Investigation of interior post-insulated masonry walls with wooden beam ends

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Published in:
Journal of Building Physics

Link to article, DOI:
[10.1177/1744259112447928](https://doi.org/10.1177/1744259112447928)

Publication date:
2013

Document Version
Early version, also known as pre-print

[Link back to DTU Orbit](#)

Citation (APA):
Morelli, M., & Svendsen, S. (2013). Investigation of interior post-insulated masonry walls with wooden beam ends. *Journal of Building Physics*, 36(3), 265-293. <https://doi.org/10.1177/1744259112447928>

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Paper title: Method for Investigation of Interior Post-Insulated Masonry Walls with Wooden Beam Ends

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ACKNOWLEDGEMENTS

The financial support for this research is provided by the Landowners' Investment Association and by LavEByg, an innovation network for low-energy measures in buildings; this support is gratefully acknowledged. The authors would also like to thank Gregor A. Scheffler for initiating these investigations when he was a post-doctoral fellow at DTU Civil Engineering and as well Hans Janssen for the thorough discussions in which he engaged regarding moisture simulations and the highly useful information that we obtained through these efforts.

METHOD FOR INVESTIGATION OF INTERIOR POST-INSULATED MASONRY WALLS WITH WOODEN BEAM ENDS

ABSTRACT

The preponderant number of multi-story buildings constructed in Denmark (Northern Europe) in the period between 1850–1930 were built with masonry walls incorporating wooden floor beams. Given the nature of this construction, it is supposed that significant energy savings could be achieved by simply insulating the facades of such buildings. To maintain the exterior appearance of the facade the only possible means of installing the required insulation is placing it on the interior of the wall. However, the installation of insulation on the interior of the wall assembly reduces the overall drying potential of the wall, and this in turn may lead to moisture problems at the beam ends embedded in the masonry, when the masonry facade is subjected to driving rain. This paper presents a method to investigate retrofit measures of interior insulated masonry walls having wooden floor beams based on Failure Mode and Effect Analysis combined with hygrothermal simulations. The method was first used to determine the potential for failure in retrofitted walls, their effects and causes, and thereafter, the expected hygrothermal performance of the retrofit measures were further investigated using both thermal and hygrothermal simulation software. The results show that the risk to incurring moisture problems at wooden beam ends can be resolved by not insulating that portion of the wall directly above and below the floor division. Additionally, this proposed retrofit measure would reduce the heat loss of the original wall structure by half.

KEYWORDS

Failure Mode and Effect Analysis, Hygrothermal Performance, Energy Savings, Insulation, Wooden Beam, Wind-Driven Rain, Masonry

INTRODUCTION

Within the Energy Performance of Buildings Directive it is stated, that buildings account for about 40% of the total energy consumption in Europe (EU, 2010). In other terms, this implies that energy consumption, as indicated in the directive, must be reduced by 20% by 2020. However, to meet this objective, it has become apparent that simply building new energy efficient buildings would not permit meeting the energy reduction targets by 2020; the existing building stock would also need to be retrofit given that new buildings only represent a small portion of the total building stock in the EU. But which set of existing buildings would be considered the most likely for energy retrofits? It has been shown that multi-storey buildings erected in the period between 1850 and 1930 have a substantial energy savings potential if considering the retrofitting of the facades of such buildings (Tommerup & Svendsen, 2006; Wittchen, 2009). These buildings were built with solid masonry walls in which wooden floor beams are incorporated in and supported by the wall; a typical wall, as shown in Figure 1, has been described by Engelmark (1983).

Figure 1. Beam ends supported in the pier. a) gap around the beam end seen from the front, b) the beam end seen from the side.

Given that the facade of such buildings are often worthy of preservation the only possible measure for retrofitting the walls is by installation of insulation on the interior of the wall.

The installation of insulation on the interior of the wall reduces the heat loss through the wall but it also reduces the drying potential of the wall by lowering temperatures. The lower wall temperatures increase the risk of condensation of water vapour that penetrates from the interior. This moisture penetration can be prevented by using a vapour barrier which then reduces the drying to the interior. However it has been shown that the amount of insulation installed on the interior, and that includes vapour barrier, might be affected in instances where the facade is subjected to high wind driven rain (WDR) loads (Morelli et al., 2010). In such instances where the WDR load is high, rain may accumulate in the masonry and thereafter cause a prolonged period of elevated moisture content of wooden beam ends that would cause the onset of the deterioration of the beams. Application of insulation on the interior of the wall does not only increase the risk of wood decay and mould growth of embedded wooden beams, it also takes up room space, and depending on the depth of the insulation installed, may take up to 0.2 m/m² floor area for insulation of 200 mm depth.

This paper presents a methodology for thoroughly assessing retrofit measures on brick masonry walls based on Failure Mode and Effect Analysis (FMEA) combined with hygrothermal simulation. The study focuses on the retrofit of solid masonry walls having embedded wooden beams and the development of appropriate retrofit measures in which the long-term hygrothermal performance of the wall is ensured. This is an important consideration as without some assurance that the retrofit can function adequately over the long-term, the potential energy savings from the addition of insulation cannot be realised. The use of FMEA permits identifying possible failures whereas the use of hygrothermal simulation allows understating the consequences of such failures on the performance of individual components as well as the wall as a whole. In instances where retrofit measures are not shown to provide advantage to the long-term performance of the wall assembly, alternative measures can be proposed and re-evaluated through simulation.

Overview of Related Studies on Masonry Walls having Wooden Beams

Krebs and Collet (1981) undertook temperature and moisture content measurements in 30 wooden beam ends where some walls were insulated on the interior of the wall with 150 mm insulation and others not insulated. They concluded that the driving rain did not have a significant influence on moisture uptake and consequently there would only be a very limited risk for moisture problems to occur at beam ends. Christensen and Bunch-Nielsen (2009) collected information from several measurements and concluded that driving rain could be problematic if the facade had cracks. However, if no cracks were present in the masonry facade through which water could penetrate during rain events, then up to 150 mm of insulation could be applied to the interior of the wall and not cause any deterioration of wooden beam ends. Munch-Andersen (2008) described the application of mineral wool insulation together with a vapour barrier as sufficient set of components in the wall assembly to prevent vapour penetration from the interior. The vapour barrier was made tight to the floor; therefore diffusion through the floor could still be possible. In this particular study the driving rain was not seen as a problem as long as the facade was free of cracks and also included fully bedded joints. Rasmussen (2010) further investigated the critical moisture conditions for wooden beam ends based entirely on the effects of vapour diffusion. He concluded that exterior moisture did not pose a problem to the risk of heightened moisture content at beam ends given that the exterior moisture content was below that evident at beam ends. Rasmussen (2010) also listed limitations for the indoor environment to ensure that diffusion from inside would not contribute to any risk of damage to beam ends. Häupl (2010) investigated infiltration of room air into beam ends. The results showed that, on the one hand, at higher air velocities there was temperature increase hence a reduce risk to the formation of high moisture contents at beam ends, whereas on the other hand, condensation in cavities at beam ends did occur at intermediate air velocities. Häupl (2010) suggested therefore insulating the beam end cavity or applying a local outside insulation to increase the temperature of the surfaces around the beam end. Insulation on the interior of the wall was applied between floor and ceiling (Feist, 2005) but also applied insulation between

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the beams in the floor division. For this safe measure measurements of wood moisture content are in the range of 10-20%.

A capillary-active insulation material could be used instead of mineral wool and vapour barrier. Häupl et al. (2004) investigated the use of calcium silicate as an insulation component and found no problems with the wooden beam structure after two years of study. However, the test building in which the studies were completed did not have high wind-driven rain loads in part due to a large roof overhang that shielded the facade during less intense rain events. The investigations showed no problems with an interior climate having 70% relative humidity. Another comparable study by Häupl et al. (2006) provided similar results. In this more recent study, driving rain penetrated 300 mm into the outer brick masonry wall (i.e. halfway into wall assembly), and such occurrences could have been critical for ensuring the durability of wooden beam ends in this wall. In Häupl et al. (2003) and Stopp and Strangfeld (2006) a measure in which calcium silicate was used together with that of elevating the temperature of beam ends with heating pipes were investigated. Using heating pipes the measured moisture content in the beam end was below the calculated moisture content. Under operation the heating pipes had a negligible thermal bridging effect.

In all investigations the U-value of the wall was reduced by 33-50% and the temperature at the beam end dropped by only about 3°C.

On the one hand the information obtained from the literature review indicates that insulation installed on the interior of the wall is not at problem as long as wind-driven rain is kept out of the wall. In the studies completed by Krebs and Collet (1981) and Christensen and Bunch-Nielsen (2009) the amount of wind-driven rain to which the facades were subjected was not provided; it is unclear then under which climate conditions and hence locations the retrofit measure might be durable. Munch-Andersen (2008) suggested a retrofit measure based entirely on thermal simulations and Rasmussen (2010) followed up with hand calculations based on temperature and relative humidity. In none of the above studies was a detailed hygrothermal simulation conducted in which

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wind-driven rain intensity also considered as a parameter. On the other hand, several studies, such as those undertaken by Häupl et al. (2003), Feist (2005), Stopp and Strangfeld (2006) and Häupl (2010) have suggested measures to reduce the moisture content at the wooden beam, i.e., by increasing the temperature at this location. The retrofit measures suggested from these studies were all very extensive and would not likely be affordable. According to Krebs and Collet (1981), the problems with insulation installed on the interior of masonry brick walls, and in which wooden beams are embedded are that the moisture conditions at the beam end depend on many factors, the most significant of which are:

- Geometry of the structure
- Interior temperature and relative humidity
- Production of interior moisture
- Outside climate (i.e. temperature, relative humidity, driving rain intensity and wind velocity)
- Material properties for wood and masonry
- Air changes around the beam end

Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) is a quality planning tool that provides a systematic and analytical process for identifying hazards and risks for manufactured or built components. FMEA was developed in the aerospace industry and has been adapted in many other lines of business. In Figure 2, the three general steps of the FMEA process are shown as described by McDermott et al. (2009) and Stamatis (2003). The FMEA method is chosen based on the bottom-up approach where failures are exhaustively catalogued and the corresponding effects that ensue from these failures identified. In instances where retrofitting scenarios of buildings is considered, the FMEA was determined as a usable tool to help assess the effect of failure of different building components on the overall performance of the building.

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Figure 2. Failure Mode and Effect Analysis processes based on work by McDermott et al. (2009) and Stamatis (2003).

A state of the art work on the use of FMEA in building construction was prepared by Talon et al. (2006) in which several examples on the use of FMEA are presented and in Talon (2006) the FMEA for an insulated brick cavity wall is presented. The FMEA used in this study, and described in this paper, only focused on Step 1 (Figure 2) which is the identification of failure modes and related effects. According to Mao et al. (2011) moisture is the most crucial factor causing deterioration of the building envelope. Hence the focus of the hygrothermal simulations is therefore found on the basis of the failures identified from the FMEA process.

STRUCTURE OF ASSEMBLY

The existing masonry wall had a thickness of 460 mm. The wall consisted of brick masonry units (80 x 220 mm) separated by 20 mm lime-cement mortar. The inside of the existing wall was 30 mm lime plaster layer. The outer 220 mm of the beam end was supported in the wall on one side and there was an air gap of 20 mm on all other

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sides between the beam and the masonry wall. The beam was 140 mm high with wooden floor boards of 30 mm on top.

The retrofitted structure was investigated with 100 mm and 200 mm inside insulation. The inside insulation was investigated with a gap of 200 mm and without a gap towards the floor, see Figure 3. Between the insulation and gypsum board a vapour barrier was placed. In the cases with an insulation gap the vapour barrier was placed horizontally under the insulation. The framework in the insulation should preferably be built up by steel than wood due to deterioration.

Figure 3. Detailed description of beam end and wall joint. Between the gypsum board and mineral wool the vapour barrier was placed. a) Show the measure without a gap and b) show the applied insulation with a gap.

Materials and Boundary Conditions

The basic material properties used for the heat and moisture simulations are listed in Table 1 and taken from DELPHIN (Grunewald, 1997; Nicolai et al., 2010). The vapour barrier had a vapour diffusion thickness of 2 m.

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Table 1. Material properties for hygrothermal simulations.

	<i>Thermal</i>	<i>Density</i>	<i>Water vapour diffusion</i>	<i>Water absorption</i>
	<i>conductivity</i>		<i>resistance factor</i>	<i>coefficient</i>
	λ_{dry}	ρ	μ	A_w
	$W/(m \cdot K)$	kg/m^3	[-]	$Kg/(m^2 \cdot s^{0.5})$
Brick	0.91	1800	13	0.227
Lime-cement mortar	0.70	1600	30	0.300
Lime Plaster	0.82	1800	12	0.127
Spruce (wood)	0.13	530	40	0.058
Air layer (25 mm)	0.14	1.29	0.5	-
Mineral wool	0.04	30	1	-
Gypsum board	0.20	850	10	0.277

The interior climate was described by boundary conditions with a constant air temperature of 20°C and 50% relative humidity. When carrying out simulations in respect to determining the thermal performance for the wall assembly in respect to energy losses, the exterior climate was described by a constant temperature of 0°C. This temperature was chosen to give an early indication of the energy saving potential of the different retrofit measures. In respect to completing the hygrothermal simulations the hourly test reference year for Bremerhaven (Germany) was used as exterior climate and this information was obtained from Nicolai et al. (2010). Figure 4 shows the hourly values for the temperature and relative humidity of Bremerhaven over a year based on average data from 1961-1990. This reference year was the best representative for Denmark in which rain data is also available, as there is currently no corresponding reference year data available for locations in Denmark. In Figure 5 the average wind speed and wind driven rain index (I_{WDR}) are provided for the same location and the same year. The wind driven rain index was obtained from Eq. (1) where i is the azimuth angle (0 = North). It is

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apparent from the information provided in Figure 5 that the prevalent direction for both the wind and wind-driven rain is southwest.

$$I_{WDR} = \frac{\sum_{i=1}^{i+15} v_{wind_i} \cdot R_{H_i}}{\sum_0^{360} R_{WDR}}; i = [0, 30, \dots, 360] \quad (1)$$

Figure 4. Temperature and relative humidity for Bremerhaven.

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Figure 5. Weather data for Bremerhaven. a) Average air velocity and b) Wind-driven rain.

The thermal surface resistances of the different building components were defined according to (EN ISO 6946, 2007) and the values are given in Table 2. The outside surface resistance was consistent with values obtained using the approach described by Blocken et al. (2009) and Sharples (1984) for forced convective heat transfer coefficients on a windward surface in which the radiant heat transfer coefficient is also considered.

Table 2. Thermal surface resistances for thermal simulations.

<i>Surface</i>	<i>Heat flow (upwards)</i>	<i>Heat flow (horizontal)</i>	<i>Heat flow (downwards)</i>
	$(m^2 \cdot K)/W$	$(m^2 \cdot K)/W$	$(m^2 \cdot K)/W$
Inside	0.10	0.13	0.17
Outside	0.04	0.04	0.04

The values for the vapour diffusion coefficients influence the evaporative drying of the facade. High values for the vapour diffusion coefficients increase evaporation during rain events but decrease the amount of surface runoff. The values for the vapour diffusion coefficients were calculated according to (Janssen et al., 2007) using the Lewis analogy of $16.8 \cdot 10^{-8}$ s/m (windward) and $7.6 \cdot 10^{-8}$ s/m (leeward). The values for the vapour diffusion coefficients, for the interior and exterior surfaces respectively, were $3 \cdot 10^{-8}$ s/m and $8 \cdot 10^{-8}$ s/m. The latter choices were considered conservative values.

The hydraulic contact at the brick-mortar interface was considered to be imperfect (Derluyn et al., 2011), which meant that a hydraulic resistance was present at this interface. The interface resistance were found in the range $1.25 \cdot 10^{10}$ - $2.5 \cdot 10^{10}$ m/s. The degree of water transport between the brick and lime-cement mortar was calculated assuming a surface water resistance of $5 \cdot 10^{10}$ m/s.

CALCULATION METHOD

Thermal Calculations

The energy saving potential was investigated using the 2D thermal calculation as is configured in HEAT2 (Blomberg, 1996, 2010). The thermal performance of the structures was assessed based on the coupling coefficient, L_{2D} , that is directly available from HEAT2. Using the coupling coefficient, the different retrofit measures for which the installation of insulation with and without a gap above the floor plate were considered, were directly compared in respect to the heat loss.

Hygrothermal Calculations

The coupled heat and moisture investigations were completed using DELPHIN (Grunewald, 1997; Nicolai et al., 2010). The wall assemblies that were analysed faced west in respect to the rain and wind load in the weather data. The masonry was assumed to be perfect; hence, cracks and infiltration were neglected. The rain exposure coefficient, k_{rain} , was varied between 0.1 and 0.5 and was a way to reduce the wind-driven rain on the facade. The results of this simulation study were focused on obtaining the relative humidity and moisture content at the top corner of the beam end that was embedded in the masonry structure. As well, the likelihood of the presence of mould growth, the inside masonry in which a gap was present in the insulation at the interior was investigated.

Wind-Driven Rain

The rain flux density normal to the wall surface was calculated from information on wall inclination and orientation, the rain flux density on a horizontal plane, the wind direction and wind velocity as provided in Eq. (2) to Eq. (4).

$$j_{rain,nor} = k_{wind} \cdot k_{rain} \cdot j_{rain,hor} \quad (2)$$

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where k_{wind} is the wind coefficient (catch ratio) [-] determined from Eq. (3), k_{rain} is the rain exposure coefficient [-] and $j_{rain,hor}$ is the rain flux density on a horizontal plane [$kg/(m^2 \cdot s)$].

$$k_{wind} = \begin{cases} 0 & \text{if } \left(\beta_{wind} \geq \frac{\pi}{2} \right) \vee (v_{wind} \leq 0) \\ \frac{\cos(\beta_{wind})}{\sqrt{1 + 1141 \cdot \sqrt{\frac{3600 \cdot j_{rain,hor}}{v_{wind}^4}}}} \cdot \exp\left(-\frac{12}{5 \cdot \sqrt[4]{3600 \cdot j_{rain,hor}}}\right) & \end{cases} \quad (3)$$

where β_{wind} is the wind angle [$^\circ$] determined from Eq. (4) and v_{wind} is the wind velocity [m/s].

$$\beta_{wind} = \begin{cases} |\alpha_{wall} - \alpha_{wind}| & \text{if } |\alpha_{wall} - \alpha_{wind}| \leq \pi \\ 2\pi - |\alpha_{wall} - \alpha_{wind}| & \end{cases} \quad (4)$$

where α_{wall} and α_{wind} is the wall orientation and wind direction.

RESULTS

The masonry brick wall assembly was investigated in various configurations that included: (i) the reference condition in which the assembly prior to retrofit measures is considered and for which no insulation was used, i.e. 0 mm; (ii) retrofitted wall assembly where 100 mm and 200 mm of mineral wool insulation with a vapour barrier were installed to the interior of the assembly.

The FMEA was carried out in regards to the different functions of individual components of the wall assembly; these functions are given in Table 3. The primary functions are the ones concerning the hygrothermal performance (i.e. items 1-7) and each of these is considered in the FMEA. Table 4 shows the FMEA for each of the different components in the wall assembly and for which the related potential failures, and their effects and causes are also provided.

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Table 3. Functions of outer wall and beam end.

<i>Primary</i>	<i>Secondary</i>
1 Structural performance	8 Sound
2 Water resistance	9 Fire safety
3 Air tightness (infiltration)	10 Security
4 Condensation (surface/interior)	11 Maintainability
5 Accommodate movement	12 Constructability
6 Energy conservation	13 Aesthetics
7 Durability	14 Economy

Table 4. Failure Mode and Effect Analysis for inside insulated masonry wall with wooden floor beam.

<i>Component</i>	<i>Potential Failure Mode</i>	<i>Potential Effect(s) of Failure</i>	<i>Potential Cause(s) of Failure</i>
Brick	Cracking	Water permeability Collapse	- Manufacturing fault - Shock - Movements (moisture, temperature, structural) - Freeze-thaw cycles - Foundation subsidence - Cleaning (graffiti)
	Porosity	Water permeability Freezing sensitivity	- Material selection - Freeze-thaw cycles - Cleaning (graffiti)
	Loose bricks	Water permeability Loss of load carrying capacity Collapse	- Movements of wall - Movement of beam end - Shock

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			- Mortar adherence
	Salt precipitation	Water absorption	- Salting in winter - Salts in bricks
	Low temperatures (insulation)	Moisture accumulation Loss of drying potential	- Inside insulation
	Spalling	Water permeability Freezing sensitivity	- Freeze-thaw cycles - Cleaning (graffiti)
Mortar	Cracking	Water permeability	- Shock - Movements(moisture, temperature, structural) - Freeze-thaw cycles - Foundation subsidence - Cleaning (graffiti)
	Loss of adherence to bricks	Water permeability	- Amount of mortar - Drying of mortar - Movements in wall
	Weathered	Water permeability Infiltration	- Wind and rain (weather)
	Joints not filled with mortar	Water permeability	- Workmanship
Beam end	Moisture absorption	Wood decay Swelling	- Built in moisture - Change in moisture balance - Reduced drying potential
	Reduce drying from beam end	Moisture accumulation Swelling	- Roofing membrane (other treatment of beam end)
	Condensation	Mould	- Temperature variation

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			- Infiltration of warm humid air
	Loss of base	Collapse	- Movement of wall - Deterioration of wood
	Wood decay	Collapse	- Moisture accumulation - Wood rot
	Air movement into the beam	Condensation	- Vapour open floor - Draughty vapour barrier
	Shrinking	Cracks in bricks Subsidence	- Lack of fit - Increased drying
Lime Plaster	Mould growth	Hygiene (mould)	- Local cold surface
	Cracks (fall off)	Moisture diffusion	- Shock - Movements (moisture, temperature, structural)
Insulation (Mineral wool)	Rot of wood framework	Structural	- Condensation - Moisture from in-/outside
	Moisten	Loss of thermal performance	- Condensation - Moisture from in-/outside
	Increased cold bridges	Mould in corners / surfaces	- Reduced temperatures
	Mould (brick-insulation)	Hygiene	- Draughty vapour barrier - Moisture from outside
	Summer condensation	Mould and rot on floor where vapour barrier is tighten	- Choice of vapour barrier - Reduced drying to the inside
	Loss of thermal insulation performance	Increase heat loss	- Integrated cold bridge
Vapour barrier	Piercing, tear, bad joints	Vapour diffusion into the wall	- Workmanship
		Interstitial condensation	- Occupant behaviour

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			- Design
	Missing	Mould	- Workmanship
	Wrong position in wall	Rot of framework	- Design
	Type of vapour barrier		
Gypsum board	Surface mould	Hygiene	- Increased RH in indoor air
			- Tighter building

From Table 4 it is seen that most failures relate to the masonry including mortar, the beam ends and the interior insulation. The most consequential effect appears to be the collapse of the assembly as a result of the deterioration of the beam end. This is a long term process and it is located in an area without direct access. This effect comes about due to the influence of water intrusion to the wall assembly. The most common effect is the moisture sources from inside, outside and when condensation inside the structure occurs. A side effect of this is the growth of mould and wood decay. It is therefore, necessary to investigate how the beam end will perform in the presence of moisture at the beam end but also determine how the brick-insulation interface may affect the growth of mould at these locations.

Energy Savings

The U-value for the existing wall is $1.40 \text{ W}/(\text{m}^2 \cdot \text{K})$ (no insulation), and for the two insulated walls is $0.30 \text{ W}/(\text{m}^2 \cdot \text{K})$ (100 mm insulation) and $0.17 \text{ W}/(\text{m}^2 \cdot \text{K})$ (200 mm insulation) respectively. In Table 5, the coupling coefficients and linear heat loss transmittances are given for the existing structure, as well as those two wall assemblies for which interior retrofit measures to install insulation were made. The heat loss through the floor and wall is lowest if the insulation is applied to the floor and ceiling and no gap is present in the insulation, as shown in Figure 3a.

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Table 5. Heat loss through wall and beam end.

<i>Insulation,</i>	<i>Gap size,</i>	<i>L_{2D},</i>
<i>mm</i>	<i>Mm</i>	<i>W/(m)</i>
0	0	58.3
100	0	13.8
100	200	28.4
200	0	8.1
200	200	25.5

Hygrothermal Calculations

The points where the temperature, relative humidity and moisture content are measured are shown in

Figure 6.

Figure 6. Points for measurement of temperature, relative humidity and moisture content.

In regards to the potential for the formation of mould, wooden structures would normally be assessed in respect to the relative humidity (RH) in the component with a critical level of 80-90% RH for mould growth depending on the duration and temperature ($>5^{\circ}\text{C}$) (Sedlbauer, 2002). The critical moisture content (MC) for the initiation of growth of fungi in wood components would be 0.2 kg/kg (Viitanen et al., 2010). The results of the simulation indicated that the reference case was shown to be durable given that the RH and MC of the components did not at any time exceed the critical values. Accordingly, it was assumed that the retrofit measures would likewise be

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lasting if the RH and MC do not exceed the critical limits as was found for the reference wall assembly. The results for temperature, RH and MC are average values for periods of 10 hours; for this reason some peaks values are not apparent.

Influence of wind-driven rain on reference structure

The wind-driven rain has a large influence on the RH and MC at the beam end. Figure 7 shows the variation in RH and MC at the beam end over a four year period for an un-insulated wall (reference) and for different rain exposure coefficients (0.1, 0.3 and 0.5). At lower rain exposure coefficients (i.e. $k_{rain} = 0.1$ and 0.3), the trend in relative humidity (Figure 7a) in the beam end over the months tends towards dropping below the critical RH of 80% after four years of exposure. The temperature is above 5°C in all 4 years, which could be an onset of mould growth ($k_{rain} = 0.3$), but as the model needs to reach two consecutive uniform years, the structure is assessed to be durable. Also the structure has already existed for about 100 years. In the case of a wall subjected to a high rain exposure coefficient ($k_{rain} = 0.5$) an upwards trend in RH is evident from the initial conditions of 80% RH towards 100% RH.

Figure 7. a) Relative humidity and temperature and b) moisture content in the beam end without inside insulation where k_{rain} is equal to 0.1, 0.3 and 0.5.

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It is apparent from Figure 7b that the MC in the beam end at a rain exposure coefficient of 0.1 and 0.3 slightly decreases over four years. This in essence is the same trend as that for the relative humidity. Hence, with a rain exposure coefficient above 0.3 there is a risk that the MC curve will exceed the normal critical MC of 0.2 kg/kg over a four year period.

Retrofitted wooden beam end

In the winter the temperature at the beam end drops 5-6°C down to the freezing point if insulation is installed at the interior of the wall in thicknesses of either 100 mm or 200 mm (Figure 8). If however a gap in the insulation is permitted the temperature will drop about 1°C and still be about the 5°C, whereas in the summer period there is no large difference in the temperature at the beam end regardless of the retrofit measures.

Figure 8. a) Temperature in the beam end for the reference, full insulated and partly insulated wall. b) The temperature deviation between the reference and retrofit measures.

Changes in RH and MC at the beam end for the different retrofit measures with a rain exposure coefficient of 0.1 are shown in Figure 9. It is apparent that development over the four year simulation period is the same whether

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the retrofit measure is for the installation of 100 mm or 200 mm insulation thickness. The absolute maximum deviation between the results for 100 mm and 200 mm is about $\pm 7\%$ RH and MC of ± 0.02 kg/kg. At the low rain exposure coefficient, moisture dries out over a yearly cycle which gives larger intervals in the RH depending on the season. Installing insulation on the interior of the wall with a gap only raises the RH a few percentage points. For high rain exposure coefficients (e.g. 0.5) the retrofit measures will exceed the threshold values for mould growth and wood decay as shown for the reference case in Figure 7 as the trend for the retrofit measures are identical with the trend for $k_{\text{rain}} = 0.1$.

Figure 9. a) Relative humidity with temperature (for an entire insulated wall) and b) moisture content in the top corner of the beam end when applying 200 mm insulation with and without a gap where k_{rain} is 0.1.

At an intermediate rain load ($k_{\text{rain}} = 0.3$) an assessment can be based on the development found for the lower rain loads (Figure 9). The RH has a limited increase for retrofit measures that include a gap as compared to that of the reference wall, but the temperature will still remain above 5°C . If insulation is installed on the entire interior wall there is a slight increase in RH, but on the other hand the temperature drops below 5°C during the critical periods. Figure 10 shows the development in RH and MC if insulation is installed on the entire interior wall. As is perhaps evident in this Figure, this retrofit measure will not work if subjected to intermediate rain loads;

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however, leaving a gap in the insulation could be a durable measure when considering the development of the lower rain loads.

Figure 10. a) Relative humidity and temperature and b) moisture content in the beam end with 100 mm insulation and without insulation. k_{rain} is 0.3.

For a rain exposure coefficient of 0.3 there is a change in the development in RH in the non-insulated wall and the fully insulated wall. The wall without insulation has a declining trend below 80% RH over four years whereas the insulated wall increases above 80% RH and thus the MC will likely exceed the critical limit. Based on this information it is suggested that for this particular wall configuration, a rain exposure coefficient of 0.1 is the upper limit for acceptable long-term retrofit measures.

Drying potential to the inside

The retrofit measure in which there is a gap in the insulation would permit drying to both the inside and outside when a vapour barrier is not placed on the un-insulated portion of the wall (referred to as free wall in Figure 6). Whereas, if a vapour barrier is placed on the free wall the drying potential would be limited to only the outside.

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After four years of simulation the RH and MC is equal to the retrofit measure with or without a vapour barrier on the free wall as shown in Figure 11.

Figure 11. Indication of the drying potential through the free wall expressed by a) relative humidity, temperature and b) moisture content. Measure with 100 mm insulation, 200 mm gap and $k_{rain} = 0.1$.

Mould growth in the gap

As is evident in Figure 12 the RH at the interface between the brick masonry and insulation (see Figure 6) increases above the 80% for long periods of the year when insulation is applied to the interior of the wall assembly and without gaps at the base of the wall. However, in walls that have a gap in the insulation at the base of the wall on the interior, the same problem could arise, that is, prolonged periods of elevated RH may occur at the brick masonry-insulation interface. In Figure 12b there is shown a rise in RH above 80% for a short period of time during the winter period where the temperature also is about 12°C. The increase in RH is brought about due to the lower wall temperatures that occur when insulation is applied to the interior of the wall assembly.

Applying 100 mm or 200 mm insulation implies small and less significant changes in temperature and RH at this interface. As compared to the un-insulated wall, the RH in this instance is about 20%-30% greater. The drying

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potential through the free wall is insignificant and again a rain exposure coefficient of 0.1 is the upper limit for this particular wall configuration.

Figure 12. Temperature and relative humidity in the corner where the inside insulation stops 200 mm above the floor.

DISCUSSION

Many factors may influence the long-term hygrothermal performance of the wooden beam ends; for example, the actual material properties (as compared to assumed properties), climatic conditions and orientation of the wall. The result obtained in this paper represent those for one particular case in which insulation, of 100 mm or 200 mm thickness, has been installed on the interior of a brick masonry wall assembly; however this measure is considered to be valid for west-facing facades of buildings located in comparable cool and humid northern European climates. The results of the simulation that relate to thermal effects indicate a significant potential for energy saving when insulation is applied to the interior of the wall assembly. Referring to the coupling coefficient, it appears that a saving of 51-86% in energy can be achieved depending on the measures chosen. Specifically, leaving a gap in the insulation necessarily reduces the thermal performance and in comparison to a fully insulated wall, performs 2-3 times better than a retrofit measure with a 200 mm gap in the insulation. An internal retrofitting can halve the heat loss compared with the original wall, even with a 200 mm un-insulated

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gap in the insulation. This is in good agreement with previously studies of walls with wooden beam end that have insulation installed on the interior of the wall. Thus an un-insulated gap in the insulation will be a good retrofit measure when looking at the thermal performance of the structure. Still there is a risk of degradation of the wooden beam end due to the inside insulation. Therefore, both care and special case measures are required to make this big energy saving potential accessible.

The FMEA listed the potential failures, effects and causes for the different components in the wall assembly. Among the most critical effects was the collapse of the beam end which is a side effect of moisture penetration into the structure. In the FMEA a rating of the failures was not performed and therefore it can be discussed if focus should be put on the beam end or other failures. Other failures could lead to more maintenance than the beam end. The worst failure that can happen is that after 50 years the beam will deteriorate due to the applied inside insulation and thereby cause loss of human life. The use of FMEA in the development of retrofit measures clarifies the potential to identify failures and effects which then should be investigated using e.g. hygrothermal simulations. To obtain the full value of the FMEA process, a ranking of the failures should be performed but this can easily become a subjective ranking if it is based on expert knowledge. In the present case, applying the FMEA to the masonry wall with embedded wooden beams, was time consuming and little, if any, new knowledge in respect to the long-term performance of the wall assembly was obtained. When considering the suitability of specific retrofit measures, control of moisture within components of the wall assembly is the overriding issue and can roughly be divided into failures that arise due to the effects of condensation, freeze-thaw action, and water intrusion depending on the constituent materials of the respective wall components. Perhaps the use of 1D simulation to investigate the hygrothermal performance of the wall assembly would provide more useful information as that obtained from performing the FMEA.

The wind-driven rain has a large influence on the moisture performance of the wooden beam which is shown with by changing the rain exposure coefficient. A low value of wind-driven rain ($k_{\text{rain}} < 0.1$) indicates no moisture

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problems in the beam end. A retrofit measure with installation of an inside insulation with a gap in the insulation could be durable at intermediate values ($k_{\text{rain}} < 0.3$) extrapolated from the trends for low and high rain loads.

Earlier measurements of moisture content in wooden beam ends showed in general no moisture problems but the amount of wind-driven rain was not stated clearly in these investigations. Therefore it is difficult to validate the results in this paper with previously measured values. From Blocken and Carmeliet (2006) it is known that the catch ratio is highest in the top corners of buildings and lowest in the middle close to the ground. On the one hand it can be questioned if the low values of rain exposure coefficients are realistic and representative for the most critical beam end. On the other hand the rain amount depends significantly on the climate and location of the buildings. The wind driven rain applied using a test reference year does not account for extreme years that might occur every 20, 30 or 50 years. This could be very important consideration if the trends in hygrothermal response of the wall assembly are at the critical limits for onset of mould growth or wood decay.

Comparing the retrofit measures with the reference measure gives clear indications on the performance of the retrofit measure. The reference measure has nonetheless existed for around 100 year and if the new retrofit measure performs equally well the long term-performance must be intact as it is assessed that the existing structure can last for another 100 years. It is seen that when installing insulation to the interior and with at gap at the base of the wall there is an insignificant change in the temperature, relative humidity and moisture content of the beam end as compared to the deviations occurring when insulation is installed over the entire wall.

The inside effects the drying to the inside which is all eliminated even for the measure implementing a gap at the base of the insulation. The effect of placing a vapour barrier or not on the free wall showed no changes in the relative humidity or moisture content in the beam end. Therefore, the lower relative humidity and moisture content at the beam end compared to the entire insulated wall is due to the extra heat loss through the gap. The minor increase in relative humidity when leaving a gap in the insulation compared to the reference measure shows that even a halved heat loss will be sufficient to heat up the beam end to secure the long-term durability.

Applying inside insulation normally gives relative humidity above the critical level in the brick-insulation interface. This is also the case when applying the insulation all the way to the floor. If instead a gap is left in the

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insulation towards the floor the corner between the insulation and existing inside wall perform much better than the fully insulated measure. The surface temperature stays above 10°C with an insulation gap and therefore is not critical for mould growth or condensation.

The proposed retrofit measures leaving a gap in the insulation could be a usable measure when looking at the modest increase in relative humidity and moisture content compared with the un-insulated wall. The question is how practicable the measure is leaving a gap in the insulation of 200 mm. From an aesthetic point of view this measure can be questioned. One would probably not apply the inside insulation leaving a gap under the ceiling and towards the floor. The height of the gap is the same as the existing skirting which could be made so warm air could enter the gap and not perform insulation layer of air which then could lead to increases of relative humidity and moisture content for rain loads on the threshold for onset of mould growth or wood decay.

CONCLUSION

This paper presented a methodology for developing new retrofit measures using failure mode and effect analysis combined with hygrothermal simulations. The results from this study appear to indicate that significant energy savings can be achieved when applying insulation to the interior of a masonry walls. Nonetheless, the installation of insulation on the interior of the wall, in which wooden beams are incorporated, can lead to moisture problems at beam ends and ultimately in the worst case, deterioration of the beam end. A straightforward way of dealing with this problem is leaving a 200 mm gap in the insulation. The relative humidity and moisture content at the beam end would then be very much like that of the un-insulated structure. Based on these findings it is concluded that the new retrofit measure leaving a gap in the insulation will be an adequate retrofit measure. The hazards identification of applying inside insulation on masonry walls with wooden beam ends were investigated using failure mode and effect analysis (FMEA). Two measures were investigated; one fully insulated wall and one with a 200 mm un-insulated at the base of the wall. From the FMEA the effect of moisture entering the structure leading to deterioration of the beam end was assessed as the worst case failure and further analysed regarding the durability. The use of FMEA was very time consuming and the results

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obtained from this analysis was not considered proportional to any new knowledge gained through the process. No ranking of the failures were performed which easily can be subjective evaluation. Therefore, it was concluded that the FMEA was not useful in the assessment of moisture durability of such wall assemblies. From an energy point of view the suggested retrofit measures can contribute to significant energy savings. Leaving an un-insulated part of the wall will still half the heat loss compared to the existing wall. This extra heat loss through the non-insulated wall part and beam end shows only a minor increase in the relative humidity and moisture content in the beam end. For low rain loads ($k_{\text{rain}} = 0.1$) installation of insulation on the interior can be done over the entire wall, whereas for intermediate rain loads ($k_{\text{rain}} = 0.3$) will be on the edge and a gap measure could be the measure to the moisture durability issue. Therefore, it is concluded that the measure with a gap will be durable retrofitting even though the drying through the gap has no influence on the moisture content in the beam end. From the simulation it is also concluded that the wind-driven rain has a great influence on the performance of the wooden beam end. The rain amount is crucial for the durability of the structure when applying inside insulation. The un-insulated wall part will not be exposed for mould growth as the part of the wall behind the insulation. Finally it is concluded that the use of the retrofit measure cannot be placed in a Northern European context before performing further studies related to assessing the performance for different climate locations having different values of rain intensity.

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