Hygrothermal performance of corners and floor junctions of timber-framed exterior walls: a simulation study

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Abstract. Corners and basement junctions of different timber-framed walls were studied by computer simulation using Delphin 5.8.3 software. Wooden cladding and brick veneer were compared with each other, as well as different wind barrier solutions. Both internal and external corners were studied, first assuming them airtight and then modelling an air leak. Simulations were performed both in present and future climate conditions. According to the results, the walls with wooden cladding and brick veneer had a big difference in their hygrothermal behaviour. Mould index rose considerably after construction in sole plate of brick clad wall, even if the plate was originally dry. Wet sole plates dried up very slowly. Almost all corner junctions of walls with wooden cladding performed well when there was no air leak. Corners of brick clad walls were more problematic. With an air leak, all studied walls developed considerably high mould indices, underlining the importance of building airtightness.

Keywords: Timber-framed wall, corner junction, floor junction, mould index, simulation

1. Introduction

Junctions between various parts of the building envelope can be problematic in design and construction phases. Floor junctions of timber-framed exterior walls tend to be especially difficult because the junction must transfer structural loads while avoiding thermal bridges. Damages can occur also if the sole plate gets wet due to rainwater, capillary suction or other moisture sources during construction or building use. Mould growth and even rotting of sole plate are common problems in Finnish building stock [1]. In addition to floor junctions, wall-to-wall corner junctions of timber-framed exterior walls can be done in many ways, but also there thermal bridges can be difficult to avoid due to several studs. Air leakages are also a common concern in the junctions between walls and adjacent construction parts.

In most cases, design of junctions is based on standard practices or previous examples. Understanding about the construction techniques as well as the conditions at building site are needed to design details which can be built on site with sufficient quality. However, either calculations or experimental studies are needed to evaluate whether thermal bridges in various building components are acceptable or not, and if there is a sufficient drying potential in those construction parts which can get wet at some point. Another factor is that the demands for energy efficiency have increased the insulation thicknesses in the building envelope. This can decrease temperature, increase relative humidity and consequently increase mould risk in the exterior parts of the building envelope, if those changes are not compensated by placing some additional thermal insulation on the exterior side of the structure. The various requirements and changes create a need to study how well the traditional junction types perform with regards to current targets for moisture safety and energy efficiency.

Performance of junctions has been investigated using laboratory and field studies. Kalamees et al. [2] measured the airtightness of various junctions both in laboratory and in real buildings. Differences between laboratory and field conditions proved to be considerably large, emphasizing the difficulties on construction site. The studies of Kayello et al. [3] underline the importance of junctions in cold climate where condensation and frost occur easily in outer parts of building envelope. Relander et al. [4] compared different methods to predict airtightness of buildings, and also measured the airtightness of joints [5]. According to the mentioned studies [2] [3] [4] [5], predicting hygrothermal performance of joints is both important and also difficult due to imperfections in building construction.

Numerical methods are commonly used to evaluate the steady-state temperature and heat flux conditions in building envelope junctions [6]. When moisture is also considered, the number of studies decreases considerably, but there are studies related to e.g. wooden beam ends in masonry walls [7] and rain penetration to wall-window junction [8]. Two previous publications [9] [10] analysed the hygrothermal behaviour of timber-framed walls using simulations and found that the predicted climate change, air leakages through the structure and the thermal resistance of the wind barrier all had an important effect on the conditions inside the wall structure. This paper is based on a finished M.Sc. thesis [11] and was part of the same project.

The aim of this study was to analyse the hygrothermal behaviour of typical wall-to-wall corners and floor junctions of timber-framed exterior walls. More specifically, it was on interest to study the impacts of stud placement, air leakages and thermal insulation on the moisture safety and drying capability of the junctions.

2. Materials and methods

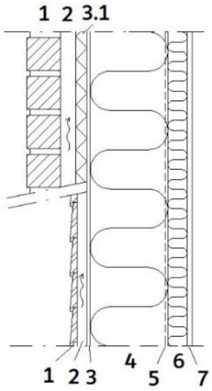
2.1. Junctions in the simulations

To simulate junctions in realistic conditions, a two-story single-family house was modelled to accommodate different wall constructions and their junctions. The house was assumed to situate in Southern Finland on a flat and open site. Terrain category I according to standard EN 1991-1-4 + AC + A1 2011 [12] was applied for calculating air pressure differences and intensity of wind-driven rain. Length, width and height of the house were 10 m, 10 m and 6 m. During the study, the external wall constructions of the house were varied. Six different base cases were studied.

All studied walls were timber-framed walls with mineral wool insulation, see Fig. 1. There was a polyethylene vapour barrier, mineral wool layer of 48 mm and interior gypsum board inside the timber frame. All walls had also an exterior grade gypsum board 9 mm outside timber frame as a wind barrier (WB). Thickness of the timber frame was varied within the range of 98…315 mm. In most cases, there was an additional mineral wool wind barrier outside the 9 mm gypsum board. The purpose of this expensive but hygrothermally good solution was to increase thermal resistance of the wall as well as keep timber frame and gypsum board warm. This decreases relative humidity and hence also mould index. The 9 mm gypsum board was always used under mineral wool wind barrier for structural reasons. Wood cladding (23 mm) and brick veneer (85 mm) were used as facade constructions. In both cases, there was a ventilation gap behind the façade. Junctions of walls with wooden cladding were assumed to be less sensitive to moisture loads than those with brick veneer. Therefore, walls with wooden cladding were studied with wind barriers which had low or moderate thermal resistance.

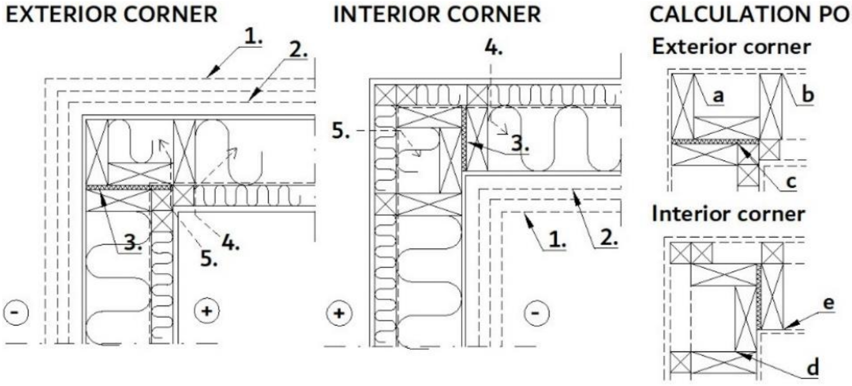
Simulated junctions included floor junctions as well as internal (inside) and external (outside) corners. Corners of all wall variations presented in Fig. 1 were studied, see Fig. 2. They were first modelled as airtight and then with air leaks. A 10 mm gap filled with mineral wool was modelled between two wall lines to demonstrate joint between prefabricated wall panels (Fig. 2).

Floor junction models included the bottom part of exterior wall, concrete foundation, edge of slab-on-ground floor (including insulation next to the foundation wall and under concrete slab) and soil around foundations. Unlike with corners, only two wall cases (W1-C and W5-B) were studied. This was compensated by assuming several different initial conditions of sole plate (SP) as well as adding insulation strips under and beside sole plate. The aim was to increase the temperature of sole plate, thus providing better conditions and speeding up drying of built-in moisture. The junctions are shown in Fig. 3.



Layers from exterior to interior:	Wall structures and layer thicknesses (mm): W1-B/ W1-C	W2-B/ W2-C	W3-B / W3-C	W4-B	W5-B	W6-B
1 Facade (brick veneer/ cladding)	85/23	85/23	85/23	85	85	85
2 Ventilation gap	40/25	40/25	40/25	40	40	40
3.1 Wind barrier, mineral wool	-	-	30	50	75	100
3 Wind barrier, gypsum board	9	9	9	9	9	9
4 Mineral wool + studs c/c600	198	315	198	148	123	98
5 Vapour barrier, PE plastic foil	0,2	0,2	0,2	0,2	0,2	0,2
6 Mineral wool + battens c/c600	48	48	48	48	48	48
7 Interior sheathing, gypsum board	13	13	13	13	13	13
Thermal transmittance value (W/m²K):	0,17	0,12	0,15	0,15	0,15	0,14

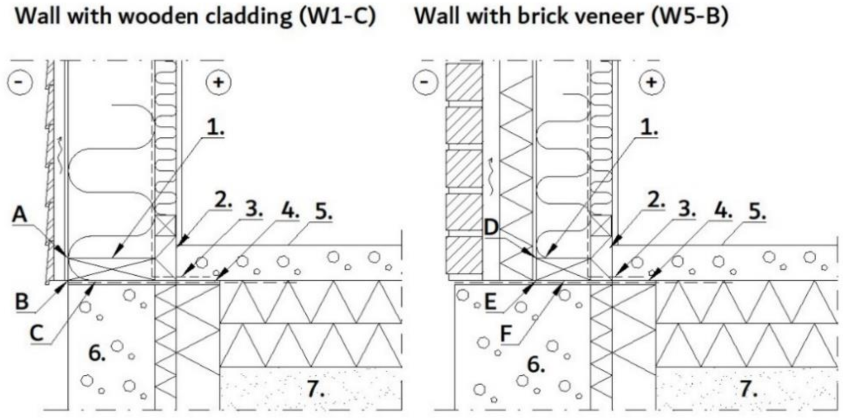
Figure 1. Layer thicknesses, thermal transmittance values and façade variations of wall structures. The base cases are numbered from 1 to 6. Walls from 1 to 3 have two façade variations (B = brick veneer, C = wooden cladding). Wall structures W3-B and W1-C are shown as examples.



1. Facade
2. Mineral wool wind barrier (structures W3…W6)
3. 10 mm gap between studs, filled with mineral wool (demonstrates joint between two prefabricated wall panels)
4. Modelled air leakage path
5. Modelled air leakage path

⊖ Outside
⊕ Inside

Figure 2. Simulated corner junctions (W3-B and W1-C), top view (horizontal section).



1. Sole plate
2. Expanded polystyrene 50 mm
3. Vapour barrier, folded under concrete slab
4. Bitumen membrane as radon and capillary break, on top of foundation and under edge of concrete slab
5. Concrete slab
6. Foundation wall, concrete
7. Gravel fill

⊖ Outside
⊕ Inside
A, B, C, D, E, F Calculation points

Figure 3. Simulated floor junctions, vertical section, side view (vertical section).

2.2. Simulation software, modelling principles and sources of material data

The simulations were performed using Delphin program, version 5.8.3 [13] using 2-D calculations.

The corner junctions (Fig. 2) were cut vertically halfway the edge and adjacent studs. Adiabatic surfaces were set to the model edges. In floor junction, exterior wall on top of the foundation was 500 mm high. Distance between the foundation wall and model edges in other directions was 3 m with timber-clad walls and 1 m with walls having brick veneer. The difference was due to the much longer simulation times in the case of brick veneer. Soil temperature at the bottom of model area was set to +5 ºC. This is near annual mean temperature in southern Finland.

Several initial moisture conditions of the sole plate were studied. The moisture content varied between equilibrium moisture content at 80 % RH (representing dry conditions) to saturated state with 470 kg/m^3 amount of moisture ("wet" conditions). In real-life conditions, a sole plate can absorb a lot of moisture due to improper protection in storage as well as during erection of the building frame. The main drying directions of the sole plate were towards exterior air and towards the mineral wool layer.

Air leakages in corner junctions were simulated by adding a 1 mm gap to the air/vapour barrier and using either the material-level air permeability of the wind barrier (tight) or an increased value for it (leaky). Air permeabilities of drywall and façade were set to 0.1 kg/(m·s·Pa) to allow setting air pressure boundary conditions. Air pressure inside the building was either constant or varied hourly according to thermal gradient and wind speed and direction. For constant air pressure difference, two values of 10 Pa and 20 Pa (overpressure indoors) were used. When calculating effects of wind pressure, pressure coefficients were taken from standard EN 1991-1-4 + AC + A1 2011 [12]. Modelling details, coefficients and initial conditions of material layers are presented in [11].

Part of the material properties of gypsum boards, mineral wool insulation and wind barriers, vapour barrier and timber (Scotch Pine, pinus sylvestris) have been determined at Tampere University [14]. Air permeability values were obtained from handbook RIL 255-1-2014 [1]. Properties for other materials (plastic-based insulation materials, bitumen membrane, concrete, brick, sand and gravel) as well as apparent properties for air gaps were obtained from the database of simulation software [13].

The simulation period was one year with corners and two years with basement junctions.

2.3. Outdoor and indoor conditions

Building physical test reference years (TRY) [14] were used to simulate outdoor conditions in present climate. The TRYs are one-year weather observation periods measured in Finnish localities. Different TRYs are used for different purposes. For walls with timber cladding, the data measured at Jokioinen (latitude 60.81 °N, longitude 23.50 °E) in year 2004 was used. This year was selected to be suitable for modelling timber-framed walls with wooden cladding. For walls with brick veneer, the data measured at Vantaa (60.31 °N, 24.97 °E) in year 2007 was used instead. The latter year was selected as critical concerning driving rain, which is a major issue with brick veneer.

The future climate dataset for years 2050 and 2100 were produced by the Finnish Meteorological Institute (FMI) by modifying the measured climate data according to the climate change projections. The predictions were based on the SRES A2 greenhouse gas scenario [15].

Indoor temperature of 21 °C was used year-round. Water vapour excess indoors was assumed to be 5 g/m^3 when outdoor temperature was below +5 °C and 2 g/m^3 when outdoor temperature was over +15 °C. The values on temperature range +5…+15 °C were linearly interpolated.

2.4. Performance criteria

Mould indices calculated using the Finnish mould growth model [16,17] were used to evaluate hygrothermal performance. The value of mould index (MI) can vary between 0 and 6, the value of 1 indicating the start of growth and 6 indicating full cover of visible mould. The limit value in the inside of gypsum wind barrier and all components inside it was set to 1.0. The chosen limit value 1.0 is considered strict but gives a margin of safety for flaws in building construction and use. Mould sensitivity classes of materials (MSC) were chosen according to [16,17]. MSC1 (very sensitive) was used for all timber parts, MSC 2 (sensitive) for gypsum board, including gypsum board WB and MSC 3 (resistant) for mineral wool products, including mineral wool WB.

3. Results

3.1. Exterior corner junctions

In airtight corners of wooden-clad walls, mould index did not exceed 1.0 on exterior side of studs (points a and b). Inside vapour barrier, in point c, it exceeded 1.0 with wall W1-C in year 2100 conditions. This was due to thermal bridge effect of studs outside vapour barrier. W2-C performed well in this instance because the 315 mm studs provided greater thermal resistance compared to the two other cases. Cool inside surface due to thermal bridging may become an issue in older houses with thin timber frame.

In walls with brick veneer, calculated mould indices were inversely proportional to the thickness on mineral wool wind barrier. This was especially distinctive in the points a and b right behind 9 mm gypsum board. In W6-B having 100 mm mineral wool insulation, the mould index remained below 1.0 except in year 2100 climate. On the contrary, mould indices of walls W1-B, W2-B and W3-B were between 5 and 6 in all studied situations.

The results of walls W1-B, W2-B and W3-B differ from their variants with wooden cladding, W1-C, W2-C and W3-C. The former developed the mould index over 1.0 in most situations. Pressure of 20 Pa inside house was an acceptable situation only with W1-C having tight wind barrier, except in year 2100 climate. The simulation results are presented in table 1.

Table 1. Maximum mould indices in various points of outside corners of all studied variations. ΔP indicates constant overpressure inside house. Cases with “C” are north-oriented and “B” south-oriented.

Wall ID	Condition	Point a			Point b			Point c		
		Present	2050	2100	Present	2050	2100	Present	2050	2100
W1-C	No air leak	*0.2*	*0.2*	*0.9*	*0.1*	*0.2*	*0.8*	*0.3*	*0.7*	1.4
	Air leak, tight WB, ΔP = 20 Pa	*0.4*	*0.6*	1.6	*0.4*	*0.6*	1.5			
	Air leak, leaky WB, ΔP = 20 Pa	5.3	5.3	5.4	*0.5*	*0.7*	2.2			
W2-C	No air leak	*0.1*	*0.3*	*0.9*	*0.1*	*0.2*	*0.9*	*0.0*	*0.0*	*0.5*
W3-C	No air leak	*0.0*	*<0.1*	*0.3*	*0*	*0*	*<0.1*	*0.0*	*0.1*	*0.8*
W1-B	No air leak	5.7	5.7	5.7	5.1	5.1	5.2	*0.4*	*0.7*	3.0
W2-B	No air leak	5.8	5.8	5.8	5.2	5.4	5.5	*0.4*	*0.7*	2.6
W3-B	No air leak	5.2	5.4	5.5	3.2	3.8	4.3			
W4-B	No air leak	3.7	3.9	4.3	1.1	2.0	3.5	*0.2*	*0.5*	1.8
W5-B	No air leak	*0.9*	1.7	3.3	*0.6*	1.0	2.4	*0.2*	*0.4*	1.6
	Air leak, tight WB, ΔP = 20 Pa	1.1	2.2	3.5	*0.6*	1.1	2.7			
	Air leak, leaky WB, ΔP = 20 Pa	5.5	5.5	5.5	3.7	4.0	4.2			
W6-B	No air leak	*0.4*	*0.7*	1.4	*0.3*	*0.6*	1.8	*0.2*	*0.4*	1.5

3.2. Interior corner junctions

The studied interior corner represents a situation where wooden studs form a “box” in the corner. With a tight wind barrier, the leaky vapour barrier did not cause considerable increase of mould index at point d, except in wall W1-C. The studs were modelled ideally and there were no air spaces between them. In other words, the air could not pass the structure. With leaky wind barrier, an exfiltrating airflow occurred causing considerable increase of mould index at point e.

In walls W1, W2 and W3, there were crucial differences between wooden cladding and brick veneer variants. However, the former variants also developed MI over 1.0 at point d in future conditions. This indicates the problematic shape of the studied corner. The stud outside point d effectively blocks moisture, thus causing diffusion. In general, mould indices were inversely proportional to the thermal resistance of wind barrier. The results are presented in Table 2.

Table 2. Mould indices in various points of inside corners of all studied variations. ΔP indicates constant overpressure inside the house. Cases with "C" are north-oriented and "B" south-oriented.

Wall ID	Condition	Point d			Point e		
		Present	2050	2100	Present	2050	2100
W1-C	No air leak	*0.8*	3.4	4.8	*0*	*0*	*0*
	Air leak, tight WB, ΔP = 10 Pa	2.2	4.2	5.1	*0*	*0*	*0.1*
	Air leak, leaky WB, ΔP = 10 Pa	2.2	4.2	5.1	4.1	4.1	4.5
W2-C	No air leak	3.0	5.1	5.3	*0*	*0*	*0*
	Air leak, tight WB, ΔP = 10 Pa	3.8	5.2	5.5	*0*	*0*	*0.4*
	Air leak, leaky WB, ΔP = 10 Pa	3.9	5.2	5.5	4.7	4.7	4.9
W3-C	No air leak	*0.5*	1.9	3.1	*0*	*0*	*0*
	Air leak, tight WB, ΔP = 10 Pa	*0.7*	1.9	3.1	*0*	*0*	*0*
	Air leak, leaky WB, ΔP = 10 Pa	*0.7*	1.9	3.1	*0*	*0*	*0*
W1-B	No air leak	5.4	5.5	5.5	1.7	3.1	4.1
W2-B	No air leak	5.5	5.5	5.6	3.9	4.1	4.6
W3-B	No air leak	5.0	5.2	5.3	*0.0*	*0.1*	*0.6*
W4-B	No air leak	2.6	3.1	3.9	*0.0*	*0.0*	*0.2*
W5-B	No air leak	1.0	1.5	2.4	*0.0*	*0.0*	*0.2*
W6-B	No air leak	*0.3*	*0.6*	1.2	*0.0*	*0.0*	*0.1*

3.3. Floor junctions

The junction between wooden-clad exterior wall W1-C and foundation wall performed well in present conditions while the sole plate was dry. Mould indices increased proportionally to the initial moisture content of sole plate. An additional thermal insulation strip between the sole plate and wind barrier improved the conditions at the sole plate. A 5 mm thick extruded polystyrene (XPS) insulation was enough to keep mould indices in all studied calculation points below 1, even in future climate. Insulation under sole plate reduced the values of mould index less, only approximately 0.5 units when the sole plate was initially dry. A 20 mm XPS under sole plate was also tried to test out the possible means to improve sole plate conditions, at least at concept level. Calculated mould indices in different points and situations are presented in table 3.

Table 3. Maximum mould indices in various points of sole plate of wall W1-C.

Initial conditions	Insulation under / outside sole plate	Point A			Point B			Point C		
		2004	2050	2100	2004	2050	2100	2004	2050	2100
RH=80 % ("dry")	No insulation	*0.1*	*0.3*	1.2	*0.7*	1.7	4.1	*0.4*	*0.7*	1.2
	20 mm XPS under SP	*0.1*	*0.3*	1.0	*0.6*	1.1	3.5	*0.0*	*0.1*	*0.5*
	5 mm XPS between SP and WB	*0.0*	*0.2*	*0.9*	*0.0*	*0.0*	*0.1*	*0.0*	*0.3*	*0.8*
RH=90 %	No insulation	*0.1*			*0.7*			1.2		
RH=97 %	No insulation	*0.1*			*0.7*			2.6		
w = 470 kg/m^3 (saturated)	No insulation	*0.5*			1.0			6.0		

The floor junction of exterior wall W5-B turned out to be very problematic. Even with the case of initially "dry" sole plate (conditioned to RH 80 %), mould index was far above 1.0 in all calculation points. Thermal insulation between sole plate and foundation improved the situation, although mould indices in outer edge of the sole plate were still too high. The results are presented in table 4.

Table 4. Mould indices in various points of sole plate of wall W5-B.

Initial conditions	Insulation under / outside sole plate	Point D			Point E			Point F		
		2007	2050	2100	2007	2050	2100	2007	2050	2100
RH=80 % (“dry”)	No insulation	4.3	4.5	4.7	4.5	5.0	5.2	2.5	2.9	3.3
	20 mm XPS under SP	3.7			4.0			1.0		
RH=90 %	No insulation	4.5			5.0			3.6		
RH=97 %	No insulation	4.7			5.3			4.3		
w = 470 kg/m^3 (saturated)	No insulation	5.6			5.8			6.0		

The conditions in both studied floor junction cases were on the safe side because the foundation wall was modelled as a solid concrete block, see Fig. 3. In Finland, the foundation walls as well as basements are normally made either of concrete sandwich panels, lightweight aggregate concrete blocks or concrete form blocks having thermal insulation layer(s). All these solutions provide warmer and thus better conditions for sole plate than the solid concrete basement used in this study.

4. Discussion and conclusions

Differences between various wall types and their hygrothermal performance were highlighted in junctions. Because hygrothermal conditions can be harsher in junctions than on plain walls, mould problems are more likely to occur in junctions. Corners and foundation junctions of walls with brick veneer proved to be especially vulnerable.

Both wall structures and junction details should be developed to meet future challenges. There are junctions which perform well in present climate but are prone to mould growth in future climate. Wind barriers should have adequate thermal resistance to keep relative humidity of timber frame sufficiently low, and they should preferably be vapor permeable to allow built-in moisture to dry out. The significance of thermal resistance of the wind barrier has been already stated in earlier studies [18] [19] [20]. It is also recommended to prevent vapor-tight boxes from being created into the junctions, see location and results of point d (Fig. 2 and Table 2).

According to the simulations, walls W1-C and W3-C would be safe choices in present climate, providing the possibility of air leak is eliminated and sole plate is kept dry during construction phase. The basement junction of W3-C was not studied but it is reasonable to assume that it performs as well as that of wall W1-C. W5-B and W6-B would also perform well in present climate conditions if the basement junction was revised. The most severe challenges are involved in the future climate. It seems that the walls with wooden cladding could be adapted to future climate by increasing thermal resistance of wind barrier and redesigning interior corner (and other similar details). On the other hand, use of brick veneers requires other solutions than what was included in this study.

Choice of climate change scenario, moisture excess and air pressure difference over building envelope can affect significantly on results. The factors were targeted to be on the safe side, such that most practical situation would be covered by the design values used here.

There were several important findings despite many simplifications of the simulation study. Exterior walls must absolutely be developed to meet future challenges. Improvements in wind barrier practices would help decrease RH and hence also mould index of timber parts. The sole plate should always be protected from moisture during the whole construction phase.

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