Post-Insulation of Existing Buildings Constructed between 1850 and 1920

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ABSTRACT

Tightened requirements for thermal insulation of new buildings and the demand for a reduction of energy consumption for heating and comfort in order to reduce carbon dioxide (CO_2) emissions mean that existing and especially older buildings have a very low thermal standard compared with today's requirements. Therefore, there is an increased interest in improving the insulation standard of many existing and older buildings.

However, special attention should be paid to prevent degradation of the existing construction when the energy demand for heating and thermal comfort of a building decreases as a result of post-insulation measures. Besides lower heating costs and reduced CO_2 emissions, improvement of the insulation standard could contribute to the elimination of other aspects of discomfort, such as draught originating from cold surfaces inside.

This paper considers post-insulation of a simulated building constructed as a typical building constructed in the period of 1850 to 1920. Like many of the existing buildings from that period, this building was recognized as a building with a unique architecture. It is a prerequisite for the improvement of the insulation standard that customized post-insulation solutions should be economically profitable for the owner. This paper focuses on good technical solutions for post-insulation of the building envelope and how the savings resulting from decreased energy demand can be estimated in a simple and accurate manner; at the same time the paper addresses related building physics requirements of importance.

INTRODUCTION

In Denmark the requirements for the thermal insulation of buildings has been significantly tightened over the last 30 years. Before the introduction of the first Danish Building Regulations in 1961 (NAEC 1961), no requirements for thermal insulation of buildings existed. In fact, the first Danish Building Regulations did not focus on the energy consumption of buildings. The average coefficient of heat transmission was stated for primary building components such as exterior walls, ground slabs, and roof constructions that complied with the existing building tradition. Table 1 shows that the requirements for thermal insulation of buildings remained much less stringent until 1977 compared with today's requirements.

The average coefficient of heat transmission was tightened several times before 2006. In 2006, individual requirements for the average coefficient of heat transmission and for building components were changed to requirements covering the overall energy consumption of buildings (Supplement 12 to the Danish Building Regulations [NAEC 1995] and Supplement 11 to the Danish Building Regulations for Small Dwellings [NAEC 1998]). Introduced in 2006, the tightened energy provisions were estimated to result in an energy reduction of 25% for new buildings compared with buildings constructed according to the former editions of the Danish Building Regulations (NAEC 1995, 1998).

The tightened energy provisions paved the way for further tightening in 2010, 2015, and 2020. Each tightening is expected to result in a 25% energy reduction. This means that buildings older than 30 years are outdated with respect to their thermal insulation standard and that the need to reduce energy

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Table 1. Development of Requirements for U-Factors (W/m²·K) in Denmark

Period	Walls[1]	Roof	Floor Slab	Windows
From 2006[2,3]	0.2	0.15	0.15	1.5[4]
1995–2006[3]	0.2	0.15	0.2	1.8[4]
1977–1995	0.4	0.2	0.3	2.9
1961–1977 (approx)	1.0–1.3	0.45	0.45	2.9[5]

[1] Value yields for heavyweight walls. Until 1995, the required U-factors for lightweight walls were lower due to less heat accumulation ability.
[2] Value yields for extensions; for new buildings the requirement is given mainly as allowable overall energy consumption.
[3] Since 2001 there have also been specific requirements for thermal bridges, e.g., around windows and along the foundation.
[4] Value yields for the entire window including the frame.
[5] No requirements before 1972.

consumption will be even more important in the future. As pre-2006 buildings constitute by far the biggest part of the building stock, a significant reduction of carbon dioxide (CO_2) emissions must consequently include a marked reduction of the energy used for heating and comfort in these buildings.

Special attention must be paid to buildings constructed in the period from 1850 to 1920 because approximately 20% of all dwellings registered in Denmark today are located in buildings from that period (SD 2009). Buildings from that period have typically not been retrofitted due to their recognised unique architecture (see Figure 1), and with time it has become ever more obvious that they need customized post-insulation, as experience shows that different sorts of degradation often occur after such measures have been implemented. The number of dwellings constructed between 1850 and 1920 has not diminished significantly and has stayed fairly stable for the last 25 years.

It is important to update the insulation standard of the building envelope of buildings older than 30 years. This is supported by the Danish Building Regulations (NAEC 2008). The Danish Building Regulations implement the Energy Performance of Buildings Directive (EPBD) (EC 2002) and stipulate that when major work is carried out on the building envelope, the insulation should be increased to a level comparable to the requirements governing new buildings or change of use and extensions of buildings. provided that the extra costs incurred by the improvement are economically profitable for the owner and the tenants in relation to service life and energy price. However, it appears not to be profitable to establish such levels; this significantly reduces the practical impact of the Danish Building Regulations.

This paper is based on guidelines published by the Danish Building Research Institute (SBi) on how to improve thermal insulation of existing buildings and blocks of flats (Munch-Andersen 2008). The guidelines focus on typical building techniques used in Denmark. The paper presents the case of a simulated building constructed as a typical building constructed in the period of 1850 to 1920. The building is recognized as a building with a unique architecture. The paper

Figure 1 *Multi-story building with flats constructed typical of the period 1850 to 1920.*

includes technical solutions to improve the insulation standard by showing customized post-insulation measures of the building envelope. Savings obtained by means of decreased energy demand are presented and estimated in a simple and accurate manner; at the same time, the paper addresses related building physics requirements of importance in order to prevent degradation of the building envelope.

INSULATION

Existing Building

As is typical of buildings constructed between 1850 and 1920, the building has an exterior wall of solid brick and horizontal divisions of timber beams (see Figure 2). The brickwork of the exterior wall is three bricks in thickness at the base of the building and decreases to one and a half bricks at the top level (see Figure 3). The two top stories have a cavity wall with solid wall ties. Where the load-bearing exterior wall supports the timber beams, the solid brick wall decreases in thickness by half a brick every two stories. The timber beams reach into the brick wall (see Figure 3), and at the top level of the building the protecting shield reaches half a brick. The window wall under the windows is one brick in thickness (see Figure 4). The non-load-bearing house ends have a thickness of one and a half bricks (see Figure 5).

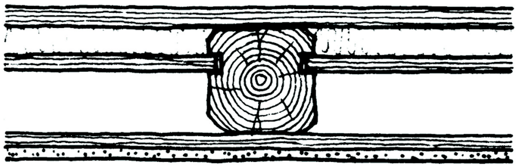

Figure 2 Horizontal division by timber beams. From the top: floor board, clay infill, wooden boards, empty space, wooden boards, and a layer of plaster on straw. The timber beams are of a good quality with the dimensions 200 × 200 mm with a tolerance from top to bottom of 6.25 mm.

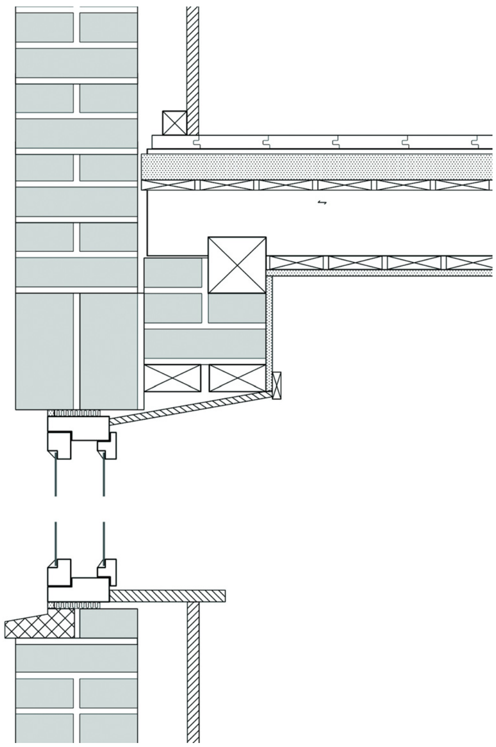

Figure 4 Vertical section of the joint between the load-bearing exterior wall and the horizontal division at the window wall.

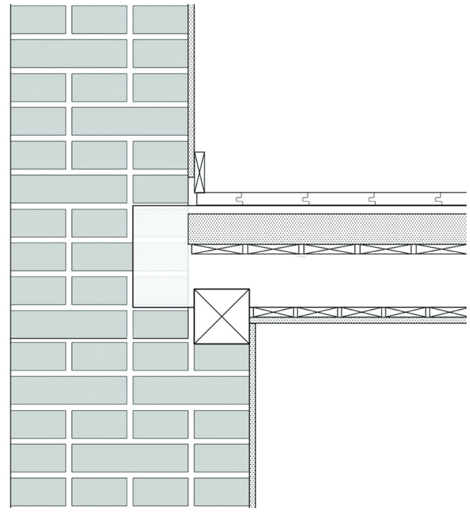

Figure 3 Vertical section of the joint between the exterior load-bearing wall, which is the facade, and the horizontal division. The exterior wall is a solid brick wall that decreases in thickness by half a brick every two stories. The timber beams reach into the brick wall.

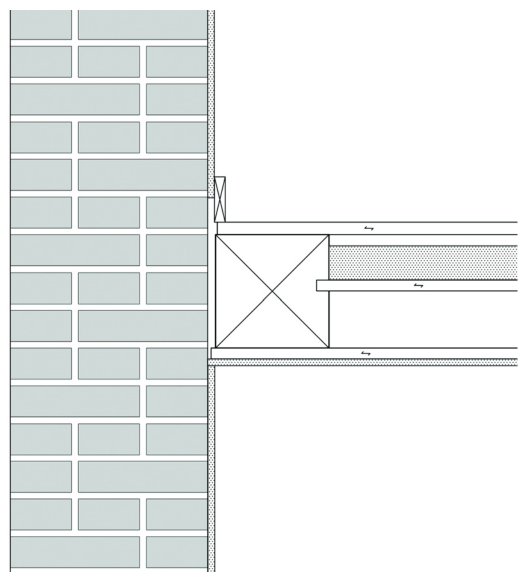

Figure 5 Vertical section of the joint between the horizontal division and the non-load-bearing house end.

The building has a basement and a cold attic room. The roof is a double-pitched roof with a 45 degree angle. The vertical section of the junction between the bases of the roof at the load-bearing exterior wall at the facade is shown in Figure 6. The joint of the roof base at the non-load-bearing house end is similar to the joint of the horizontal division at the non-load-bearing house end (see Figure 5).

The basement was originally used for storage (e.g., of coal for heating). The exterior wall of the basement is three bricks in thickness. However, under the windows the wall is one and a half bricks. The horizontal division to the basement is constructed as shown in Figure 2. The basement floor is of stamped clay covered with concrete. The basement wall is on a foundation of brick, five bricks in thickness, based on earth fill that includes stones and bricks.

Post-Insulation

Although outside insulation is the most efficient way to improve the insulation standard of an old building, this is not an option for buildings with a recognized unique architecture.

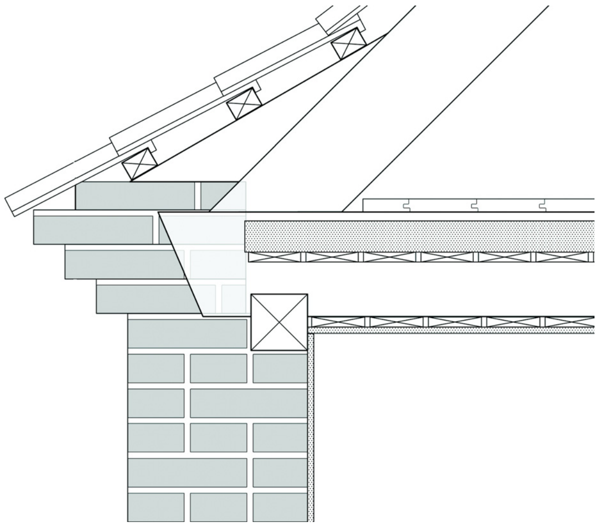

Figure 6 *Vertical section of the joint between the base of the roof and the load-bearing exterior wall.*

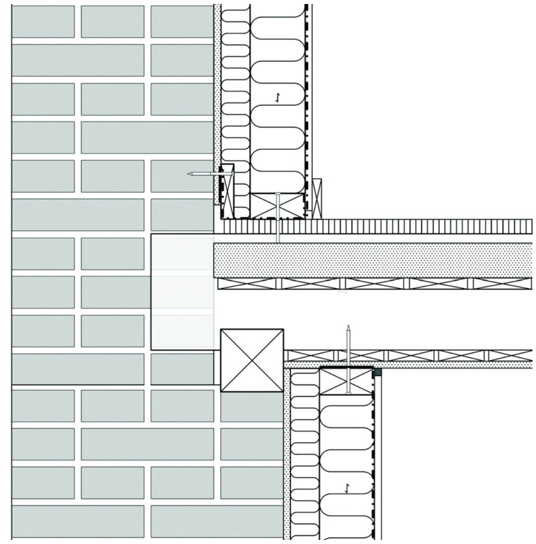

Figure 7 *Vertical section of the joint between the load-bearing wall, which is the facade, and the horizontal division after post-insulation.*

Therefore, post-insulation must be carried out at the inside of the exterior wall. When designing the solution for the post-insulation, special attention must be paid to prevent the risk of condensation in the exterior wall due to air leakage and moisture penetrating into the building envelope from the inside. It must be realized that at post-insulation it might not be possible to eliminate thermal bridges. However, in some cases thermal bridges can be used to maintain the temperature at critical locations in the building envelope at a high temperature level and thereby decrease the moisture level. Figures 7 and 8 show the post-insulation system used, which consisted of a timber stud frame with 95 mm mineral fiber insulation. The thermal conductivity of the mineral fiber insulation was 0.037 W/m·K. The timber stud frame was attached to the horizontal division between the individual floors of the building and kept clear of the exterior wall of the building envelope. The cavity between the timber stud frame and the exterior wall was filled with mineral fiber insulation. To prevent air and moisture from penetrating into the insulated exterior wall from the inside, an airtight shell was established. The airtight shell was established by a 0.2 mm polyethylene foil that also served as the vapor barrier. It was crucial that the foil was located on the warm side of the dew point and that the joints between the sheets of foil were airtight and securely fixed (Valdbjørn Rasmussen 2009). Toward the bottom of the timber stud frame wall, for the load-bearing facade, the foil was brought to the exterior brick wall and fixed airtight by a lath. For the non-load-bearing wall at the house end, the foil was brought to the timber beam of the horizontal division and fixed airtight by the bottom rail of the timber frame. At the top section of the timber frame wall, the foil was fixed airtight to the top rail of the timber stud frame. The top rail of the timber stud frame was fixed airtight to the ceiling. The plaster of the ceiling as well as the floor board was intact, without cracks or openings in joints.

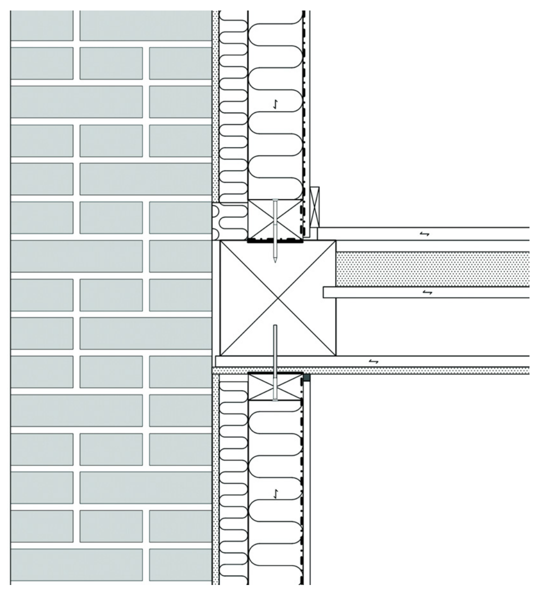

Figure 8 *Vertical section of the joint between the horizontal division and the non-load-bearing house end after post-insulation.*

The plaster of the ceiling toward the cold attic room was intact, without cracks. Post-insulation was carried out by blowing loose-fill mineral fiber insulation into the cavity between the timber beams (see Figure 9). The thermal conductivity of the loose-fill mineral fiber insulation was 0.044 W/m·K. The cavity allowed 100 mm mineral fiber insulation.

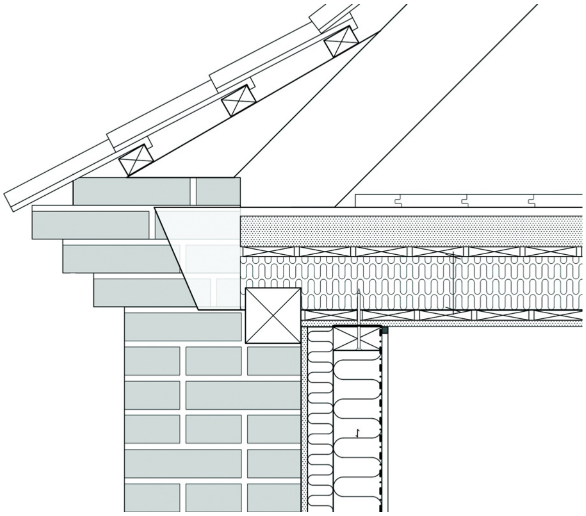

Figure 9 Vertical section of the joint between the base of the roof at the load-bearing exterior wall. Post-insulation was carried out by blowing loose-fill mineral fiber insulation material into the cavity between the timber beams underneath the clay infill.

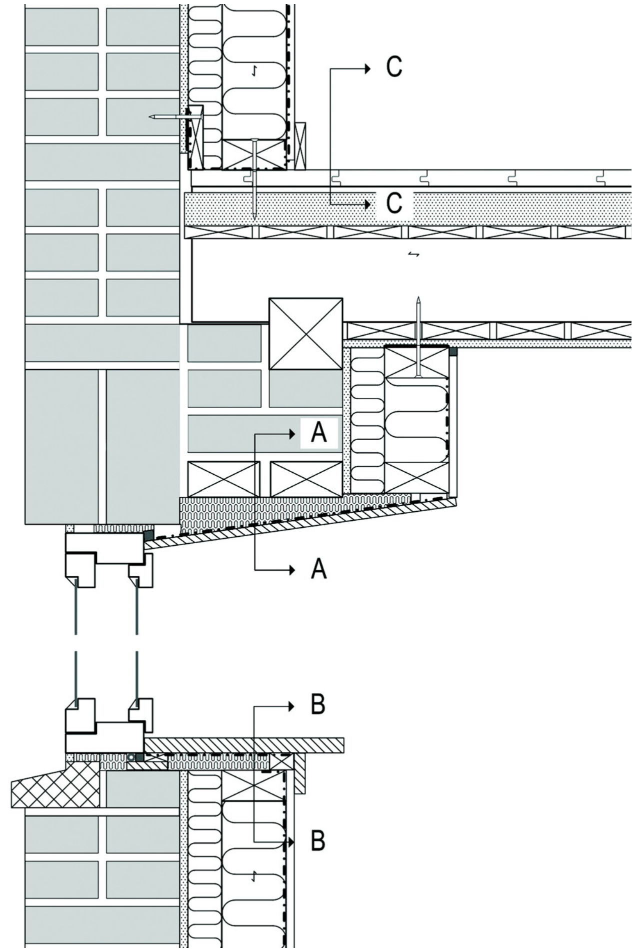

Figure 10 Vertical section of the joint between the load-bearing exterior wall and the horizontal division at the window wall after post-insulation.

Figure 10 shows post-insulation where the insulation was brought to the existing window by insulation located behind the narrow sill. The insulation located behind the narrow sill was placed there to minimize the thermal loss in the joint between the window and the exterior wall. Figure 11 shows sectional views from Figure 10.

Post-insulation of the horizontal division toward the basement was not relevant since the basement was warm, heated by uninsulated and poorly insulated installations for heating. These installations, including pipes and boiler, were not post-insulated.

TEMPERATURE CHANGES OF IMPORTANCE

Post-insulation changes the temperature changes within the building envelope. A decrease in temperature allows an increase in relative humidity. Local post-insulation measures may not introduce critical humidity levels, avoiding degradation and mold growth at the existing construction. Investigations included, in particular, a) measurements of the temperature of the existing exterior wall after post-insulation and b) measurements of the temperature at the timber beams of the horizontal division reaching into the existing load-bearing exterior brick wall after post-insulation. Calculations determining the isotherm curves within the exterior wall were carried out using a personal computer and the finite difference program HEAT2, Version 5.0 (BLOCON 2000), in accordance with the method described in Danish Standards (DS 2002).

a. Post-insulation located at the interior side of the exterior wall caused a fall in the temperature of the existing

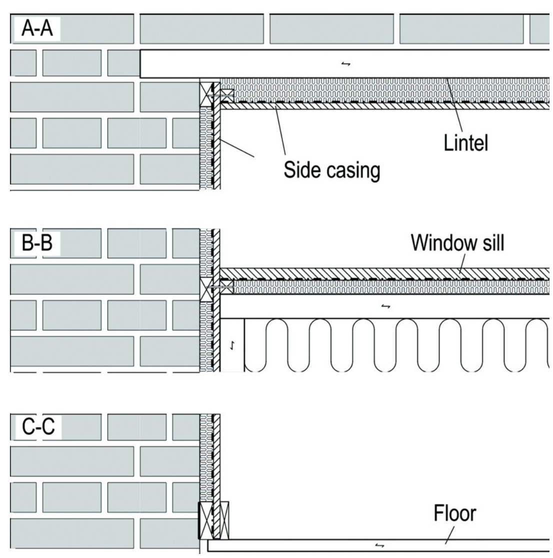

Figure 11 Sectional view of sections A-A, B-B, and C-C (see Figure 10).

exterior wall (see Figures 12, 13, and 14). Isotherm curves showed that after post-insulation the overall temperature dropped in the existing exterior brick wall (see Figure 13). The temperature difference within the existing exterior brick wall decreased from approximately 18°C before post-insulation to 4°C after post-insulation of the exterior wall. The wall was post-insulated with 95 mm mineral fiber insulation, exposed to 0°C at the outside and 20°C at the inside of the building. Calculations revealed that the temperature at thermal bridges, e.g., at the connection of the interior wall of brick, half a brick in thickness, to the existing exterior brick wall (see Figure 13), toward the inside of the dwelling was approximately 16°C.

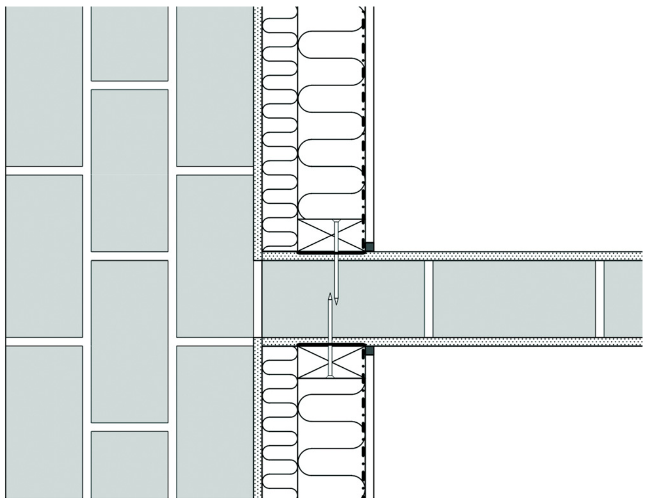

Figure 12 *Horizontal section of the connection of the interior wall of brick to the existing exterior wall after post-insulation. The timber frame was kept clear of the exterior wall. The airtight shell was established by a 0.2 mm polyethylene foil that also served as the vapor barrier. It was crucial that the foil had airtight joints and was securely fixed to the interior wall.*

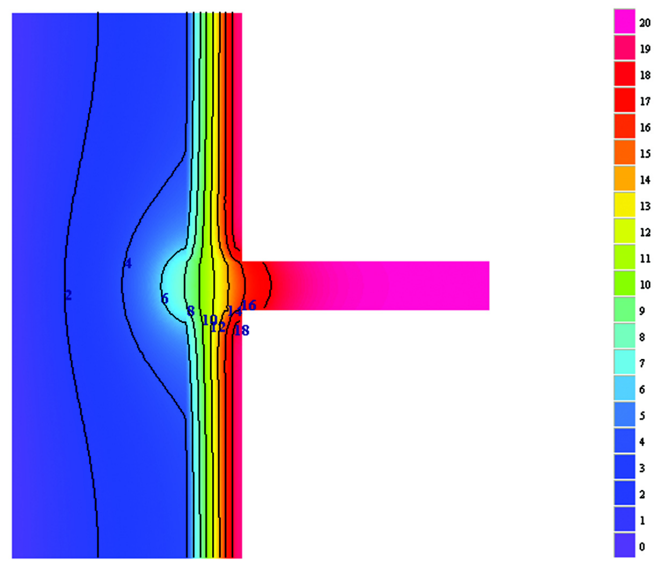

Figure 13 *Horizontal section showing isotherm curves of the connection of the interior wall of brick to the existing exterior wall after post-insulation; post-insulated with 95 mm mineral fiber insulation. The temperature was set to 0°C at the outside and 20°C at the inside.*

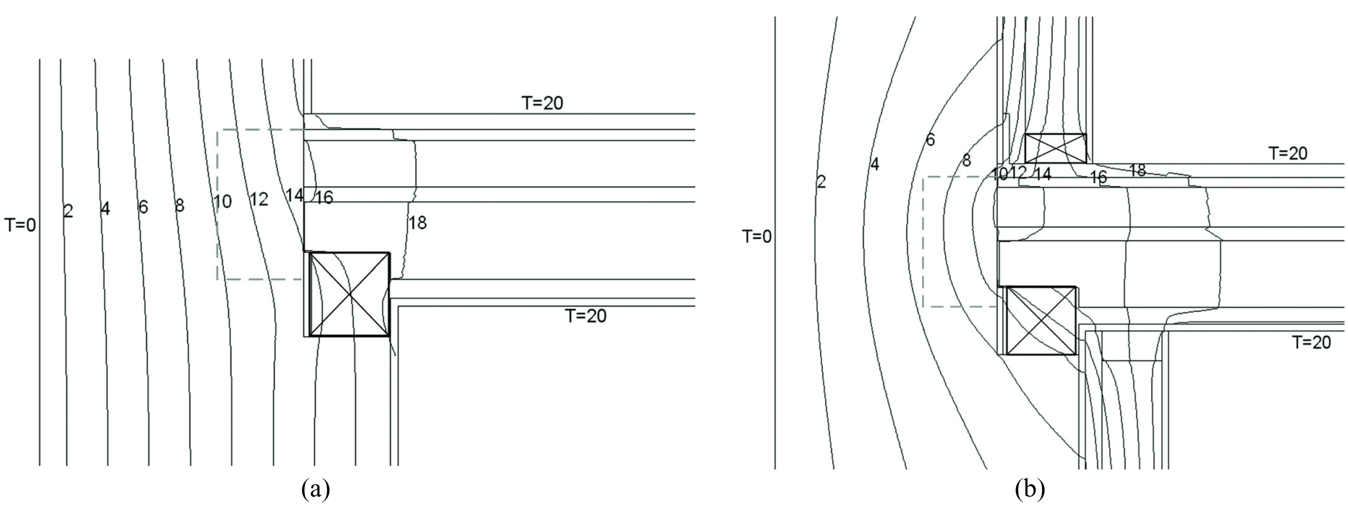

Figure 14 *Vertical section showing isotherm curves from where the timber beam of the horizontal division reaches into the exterior load-bearing wall: the vertical section of the joint (a) before post-insulation and (b) after post-insulation of the exterior wall with 95 mm mineral fiber insulation. Calculations were made for the brick wall between two timber beams.*

b. Isotherm curves from where the timber beam of the horizontal division reaches into the brick wall are shown in Figure 14. Figure 14 also shows the joint between the exterior load-bearing wall, which is the facade, and the horizontal division before and after post-insulation of the exterior wall with 95 mm mineral fiber insulation. The temperature at the end of the timber beam was reduced from 10°C before post-insulation to 7°C after post-insulation. For the calculations, the temperature was 0°C at the outside and 20°C at the inside of the building. The calculations were made for the brick wall between two timber beams.

CALCULATION OF SUPPLIED ENERGY

To decide whether a certain improvement is profitable, it is important to know how much less energy is necessary for a building to meet human demands for heating and comfort. The reduction in the transmission loss can be calculated quite simply from the reduced overall coefficient of heat transmissions, the reduction of the U-factors, and the number of degree-days. However, such a calculation does not take into account the increase of the relative contributions from solar gain, electric appliances, and people when the transmission loss is reduced. For this reason, the reduction in the demand for energy is larger than the reduction of the transmission loss, which increases the efficiency of the improved insulation.

Calculation Procedure

The energy demand of the building was calculated by the computer program Be06, described by Aggerholm and Grau (2008), which in effect is an integral part of the Danish Building Regulations and consequently an important part of the implementation of the EPBD in Denmark. The calculations are performed in accordance with the mandatory calculation procedure described in guidelines prepared by the Danish Building Research Institute concerning energy demand of buildings (Aggerholm and Grau 2008). The software uses the mandatory calculation core developed by the Danish Building Research Institute. Be06 calculates the expected energy demand for operating the heating and climate conditioning systems in all types of buildings—houses, blocks of flats, offices, institutions, schools, shops, and workshops. The Be06 software calculates the energy demand of a building for room heating, ventilation, cooling, hot water, and artificial lighting dependent on elements such as the building design, the building envelope, daylight access, the ventilation system, the heating installation, and the energy supply, including alternatives such as solar heating, solar power, and heat pumps. The energy demand of a building is compared with the energy frame in the Danish Building Regulations. Results are given as key results, detailed results, and model documentation. Results such as the transmission loss, the ventilation loss, the solar gain, and other contributions are calculated on a monthly basis in accordance with the relevant European Committee for Standardization (CEN) standards. The calculation includes the ratio of the contributions that is usable and the ratio that causes too-high temperatures.

All two-dimensional transmission coefficients are calculated using a personal computer and the finite difference program HEAT2, Version 5.0 (BLOCON 2000), in accordance with relevant CEN standards.

To calculate the reduction of the energy demand of the post-insulated building related to the individual measures, a robust and simple model was used to calculate the effective heat loss, Q (kWh/m^2).

A Simple and Robust Method

A virtual building was modelled by the program Be06 (SBi 2006). After modelling, two calculations were made. One calculation was performed to determine the energy demand of the building before post-insulation and the other to determine the energy demand of the building after post-insulation. The difference between the calculated energy demand was assumed to represent the reduction in energy demand after post-insulation measures were carried out. By introducing one post-insulation measure at a time in the model, the effects of the individual measures were revealed.

For the virtual building, the model was tested for the influence of change of built-up area. Table 2 illustrates the calculation for the wall in the model before post-insulation. A virtual change of area, $\Delta A = \pm 25\% = \pm 200$ m^2, was performed, and the change in the overall energy demand was calculated, ΔS. When the change of energy demand was divided by the change of area, the effective heat flow through 1 m^2 of the wall was obtained, $Q_{original}$. A similar calculation was performed with the model of the post-insulated building to determine $Q_{post\text{-}insulated}$. The difference in effective heat loss, $\Delta Q = Q_{original} - Q_{post\text{-}insulated}$, represented the reduction in the energy demand for the post-insulated building.

Increasing and decreasing the area of the virtual building by approximately 25% were found to result in almost similar changes, ΔS, and the determined effective heat loss, Q, was

Table 2. Example of Calculation of Effective Heat Loss through a Wall

	Overall Energy Demand, S, kWh	Change, ΔS, kWh	Effective Heat Loss, $Q = \Delta S/\Delta A$, kWh/m^2
Virtual building	170,000	—	—
Wall area + 200 m^2	175,167	+4833	24.2
Wall area – 200 m^2	165,037	–4963	24.8

found to vary insignificantly. To verify the method for the virtual building, all changes of areas were included in one calculation and compared with the sum of the post-insulation measures. The error was less than 1%.

The effective heat loss due to thermal bridges was calculated in the same way and was related to its length. Irregularities around thermal bridges were included as a loss per meter. For the building, constructed as a typical building constructed in the period between 1850 and 1920, the reduced insulation effect occurred, e.g., at the joint where the interior wall of brick was connected to the existing exterior wall (see Figure 12). For the reduced insulation effect at the horizontal division at the floor edge, see Figures 7 and 8. These contributions were added to the heat loss as loss per meter wall edge and loss per meter floor edge.

CALCULATION OF ENERGY DEMAND FOR THE ACTUAL BUILDING

The built-up area of the building was 9 m wide and 64 m long with one clean house end. The building consisted of five floors and a basement as well as four staircases; the floor height was 2.87 m between ceilings. There were 240 windows, each 1.09 m wide and 1.61 m high. The ventilation rate was 0.7 times per hour. Table 3 lists the relevant areas and lengths. Table 3 also specifies measures by listing numbers referring to figures.

Applying the simplified method, the effective heat loss values, Q, before and after post-insulation are shown in Table 3. In addition, the overall reduction of the energy demand per year was calculated and is shown in Table 3. For reference, the energy reduction is shown per square meter of floor space. The energy loss of the basement is not included.

DISCUSSION

A simulated building constructed as a typical building constructed in the period from 1850 to 1920 was investigated. Technical solutions improving the standard of insulation are shown. The post-insulation measures were carried out as internal post-insulation for individual building components in the building envelope. However, attention must be paid to the measures both at the design stage as well as at the construction stage to prevent degradation of the existing construction. As stated by Roberts (2008), reduction in the energy consumption of existing buildings mainly involves post-insulation, replacement of windows, and proper airtightness, while ensuring adequate ventilation.

Post-insulation will change the overall condition of the existing construction. It is therefore crucially important to prevent degradation of the existing construction after post-insulation. Special attention must be paid to the existing exterior solid brick wall and to the existing organic construction materials, which will be left with a colder environment after

Table 3. Example of Calculation of Potential Savings of Energy Demand

Component	Detail as in Figure No.	Area or Length	Post-Insulation Thickness	Effective Heat Loss, Q, kWh/m^2 or kWh/m		Overall Reduction, kWh/year*	Reduction per m^2 Floor Space, kWh/m^2
				Original	Post-Insulated		
Facade, 1.5 bricks solid	3, 5, 7, 12	434 m^2	95 mm	131	28	44 702	15.5
Facade, 2 bricks solid	3, 5, 7, 12	434 m^2	95 mm	103	28	32 550	11.3
Facade, 2.5 bricks solid	3, 5, 7, 12	217 m^2	95 mm	85	28	12 369	4.3
Window wall	4, 10	330 m^2	95 mm	180	28	50 160	17.4
Clean house end	8	129 m^2	95 mm	131	28	13 287	4.6
Roof	3, 11	576 m^2	100 mm	65	26	22 464	7.8
Window sill, 1.5 bricks solid	10	518 m	15 mm	9	11	–1 036	– 0.4
Window sill, 2 bricks solid	10	518 m	15 mm	13	16	–1 554	– 0.5
Window sill, 2.5 bricks solid	10	259 m	15 mm	16	21	–1 295	– 0.4
Spandrel edge at window wall		605 m	95 mm	0	6	–3 630	– 1.3
Roof base, facade	6, 9	128 m	100 mm	–39	–3	–4 608	– 1.6
Roof base, house end	5	9 m	100 mm	–13	–9	–36	~0
Horizontal division, floor edge	3, 5, 7, 8	593 m		0	11	–6 523	– 2.3
Interior wall connection, 0.5 brick	12	459 m		0	10	–4 590	– 1.6
Interior wall connection, 1 brick	12	129 m		0	14	–1 806	– 0.6
Sum 5 floors		2 880 m^2				150 454	52.2

* Determined as ($Q_{original} - Q_{post\text{-}insulated}$) × Area or Length.

post-insulation than originally. Methods that can be used to evaluate the wall system of the existing building, including requirements of the test method, application of the test method, and interpretation of the test results, can be found in Dalrymple and Whitlock's (2009) work. Historical test data are presented that illustrate use of the test method to evaluate wall systems and expected range of test results for existing and repaired wall systems.

Before carrying out internal post-insulation of the original building envelope, it must be ascertained that the existing exterior envelope will not undergo degradation from the changed moisture and temperature conditions. Furthermore, it has to be ascertained that normal weather conditions, including rain, frost, and wind, will not cause erosion of the exterior solid brick wall, i.e., the facade of the building.

The necessary additional construction work not directly related to the work of post-insulation should be estimated. If the building or some of the individual building components are not suitable, additional work must be undertaken to comply with material and technical requirements for the implementation of the measures. An important issue is whether lowering the temperature of the brick wall by adding insulation to the inside will reduce the drying potential, thereby exposing the wall to the risk of water damage and spalling.

When post-insulation measures are carried out, special attention must be paid to prevent the risk of condensation in the exterior wall due to air leakage and moisture that penetrate into the building envelope from the inside. It must be realized that in the case of post-insulation it might not be possible to eliminate thermal bridges. However, in some cases thermal bridges can be used to maintain high temperature levels at critical locations in the building envelope and thereby decrease the moisture level (see Figure 14). Besides heat loss, the thermal bridges cause low internal surface temperatures, which in turn heighten the risk of mold growth. This occurs in particular where the solid brick wall has not been post-insulated as shown in Figures 12 and 13 and where the thickness of the brick wall and insulation thickness are reduced e.g., around the windows (see Figures 4 and 10). In order that the post-insulation measures remain effective around windows, heat must be prevented from passing into the solid brick wall from the sill. Surprisingly, calculations showed that just 10 or 15 mm of insulation material would reduce this heat flow to an insignificant level (see Figures 10 and 11). Typically, thermal bridges occur at the joints of different building components, where it is difficult to achieve continuity in the thermal insulation layer. The better the insulation of the building envelope, the larger the relative contributions of thermal bridges to the overall transmission heat loss of the building, and the more important it is to implement well-designed solutions customized for the actual building (Theodosiou and Papadopoulos 2008). The effect of thermal bridges in the building envelope can be significant, either due to the length of joints per unit of the heat loss surface or due to joints with large thermal transmittance. It is estimated that thermal bridges in the building envelope increase the energy consumption by 13% to 17% compared with a continued homogeneously insulated building. When attention is paid to the prevention of thermal bridges in construction detailing, the contribution of building joints to the thermal transmittance may be reduced to less than 5% of the heat loss (Janssens et al. 2007).

The joint between the load-bearing wall and the horizontal division after post-insulation (see Figure 7) was further investigated. The level of normal indoor moisture content can be critical for the timber beam of the horizontal division where it reaches into the brick wall; it is therefore crucial that a sufficient airtight shell as well as a vapor barrier be established. Assuming that at temperatures higher than 5°C, 75% relative humidity (RH) can cause mold growth (Valdbjørn Rasmussen et al. 2006), the critical moisture content of the timber beam that reaches into the brick wall is 6 g/m^3 in winter and 13 g/m^3 in summer for normal weather conditions in Denmark (Andersen et al. 1993). The outdoor moisture content is at the highest level, 12 g/m^3, in summer (June to August) and decreases to the lowest level, 4 g/m^3, in winter (December to March) (Andersen et al. 1993). The outdoor moisture content is therefore not a risk, as long as the exterior solid brick wall does not loose its drying potential, thereby introducing the risk of water damage and spalling. If warm air with high moisture content from the inside is allowed to penetrate into the timber of the horizontal division at the load-bearing facade, a risk of degradation is introduced. In such a case, it must be ensured that the moisture content indoors does not cause, or exceed, the critical conditions at the timber beam end, i.e., 20°C with 35% RH in winter and 75% RH in summer (Andersen et al. 1993). The risk of degradation of the timber beam end is increased with critical moisture exposure for longer periods of time. Alternatively, implementation of monitoring equipment connected to decision-making process and control can be applied at the end of the timber beam as well as at other critical locations in the construction.

For the measures shown, the savings on energy demand are presented and estimated in a simple and accurate manner. The energy demand was reduced by 52.2 kWh/m^2 by taking advantage of the post-insulation measures listed in Table 3. The reduced demand for energy was the difference between an energy demand of 84.7 kWh/m^2 before and of 32.5 kWh/m^2 after post-insulation.

The biggest reduction of the calculated energy demand was related to the post-insulation of the exterior walls. Post-insulation of the exterior walls results in a reduction in the calculated needed energy supply by 153,068 kWh per year. However, the reduction in the calculated needed energy supply should have been adjusted with the energy loss at the spandrel edge at window wall, the horizontal division of the floor edge, and the interior wall connection, which was 16,549 kWh per year. But still the post-insulation of the exterior walls was significant in reducing the demand for energy.

Another big reduction of the calculated energy demand was related to the post-insulation of the roof. Post-insulation of the roof resulted in reduction of the calculated energy demand by 22,464 kWh per year, where the energy loss was reduced from 65 to 26 kWh/m^2. At the same time it was found that the energy loss through the base of the roof increased, as the effective heat loss, Q, after post-insulation was found to be less negative than that of the original construction. That the effective heat loss had a negative value along the base of the roof edge along the load-bearing facade and the house end was due to the Danish rules for calculating the heat loss. When calculating the heat loss, the height of the wall was considered to extend to the upper side of the attic floor for the post-insulated horizontal division toward the attic room, which was an extension of the height above the actual height.

For the measures to be economically profitable for the owner, the cost of the measures must not exceed the savings from the reduced demand for energy made over the lifetime of the implemented measures, i.e., the estimated payback period. At an energy price of 0.133 €/kWh, using natural gas for heating, an interest rate of 6%, and a payback period of 30 years, the expenses for the measures must not exceed 275,440 €, as the savings of 20,010 €/year has to be the installment per year. (The energy price used for the calculation was the energy price in Denmark 2009.) The economic profitability varies greatly with the energy price and interest rate. Studies of external post-insulation by exterior wall replacement, including upgrading of window systems and thermal insulation, seems more economically profitable with an estimated payback period of 14 years (Peterson and Blodgett 2009).

CONCLUSIONS

Durable methods are presented for post-insulation of a building constructed in the period between 1850 and 1920. The building investigated was simulated and constructed as a typical building constructed in the period from 1850 to 1920. It was demonstrated that the effective heat through specific parts of the building envelope could be reduced by about 61.6% just by improving the building envelope by means of viable measures. The insulation standard did not come close to today's requirements governing new buildings or change of use and extensions of buildings, but significant improvements were achieved.

When improving the insulation standard for different building parts at the building envelope by internal post-insulation, attention must be paid to the solutions for post-insulation, both at the design stage and through a critical examination of the building to ensure that the building is suitable for the planned post-insulation measures. If the building is not suitable, additional work must be done to meet the material and technical requirements for the implementation of post-insulation of the exterior wall. It should be noted that lowering the temperature of a brick wall by adding insulation to the inside exposes the wall to the risk of water damage and spalling.

At the implementation of post-insulation measures, special attention must be paid in order to the prevent the risk of condensation in the exterior wall due to air leakage and moisture penetrating into the building envelope from the inside. It must be realized that it might not be possible to eliminate thermal bridges at the implementation of post-insulation. However, in some cases thermal bridges were used for maintaining high temperatures at critical locations in the building envelope and thereby decreasing the moisture level.

A method for simple estimation of the energy savings obtainable by implementing a specific measure was described and has been verified to be robust for quite different geometries of a building. Applying the simple method revealed whether the measures were economically profitable for the owner. If the cost of the post-insulation measures did not exceed the savings gained by the reduced demand for energy over a viable payback period, i.e., a period less than the lifetime of the implemented measures, measures were economically profitable. Calculations showed measures to be economically profitable for 95.6 €/m^2 floor space with an estimated payback period of 30 years. Including wages, measures are hardly economically realistic allowing minor or non-additional work to be made to the exterior wall. The economic profitability varies greatly with the energy price and interest rate.

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