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Hygrothermal performance of light steel-framed walls

TECHNICAL RESEARCH CENTRE OF FINLAND

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Keywords building envelope, steel structures, light-gauge steel, corrosion tests, weather resistance, moisture, surface condensation, climatic conditions, heat transfer

Abstract

Hygrothermal performance of a new light-gauge steel framed building envelope system has been analyzed using 3-D thermal simulations, 2-D combined heat, air and moisture transfer simulations, laboratory testing in a calibrated and guarded hot box (ISO 8990), weather resistance tests for full-sized structures, corrosion tests and field measurements at experimental buildings in Ylöjärvi, Central Finland. The results show that a modern steel wall structure based on perforated steel profiles performs satisfactorily in the cold climate of Finland. The perforations reduce heat loss along the web of the profile significantly. The field measurements show that no condensation has occurred in the frame system. Temperature measurements and infrared surveys in demonstration buildings show that surface temperatures are sufficiently high to prevent surface condensation or even increased humidity on the surface. According to the calculations, there are no severe corrosion risks in the steel frames in the Finnish climate. The climate, however, has an important effect on the performance, and the structures should be designed with regard to climatic conditions.

Preface

New building envelope systems based on light steel framing have been developed and studied during the last 10–15 years in Finland. The focus of the research has been in the high performance exterior wall systems. Good thermal insulation properties, durability and minimised corrosion and moisture risks have been the key issues.

A number of research projects have been carried out during 1989–2000. This report gives an overview of the most important results of these studies. The research work has been funded by Rautaruukki Oyj, Outokumpu Polarit Oy, The Finnish Constructional Steelwork Association, The National Technology Agency (Tekes), VTT Steel Research Programme and The European Coal and Steel Community (ECSC).

Contents

1. Introduction

New building enevlope systems based on light steel framing have been developed during the last 10–15 years. The focus has been in commercial and public buildings, but the use of steel structures in housing has also increased. Service life of buildings and building components has become more and more important feature in marketing of building products. When new building systems are introduced, the question of the hygrothermal performance will be inevitably raised.

The purpose of the research has been to evaluate the hygrothermal performance and durability of a light steel frame system used as an exterior wall structure in various types of buildings. A number of research projects have been completed to show real, tested and verified results on the questions related to performance:

- Development of light prefabricated steel framed facade units: Development and hygrothermal testing of new light gauge steel frame systems /15/.
- Development 3-D heat transfer tools for steel structures: numerical 3-D tool for calculation of temperature and heat flow distribution in steel structures /10/.
- Service life design of steel structures: field surveys of steel buildings, long-term corrosion tests /6/.
- VTT Steel research programme’s /16/ project Performance of steel buildings: development hygrothermal calculation tools, measuring devices and methods.
- ECSC (European Coal and Steel Coalition) Mega5-project Application of steel in urban habitats: Low-energy steel house for a cold climate: development, testing and demonstration of a new steel frame system, concept for energy-efficient residential housing based on steel frame structures /7, 11/.

A new concept for steel construction based on perforated light gauge steel profiles was developed and demonstrated in Ylöjärvi, Central Finland. The aim of the ECSC funded Mega5 project /7/ were to ensure the performance and suitability of a light-gauge steel-framed house for use in a cold climate. The project included comprehensive research on the structural and hygrothermal performance of the structures as well as research on the energy performance and environmental impacts of steel buildings.

The hygrothermal performance of a number of structures have been assessed using 3-dimensional heat flow calculations and laboratory measurements with full-size structures in a calibrated and guarded hot box according to ISO 8990 standard and laboratory weather resistance tests. Also, the thermal performance of the structures was investigated in the field monitoring (1996–2000) at the Ylöjärvi steel houses. The monitoring project included temperature measurements from various locations in the building envelopes, infrared surveys of the buildings, blower door tests to assess the air tightness of the buildings and moisture monitoring from the frame structure.

In the VTT Steel research Programme’s /16/ research project ‘Performance of steel buildings’ the accuracy of various measuring methods and computerized calculation tools have been tested. The focus of the research has been on thermal measurements and calculations.

2. Thermal performance of light steel structures

2.1 Thermal bridges

Just like all frame materials in an insulated structure, a steel member is a thermal bridge. But, since thermal conductivity of steel is high, severe bridge effects are possible. The effect of thermal bridges has been reduced by three methods:

- using double frame systems
- using exterior insulation systems
- using perforated (or slotted) the steel profiles.

Light-gauge steel-framed structures based on double frame system (horizontal and vertical frame, Figure 1) have been used as external walls of office and public buildings. The distance between the frames in both directions is typically 0.6 meters, and thermal insulation is installed into the cavities between the frames. Double frame system improves thermal quality of a wall by 20–25 % compared to single frame cavity insulated wall, Table 1.

Exterior insulation systems reduce thermal bridging in a wall. The effect depends on the thermal properties of the insulation system. Exterior insulation is very advantageous in terms of moisture behavior, since the frame temperatures increase which in turn reduces moisture risks in the frame.

Perforated webs in a light-gauge steel frame give two advantages for the structure. Due to the perforations, the thermal properties of the structure are improved. This, in turn, makes it feasible to use the structure as a single-frame wall system. A light-gauge steel frame with perforated web is termed a thermoprofile, see Figures 2 and 3. U-shaped thermoprofiles are used in prefabricated facade units for high-rise buildings. The load bearing walls of detached and row houses are composed of vertical C-shaped thermoprofiles. The material thickness of the profiles is typically 1.0–1.5 mm.

The effect of the perforations or slots in a thermoprofile can be taken into account by introducing an equivalent thermal conductivity for the non-perforated material. Heat transfer in the web can be assumed to be pure heat conduction. The equivalent thermal conductivity can be defined by comparing conduction in the perforated case and in the non-perforated case. The equivalent thermal conductivity depends on the perforation system including the shape and dimensions of perforations, the dimensions of the steel necks between the perforations and the thermal conductivity of the material in the perforations, see Figure 4.

The reduced thermal bridging has a considerable effect on reducing the heat conduction in the thermoprofile relative to solid steel (Figure 5). The perforations perform as thermal breaks for the steel member reducing the heat conduction along the web by 70–80%, Figure 6. According to studies carried out in Finland and Sweden /1, 8, 9/, the equivalent thermal conductivity of a thermoprofile can be 5–10 W/m^{2}K.

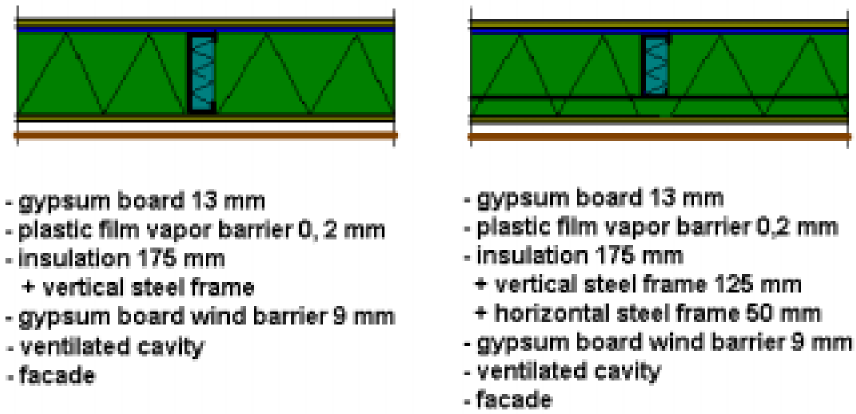


Figure 1. Single and double framed wall structures used as exterior wall in Finland.

Table 1. Relative thermal resistance of insulated steel framed wall compared to one-dimensional resistance of thermal insulation of corresponding thickness. All insulation materials mineral wool, thermal conductivity 0.037 W/mK.

Wall structure	Relative thermal resistance, %
Mineral wool insulation 175 mm	100
Single frame wall (figure 1) - vertical frame C 175–50–1.2	45
Double frame wall ■ vertical frame C 125–50–1.2 ■ horizontal frame Z 50–50–1.0	65
Single frame wall + exterior insulation 125+50 mm - vertical frame C 125–50–1.2	75
Single frame wall, thermoprofiles - vertical frame C 175–50–1.2	80

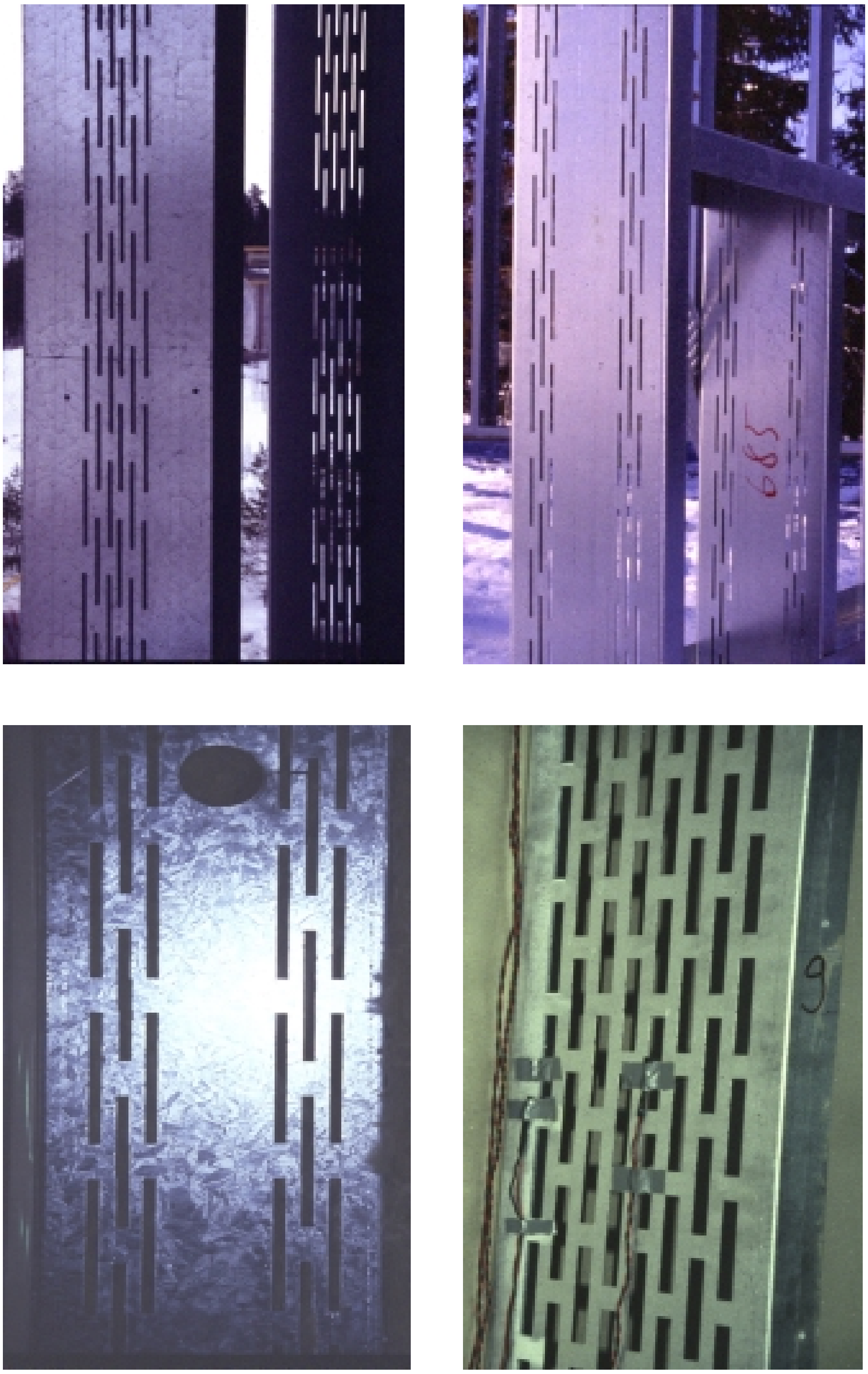


Figure 2. Thermoprofile alternatives. Profiles in the top row were used in Villa 2000 built for the Tuusula housing fair 2000 (left), and in Ylöjärvi steel houses built for the Ylöjärvi housing fair 1996 (right). Other two exmples were manufactured for testing purposes.

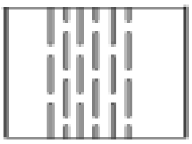
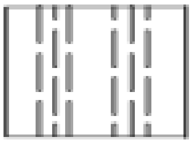
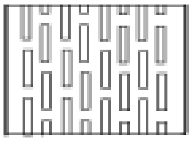
	Equivalent thermal conductivity 5,5 – 7,5 W/m²K
	Equivalent thermal conductivity 5,5 – 7,5 W/m²K
	Equivalent thermal conductivity 5,0 – 7,0 W/m²K

Figure 3. Perforation alternatives of a thermoprofile. Equivalent thermal conductivity takes into account the perforations filled with insulation material. Equivalent thermal conductivity depends on the properties of thermal insulation, the dimensions of the perforations and the dimensions of the solid steel between the perforations.

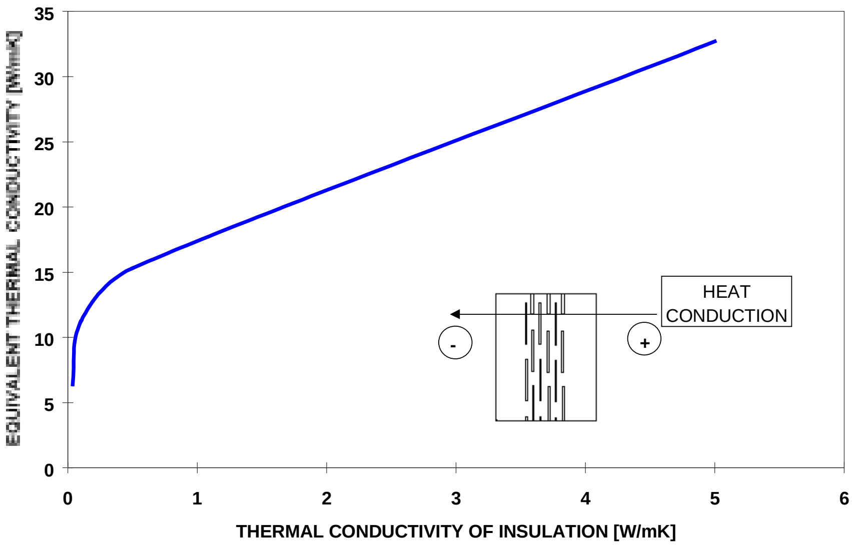


Figure 4. The effect of thermal insulation into the equivalent thermal conductivity of the typical Finnish thermoprofile /12/.

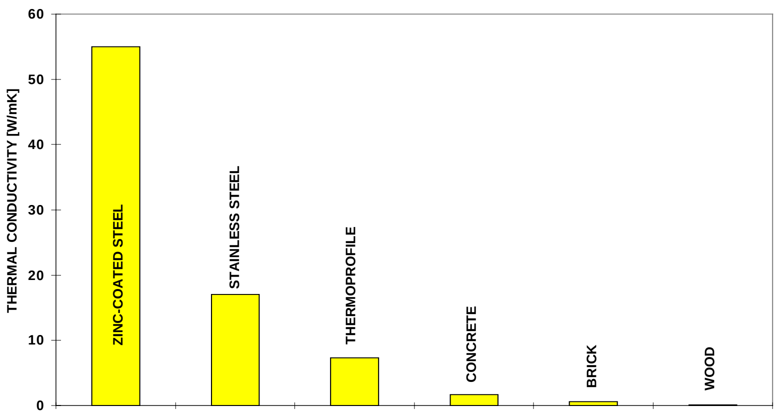


Figure 5. Thermal conductivity of various building materials used in load-bearing structures. Equivalent thermal conductivity for the thermoprofile.

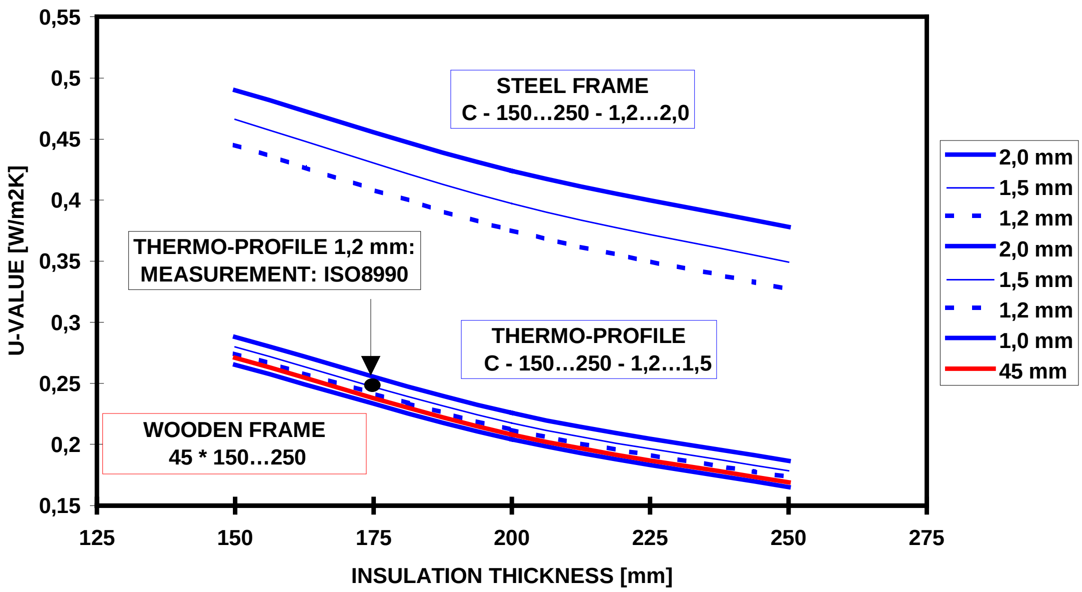


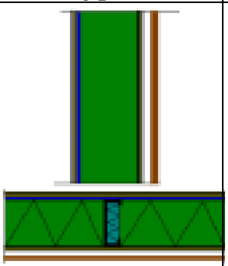
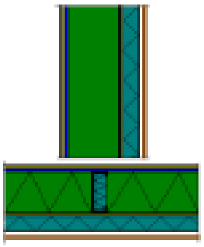
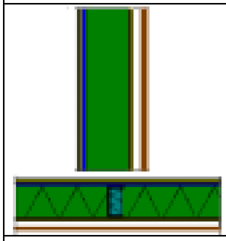
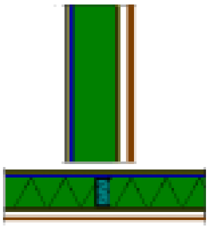
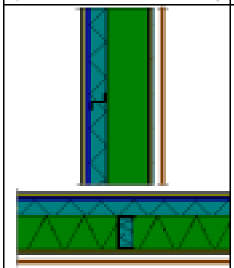
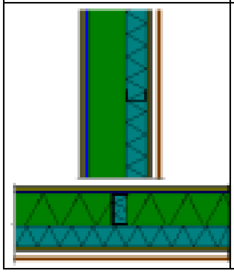
Figure 6. Calculated values of thermal transmittance for steel-framed and wood-framed walls /9/. The thermal benefit of the perforations in a steel member of a single frame structure is 40-50% depending on the insulation thickness of the wall.

2.2 Comparision of thermal analysis tools

Steel structures are typically 3-dimensional structures. Thermal analysis of these structures is complicated, since numerical methods for 3-dimensional calculations are usually required. However, single frame structures can be analysed using 2-dimensional calculations even in the case where the web of a steel profile is perforataed, using equivalent thermal conductivity as a material property for the steel member.

To facilitate the accuracy of calculational methods in comparision to measurements, a series of laboratory tests in calibrated and guarded hot box apparatus (ISO 8990, /3/) was carried out. Further more, the suitability of the heat flow method according to DIN 52611 standard /2/ for measurement of thermal transmittance was tested. The results show that the agreement between calculated and measured (ISO 8990) results is rather good, Table 2. Although only a few structures were tested, the heat flow method according to DIN 52611 shows too high values compared to other analysis methods.

Table 2. Comparision of the thermal analysis tools for assessment of thermal transmittance (U-value) of light steel framed walls. Measured values according to ISO 8990 and DIN 52611 standards and results from 2- and 3-dimensional simulations.

Wall type	Structure layers from inside	U-value [W/m²K]
	Gypsum board 13 mm PE film vapor barrier Steel frame **a)** TC 175–50–1,2 mm or **b)** C 175–50–1,2 mm + mineral wool insulation Gypsum board wind proofing 9 mm	**a)** ISO 8990: 0,263 3-D simulation: 0,257 2-D simulation: 0,257*) **b)** 3-D simulation: 0,435 2-D simulation: 0,435 *)equivalent thermal conductivity 7,3 W/mK
	Gypsum board 13 mm PE film vapor barrier Steel frame TC 175–50–1,2 mm + mineral wool insulation Gypsum board wind proofing 9 mm Wind proof rigid mineral wool 45 mm	ISO 8990: 0,188 3-D simulation: 0,190 2-D simulation: 0,190 *) *)equivalent thermal conductivity 7,3 W/mK
	Gypsum board 13 mm PE film vapor barrier Steel frame TU 150–50–1,0 mm + mineral wool insulation Gypsum board wind proofing 9 mm	ISO 8990: 0,300 DIN 52611: 0,350 3-D simulation: 0,292 2-D simulation: 0,290*) *)equivalent thermal conductivity 5,5 W/mK
	Gypsum board 13 mm PE film vapor barrier Stailess steel frame U 150–50–1,0 mm + mineral wool insulation Gypsum board wind proofing 9 mm	ISO 8990: - DIN 52611: 0,375 3-D simulation: 0,340 2-D simulation: 0,340
	Gypsum board 13 mm PE film vapor barrier Steel frame U 50–50–1,0 mm + mineral wool insulation Steel frame U 125–50–1,0 mm + mineral wool insulation **a)** air gap + over-clad steel façade **b)** no façade	**a)**ISO 8990: 0,281 3-D simulation: 0,282 **b)** DIN 52611: 0,345*) 3-D simulation: 0,321*)
	Gypsum board 13 mm PE film vapor barrier Steel frame U 150–50–2,0 mm + mineral wool insulation Steel frame TU 100–50–1,0 + mineral wool insulation Gypsum board wind proofing 9 mm	ISO 8990: DIN 52611: 0,225 3-D simulation: 0,214 3-D simulation: 0,210*) *)equivalent thermal conductivity 16 W/mK

TC = C-shaped perforated steel profile (thermoprofile)
TU = U-shaped perforated steel profile, U = U–shaped steel profile

2.3 Airtightness of steel buildings

Air tightness of steel building has been tested only in 4 cases. Table 3 shows results from measured cases and reference information from typical Finnish buildings.

Table 3. Airtightness of steel houses and typical Finnish buildings.

Building type	Air leakage rate at 50 Pa, air changes per hour
Prefabricated steel houses (row houses)	1,9–2,5
Site built steel house (row house)	3
Site built wooden detached houses	3–4
Prefabricated wooden detached houses	2–4
Prefabricated wooden row houses	3–5
Massive wooden houses (log houses)	7–15
Concrete buildings	1–4
Low-energy detached houses	0,8–2

The locations of air leaks in the steel houses were searched using an infrared camera. Insufficient sealing of electrical and ventilation installations leading through the air/vapor barrier of the envelope caused the most of the air leaks. These defects were found systematically in all of the buildings.

2.4 Temperature distribution in light gauge steel walls

Temperature distributions in the single frame structures have been measured both in a series of full-scale laboratory weather tests and in the structures of Ylöjärvi steel houses. The temperatures on inner wall surface are sufficiently high to prevent ghosting, surface condensation or even relative humidity high enough to increase the risk of mold growth on the wall surface, Figures 7 and 8. Temperature on the inner surface of the wall on top of the frame is 1–2 °C lower than the temperature between the frames.

The temperature of the outer flange of the steel frame depend on the thermal properties of the wall outside the frame, Figure 9. The outer flange of the profile is considerably warmer than outdoor air temperature due to heat conduction from the interior along the web of the steel profile. Even though the perforations in a thermoprofile reduce heat conduction along the frame, the residual conduction increases temperatures in the outer parts of the frame, thus reducing the condensation risk and increasing the drying potential in case of condensation. The use of exterior water vapor permeable insulation as in the low-energy wall further improves the hygrothermal performance of the wall.

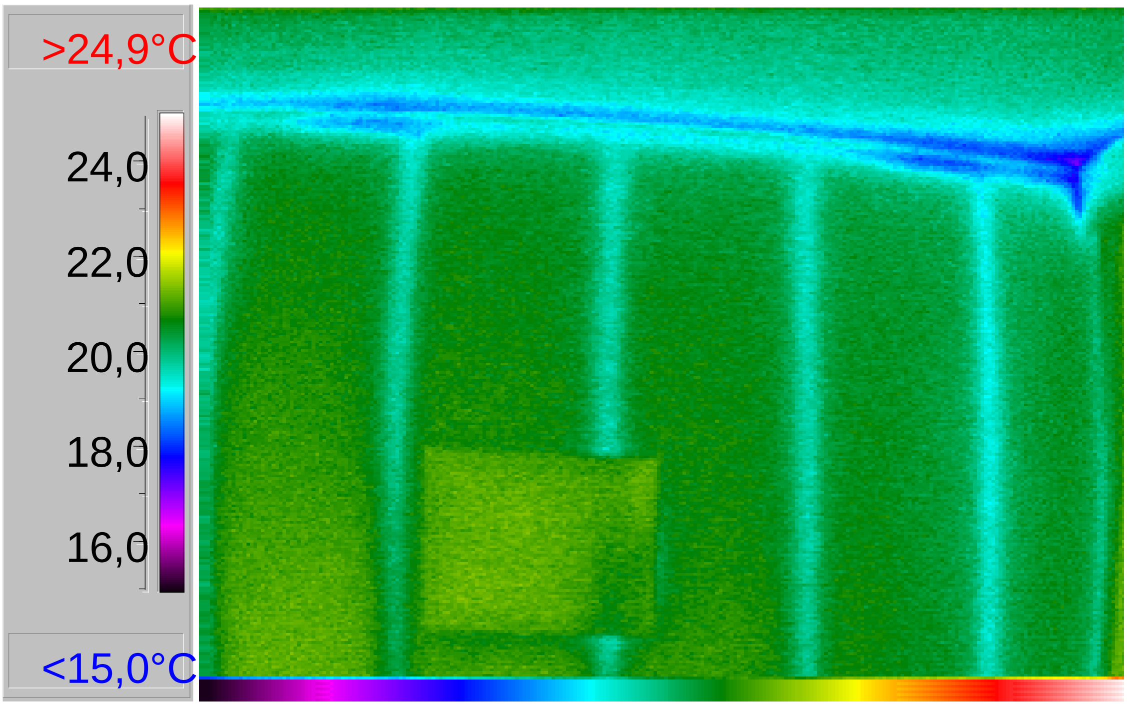


Figure 7. Infrared image of a steel wall.

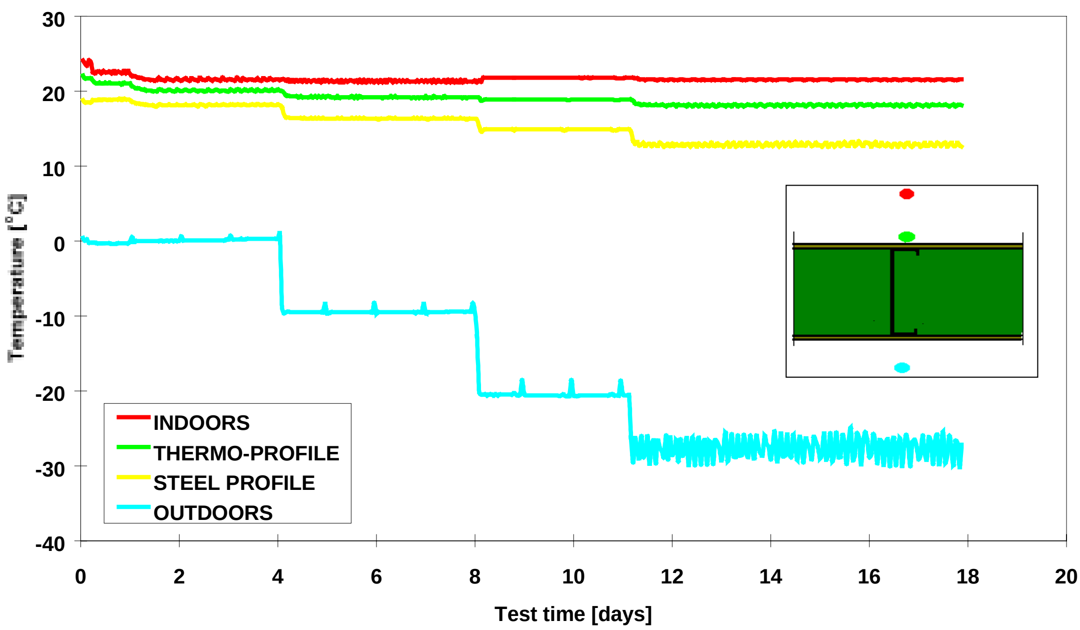


Figure 8. Surface temperatures of a light steel-framed wall according to a laboratory weather test.

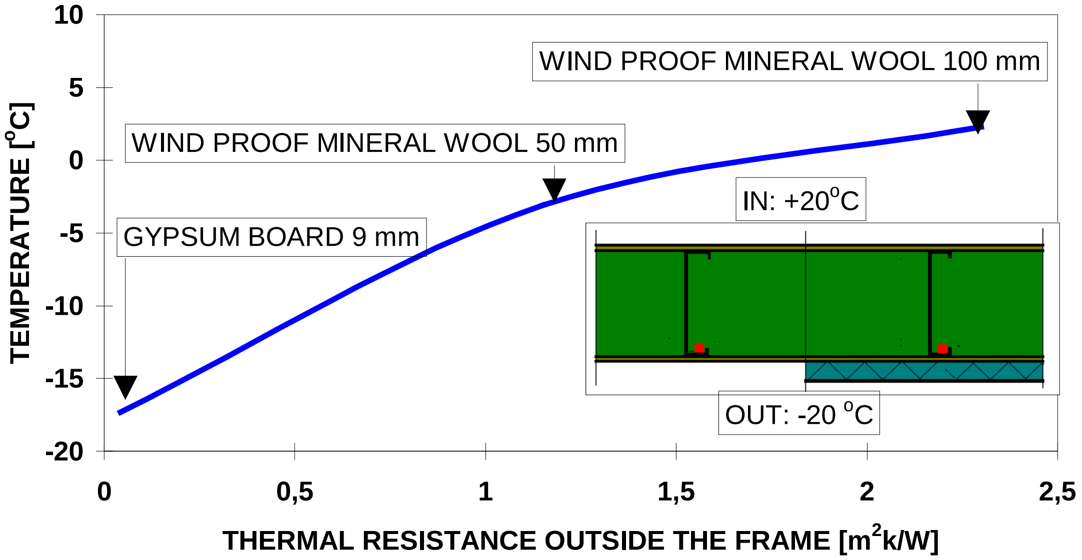


Figure 9. The effect of thermal properties of wind proofing (see Figure 1) on the temperature of outer parts of the frame /12/.

3. Durability of light steel framing

3.1 Moisture variation in steel-framed walls

The corrosion of a metal depend on the micro climate on the surface of a component. Continuous corrosion is possible, if relative humidity on the metal surface exceeds 80% at the same time as temperature is above 0°C (ISO 9223, /4/).

Figure 10 shows the monthly maximum values of relative humidity of eight measuring points in the outer flange of the steel profiles measured in the Ylöjärvi steel houses. The results show that relative humidity in wall 1 has exceeded 80%, but no condensation has occurred. The humidity in wall 2 has not exceeded 90%.

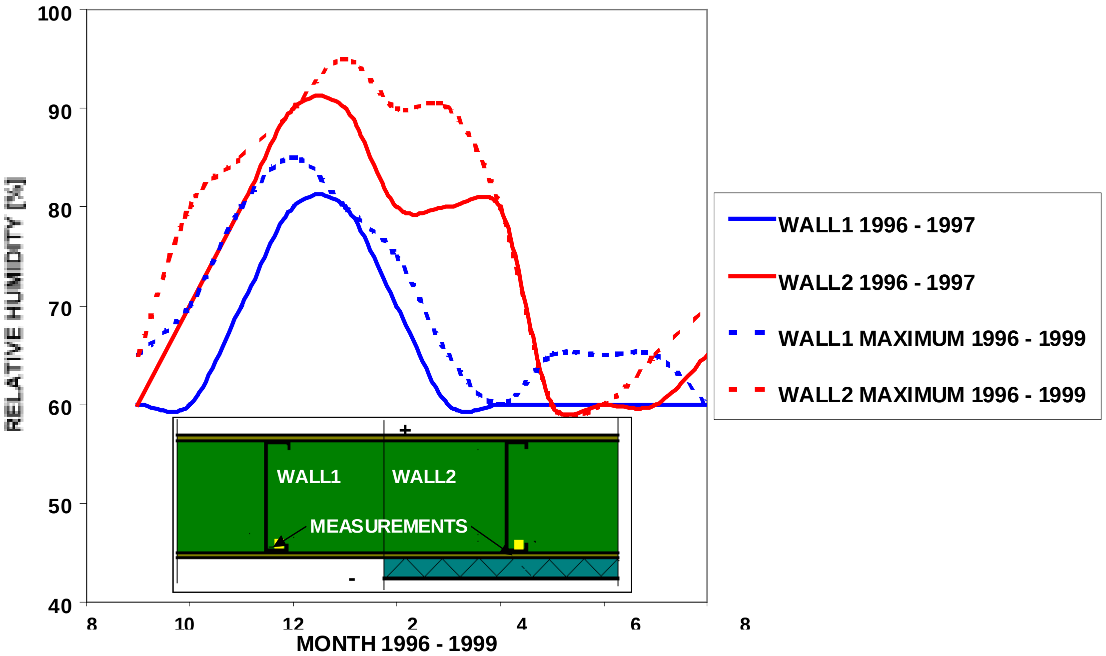


Figure 10. Monthly maximum of relative humidity in the external walls of the Ylöjärvi steel buildings. Measurements on the outer flange of the steel members.

3.2 Corrosion risks caused by materials in contact with light gauge steel

Corrosion risks caused by other building materials in contact with steel are studied in an on-going long-term laboratory test. Insulated steel frames are placed in different climates to see the effect of material and air humidity on corrosion. The materials being studied are:

- cellulose fiber insulation
- glass wool insulation
- rock wool insulation
- impregnated wood.

The laboratory test has been going on for about 4 years (35000 hours of time of wetness). Test conditions are given in Figure 11. The results show that the cellulose insulation and impregnated wood promotes zinc corrosion in humid conditions, but no corrosion products from steel were detected in any of the test pieces (Figure 12). There are no signs of zinc corrosion in the test pieces insulated with mineral wool products. In the case with continuous condensation, edge corrosion of steel was found in all the specimens. The fire retardant chemicals (borax and boric acid) of the cellulose fiber insulation were not stagnant. The chemicals re-crystallized on the steel surface, which caused stronger edge corrosion in the test specimens insulated with cellulose fiber insulation compared to other specimens.

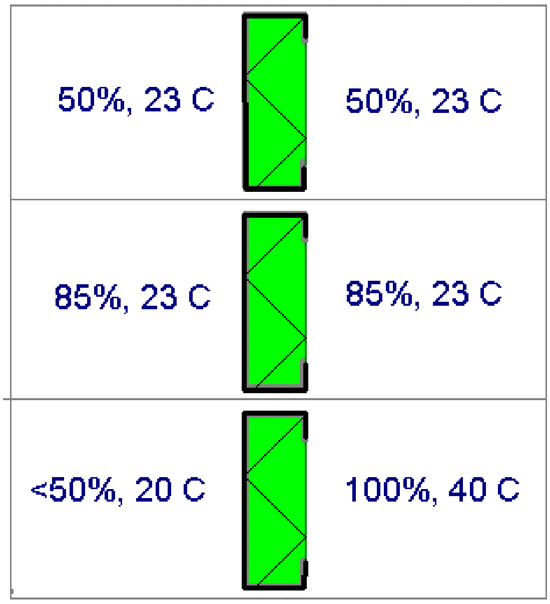


Figure 11. Test climates in corrosion tests. Normal indoor conditions are being used as reference (top). Corrosion tests are carried out in humid air (middle) and in conditions where condensation occurs continuously (bottom).

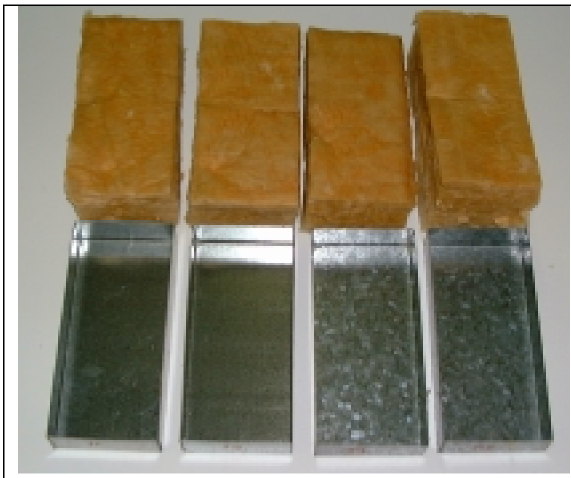
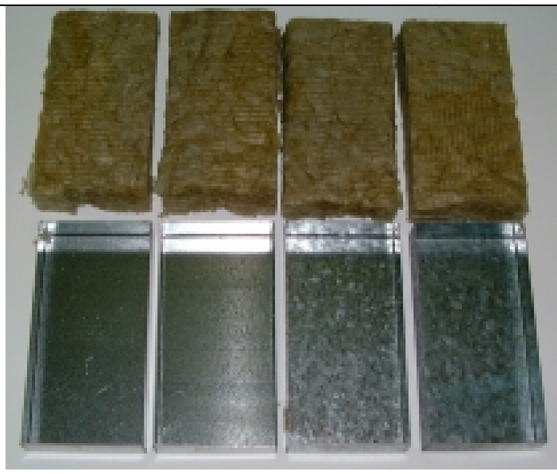
 a) Glass wool: no corrosion.	 b) Rock wool: no corrosion.
 c) Cellulose fibre: zinc corrosion	 d) Impregnated wood: zinc and steel corrosion.

Figure 12. Long-term corrosion test with steel members in contact with other materials. Test conditions +23°C and 85% relative humidity. Test time 35 000 hours.

3.3 Hygrothermal simulations

The hours of wetness were also calculated for two wall types depicted in Figure 13 using the 2-D heat, air and moisture transfer simulation program LATENITE /5, 13/:

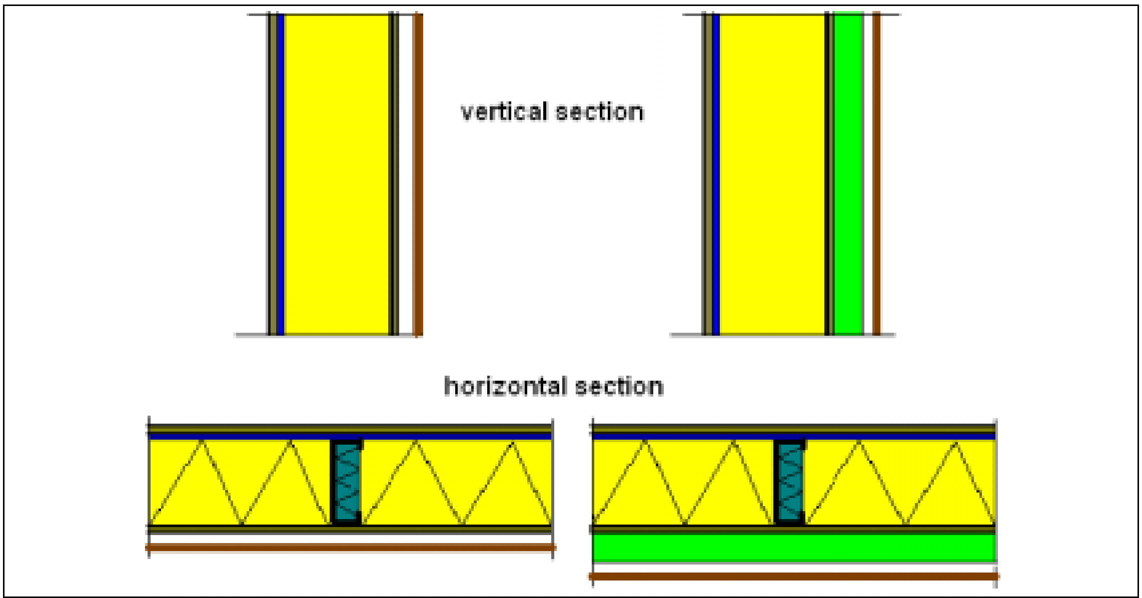
- Case A: the wall shown in Figure 6 on the left without exterior insulation and
- Case B: the wall shown in Figure 6 on the right, like case A except for an additional layer of exterior insulation of 50 mm rigid wind proof mineral wool.

The hourly climates of Helsinki, Finland and St. Hubert, Belgium were used as a starting point. The orientation of the walls was north which is considered to be the worst orientation in terms of hygrothermal performance due to low solar radiation absorption. Wind-driven rain was not taken into account in the simulations and the walls were assumed to have a cladding with good cavity ventilation behind the cladding. The initial conditions of the material layers were +20°C and 50% relative humidity. The indoor air conditions were:

- temperature +22°C or outdoor air temperature if higher than +22°C
- indoor air moisture content x_{in} was outdoor air moisture content x_{out} + 3 g/kg, but limited to 30% ≤ relative humidity ≤ 80%.

The simulations were carried out for a two-year period starting September 1.

The accumulated time of wetness for the two-year period in different parts of the wall structures is shown in Figures 14 and 15 (wall with no exterior insulation) and in Figures 16 and 17 (wall with exterior insulation). The results are valid on condition that 1) the vapor retarder in the warm side of the wall performs as intended, 2) there is no high initial moisture content in the wall and 3) the wall system has been designed and constructed to avoid moisture leaks into the wall (e.g., wind-driven rain).



Gypsum board 13 mm PE-film 0,2 mm Thermoprofile TC 175–50–1,2 mm + insulation 175 mm Gypsum board wind proofing 9 mm Ventilated air gap 22 mm Wooden facade	Gypsum board 13 mm PE-film 0,2 mm Thermoprofile TC 175–50–1,2 mm + insulation 175 mm Gypsum board wind proofing 9 mm Wind proof rigid mineral wool 50 mm Ventilated air gap 22 mm Wooden facade

Figure 13. Illustration of the structure with perforated light gauge steel frame without and with exterior insulation.

The results show, that the durability of the walls depends mainly on the outdoor climate and the hygrothermal properties of the wind proofing attached on the outside of the profiles. The hygroscopicity of the gypsum board is fairly low, but when moistened by the outdoor air, it dries out rather slowly. This phenomenon increases the time of wetness on the outer surface of the outer flange of a profile.

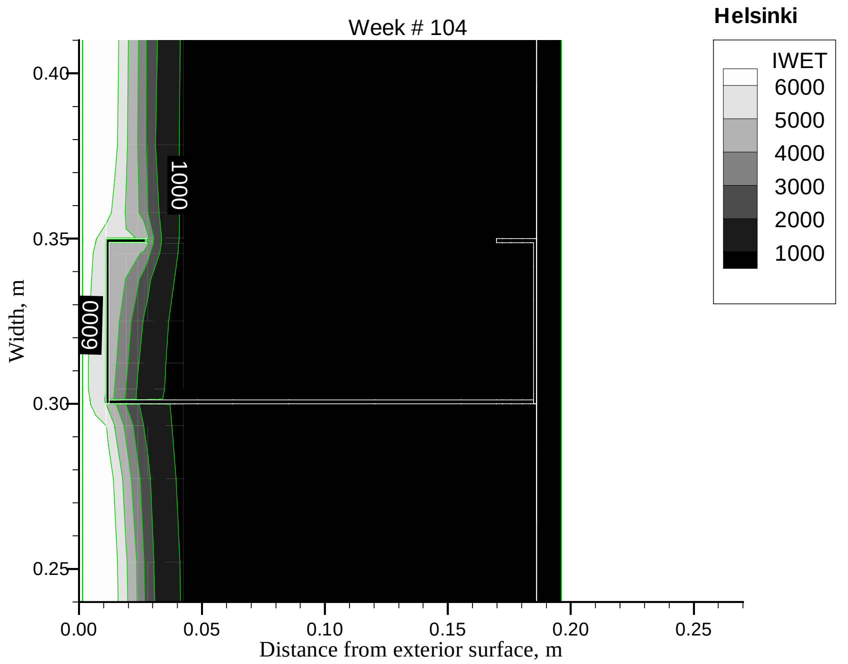


Figure 14. Contour plot of the accumulated time of wetness in the layers of the steel frame wall without exterior insulation. Exterior conditions: Helsinki weather data. Length of the simulated period is 2 years (104 weeks). Arrow shows the location of the highest contour value /14/.

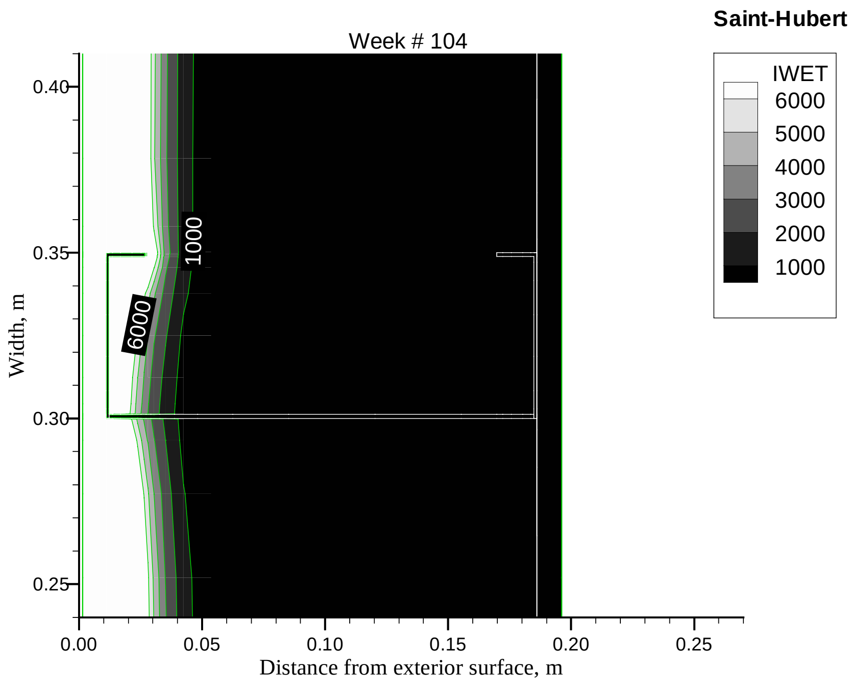


Figure 15. Contour plot of the accumulated time of wetness in the layers of the steel frame wall without exterior insulation. Exterior conditions: Saint Hubert weather data. Length of the simulated period is 2 years (104 weeks) /14/.

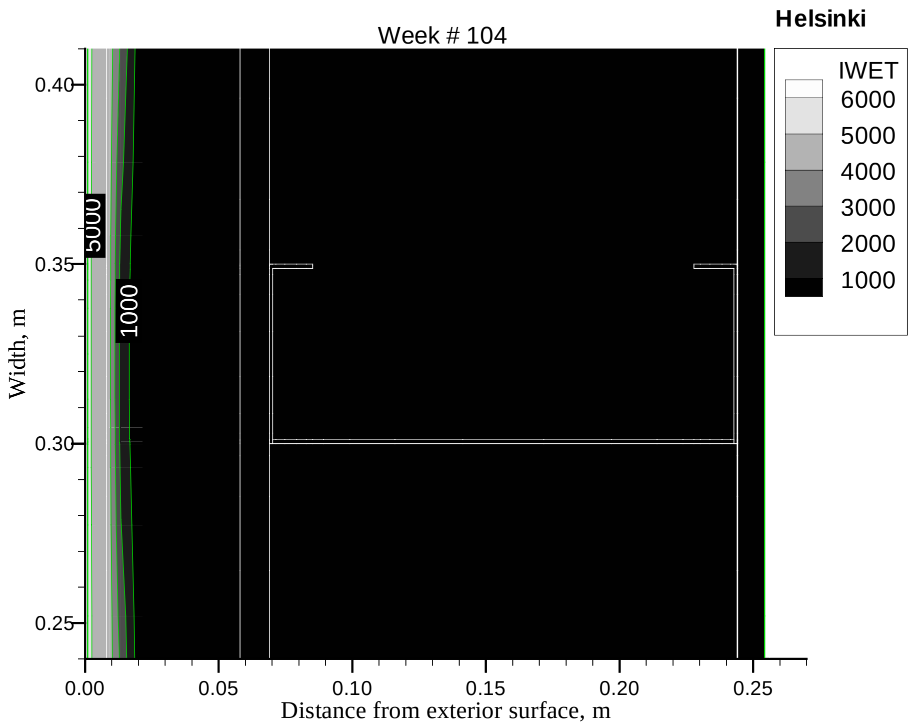


Figure 16. Contour plot of the accumulated time of wetness in the layers of the steel frame wall with 50-mm exterior insulation. Exterior conditions: Helsinki weather data. Length of the simulated period is 2 years (104 weeks) /14/.

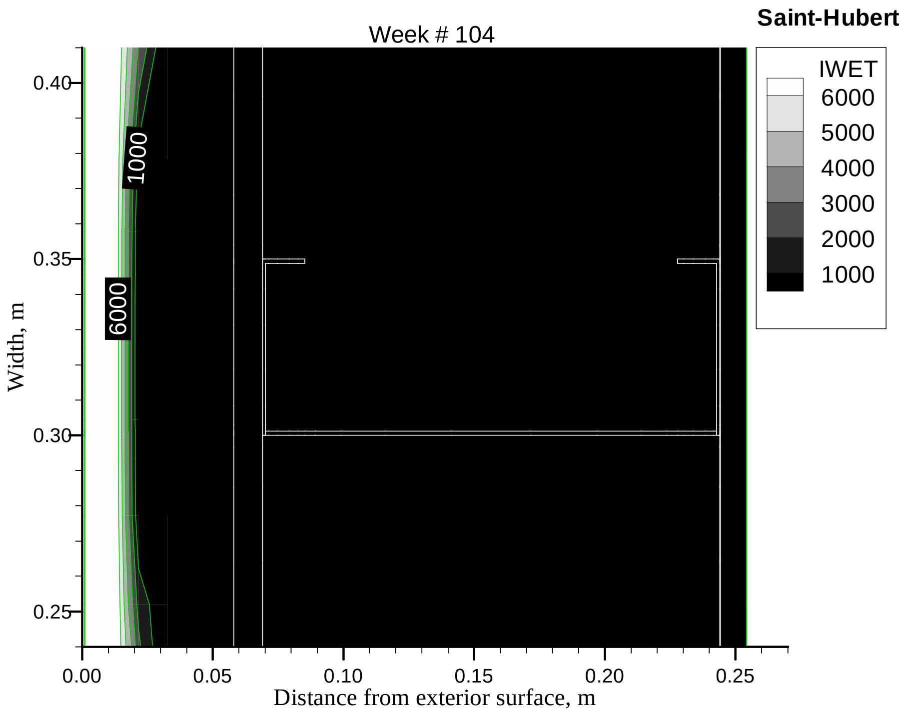


Figure 17. Contour plot of the accumulated time of wetness in the layers of the steel frame wall with 50 mm exterior insulation. Exterior conditions: Saint Hubert weather data. Length of the simulated period is 2 years (104 weeks) /14/.

4. Summary

Irrespective of the materials from which frame structures are made, they form thermal bridges to varying degrees across the thermal insulation layer. Thermal conductivity of steel is high. A steel frame in a light-gauge construction extending uninterrupted across the thermal insulation layer has a considerable effect on the thermal performance of the structure. The development of thermal assessment tools has helped for the rapid development of well insulated light-gauge single framed steel structures introducing perforated webs of a steel member as thermal breaks in the structure. Due to the perforations, the thermal properties of the structure are improved. The analysis carried out shows that the new application of perforated light gauge steel frames fulfills the requirements set for performance and durability in a cold climate of Finland.

If adequately designed and constructed, there are no major moisture or corrosion risks involved with the structures. The long-term laboratory test and the field survey suggest, that a steel frame insulated with mineral wool has a very good corrosion resistance and thus a long service life.

The performance of an insulated structure depends on the performance of different material layers together as a structure. Connection of gypsum board windproofing to steel frame may reduce the corrosion resistance of the zinc layer by the slow humidity variations due to hygrothermal properties of gypsum board with cardboard surfaces. In moist conditions, cellulose fibre insulation and impregnated wood form alcalinous environment, and thus increase the zinc corrosion rate. However, proper design and installation may avoid the risks.

According to the calculation results and field measurements at Ylöjärvi steel houses, the properties of the wind proofing material and the façade structure have an important effect on the overall performance of the structure. By increasing the thermal resistance of the wind proofing material the durability risk of corrosion due to exterior or interior moisture loading can be totally neglected. Water vapor permeable and windproof exterior insulation system increases the drying potential of a structure.

The service life of the structure can be estimated using the standard ISO 9223 Corrosion of Metals. The corrosion is dependent on the time of wetness hours. With regard to all the results from various research projects, the time of wetness hours in the most critical point of the structure are between 0 and 2600 in the climate of Helsinki and 0–6100 in the climate of St. Hubert depending on the composition of the structure. The corrosion classification of the zinc layer is C1 or C2 (ISO 9223), where the service life of the zinc layer is estimated to be from 40 years to more than 100 years. In the class C1, the linear corrosion speed of zinc is less than 0,05 μm and, in the class C2, less than 0,5 μm a year. If the thermal and hygrothermal effects of facade claddings are taken into account, a reduced number of time of wetness hours can be expected, and thus a longer service life for the zinc layers.

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Title

Hygrothermal performance of light steel-framed walls

Abstract

Hygrothermal performance of a new light-gauge steel framed building envelope system has been analyzed using 3-D thermal simulations, 2-D combined heat, air and moisture transfer simulations, laboratory testing in a calibrated and guarded hot box (ISO 8990), weather resistance tests for full-sized structures, corrosion tests and field measurements at experimental buildings in Ylöjärvi, Central Finland. The results show that a modern steel wall structure based on perforated steel profiles performs satisfactorily in the cold climate of Finland. The perforations reduce heat loss along the web of the profile significantly. The field measurements show that no condensation has occurred in the frame system. Temperature measurements and infrared surveys in demonstration buildings show that surface temperatures are sufficiently high to prevent surface condensation or even increased humidity on the surface. According to the calculations, there are no severe corrosion risks in the steel frames in the Finnish climate. The climate, however, has an important effect on the performance, and the structures should be designed with regard to climatic conditions.

Keywords
building envelope, steel structures, light-gauge steel, corrosion tests, weather resistance, moisture, surface condensation, climatic conditions, heat transfer

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