SI)

Insulation, mm	Gap Size, mm	L_{2D}, W/(m·K)	L_{3D}, W/(m·K)
0	0	–0.112	0.134
200	0	0.031	0.713
200	300	0.961	1.126

The vapor barrier between the gypsum board and insulation had a vapor diffusion thickness of 2 m. Water transport between the brick and lime-cement mortar was calculated with a surface water resistance of $5 \cdot 10^{10}$ m/s according to Janssen (2010). The masonry was assumed to be perfect; hence, cracks were neglected. The applied transfer coefficients for heat flow and vapor diffusion are shown in Tables 2a and 2b as well as absorption coefficient etc. for rain and long and short wave radiation on the surfaces was applied to the model.

The shielding factor for the wind-driven rain was determined by a two-dimensional calculation to 0.5. The criterion was that the existing construction does not have problems with rain water. The calculations were done for four years and no moisture accumulation was allowed. For the determined value of 0.5, the drying potential in the wall was high enough to dry out the amount of rain entering the wall.

The evaluated results of this simulation study are relative humidity and moisture content in the top corner of the beam end embedded in the masonry. The point is indicated in Figure 4.

RESULTS

Thermal Calculations

The U-factor for the existing construction was 1.24 W/(m^2·K) (0.22 Btu/(ft^2·h·°F)) and for the reference wall with 200 mm (7.87 in.) insulation, the U-factor was 0.17 W/(m^2·K) (0.03 Btu/(ft^2·h·°F)).

In Tables 3a and 3b, the coupling coefficients are shown for the existing old structure, and two internal insulation solutions. The heat loss through the floor division and non-insulated part of the wall increases with the gap size, as shown in Figure 2.

The two-dimensional coupling coefficient for the existing structure is negative and the structure has therefore a heat gain through the wooden beam. The beam end is insulating better than the bricks in the two-dimensional case. For three dimensions, the distance between the beam ends is taken into account, which is not the case in two dimensions. In two dimensions, it is assumed that the floor division is made completely of wood in the wall length. The bigger wall area without beam ends gives a higher heat loss through the floor division. The effect of calculating in three dimensions is significantly larger without a gap between the floor division

Table 4a. Heat Losses through a Typical Facade Section from Three-Dimensional Calculations (I-P)

Insulation Thickness, in.	Gap Size, in.	Total Heat Loss, Btu/h
0	0	498
7.87	0	198
7.87	11.81	273

Table 4b. Heat Losses through a Typical Facade Section from Three-Dimensional Calculations (SI)

Insulation Thickness, mm	Gap Size, mm	Total Heat Loss, W
0	0	146
200	0	58
200	300	80

and the insulation than with a 300 mm (11.81 in.) gap. In three dimensions, the distance between the wooden beams has a higher heat loss and therefore a larger coupling coefficient.

Tables 4a and 4b shows the total heat loss through the outer wall and floor division for the typical facade section based on the three-dimensional calculations and a temperature difference of 14.5°C (58°F). The existing structure had a heat loss of 146 W (498 Btu/h). The total heat loss is almost halved using 200 mm (7.87 in.) internal insulation and a gap size of 300 mm (11.81 in.). The solution with a gap compared to the solution without a gap in the interior insulation has a 38% higher heat loss.

Coupled Heat and Moisture Calculations

The development in relative humidity in the upper corner of the beam end embedded in the wall is shown in Figure 5. The relative humidity in the beam end in the original wall structure has a declining tendency. The values are below the critical relative humidity of 80% to 90% for mold growth. An internal insulation from floor to ceiling (red curve in Figure 5) shows an increasing relative humidity in the beam end over four years, reaching almost 100%. Results for leaving 300 mm (11.81 in.) above and below the floor division uninsulated is only obtained for around two and a half years. The relative humidity is in the critical area for mold growth and the tendency is growing. It is not yet possible to say if it will stabilize around 90% relative humidity. The effect due to the extra heat loss through the 300 mm (11.81 in.) non-insulated wall part is apparent compared to the fully insulated wall. The difference in relative humidity to the uninsulated old structure is not increasing as rapidly as for the fully insulated wall.

Figure 6 shows the trend of the moisture content in the beam end as indicated in Figure 4. The critical moisture content in wood is said to be 0.2 kg/kg for growth of fungi. For the existing structure, the moisture content is below 0.15 kg/kg. The fully insulated wall exceeds the critical moisture content level after two years. The solution with a gap of 300 mm (11.81 in.) is in the range of 0.14 kg/kg to 0.18 kg/kg with an increasing tendency after two and a half years. As the research is ongoing, it is not possible to say how the development will be for the moisture mass in the wooden beam end with this solution. From the preliminary results a solution with a gap could be able to keep the moisture content below the 0.2 kg/kg.

Influence of Wind-Driven Rain

The previous results were determined with a shielding factor of 0.5. The shielding factor was determined under the conditions that the existing structure was on the safe side with respect to the relative humidity and moisture content at the beam end. Figure 7 and 8 shows the trend for the moisture content and relative humidity at the beam end with shielding factors of 0.1 and 0.5 for a structure with inside insulation and a 300 mm (11.81 in.) gap towards the floor. The results for a shielding factor of 0.5 deviate with about 7% and 0.3 kg/kg regarding relative humidity and moisture content respectively due to an increase in calculation speed.

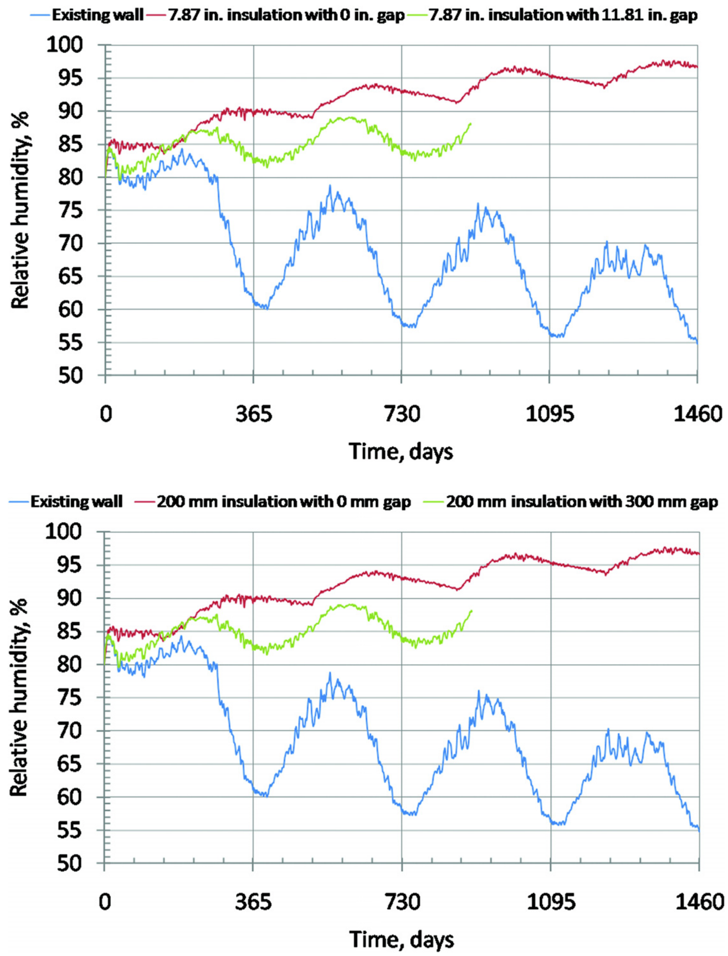
The solution with a shielding factor of 0.1 could be a safe solution as shown in Figure 7 and Figure 8. The tendency for the relative humidity is declining over four years and just under the critical 80%. Having a shielding factor of 0.5 the critical interval is above 80% relative humidity as shown in Figure 5 and Figure 7.

The moisture content in the beam end at a shielding factor of 0.1 is slightly decreasing over four years see Figure 8. The moisture content is below 0.15 kg/kg which is 0.05 kg/kg under the critical level of 0.2 kg/kg.

The size of the shielding factor influences the probability of mold and rot in the beam end. At low wind-driven rain load (shielding factor of 0.1) it might be safe with regard to mold and rot to use the solution with an insulated wall and a 300 mm (11.81 in.) gap in insulation towards the floor.

DISCUSSION AND CONCLUSION

The heat transfer calculations show that a three-dimensional representation is needed to accurately calculate the heat loss through the floor division with wooden beams. The thermal results show that three-dimensional calculations give higher temperatures near the beam end compared to two-dimensional calculations. Therefore, the drying potential is



(a)

(b)

Figure 5 *Relative humidity in the upper corner of the beam end. (Blue) is the existing structure, (red) is with 200 mm (7.87 in.) insulation from floor to ceiling, and (green) is 200 mm (7.87 in.) insulation with a gap of 300 mm (11.81 in.) between floor and insulation in (a) I-P units and (b) SI units.*

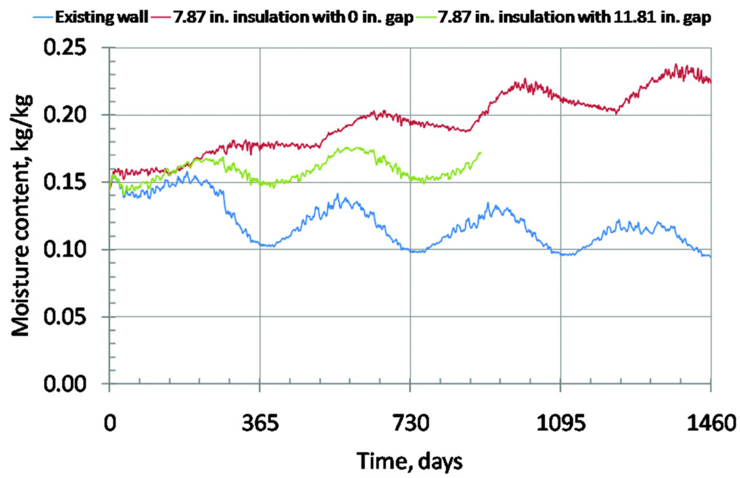
higher than what is calculated in two dimensions. For the moisture calculations it means that if the two-dimensional analysis is just on the edge to give problems, the structure might work in reality due to the better thermal behavior. On the other hand, if the two-dimensional moisture analysis shows no problem with moisture content and relative humidity, the construction should be on the safe side.

The obtained results depend on many things like material properties, climatic conditions, the urban areas, and the orientation of the wall. The results are therefore obtained for one particular case. They are, however, considered to be valid for other northern humid climates and west-facing facades.

The results indicate that on the one hand, there is a large energy-saving potential in the building stock. On the other hand, renovation measures can cause moisture problems and, in the worst case, degradation of parts of the load-bearing structure. Therefore both care and special case solutions are required to make this big energy saving potential accessible.

The study reported here is understood to be at the start of research and investigations in the field of moisture problems and solutions in old buildings with masonry and wooden floor beams. Retrofitting the facade with 200 mm (7.87 in.) internal insulation from floor to ceiling might cause moisture problems in the upper corner of the beam end. The relative humidity can increase to over the critical 80% to 90%, and the moisture content can also exceed 0.2 kg/kg.

Insulating the wall with a non-insulated zone of 300 mm (11.81 in) above and below the floor division might be a possible solution to the moisture problem and still give a high energy savings. The results are very dependent on the wind-driven rain loads. For high wind-driven rain loads (shielding factor of 0.5) the moisture content has not exceeded the critical



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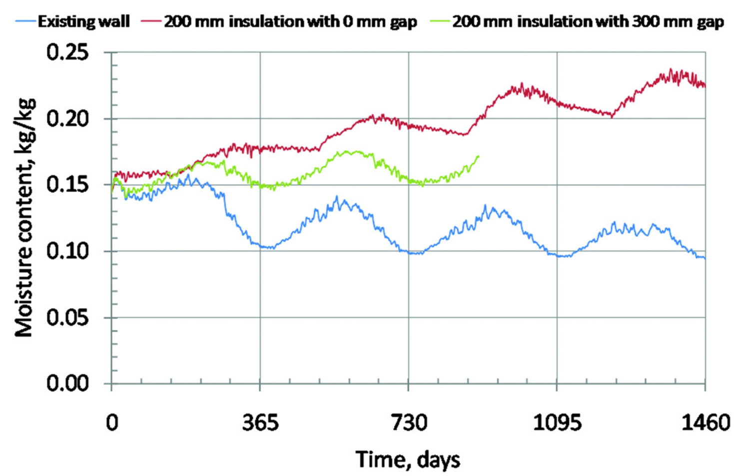

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Figure 6 *Moisture content in the upper corner of the beam end over four years. (blue) is the existing structure, (red) is a fully insulated wall and (green) is a wall with 300 mm (11.81 in.) gap in the insulation towards the floor in (a) I-P units and (b) SI units.*

point after two and a half years of simulation. On the other hand, the relative humidity is in the critical range from 80% to 90%. For the first two and a half years, the tendency is slightly increasing for the moisture mass and relative humidity, but it is not possible to conclude how the development will continue. For low wind-driven rain loads (shielding factor of 0.1) the relative humidity and moisture content is below the critical values of 80% and 0.2 kg/kg respectively. At the same time the tendency for both cases the tendency is decreasing after four years. This indicates that the wind-driven rain loads are of great importance analysing moisture problems in old building with masonry walls and wooden floor beams.

An internal retrofitting can almost halve the heat loss compared with the original wall, even with a 300 mm (11.81 in.) uninsulated zone above and below the floor division.

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REFERENCES

Blomberg, T. 1996 HEAT CONDUCTION IN TWO AND THREE DIMENSIONS Computer Modelling of Building

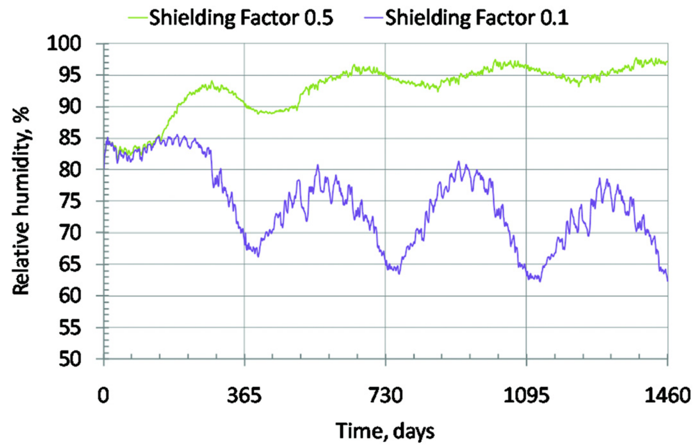

Figure 7 *Relative humidity in the beam end with shielding factor of 0.1 and 0.5 for an insulated wall with a 300 mm (11.81 in.) gap in the insulation towards the floor.*

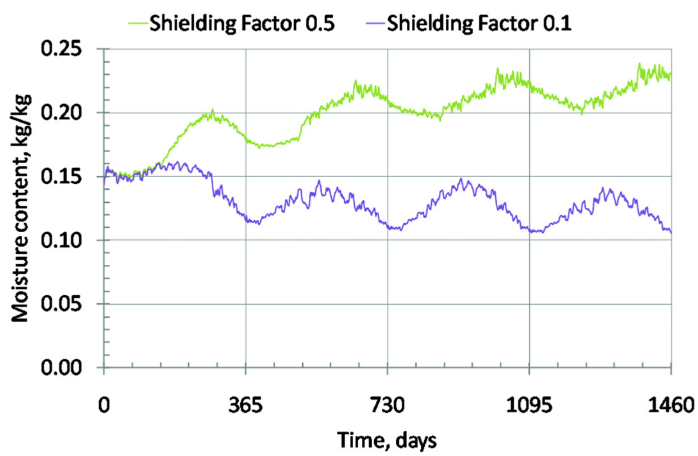

Figure 8 *Moisture content in the beam end with shielding factor of 0.1 and 0.5 for an insulated wall with a 300 mm (11.81 in.) gap in the insulation towards the floor.*

Physics Applications. Report TVBH-1008, Department of Building Physics, Lund University, Sweden.

Brandt, E, et al. 2009. *SBi-anvisning 224: Fugt i bygninger*, 1st Ed. Chapter 10, Fugt og ydervægge, Statens Byggeforskningsinstitut, Aalborg Universitet (in Danish).

EN ISO 10211:2007. Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations.

EN ISO 6946:2007. Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.

Engelmark, J. 1983. SBi-*rapport 142: Københavnsk etageboligbyggeri 1850-1900. En byggeteknisk undersøgelse.* SBi-rapport 142, Statens Byggeforskningsinstitut, Denmark (in Danish).

Engelmark, J. 2010. Photographs taken by Jesper Engelmark, Department of Civil Engineering, Technical University of Denmark. Given to the author January 18, 2010.

Grunewald, J. 1997. Diffusiver und konvektiver Stoff- und Energietransport in kapillarporösen Baustoffen, PhD thesis at Dresden University of Technology, Germany.

Häupl, P., H. Fechner and H. Petzold. 2004. Interior Retrofit of Masonry Wall to Reduce Energy and Eliminate Moisture Damage: Comparison of Modeling and Field Performance. *Performance of Exterior Envelopes of Whole*

Buildings IX, *International Conference Clearwater Beach December 5-10, 2004, proceedings. Atlanta: ASHRAE.*

Janssen, H. 2010. Department of Civil Engineering, Technical University of Denmark. Conversation with the author, January 20, 2010.

Munch-Andersen, J. 2008. *SBi-anvisning 221: Efterisolering af etageboliger*, 1st Ed. Chapter: Ældre Muret Byggeri, Statens Byggeforskningsinstitut, Aalborg Universitet (in Dansih).

Nicolai, A., Grunewald, J., Fechner, H. 2010. DELPHIN: Simulation program for coupled heat, air, moisture, salt and VOC transport. www.bauklimatik-dresden.de/delphin, viewed on 13.01.2010.

Scheffler, G.A. 2009. Moisture problems at wooden beam ends after building renovation. LavEByg konference om strategi for lavenergirenovering, 22. April 2009, Hørsholm, Denmark.

Sedlbauer, K. 2002. Prediction of Mould Growth by Hygrothermal Calculation. *Journal of Thermal Env. & Bldg. Sci*. 25-4: 321-336, 2002.

Tommerup, H., and S. Svendsen. 2006. Energy savings in Danish residential building stock. *Energy and Buildings* 38:618-626.

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., Lähdesmäki, K. 2009. Moisture and Bio-deterioration Risk of Building Materials and Structures, *Journal of Building Physics* 2009, doi:10.1177/1744259109343511.

Wittchen, K.B. 2009. SBi 2009:05: Potentielle energibesparelser i det eksisterende byggeri. SBi2009:05, Statens Byggeforskningsinstitut, Denmark (in Danish).