European Commission

technical steel research

Steel structures

Low-energy steel house for cold climates

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PO Box 860
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Final report

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FOREWORD

This report is Final Report of "Low Energy Steel House for Cold Climate" carried out under the Agreement number 7210/SA/902 - 95-F6.01 with Rautaruukki Oy. Project is part of ECSC funded project "The Application of Steel in Urban Habitat". The report was prepared by Mr. P.Aromaa of Rautaruukki Oy, Mr. J.Nieminen and Mr. P.Salmi of the Technical Research Centre of Finland (VTT, Building technology), Espoo. The following individuals and companies have taken part of the project and provided additional information:

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Demonstration buildings:

Owner:	Ylöjärven Kunta
Architect:	Arkkitehtitoimisto Erkki Helamaa ja Keijo Heiskanen Oy
Structural engineer:	Finnmap Consulting Oy
Main Contractor:	YIT-Yhtymä Oy
Light steel products:	Mäkelä Metals Oy and Rannila Steel Oy

Demonstration project was carried out under co-ordination of Rautaruukki Oy. The Technical Research Centre Of Finland (VTT, Building technology), Espoo contributed their expertise both in product development and building design by research work, evaluation and laboratory testing of new building components, documentation of building process at site and on site testing and monitoring work with completed buildings.

Ylöjärven Kunta owns demonstration houses and the apartments are part of their social housing. YIT-Yhtymä Oy as main contractor to the owner constructed buildings. Rautaruukki Oy acted as supervisor in development of new steel structures and utilising steel concepts to construction. Mäkelä Metals Oy and Rannila Steel Oy, both subsidiaries to Rautaruukki Oy, supplied light-steel components to main contractor.

1. INTRODUCTION

In Finland steel products, structures and constructions for house building have been developed effectively during past 10 years The market share of steel buildings in area of apartment houses and single family houses is still very low. The construction industry does not have a tradition of using steel in their housing projects. Need for practical demonstrations of steel are evident.

Rautaruukki aims at promoting the use of steel in the Finnish residential housing production by implementation of the results of this study. Previously developed steel structures will be demonstrated, and the performance of which will be tested by calculations, laboratory tests and follow-up studies.

The objectives of the project is to demonstrate by experimental buildings, that steel components are economically and technically suitable to be used in the structures of low-energy buildings, an essential reduction of the costs of heating energy can be achieved in the experimental houses compared to conventionally constructed houses, show that also the environmental effects of steel structures are competitive to conventionally constructed houses in Finland. The secondary aim is to show in practice the advantages of steel products and concepts in different phases of building process for builders, construction companies and building owners.

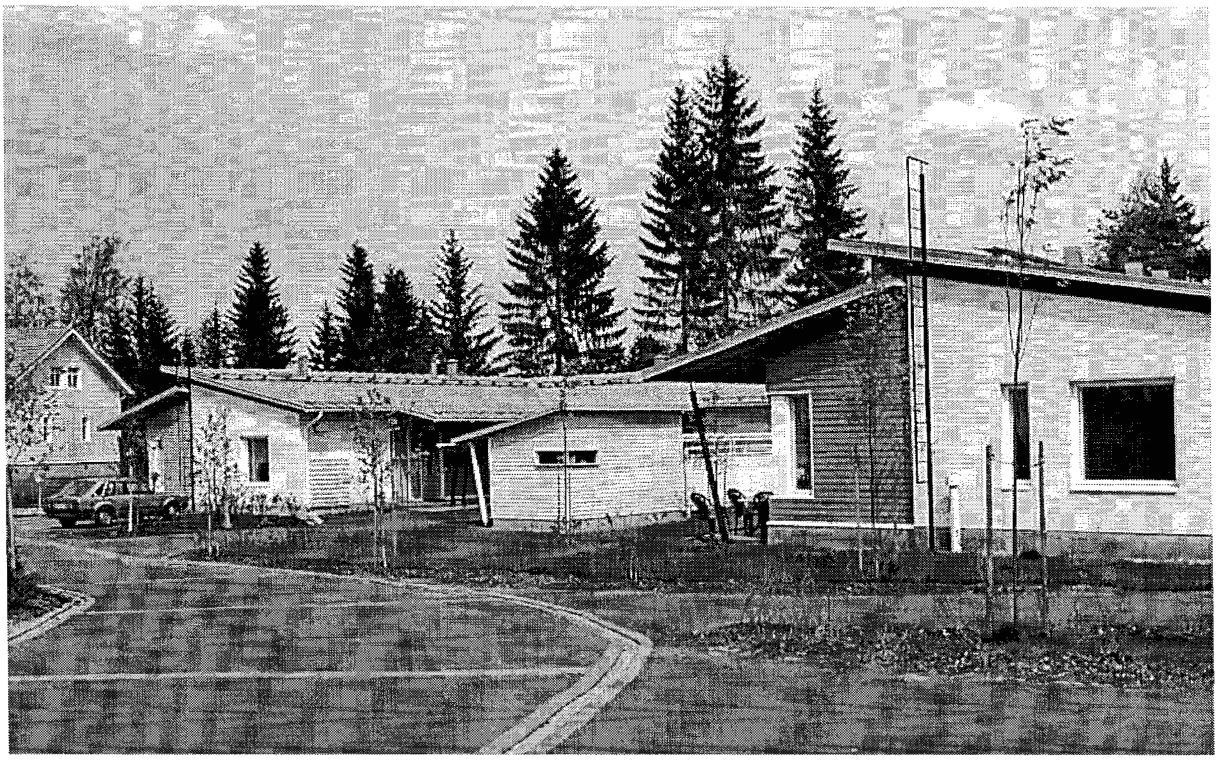


Figure 1.1 Two experimental steel houses, Ylöjärvi, Finland. Low-Energy House (left), Reference House (Right)

2. DESCRIPTION OF PROJECT ACTIVITIES

The objectives of this demonstration project are technical, economical and environmental. In order to achieve the objectives, project was divided in three phases.

I. Design and execution of experimental houses

- Design and construction of entire system (Building concept) for low-energy steel houses for cold climate using system, which is based on cold formed sections as load bearing members and using components already developed.
- Design and execution (manufacturing and erection) of two experimental buildings, where the suitability and constructability of the developed components and system were tested in practice. The aim of the structural system was to improve the performance of the entire building. Special attention was given to constructability, mechanical connection methods and logistics of the entire execution process.

II. Monitoring and follow up studies

- Collection of short- and long term information of the thermal and moisture performance of the envelope structures and energy consumption of houses. The short-term studies concentrated on the monitoring and measurements during construction in areas as measurements of hygrothermal behaviour of structures, moisture behaviour of structures and moisture condensation, temperature distributions in structures, IR-thermography, measurements of airtightness of structures and evaluation of technical condition of structures.
- The long-term monitoring gained information on the energy consumption of the houses and performance of the structures. Monitored items were energy consumption (long term monitoring for 2 years), heating, domestic hot water, lighting, household electricity, fans and pumps (HVAC equipment)
- Study environmental impact of building will be studied in this phase.

III. Production of design and execution guide

- Design and execution guidelines for architects, designers and constructors were produced including e.g. architectural solutions, building components and structures, HVAC-design, requirements of system unit contracting and considerations for customer oriented design

2.1 Steel products

Research and development work during past 10 years has produced many steel products and building systems for residential buildings.

- **Thermo-profile.** Light gauge steel profile with slotted web acting as thermal break. Profile is used as load bearing frame member. Profile is presented closely in chapter 3.
- **Pre-cut frame system** for detached houses. The frame will be assembled at using dimensionally accurately cut steel parts. Thermal insulation, vapour barriers and

boarding will assembled at site too. System is material efficient with minimum vaste. Builders appreciate accuracy in dimensioning of components and savings also in material. Traditional method for construction of single family houses. Most of builders like to construct their own home by own hands and by this do it yourself principle quarantee the quality of work.

- **Large panel frame system** for detached houses. Partly pre-fabricated building system for both private and professional builders who consider the speed of construction as one way of saving money. In this system all external walls are delivered to the site as assembled panels consisting frame, thermal insulation and boarding. Even the windows can be assembled at the factory. Outer cladding of the walls will be assembled at site.
- **Floor panels,** where load bearing beams are made of light-gauge steel profiles. Panels are applicable for ventilated floors, intermediate slabs and in ceilings.
- **Pre-fabricated room module system**, where frame is made of steel profiles and walls are made of steel cassettes. Modules are internally fully completed for designed purposes, such as bathrooms, saunas, kitchen etc. Most of work is done at the factory, which speed up work at site.
- **Roof trusses and purlins.** Light gauge steel profiles can be a load bearing members of roof structures. Steel offers a non-combustible solution for roof structures of steel-framed house.
- **New roofing system.** Plane steel roof with high visible seams is traditional solution, but expensive to assemble. New product has traditional look, but can be assembled like formed roofing sheets.

All products are new in residential housing. The planned development of entire light frame system for housing and large scale use needed further development with testing and evaluation of components and construction work in practice. Therefore they were selected to this demonstration project as basis element of prototype system.

2.2 Research and testing programme

The purpose of the research work was to recognise and solve both critical mechanisms and problems arising during the design of the new frame system for "Low-Energy Steel House" housing concept and verify the performance of the design using computer simulations, laboratory tests, follow-up studies, measurements at site and monitoring of the houses.

The research activities divided into three main areas: basic studies, construction and follow-up studies and monitoring. The basic studies include laboratory testing and calculation work needed for verification of reliability and durability of structures thus providing input data for concept design and construction of the houses.

Short and long term information of the thermal and moisture performance of the structures and energy consumption of the houses were collected. The short-term studies concentrated on the follow-up measurements during construction. The long term monitoring gained information of the performance of the building envelope structures and energy consumption of the houses. The logistics of the entire design and construction process were documented carefully, and the information was exploited in compiling of the design guidelines and design systems for steel houses. An overview of the research activities is shown in table 2.1.

Main area	Technical area	Activity	Expected results
Basic studies	Structural mechanics	Laboratory testing with full scale specimens and computer simulations for prefabricated units and site-built system	Performance criteria for strength and stiffness. Verification of structural capacity in ultimate limit state and serviceability limit state 1)
	Building physics	Computer calculations 2) and laboratory tests of thermal performance of structures	U-values including thermal bridges
		Acoustical analyse using calculations and laboratory tests	Acoustical properties of structures
		Health issues	Good and safe indoor air quality
	Fire technology	Evaluation of external wall structure and intermediate floor-wall connection	Classification of structures Safety
	Energy technology	Computer simulations for energy consumption of buildings	Estimation of energy consumption
Construction	Building physics	IR-thermography and blower door tests	Assessment of technical condition of the thermal envelope and air leakage rates of structures
	Environmental technology	Environmental impact analyses	Environmental profiles for construction and use of buildings
	Documentation	Video recording and photography	Video and information packages for technical presentations and commercial purposes
Monitoring and follow-up studies	Building physics	Temperature and moisture measurements	Feed back information of thermal and hygro-thermal performance of steel components
		Regular field surveys	Assessment of physical condition of structures
	Energy technology	Monitoring - heating - DHW use and circulation losses - household electricity - ventilation - sauna	Energy consumption of buildings during two year's monitoring period
	Design systems	Documentation of all experiences and technical data Development of design methods Design guide	Design aid for designers and architects

1) Eurocode 3 part 1.1, 2) 3-D simulation tool for steel constructions

Table 2.1. Research programme.

2.3 Ylöjärvi Steel Houses

The Annual Fair for Habitation in Finland 1996 took place at Ylöjärvi. Rautaruukki decided to take part of the fair with four experimental steel framed houses, demonstrating newest steel products and steel intensive construction methods, specially suitable for small house construction and low energy construction too. Different materials like wood, brick, plaster, were combined with steel successfully in these houses.

Design and construction of the demonstration houses was very short. Architect for the project was chosen through a contest in September 1995. The winner started design work in the beginning of October 1995. Project continued with very rapid period of research work, product development, enabling tests, evaluation of frame components and production of steel components. Construction work at site started in the beginning of February 1996 and demonstration buildings were completed in the end of June 1996. In spite of totally new products, new building methods and concepts, construction time was very short, only 5 months, showing clearly advantages of steel products and structures: high quality, accuracy, pre-fabrication and component construction.

Figure 2.3 Low energy Steel House, winter 1997

Low-Energy steel house

Load-bearing frame-structure were assembled at site using pre-cut profiles. Modular bath rooms. In order to obtain better energy efficiency, enhanced thermal insulation in floor, walls and roof, special windows and special floor heating system and heat recovery system in ventilation were applied. The extra cost for these special arrangements were estimated in advance to be economical in comparison between the advantages reached in savings in the heating energy costs.

Reference house

The "Normal" house constructed according to Finnish building code for thermal insulation regulations. Technically there are normal thermal insulation in floor, walls and roof, normal windows and normal heating radiator equipment and ventilation systems. Frame of this house was built using load-bearing large panel element system and ventilated floor constructed of floor panel elements with light steel frame. Bathrooms are pre-fabricated modules.

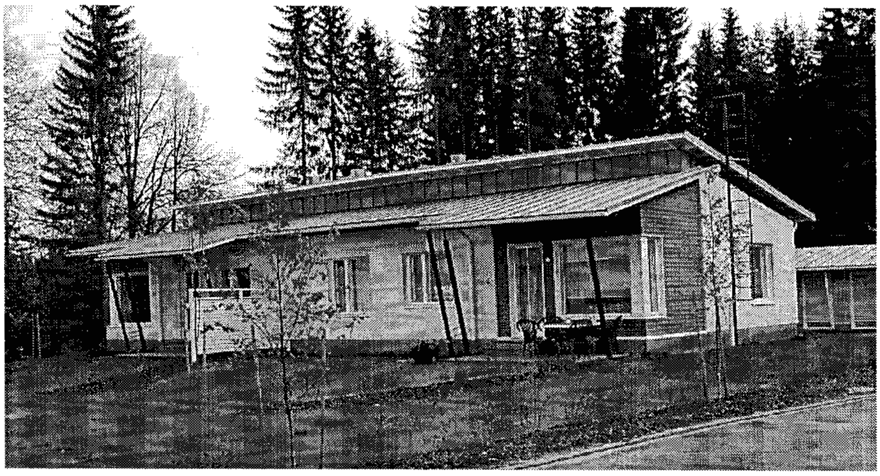


Figure 2.4 Reference house, summer 1997

Both one level 3 family row houses were designed and planned with exactly the same room areas and lay-outs in order to make comparison possible. House size in respect of living area (208 m^2) can also be considered as single family house.

Two level row house

Load bearing large panel steel frame, load bearing bathroom modules, light steel framed intermediate floor, load-bearing bathroom modules acting as part of structural frame of the house. This house represents popular and efficient Finnish solution of apartment house.

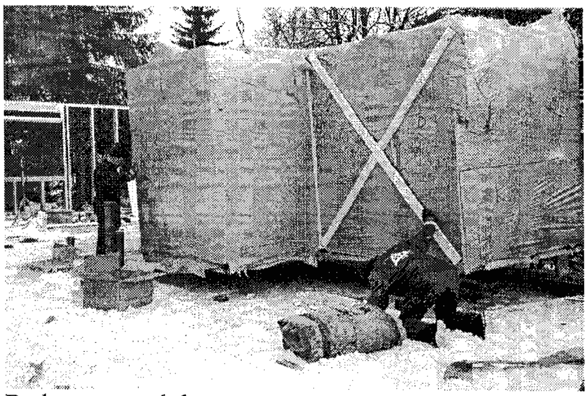
Three level apartment house

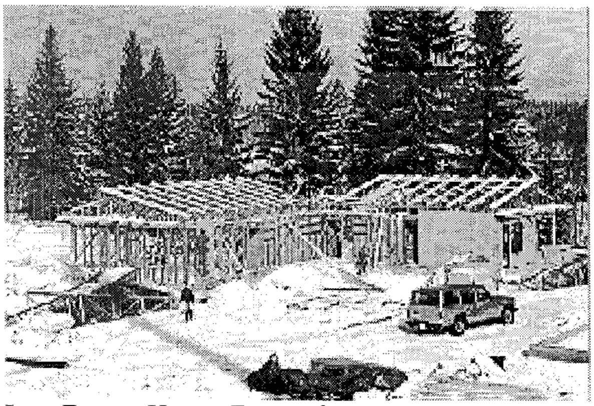
Tubular steel frame, composite intermediate floors, non-load bearing large panel walls, load bearing bathroom modules and pre-fabricated balconies.

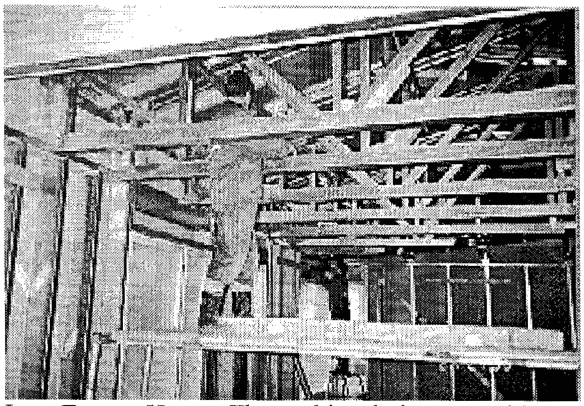
In all houses load bearing roof structures were made of steel. Trusses, purlins and new snap-lock roofing system were adapted to all houses.

The results of "Ylöjärvi-project", four normal looking experimental steel houses attracted interest broadly. "Low energy steel house" was the most important new steel object for the Finnish house builders. The "normal" house with ventilated floor raised interest also. Steel trusses, new roofing and pre-fabricated bathrooms in small houses were interesting new applications. After the fair, in September 1996, demonstration houses were completed to habitable condition. Houses were carefully evaluated with field surveys before inhabitants moved in to the experimental houses. Two year long monitoring programme started and continues as planned. Results of this programme will be used in further development of light-steel frame steel house products and system.


Foundations, February 1996


Bathroom modules


Low Energy House, Frame phase


Low Energy House, Thermal insulation assembly


Low Energy House, Roofing assembly

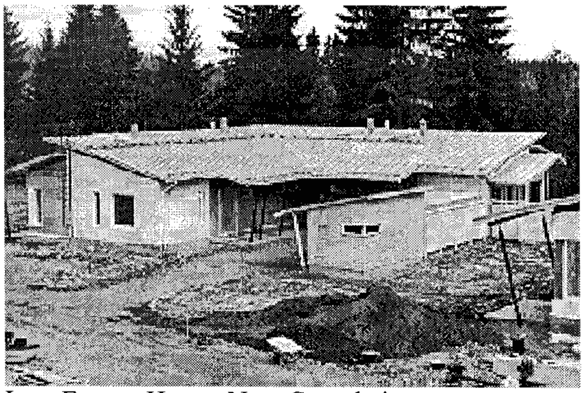

Low Energy House, Near Completion

Figure 2.7 Construction of Low energy Steel House, Pictorial review, Ylöjärvi 1996

2.4 Design guides

Main activities of design, testing and building process were documented carefully. Huge amount of written notes, photographs from different phases of testing, product manufacture and construction at site were collected.

Main activities at the factory production and construction at site were recorded on video too. This material was used in production of three promotional films and one educational film.

The documentation of development and construction processes gave valuable aid and good material for production of design guides for architects, designers and builders. The guides were produced to draft phase and will be completed to more detailed level within the further development work of Rannila Thermo building system.

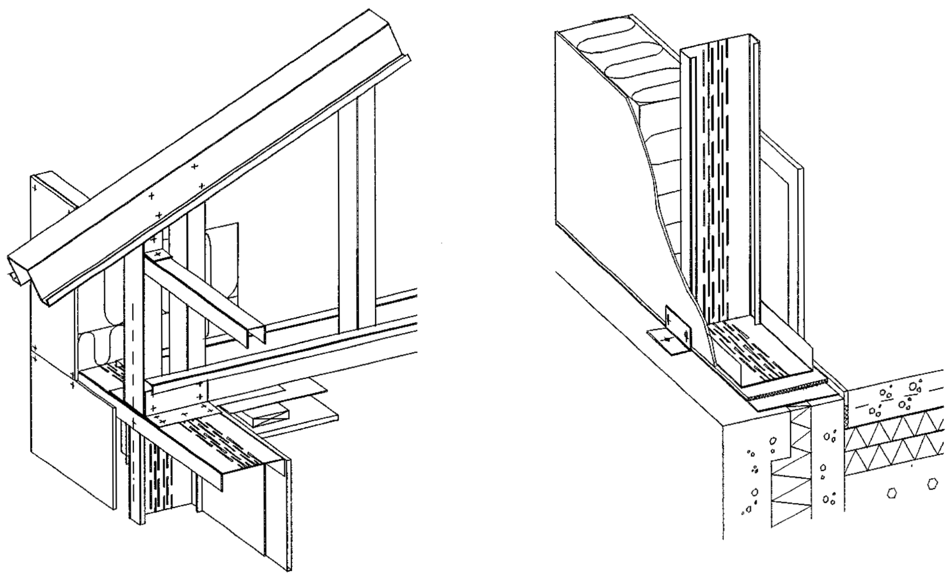


Figure 2.8 Details of developed light frame system

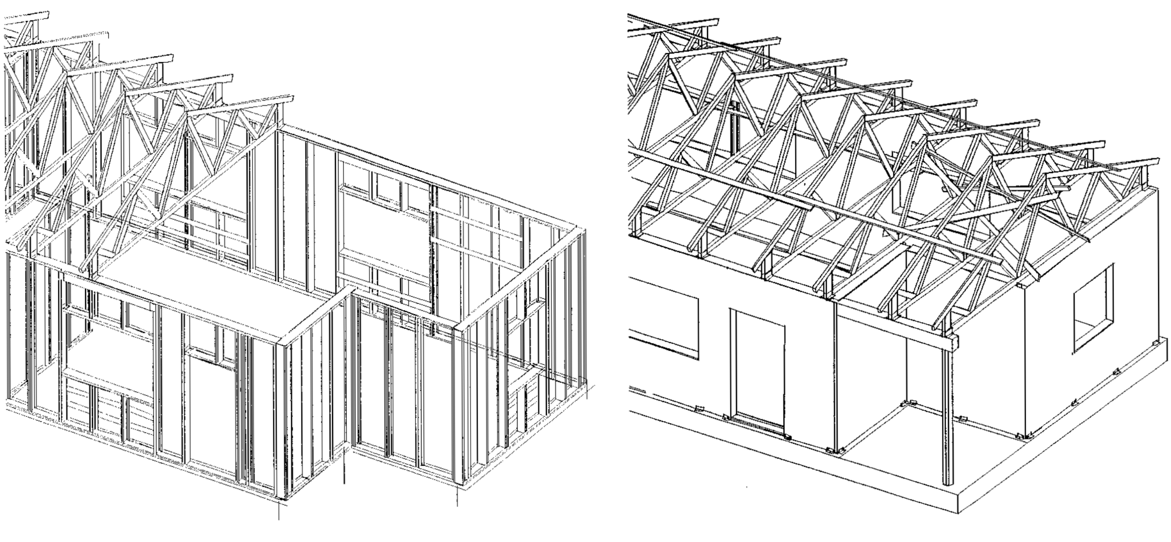


Figure 2.9 Light steel frame, Pre-cut system (left), Large panel system (right).

2.5 Dissemination

Rautaruukki organised promotional events to the press and professionals at site during the project. The Ylöjärvi Housing Fair provided a good oppoturnity to show the newest developments to public. The fair opened 12th July and was closed 11th August. Publicity was good and broad. Totally 267000 national and even foreign visitors were counted. Many of them were professionals in construction business, authorities, researchers, developers, constructors, designers, planners, builders etc. Private house builders, seeking new innovations, were very interested in steel construction. According to collected backup and many requests for more detailed informational material, interest upon new steel products and constructions was significant.

The Ylöjärvi Fair was a great success for all participants and organisers. The event was organised thoroughly. Customers were guided through different objects effectively and information was within reach for the visitors. Customers were well informed about new ideas, constructional solutions and new products and building methods by distributed prochure material and special demonstrational and promotional events organised beside the fair.

The steel buildings presented new steel constructions and new steel products and pointed clearly out advantages of steel construction. The fair was also a very good oppoturnity to show both to professionals and common visitors how modern steel building concepts and solutions can be used in architecturally, attractively, effectively and economically in normal apartment houses.

After the fair more promotional arrangements were organised for potential architects, designers, building companies and individual homebuilders. Demonstration houses have acted as good reference to new customers too.

The results of the Finnish part of MEGA 5 programme will be submitted to Rautaruukki's Internet pages and be available for public attention after the completion of the whole project, summer 1999.

Rannila Steel OY have started further development work with the new light steel frame system, using the results of the basic development work done during MEGA 5 project. This frame system is marketed as Rannila-Thermo both to domestic markets in Finland and also to export markets, mainly within Baltic area.

According to interest from customers, markets for new building concepts are rising. New products and new construction methods have been accepted among suspicious professional builders. Without this demonstration project, it would have taken many more years to reach this level in markets.

3. THERMOPROFILE

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 may be reduced; for instance, by perforating (slotted web) the steel profiles or by using other thermal breaks in the structure, such as exterior insulation.

Light-gauge steel framed structures based on double frame system (horizontal and vertical frame) have been used as external walls of office and public buildings in Finland for about 10 years. The purpose of the horizontal steel profile is to reduce thermal bridging. The distance between the frames in both directions is typically 0.6 meters, and thermal insulation is installed into the cavities between the frames.

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. The development of thermal assessment tools has helped the rapid development of well-insulated light-gauge single framed steel structures introducing perforated webs as thermal breaks in the structure.

A light-gauge steel frame with perforated web is termed a thermoprofile, see figure 3.1. The load bearing walls of detached and row houses are composed of vertical C-shaped thermoprofiles. U-shaped thermoprofiles are used in non-load bearing structures e.g. prefabricated facade units for high-rise buildings. The material thickness of the profiles is typically 1.2 - 1.5 mm. The profiles have zinc coating of about 20 μm.

The perforations in a thermoprofile can be taken into account in two-dimensional heat transfer calculations 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.

The reduced thermal bridging has a considerable effect on reducing the heat conduction in the thermoprofile relative to solid steel (see Figure 3.2). The perforations perform as thermal breaks for the steel member reducing the heat conduction along the web by 70 - 80%. The perforations reduce the structural strength of a steel frame, and thus the extent of perforations must be a compromise between the desired structural and thermal properties of the frame member.

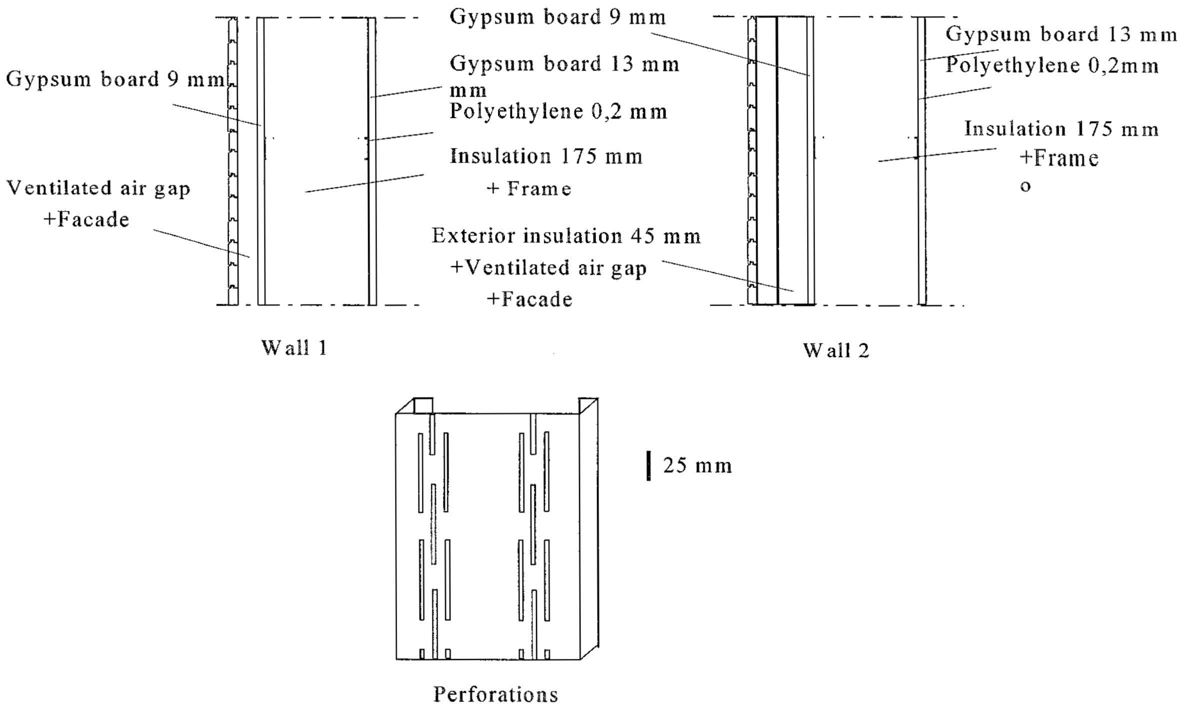


Figure 3.1 Cross-sections of the walls in Ylöjärvi demonstration buildings (wall 1= reference, wall 2 = low-energy). The web of the thermoprofile is perforated for better thermal performance.

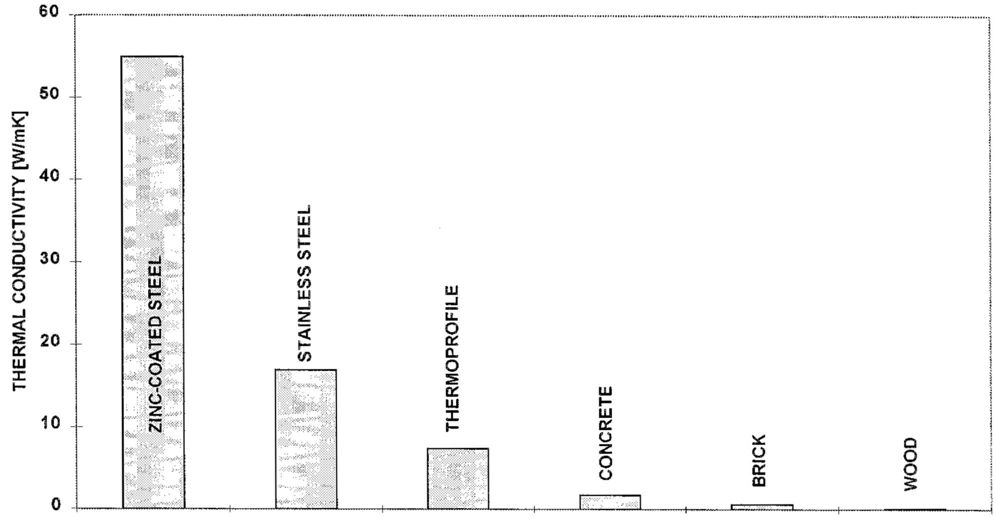


Figure 3.2. Thermal conductivity of various building materials used in load-bearing structures. Equivalent thermal conductivity for the thermoprofile is shown in figure 3.1.

4. LOW-ENERGY STEEL HOUSE

4.1 Energy saving technology

The basic energy saving strategies used in the low-energy steel houses are:
- reducing transmission losses by designing a well insulated and airtight envelope
- recovering heat from exhaust air
- using passive solar gains by sufficient thermal mass of the light-weight envelope
- satisfying the remaining heating requirement by producing and using auxiliary heat efficiently.

Table 4.1 shows the thermal transmittance values of different building components. Thermal mass of the lightweight building envelope is based on massive slab-on-ground floor, insulated underneath with 150 mm of EPS (expanded polystyrene) insulation.

Low-energy steel house has a low-temperature floor heating system based on water circulation. Room temperatures are controlled on room basis. Mechanical ventilation system has a heat recovery unit with a temperature efficiency of about 55 - 60% and total efficiency including fan power of about 45 - 50%.

Table 4.1. Building features of low-energy and references houses and the Finnish Building Code requirements.

Component	Reference house	Low-energy house	Code requirement
Wall U-value [W/m^{2}K]	0,27	0,19	0,28
Roof U-value [W/m^{2}K]	0,22	0,17	0,22
Floor U-value [W/m^{2}K]	0,22	0,19	0,36/0,22
Window U-value [W/m^{2}K]	1,9	1,1	2,1
Ventilation [1/h]	0,5	0,62	0,5

4.2 Energy monitoring

The goal of the project was to design and built steel framed house that needs energy for space heating only 50% of the consumption of a standard Finnish house. The energy performance of the design was analysed with energy calculations. The results showed that the means of energy saving (see chapter 4.1) are sufficient to reduce the heating energy demand by 50% compared to a typical Finnish row house.

Figure 4.1 shows the measured heating energy consumption in the Ylöjärvi steel houses. The heating energy consumption in the low-energy house has been about 65% of the consumption in the reference house in the first monitoring year. It was found out that the heating and control systems of the low-energy house did not perform as expected. After adjustments carried out in October 1997, the energy performance has improved, and the heating energy consumption has decreased close to the original goal of 50% of the consumption in the reference house.

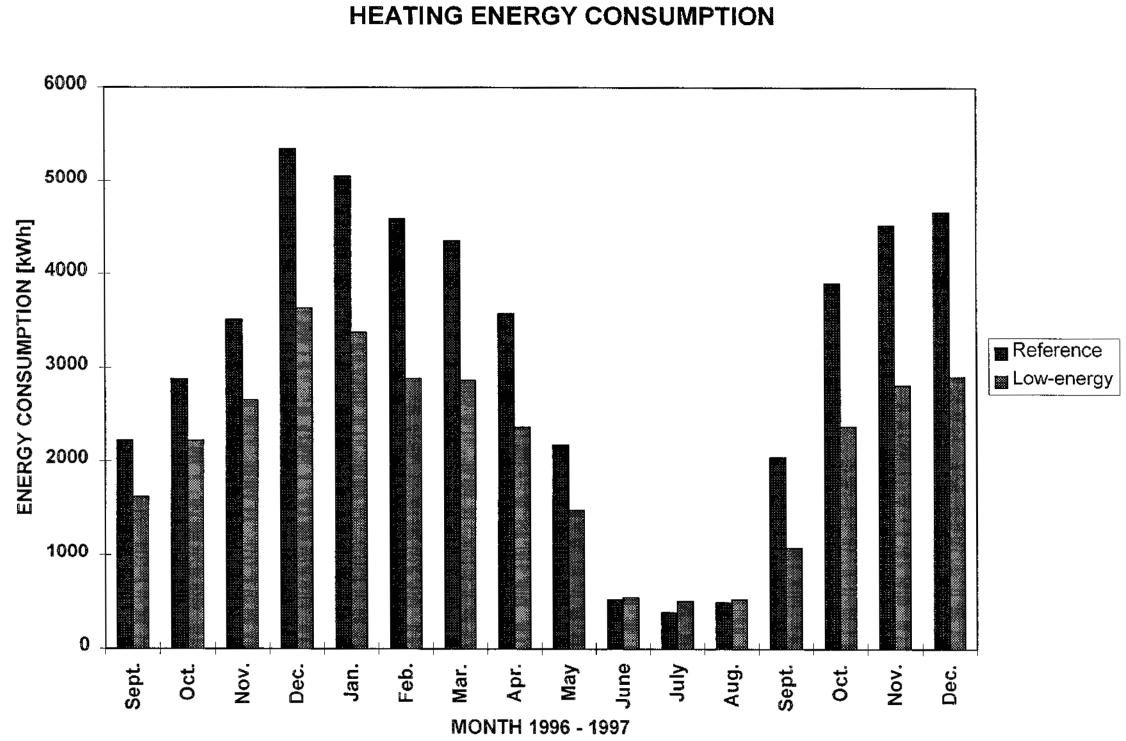


Figure 4.1. Monthly heating energy consumption in the Ylöjärvi steel houses.

The reference house performs somewhat better than expected. The annual consumption is some 13 % lower than the original goal. Table 4.2 shows heating energy consumption in standard row houses and Ylöjärvi steel houses. The energy saving in the low-energy steel house compared to the standard Finnish row house is 19400 kWh/m^2.

Table 4.2. Heating energy consumption in the Finnish row houses.

House	Heating energy consumption		Energy saving compared to standard house	
	kWh/m^2	kWh	kWh/m^2	kWh
Standard house	195	40560	0	0
Ylöjärvi reference	168	35091	26	5408
Ylöjärvi Low-energy	102	21216	93	19344

4.3 Profitability of energy saving measures

Table 4.3 shows the extra costs of the low-energy house compared to the reference building. The largest single extra cost was caused by labour man-hours including installation of extra insulation, duct work and installation of control devices.

Table 4.3. Extra building costs of the low-energy concept

Cost factor	Units	Total extra costs FIM	Extra costs FIM/m^2
Labour	100 man-hours	15 000	72
Extra insulation	56 m^3	8 500	41
Super windows	30 m^2	9000	43
Ventilation heat recovery		6000	29
Control device		5000	24
Total costs		43500	209

Typical energy saving costs of a detached house range from 200 FIM/m^2 up to 500 FIM/m^2. The average costs of the four Ylöjärvi steel houses (Buildings only) were FIM 6800/ m^2 (VAT incl.). The total building costs of a 208 m^2 row house were 1414400 FIM. The total extra investment for better energy efficiency was totally 43500 FIM or 3,1% of the total construction costs.

Table 4.4 shows the payback time for the extra building costs using current price for the most common alternative heating energy sources as reference. Without taking into account any interest for extra investments, the payback time vary from less than 7 years with direct electric heating to about 16 years with district heat.

Table 4.4. Payback time for extra investment costs.

Energy source	Price FIM/kWh	Annual savings FIM	Payback time years
Electricity [1)]	0,35	6770	6,4
Oil	0,18	3481	12,5
District heat	0,14	2776	16,0

1) Average price: 45% day time (FIM 0,52/kWh), 55% night time (FIM 0,22/kWh)

5. HYGROTHERMAL PERFORMANCE OF STEEL FRAMED BUILDING ENVELOPE

5.1 Thermal performance of steel structures

5.1.1 Thermal transmittance of steel framed walls

The thermal performance of the light-gauge steel framed wall structures used in Ylöjärvi were analysed using 3-D thermal simulations, full scale laboratory weather testing in a hot box apparatus and field measurements in Ylöjärvi. In addition, the thermal properties of the structures were also measured in a calibrated and guarded hot box (ISO 8990).

Table 5.1 shows the calculated and measured U-values for a thermoprofile used in the Ylöjärvi demonstration project. The agreement of the results is good. Calculated values of thermal transmittance for steel-framed and wood-framed walls are shown in figures 5.1 and 5.2. 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. The results show that the thermal behaviour of a wall with thermoprofiles as load bearing system corresponds to a comparable wooden wall structure used in Finnish detached houses.

Table 5.1. Calculated and measured U-values for external wall structures of the Ylöjärvi steel houses.

Wall/method	3-dimensional calculation W/m²K	Measured [1)] W/m²K
Reference house	0,257	0,263
Low-energy house	0,191	0,188

1) Standard ISO 8990

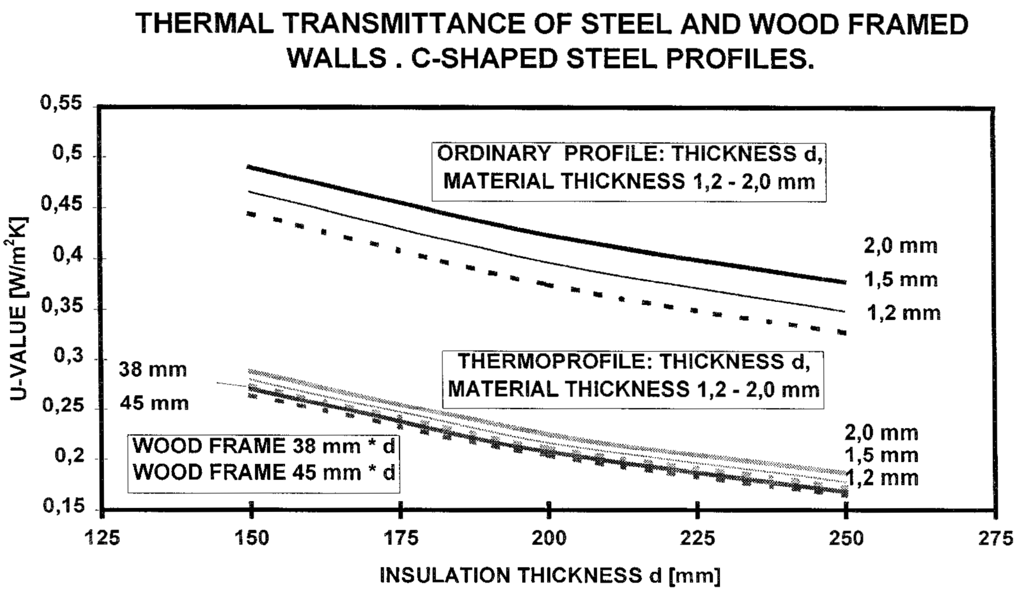


Figure 5.1. Thermal transmittance of light-gauge steel framed structures.

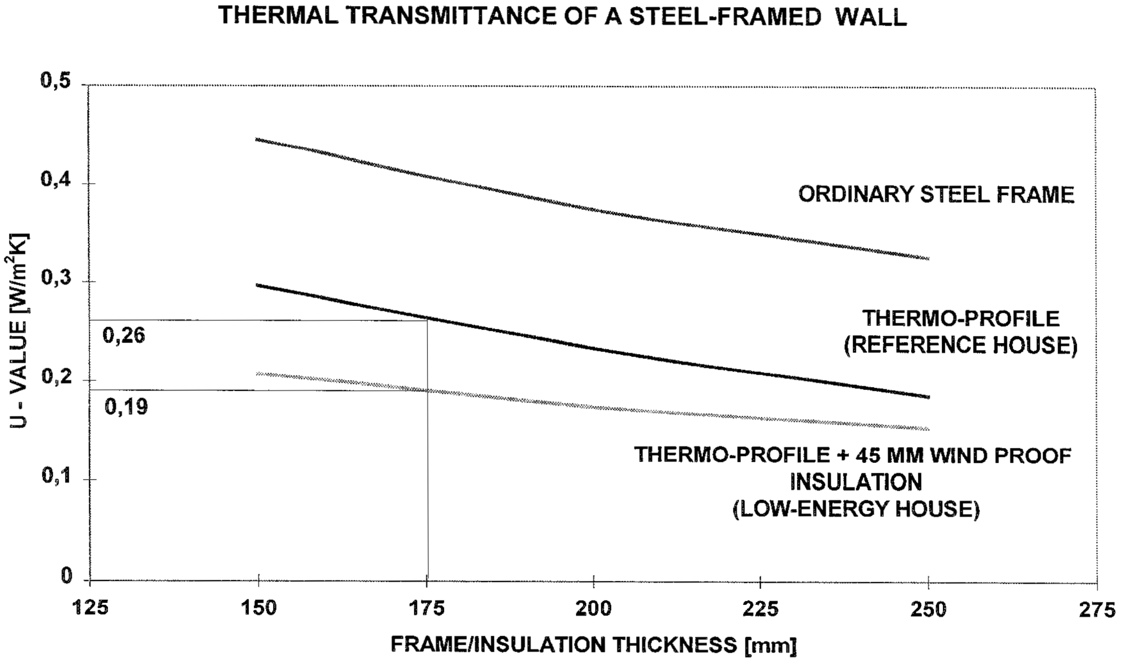


Figure 5.2. Thermal transmittance of the wall structures of the Ylöjärvi steel houses.

5.1.2 Air tightness

Blower door tests were used to measure the air tightness of the buildings. The three apartments of each of the houses were pressurised at the same time, thus preventing the airflow between the apartments. The measurements gave following results:

- Low-energy house: air leakage rate at 50 Pa under pressure 3,0 ACH (air changes per hour)
- Reference building: air leakage rate at 50 Pa under pressure 2,0 ACH.

The reference building was erected from prefabricated large units while the low-energy house was site-built from pre-cut steel components. The air leakage rate of the reference house is somewhat better than the average air leakage rate of lightweight buildings in Finland. Typically the air tightness of such buildings ranges from 2,5 to 4,0 ACH. It has also been concluded that he air tightness of buildings built of prefabricated wall units is in general better than the air tightness of site-built houses.

The locations of air leaks in the low-energy house were searched using an infrared camera. Insufficient sealing of electrical and ventilation installations leading through the air/vapour barrier of the envelope caused the most of the air leaks. These defects were found systematically in all of the three apartments of the low-energy house. The defects were also repaired, which has improved the tightness of the envelope.

5.1.3 Temperature in structure layers

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. An example of results from laboratory tests is given in figure 5.3. The temperatures on inner wall surface are sufficiently high to prevent surface condensation or even relative humidity high enough to increase the risk of mould growth on the wall surface, figure 5.4. 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 in the reference wall is 5 °C higher 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 vapour permeable insulation as in the low-energy wall further improves the hygrothermal performance of the wall.

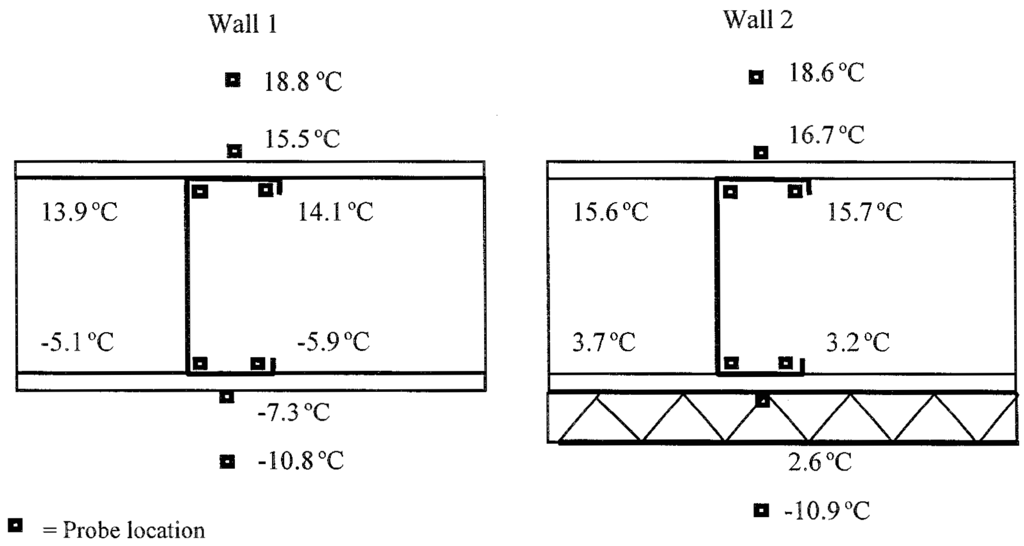


Figure 5.3. Temperature distribution in the steel framed walls according to laboratory measurements.

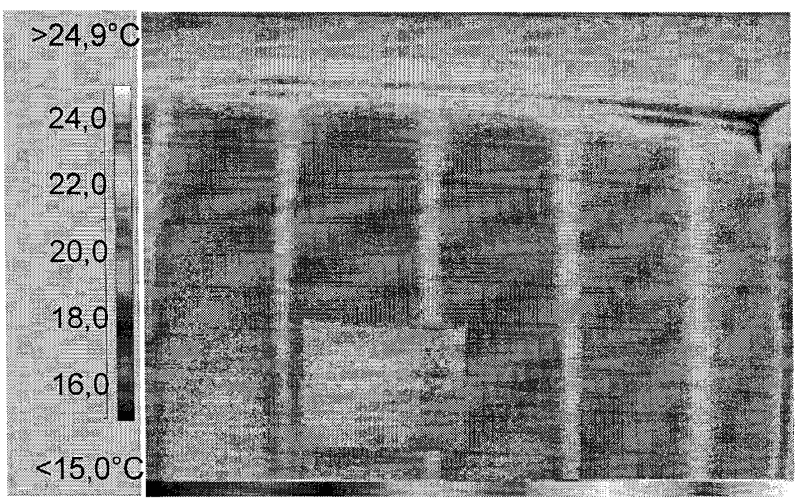


Figure 5.4. Infrared image of temperature distribution on the inner surface of reference wall.

5.2 Humidity variations in steel framed walls

5.2.1 Laboratory weather resistance tests for steel framed walls

Moisture risks of the steel frames were studied experimentally in a hot box apparatus and by field measurements in Ylöjärvi. The purpose of the laboratory measurements was to gain knowledge on the performance of the steel framed walls and to investigate moisture measurement methods suitable for field measurements. Test climate included outdoor air temperature variations from about -30°C up to +30°C, constant indoor climate of +18 ... 20°C and positive pressure of 10 - 20 Pa on the inner side of the wall.

Laboratory measurements showed that the risk for internal condensation in the walls built with proper quality of workmanship is extremely low. The highest relative humidity in the wall structures was measured on the inner surface of the outer flange of the thermoprofile. In the extreme weather conditions the relative humidity in the reference wall was about 90% and in the low-energy wall 70%. Small wooden moisture probes attached to steel frames were used. The moisture contents of the probes were measured electrically. The probes were calibrated and tested in laboratory conditions. A sorption curve was measured. The conversion from moisture content to relative humidity was carried out using the sorption curve. The method was adapted to the field monitoring, where a safety addition of 10% relative humidity was added to each conversion result to increase the confidence of the results.

5.2.2 Moisture monitoring in the Ylöjärvi steel houses

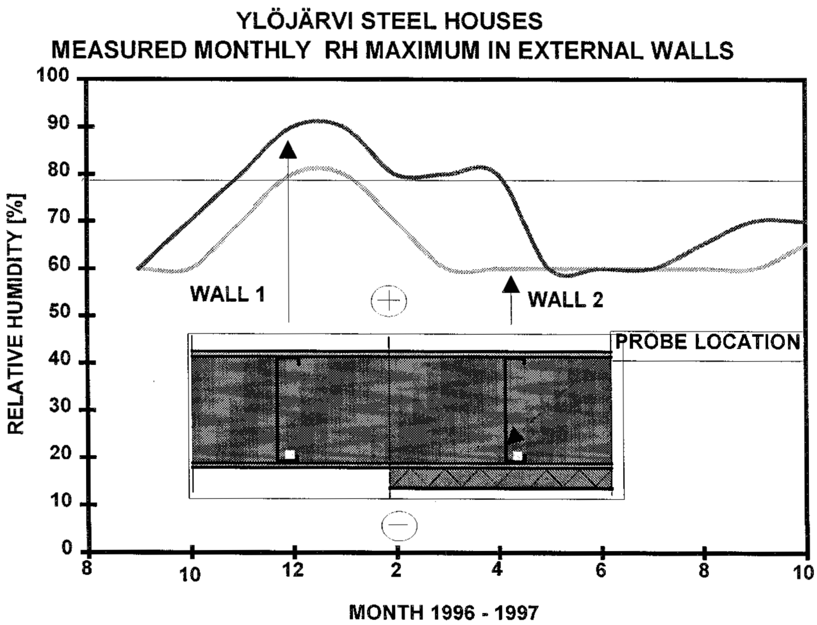


Figure 5.6. Monthly maximum of relative humidity on the outer flange of the steel members in the external walls of the Ylöjärvi steel buildings.

Field monitoring of the experimental buildings started in May 1996 with moisture checks in the building envelope structures. Due to heavy snow during the construction, the materials used in the structures were quite wet in some locations after the erection of the houses. The structures were opened in the spring. It was found out that the moisture had dried out, and no damage caused by the built-in moisture was found.

Humidity measurements started in September 1996. Figure 5.6 shows the monthly maximum values of relative humidity of eight measuring points in the outer flange of the steel profiles. The results show that relative humidity in the reference wall has exceeded 80%, but no conensation has occurred. The humidity in the low-energy wall has not exceeded 80%.

5.3 Hygrothermal simulations

5.3.1 Scope

Hygrothermal simulations were used to analyse the performance of the steel-framed walls in different climatic conditions. 2-D heat, air and moisture transfer simulation program LATENITE /2, 3/ was used in the calculations. Time of wetness was used as the performance criteria. The time of wetness is defined in the ISO standard 9223 'Corrosion of metals and alloys' /4/ as time in hours when:

- Temperature > 0°C at the same time as
- Relative humidity > 80%

In the 2-D LATENITE hygrothermal model, the moisture transport potentials used in the model are moisture content and vapour pressure; for energy transport, temperature is used. The porous media transport of moisture (vapour and liquid) through each material layer is considered strongly coupled to the material properties (i.e., the sorption-suction curves). The corresponding moisture fluxes are decomposed for each phase and are treated separately. Energy and moisture conservation equations are coupled via phase changes of moisture (latent heat of evaporation, freezing of liquid). Hourly weather data can be used to create the boundary conditions. A typical weather data file used in the simulations includes: ambient temperature and relative humidity, wind speed, wind direction, hourly precipitation, direct and diffuse solar radiation and cloud cover index.

The hours of wetness were calculated for both the reference wall and the low-energy wall of the Ylöjärvi demonstration houses.

5.3.2 Initial and boundary conditions

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.

5.3.3 Results

The results are given in Figures 5.7 - 5.10. The accumulated time of wetness for the two-year period in different parts of the wall structures is shown in Figures 5.7 and 5.8 (wall with no exterior insulation) and in Figures 5.9 and 5.10 (wall with exterior insulation). The climate in St Hubert (Belgium) is milder and more humid than in Helsinki (Finland). The climate effect can be seen in the time of wetness in the layers exposed to the ambient air. For example, in wall 1 in worst location (the exterior side of the coldest corner of the profile, Figure 5.7) within the steel profile, the accumulated time of wetness during the two-year simulation period is 5596 h in Helsinki whereas in St Hubert the value is 10320 h. In wall 2 the thermoprofile is at higher temperature throughout and the relative humidity hardly ever exceeds 80% resulting in almost no time of wetness both in Helsinki and St Hubert. These results are valid on condition that 1) the vapour 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).

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.

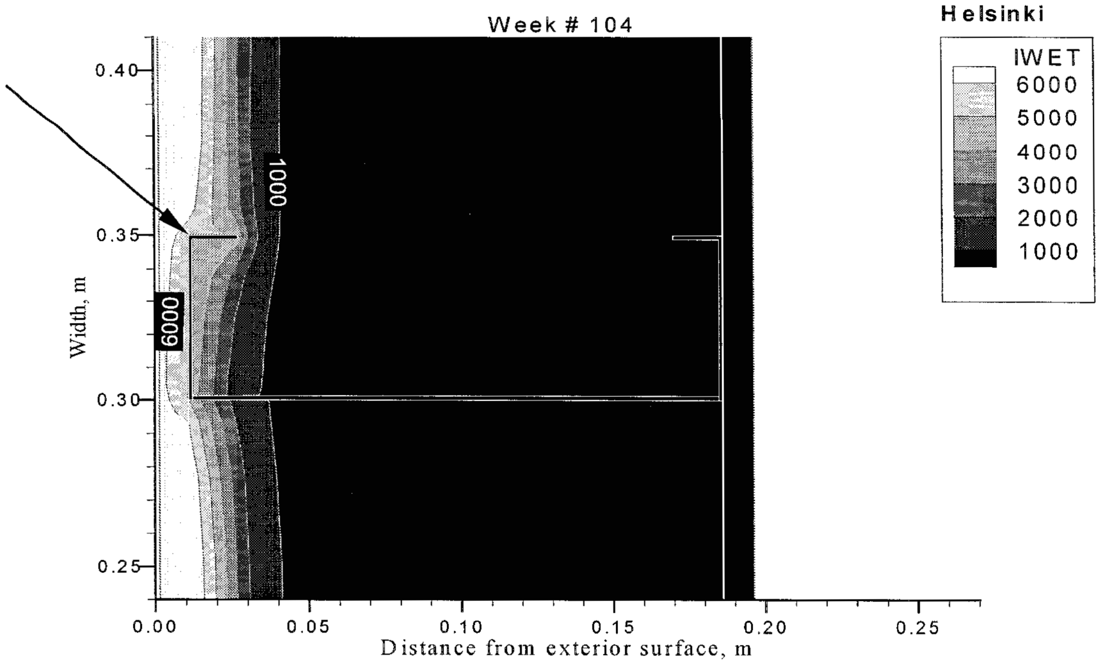


Figure 5.7. Contour plot of the accumulated time of wetness in the layers of the steel frame wall without exterior insulation. Exterior conditions: Helsinki weather data. Length of the simulated period is 2 years (104 weeks). Arrow shows the location of the highest contour value.

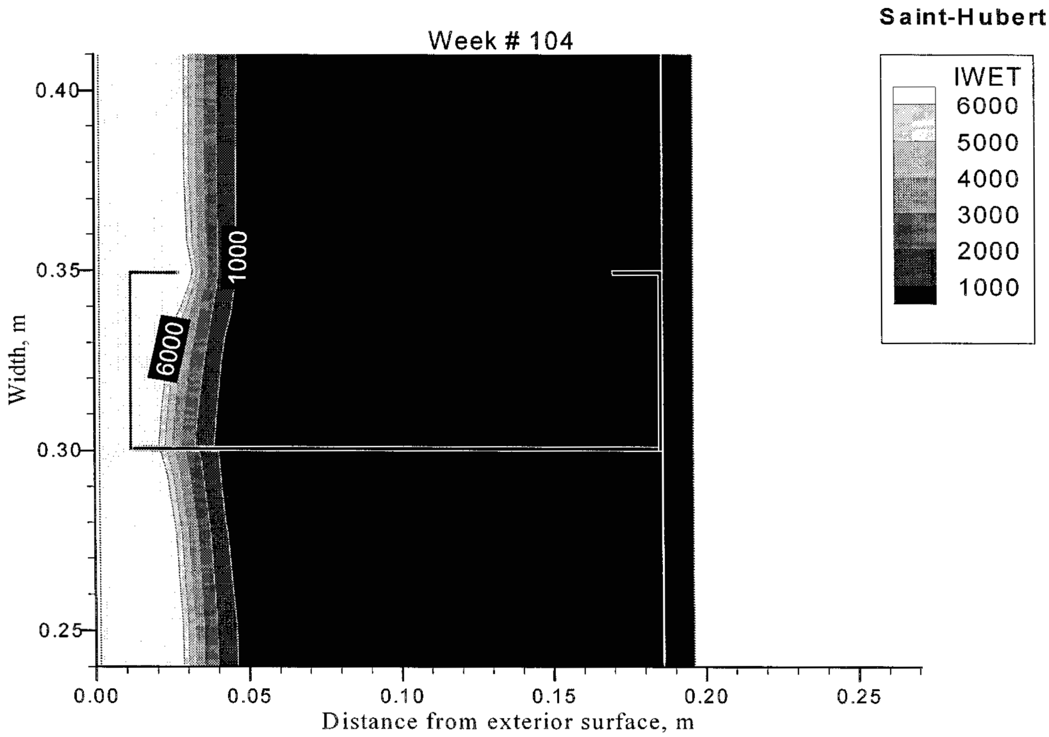


Figure 5.8. Contour plot of the accumulated time of wetness in the layers of the steel frame wall without exterior insulation. Exterior conditions: Saint Hubert weather data. Length of the simulated period is 2 years (104 weeks).

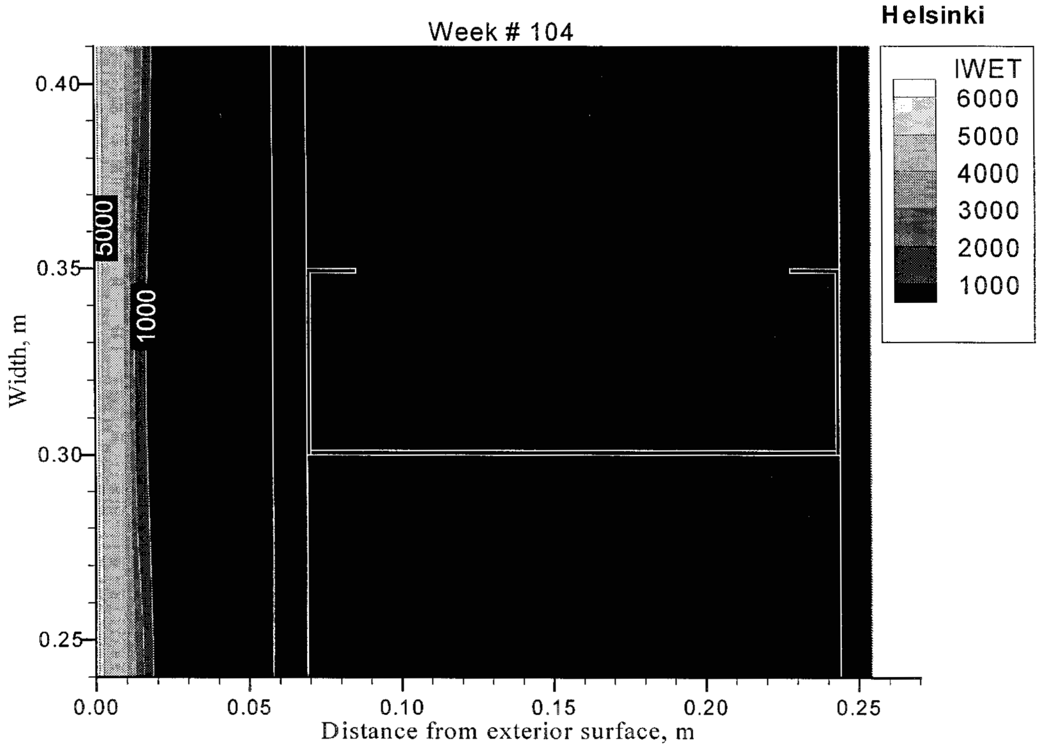


Figure 5.9. Contour plot of the accumulated time of wetness in the layers of the steel frame wall with 50 mm exterior insulation. Exterior conditions: Helsinki weather data. Length of the simulated period is 2 years (104 weeks).

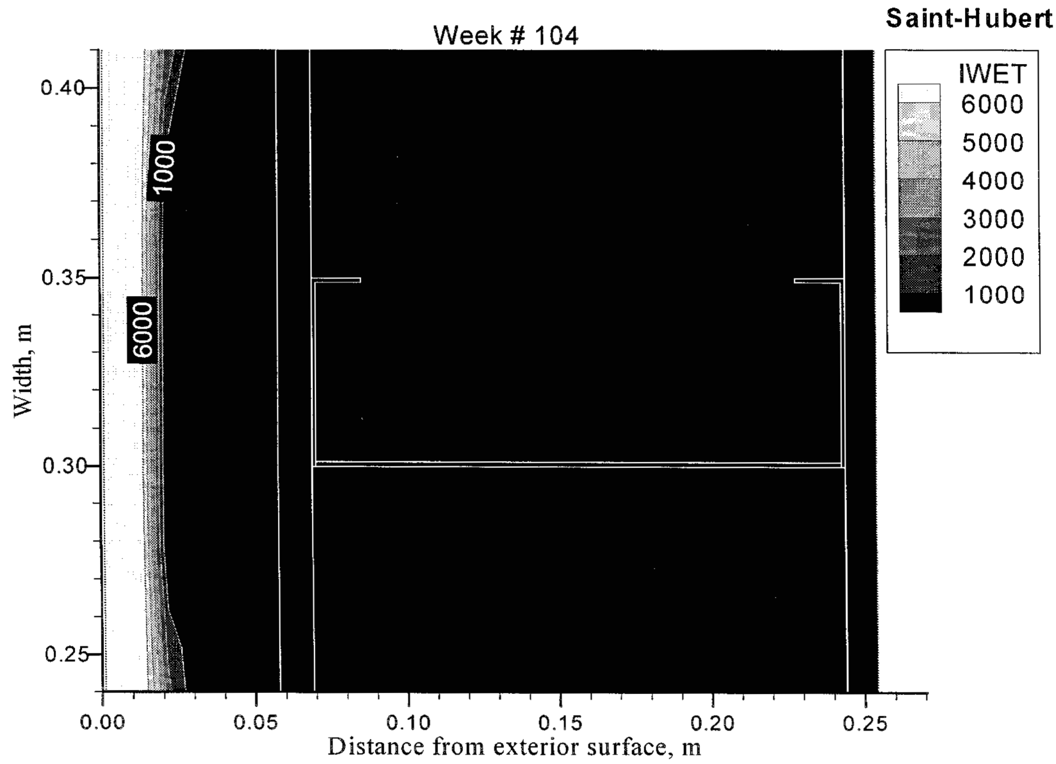


Figure 5.10. Contour plot of the accumulated time of wetness in the layers of the steel frame wall with 50 mm exterior insulation. Exterior conditions: Saint Hubert weather data. Length of the simulated period is 2 years (104 weeks).

5.4 Conclusions

The application of perforated light gauge steel frames, called the thermoprofiles, allows new possibilities for building energy efficient buildings. The thermal properties of a thermoprofile are comparable to wooden load-bearing frame structures used in low-energy buildings, which makes it possible to use steel members in energy efficient buildings as well. The performance of the structures makes them suitable for use in a cold climate. The results from the demonstration project in Ylöjärvi including comprehensive laboratory testing of the structures and the numerical simulations show that there are no major moisture or corrosion risks involved with the structures. Thermal bridging caused by high thermal conductivity of steel can be controlled using perforated steel profiles. Steel is a non-hygroscopic material, and rapid drying of built-in moisture enables structures to remain dry.

6. DURABILITY OF LIGHT-GAUGE STEEL FRAMED WALLS

The service life of steel framed walls can be assessed using the standard ISO 9223 'Corrosion of metals and alloys'. The performance criteria used in the standard is time of wetness. Time of wetness does not refer to liquid water on the surface, but microclimate where the critical conditions for continuous corrosion is possible due to high relative humidity. Continuous corrosion is possible, if relative humidity on the metal surface exceeds 80% at the same time as temperature is above 0°C.

According to the laboratory weather tests, field measurements in Ylöjärvi and hygrothermal simulations, the time of wetness for the most critical point in the reference wall is less than 2500 hours a year in the climate of Helsinki. For the low-energy wall the time of wetness is even lower, less than 250 hours. The performance of the structures depend strongly on the outdoor climate, and the hours of time of wetness increase in more humid climates such as the climate of St. Hubert in Belgium.

A set of durability tests was carried out for the light gauge steel profiles. Insulated (glass wool, rock wool and cellulose fibre insulation) test specimens were placed in steady climatic conditions of 1) +23°C / 50% and 2) +23°C / 85%, temperature and relative humidity respectively. An additional set of test specimens were exposed to a temperature difference of 20°C (23°C / 43°C), where continuous condensation took place on the insulated surface of the steel member.

After 19 months of exposure in the steady climatic conditions (March 15, 1998, time of wetness hours 12680) no corrosion of the zinc-coating was found in the test specimens with mineral wool insulation, while in the test specimens with cellulose fibre insulation, slight corrosion of the zinc layer was found. 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 fibre insulation were not stagnant. The chemicals re-crystallised on the steel surface, which caused stronger edge corrosion in the test specimens insulated with cellulose fibre insulation compared to other specimens.

According to the laboratory weather resistance tests and the field measurements at Ylöjärvi demonstration buildings, there are no major moisture risks in the structures provided that the walls are constructed using a good standard of workmanship. This includes proper installation of thermal insulation materials, vapour barriers and wind proofing layers in the wall. The measurements show that no condensation has occurred in the profiles.

According to the standard ISO 9223 the corrosivity category of the profile is C1 - C3, where the time of wetness shall not exceed 250 hours or 2500 hours in a year, respectively. In winter the relative humidity, due to the temperature distribution in a structure, exceeded 80% only occasionally on the outer flange of a thermoprofile in the field tests. The service life of the zinc coating can be estimated to be at least 50 years, but the service life of the whole frame system can be expected to be much longer.

7. STRUCTURAL PERFORMANCE OF STEEL FRAMED WALLS AND TRUSSES

7.1 Introduction

The main component in framing systems was thermoprofile where the web of the section is perforated to cut the cold-bridge through the wall. Present design rules or guidelines do not cover their kind of perforated sections. Therefore the purpose of the research was to ensure experimentally that the steel framing systems and steel trusses had sufficient capacity in terms of stiffness and strength.

Two types of framing systems were tested. Insulated facade units are prefabricated elements, which are brought to the building site to be installed as the facade of the building. The load bearing framing system used as external wall is suitable for site built houses as well. The facade units loaded with wind pressure are composed of U-sections with a perforated web (thermoprofiles). The load-bearing wall is based on the vertical C-shaped thermoprofile. Gypsum boards are used on the internal and external surfaces of the wall systems.

There were two types of trusses. One is of a uniform depth with a span of 9,1 m (identification test number of the truss is RR05) and another is a pitcher type of truss with a span of 7,8 m (RR01). Members of the trusses are made of light gauge steel. Top chords are omega profiles, bottom chords U- (RR01) or hat profiles (RR05). Vertical members are U profiles and diagonal members in the RR01 truss U profiles and in the RR05 truss flat steels. Joining of the members were made with both screws and rivets.

The capacity of the framing systems and trusses were verified experimentally by carrying out an acceptance test on the test specimen to demonstrate the serviceability limit state capacity and a strength test to demonstrate the ultimate limit state capacity. The acceptance and strength tests were carried out by applying the principles presented in Eurocode 3 Part 1.1 and Eurocode 3 Part 1.3. Finally the ultimate capacity of load bearing framing system and roof trusses was determined by loading test specimen to failure.

7.2 Test programme and test arrangement

7.2.1 Steel framing systems

The acceptance and strength tests for insulated facade unit were carried out with two actual full-size units (size 2.7 x 5.4 m): one standard and one with opening for window. The effect of moisture content was studied with bending tests using two reference elements containing two parallel TU175-studs connected to rails and covered with gypsum boards. The same kind of test specimen was used to study the capacity of the load bearing wall system except the stud was replaced with TC175-profile. The tests were carried out for two different studs: a TC175/1.2 - stud used in the wall structure and a TC175/2.0 stud used at the edges of wall openings. The test programme and dimensions of the specimen for both framing systems are collected in Tables 7.1 and 7.2.

Table 7.1. Test programme and test specimen.

Test specimen	Element size (mm)	Test type	
Element 1	2730 x 5357	Acceptance test Strength test	Full-size element for facade
Element 2	2730 x 5358	Acceptance test Strength test	Full-size element for facade Opening 1500 x 1800 for window
Element 3	2802 x 1200	Bending test to failure	Reference element with TU175/1.2-stud
Element 4	2802 x 1198	Bending test to failure	Reference element with TU175/1.2-stud Moistening of exterior gypsum board

Table 7.2. Test programme for load-bearing wall elements with either TC175/1.2-stud (TC1) or TC175/2.0-stud (TC2). N stands for compression load, q for distributed load with additional weight and Q for bending load with hydraulic actuators.

Test	Test code	Test type	Loading	N - Eccentricity of load in top end B - Additional distributed load in failure
1	TC1-E1	Failure test	N	N: E = 10 mm B: own weight
2	TC1-E2	Failure test	Nq	N: E = 80 mm B: 100 kg per stud Failed strength test
3	TC1-E3-1	Acceptance test Strength test Failure test	Nq	N: E = 40 mm B: 100 kg per stud
4	TC1-E3-2	Acceptance test Strength test Failure test	Nq	N: E = 40 mm B: 200 kg per stud
5	TC1-E3-1-K	Failure test	Nq	N: E = 40 mm B: 100 kg per stud Moistening of exterior gypsum board
6	TC1-Q	Failure test	Q	B: Hydraulic actuators
7	TC1-Q-K	Failure test	Q	Moistening of exterior gypsum board
8	TC2-E1	Failure test	N	N: E = 10 mm B: own weight
9	TC2-E2	Failure test	Nq	N: E = 80 mm B: 100 kg per stud
10	TC2-E3-1	Acceptance test Strength test Failure test	Nq	N: E = 40 mm B: 200 kg per stud
11	TC2-E3-2	Acceptance test Strength test Failure test	Nq	N: E = 40 mm B: 400 kg per stud
12	TC2-Q	Failure test	Q	B: Hydraulic actuators

In the tests of full-size insulated facade units the support of test specimen were arranged as in reality. The specimens were loaded with limestone bars stacked incrementally on the specimen.

The reference elements were loaded in special loading arrangement, where distributed load was arranged with hydraulic actuators.

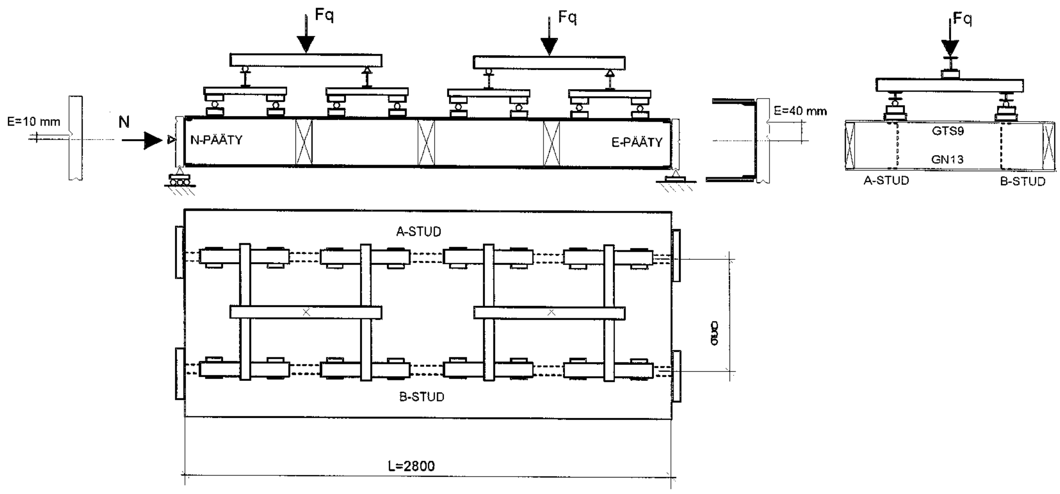


Figure 7.1. Test arrangement in the acceptance and strength tests for the load bearing framing system. The reference elements were tested with equal loading arrangement with bare distributed load arranged with hydraulic actuators.

The test arrangement of the external load-bearing wall depicted the combined effect of the suction pressure of the wind and a vertical load from the roof. The suction loading increases the moment in the stud caused by the vertical force coming eccentric from a roof truss. In the loading arrangement the boundary conditions of the test specimen were idealised as hinged. The support of the lower end was made 10 mm eccentric with respect to the stud, to depict the eccentricities arising from erection. An eccentricity of 40 mm, based on ASTM E 72-80 standard, was used in the transmission of the forces coming from the roof truss. The distributed load was arranged either by limestone bars or hydraulic actuators. The vertical load was arranged with hydraulic actuators. (Figure 7.1)

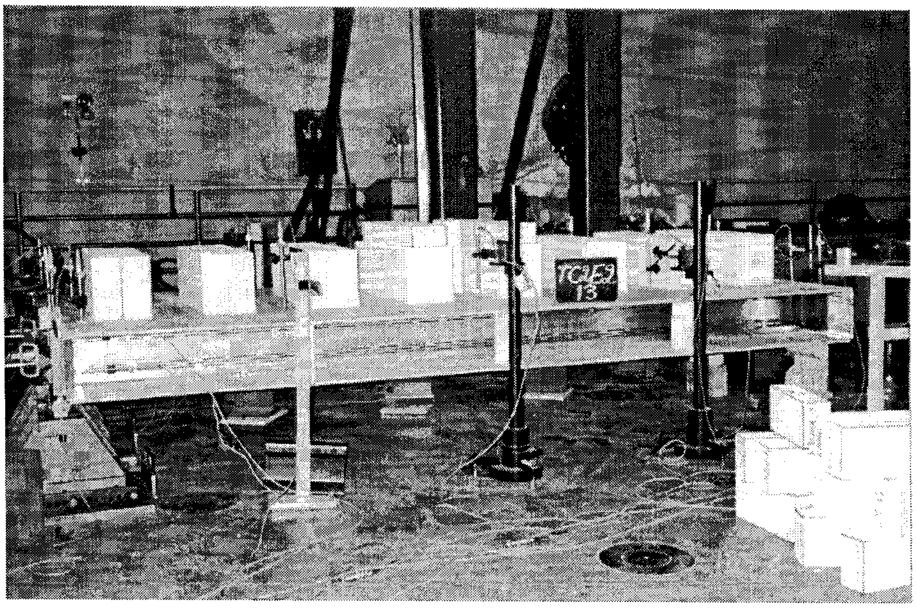


Figure 7.2. Example of test arrangement for loads bearing framing system.

The test loads used in the acceptance test and strength tests were based on the loading combinations given in the Finnish Building Regulations concerning thin sheet steel structures. A wind pressure of 0.8 kN/m^2 was used as the basis for design, when the test loads were determined for insulated facade units. The test loads for load-bearing wall were based on the design load values: a snow load of 1.8 kN/m^2, a permanent load of 0.8 kN/m^2, and a wind pressure of 0.65 kN/m^2. When demonstrating the strength of the structure, an additional safety factor was required to the loads, because of the limited number of tests and composite type of the structure. Required loads are given in Table 7.3.

Table 7.3. The required loads in the acceptance and strength tests for both combinations of live loads KY1 and KY2 given for a single stud.

Load combination	Test	TC-175-1.2		TC-175-2.0	
		N [kN]	q [kN/m]	N [kN]	q [kN/m]
KY1	Acceptance test	15,6	0,18	23,4	0,35
	Strength test	31,2	0,35	46,8	0,70
KY2	Acceptance test	10,2	0,35	15,3	0,70
	Strength test	20,4	0,70	30,6	1,40

The effect of the moisture content of the external gypsum board on the stiffness of the structure was investigated. The specimens for these tests were stored 1 - 2 months in an air-conditioned room with relative humidity of about 80%. The aim was to moisten the gypsum board wind proofing to a moisture content corresponding to the long-term winter moisture.

7.2.2 Roof trusses

The trusses were first calculated. Finnmap Consulting Oy made design and computer simulations. Then the full-scale trusses were tested in laboratory at VTT Building Technology. Testing methods had to be developed for these structures including e.g. load distribution and strain measurements.

The test arrangements were designed such that the loading system would adequately enough simulate the magnitude and distribution of the loading and allow the specimens to perform in a manner representative of service conditions.

According to Eurocode requirements, loads in acceptance and strength tests were applied in five regular increments at regular intervals (correspondingly unloading in five regular decrements) in each phase. Five minutes between each increment and decrement was allowed for the trusses to reach stationary equilibrium. On the attainment of maximum load, it was maintained at a constant value for one hour.

Acceptance test is a non-destructive test to confirm the structural performance. The structure shall prove capable of sustaining the test load and there shall be no significant local distortion or defects likely to render the structure unserviceable after the test. The structure shall demonstrate substantially elastic behaviour under service loading and on removal of the service load the residual deflection should not exceed 20% of the maximum recorded. Test load for the acceptance test was elected to be the dead load x 1,15 + imposed load x 1,3.

Strength test confirms the calculated capacity of a structure. Before carrying out the strength test, the specimens should first be submitted to and meet all the requirements of the acceptance test described above. The test load shall be based on the factored load calculated in accordance with the Eurocode. The test load shall take into account the measured yield stress of the steel in the structure determined by tension test. At test load level there shall not be failure by buckling or rupture of any part of the specimen. On removal of the test load the deflection shall be reduced by at last 20 %. Constructions had to be calculated according to Finnish building code, which in this case gives the factor 1,6 for both the dead and imposed loads, so the loads are a little bigger, compared with Eurocode.

The real modes of failures and true capacities of the trusses were determined from the tests to failure. Those tests were made after acceptance and strength tests.

The trusses in the test rig were placed horizontally on the laboratory floor. Movement upwards was prevented with beams c/c 2 m on the trusses. To let specimens deflect freely under load there were neoprene strips on floor and against beams. Regardless of neoprene strips there were left some friction, which can be seen from the difference between forces measured from the loading jacks and supporting forces the latter being smaller. So the required loads were determined from the smaller i.e. support forces. The effect of friction on displacements is on the safer side.

Locations of the load and deflection measuring transducers are presented in Figure 7.3 for RR01 truss. Photographs of test arrangements in Figures 7.4 and 7.5. Test programme with different loading and maximum loads in the tests are presented in Table 7.4 in Chapter 7.3.3. The weights of the trusses are 115 kg (RR01) and 145 kg (RR05).

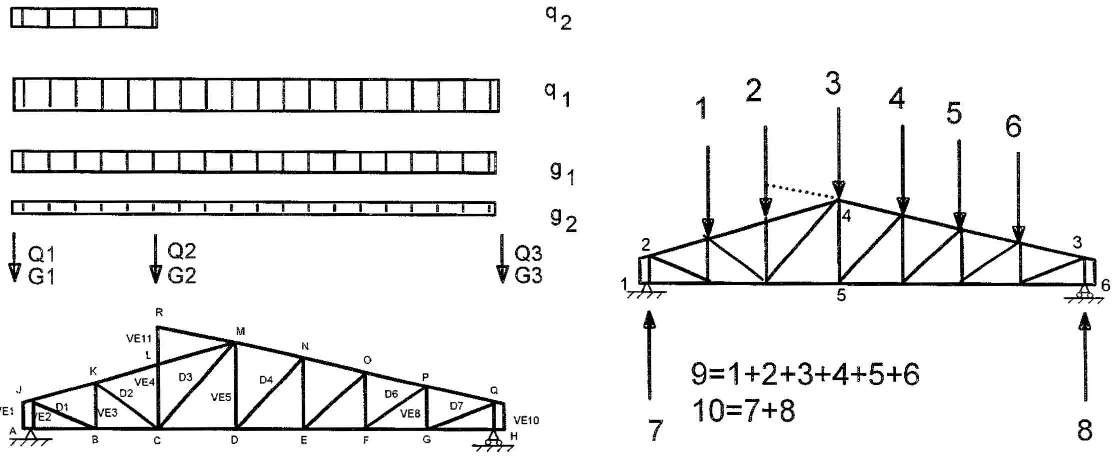
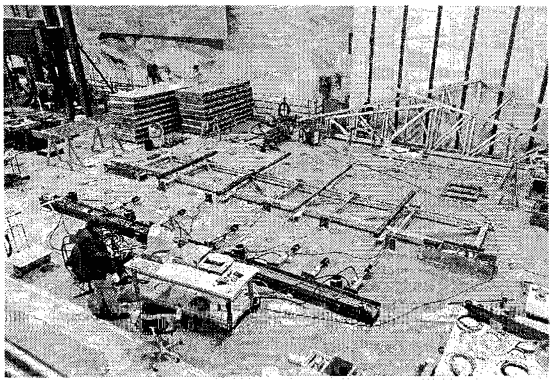
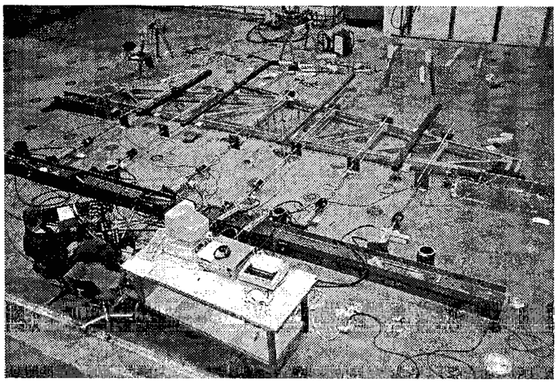


Figure 7.3. Test truss RR01 (c/c 1, 2 m). Truss depth at ridge in joint M is c. 1500 mm and total length 7980 mm. Top chord are omega profiles 100/100/50/18 x 1.5 and bottom chord U-100/100/100 x 1.5. Vertical and diagonal members are U-92 or 96/50/50 x 1.5 (VE1, 2, 9 and 10) or 1.0 (the others), flanges of VE3, 4, 7 and 8 are stiffened with L - 20 x 20 x 1.5 -profiles.

Design loads in test for the truss RR01 are $q_1 = 1.8$ kN/m^2, $q_2 = 0.42$ kN/m^2, $g = g_1 + g_2 = 0,83$ kN/m^2 (on top chord) + 0.17 kN/m^2 (on bottom chord). At joints J, R and Q there are loads $Q_1 = 2.13$ kN and $G_1 = 0.16$ kN, $Q_2 = 1.73$ kN and $G_2 = 0.16$ kN and $Q_3 = 2.34$ kN and $G_3 = 0.22$ kN. Test forces 1 - 6 are distributed into truss joints K, L, M, N, O and P. 7 and 8 are support forces and numbers 1 (at the joint A), 2 (J), 3 (Q), 6 (H), 4 (M), 5 (D) and 6 (H) show locations of the displacement transducers.

Figures 7.4 and 7.5. Test arrangements of trusses RR05 and RR01.

7.3 Results

7.3.1 Insulated facade unit

The capacity of the serviceability limit state is ensured using an acceptance test. The requirement is that the residual deflection after the removal of the load may be a maximum of 20% of the greatest deflection. The deflections of the units were examined over the entire element, so that the displacements of the attachments are also included (Example Figure 7.6 (a)). The greatest deflection of the wall unit in the acceptance test corresponds to a deflection of h/1186 for standard specimen and h/650 for specimen with window opening, where h is the height of the unit. The effect of dead weight has been taken into account. The ultimate limit state capacity is ensured with the aid of a strength test. The test specimen should withstand a loading corresponding to the dimensioning load of the ultimate limit state.

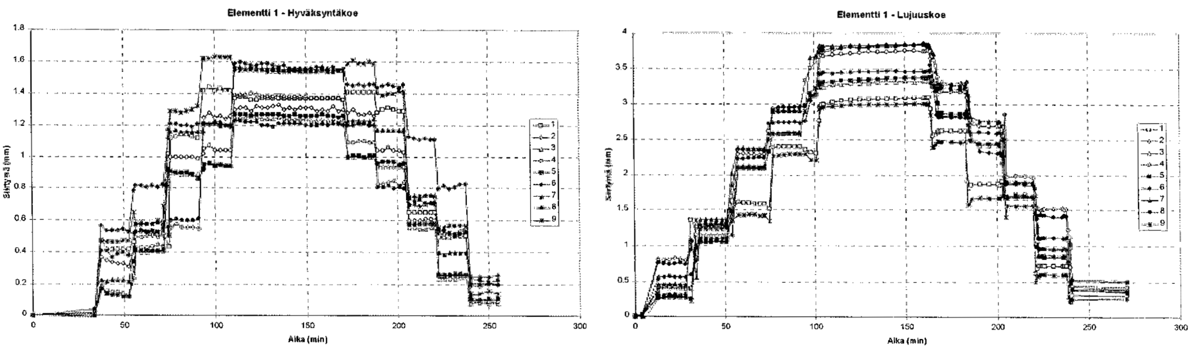


Figure 7.6. Deflection history from the acceptance test and from the strength tests of the insulated facade unit. The loading is increased incrementally to the design load in serviceability limit state and removed after time dependent effects have ceased. In the strength test additional safety of 25 % is required because of limited number of test and composite type of structure.

Full-size specimen did withstand the required test load, no permanent deformations were observed after the test. The return of the deflections was clearly more than the required 20% (Example Figure 7.6 (b)).

The effect of moisture in the gypsum board on the stiffness was evaluated with the aid of bending tests where the moistened board became compressed. The moistness of the surface board was not observed to have any significant effect on the stiffness of the specimen. Structural details, such as the stiffness of attachments, and tolerances have a greater significance in the operation of the specimen.

7.3.2 Load-bearing external wall structure

Both types of studs met the requirements set for acceptance and strength tests for both combinations of live loads. The greatest deflection of a TC175/1.2-stud for the serviceability limit state loading combination was 2.7 mm (h/1000) and of a TC175/2.0-stud 2.5 mm (h/1100).

The ultimate capacities of the load bearing framing system was determined with so-called failure tests for specimen loaded with compression, bending or combined compression and bending as in the acceptance and strength tests. In combined compression and bending tests an ultimate limit state design load was applied as a distributed load and the specimen were loaded to failure with an axial force. The ultimate capacity of the framing members with purely an axial load was obtained as the result of the compression tests. In the bending tests, the load arising from wind pressure was created with the aid of distribution beams and jacks. The results of the failure tests are collected in Table 7.4.

Table 7.4. Ultimate capacities from tests for of load bearing framing system. E stands for eccentricity of the load coming from the roof truss, Q stands for pure distributed load and K stands for moistness of the exterior gypsum board.

.Loading condition	TC175/1.2		TC175/2.0	
	N_{test} (kN)	q_{test} (kN/m)	N_{test} (kN)	q_{test} (kN/m)
E = 10 mm	36,7	0,15 [1]	93,4	0,17 [1]
E = 80 mm	25,8	0,28	53,4	0,72
E = 40 mm	35,1	0,36	70,2	0,72
	33,5	0,71	66,5	1,41
K	36,2	0,36	-	-
Q	-	1,7 [2] 2,7	-	6,5
K	-	1,4 [2] 2,8	-	-

1) Dead weight of the specimen.

2) Visible deformations can be in the perforated web of the specimen.

In the failure tests, the loss of load bearing capacity took place at the point of maximum moment. Failure took place as buckling in the compressed edge stiffener of the stud, which plasticized into a hinge in accordance with the distribution of gypsum board screws. Local buckling of the web, which reduced the torsional support of the compressed edge stiffener, proceeded the buckling of the edge stiffener. The surface boards prevented the buckling of the framing member in the plane of the wall. The loss of load bearing capacity in the bending tests took place in a corresponding manner, as buckling of the edge stiffener over the whole length of the stud. Local deformations began to take place in the perforation at the level of loading about 60 % of the ultimate capacity.

The moistness of a surface board affected the stiffness of the structure, when the moistened surface board was compressed. The stiffness of the specimen diminished by about 10 - 15 % in the moistened surface board. Same kind of comparison with the structure of facade panels showed no decrease in the stiffness.

On the other hand, under tension it did not affect the stiffness of the specimen. The interpretation of the results is hampered by other factors influencing deflections, such as including the effect of tolerances in the joints of the specimen in the results. It is not possible to draw firm conclusions from such a limited test series, and on account of the above lack of homogeneity.

7.3.3 Roof trusses

The tests and maximum loads in them are presented in Table 7.5.

Table 7.5. Test specimens and test programme.

Specimen number	Loading	Maximum total load
RR01	Preliminary loading	35,9 kN
-"-	Acceptance test	36,1 kN
-"-	Strength test	47,6 kN
-"-	Failure loading	61,4 kN
RR01	Strength test of D4	29,2 kN
RR05	Preliminary loading	48,5 kN
-"-	Acceptance test	35,9 kN
-"-	Strength test	49,7 kN
-"-	Failure loading	76,1 kN

Prior to actual tests of the trusses preliminary loading were applied and then removed in order to bed down the test specimens onto the test rig. The loads did not exceed the characteristic values of the relevant loads.

Strength of RR01-truss had to find out by testing several trusses until it was stiff and strong enough with added stiffeners, e.g. L-profiles in vertical members and extra fasteners in the joints.

Strength test with another RR01-truss for diagonal member D4 was made because force distribution with the used point loads gave too big force for D4 (in the other tests D4 was supported). With the total load of 29,2 kN compression force in D4 was equal to the required strength test force.

In acceptance tests both the trusses behaved elastic under service loading. Maximum deflections at the design load were 8.7 mm (RR01) and 9.9 mm (RR05) i.e. L/900 and L/910 when L is the span of the truss. On removal of the loads the residual deflections were 0,3 mm in RR05-truss and 0,7 mm in RR01-truss. The above deflections are correspondingly 2,5% and 6,7% of the maximum deflections recorded i.e. much less than the allowed 20%.

In strength tests there were no failures by buckling or rupture of any part of the construction and the residual deflections were 1,0 mm (= 6,1%) in RR05-truss and 2,8 mm (= 22,8%) in RR01-truss. So the above values are also far from the maximum allowed residual deflections (= 80%). Displacements in middle span with total load in the acceptance and strength tests of the trusses RR01 are presented in Figures 7.7.

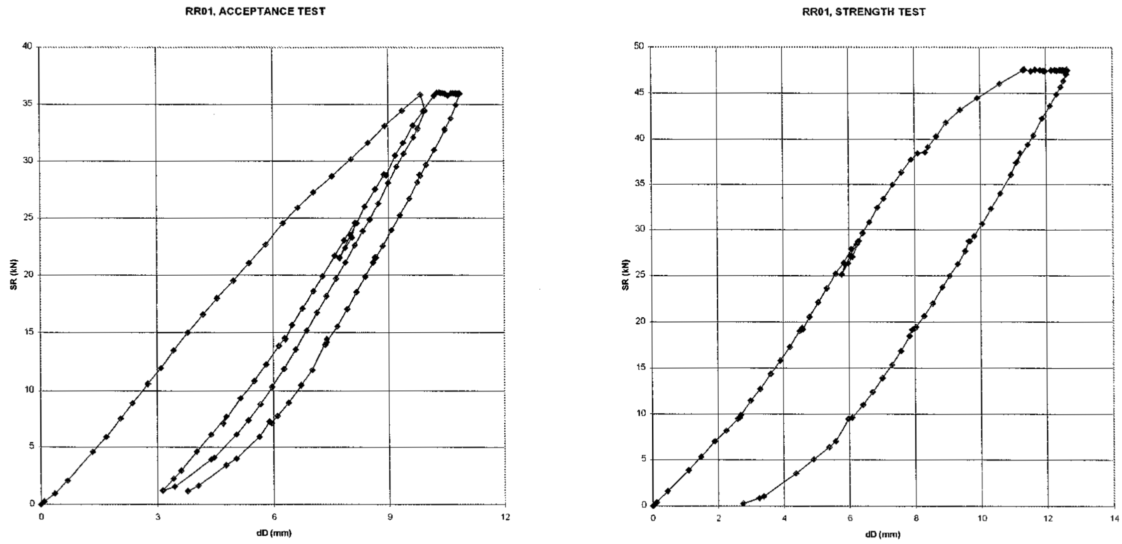


Figure 7.7. Displacements in middle span with total load in RR01 acceptance and strength tests. Acceptance test was made straight after preliminary loading without zeroing the loads.

The above results mean that both the trusses had sufficient capacity in terms of stiffness and strength.
In failure loading of RR05-truss compressed vertical member VE4 buckled suddenly at the total load of 76,1 kN and the ultimate factor is 2,5 (= failure load/design load). Failure in RR01-happened in the joint between bottom chord and diagonal member D7, which tore off at the total load of 61,4 kN. Ultimate factor in this case is 2.1.

7.4 Conclusions

The tested structural framing systems i.e. insulated facade unit and load-bearing external wall fulfilled requirements set for performance according to Eurocode 3. The structures had sufficient stiffness and strength under specified loads.

The effect of moisture content of the external gypsum board was studied with reference elements in bending for both insulated facade unit and load-bearing stud wall. It is not possible to draw firm conclusions from such a limited test series, especially when the tolerances in the joints of the specimen had an effect in the results.

In general the long-term behaviour of gypsum boards used as structural component under varying loading conditions should be verified when diaphragm action is utilised to transfer the wind loads.

Both roof trusses one with uniform depth and another pitcher type fulfilled the requirements set for acceptance test and strength test under specified loads after some modifications. When designing light gauge steel trusses, use of C profiles is recommended in compression. Using screws and rivets in the same joint are not recommended.

8. ENVIRONMENTAL PROFILE OF A STEEL-FRAMED HOUSE

8.1 LC-analysis and test cases

Environmental impacts caused by construction and use of a steel-framed single-family house was studied and compared with the corresponding wood-framed and brick buildings. The procedure of the analysis is set out in the Nordic Countries Guidelines based on the framework for environmental impact assessment originally presented by SETAC (Society of Environmental Toxicity and Chemistry). All the materials used in the comparison buildings that were included in the analysis i.e. the procurement and processing of raw materials, manufacture, distribution, use, reuse, maintenance, recycling, final waste processing and transports connected with all stages. For all the products analysed, it was assumed that

- during use there was no need for maintenance causing use of materials and energy and
- service life of the products is the same as the service life of the building.

Two cases were analysed. In case 1 all the impacts exerted by the manufacturing processes were allocated to the first usage period (case 1) and in case 2 products were assumed to be used twice (reuse), in which case the impacts resulting from the manufacturing processes were allocated evenly to both usage times. The reuse or recycling of other building supplies has not been taken into account. Furthermore, the results do not take account of the consumption of energy on site and for installations as well as related emissions.

The environmental profiles have been calculated for six houses. The materials studied were steel products, bricks and mortar, ready-mix concrete, timber, gypsum boards, glass wool insulation, polystyrene insulation, polyethylene films and windows. The functional unit was the envelope of the house including doors foundations, floor slab, frame structures, insulation, cladding materials (boarding, bricks and masonry mortar), roof trusses, roof, nail plates and nails, vapour barrier, windows and gypsum boards of the inner envelope. External doors and paints have not been taken into account. The differences in the houses are shown in table 8.1.

Table 3. Differences in the comparison houses of the environmental impact analyses.

	House 1	House 2	House 3	House 4	House 5	House 6
low-energy house	x		x			
steel frame	x	x	x	x		
steel trusses	x	x				
wood frame					x	
wood trusses			x	x	x	x
load bearing brick wall						x

8.2 Embedded energy and emissions

The environmental impacts of the light-gauge steel framed building envelope are very similar to other load bearing systems. According to the result, the energy consumption and related emissions connected with the manufacture and transport of the building materials and products of the low-energy house and the comparison houses differ fairly little from each other. The energy consumption and emissions connected with the use of domestic electricity and heating of the house and its domestic water are considerably greater during the estimated service life of the house than are the energy consumption and emissions connected with the manufacture and transport of building materials and products, figures 8.1 - 8.4.

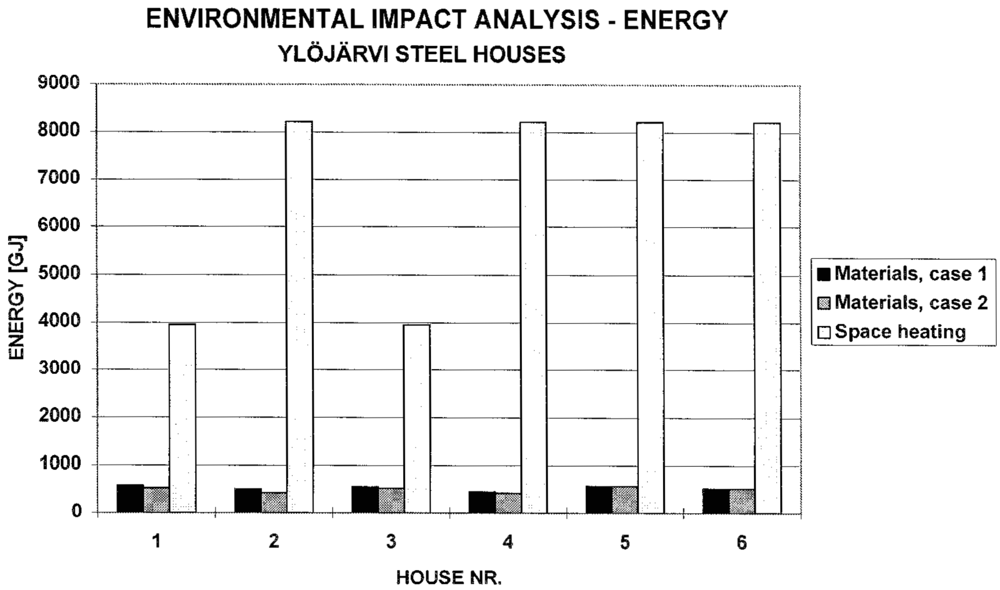


Figure 8.1. Embedded energy of the comparison buildings.

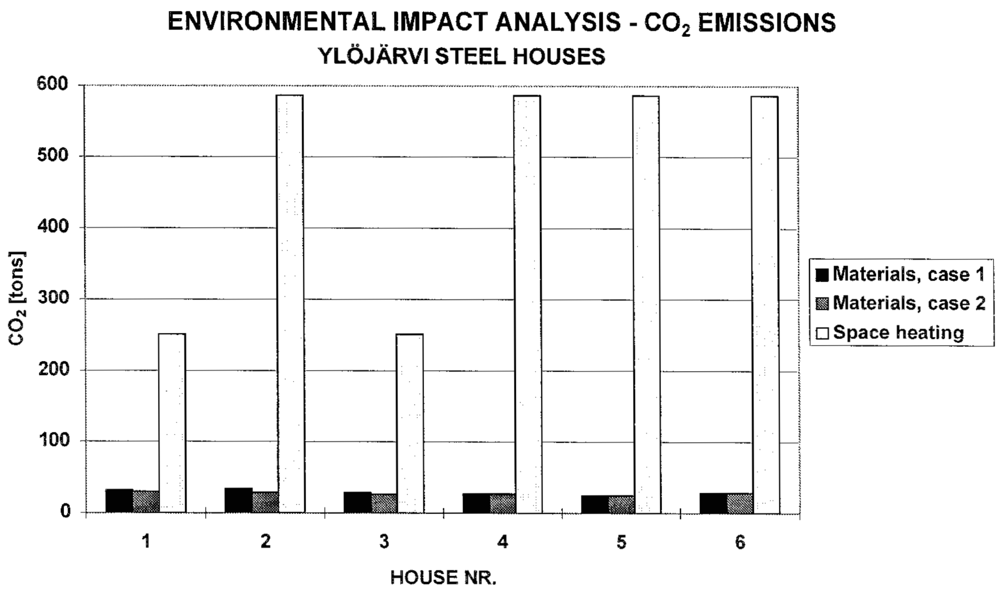


Figure 8.2. CO_2 emissions of the comparison buildings.

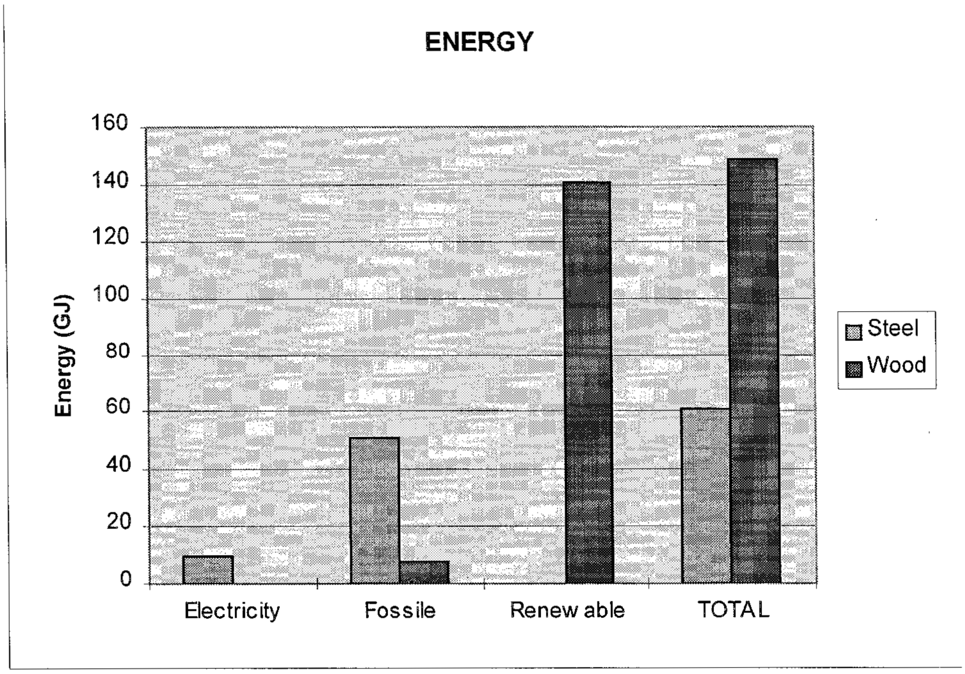


Figure 8.3. Embedded energy in wooden and steel structures.

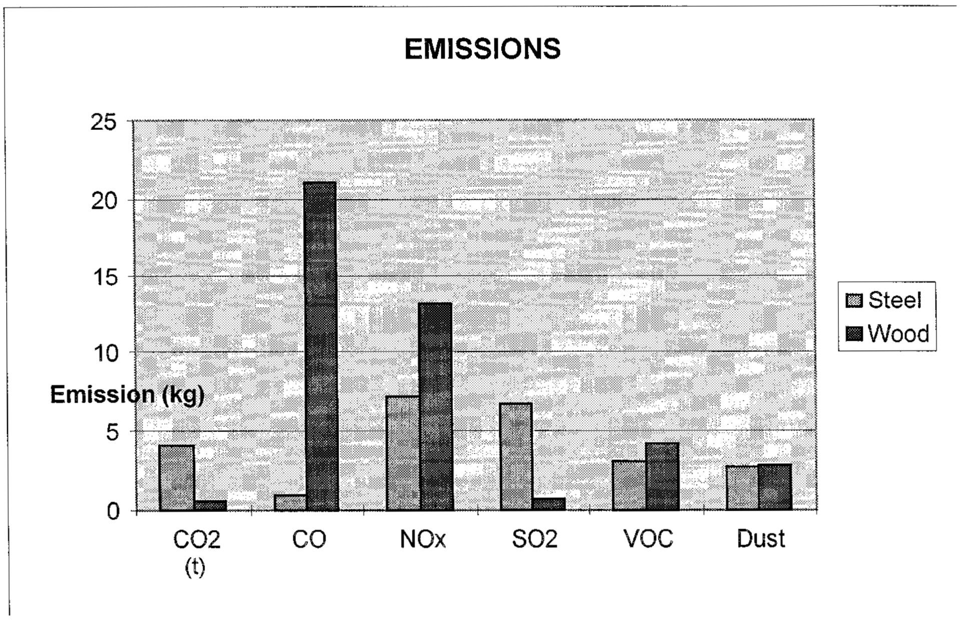


Figure 8.4. Emissions caused by manufacturing of wooden and steel structures.

8.3 Recycling and re-use

There is not any commonly accepted method for allocating the emissions and embedded energy in case of re-use or recycling. The environmental impacts of re-use depend at least on
- emissions and energy at demolition site
- transportation
- assembling
- use and maintenance

and recycling at least on
- emissions and energy at demolition site
- emissions and embedded energy of processing of steel, e.g. removal of surface coatings such as zinc or plastics
- transportation
- production of steel and product
- assembling
- use and maintenance

Due to the lack of commonly accepted allocation method, no exact results for re-use or recycling can be given. It is however clear that re-use or an efficient recycling process usually decreases the impacts in comparison to the first product cycle.

If the steel components are re-used 10 times, it is possible to allocate according to some of the models only 1/10 of the emissions and energy of manufacture to the first use. The use of this kind of allocation model is possible but not preferable because recycling causes environmental impacts also and the environmental impacts on the original manufacturing site are real, not 1/10 of the total. The other models used nowadays have also different kinds of weaknesses and therefore none of them have got common acceptance.

The re-use of steel frames can be considered to be much easier than re-use of wood frame or brick walls. The fixings in wood frames are rather scarce, and the removal of nails or nail plates tends to tear the material. Steel products should get credit of this possible reusability and also from high recyclability.

8.4 Conclusions

According to the result, the energy consumption and related emissions connected with the manufacture and transport of the building materials and products of the low-energy house and the comparison houses differ fairly little from each other. The differences are even smaller when only 50% of the environmental load exerted by steel thermo-profiles and roof trusses is taken into account during the first usage time. In this case, the energy consumption and emissions connected with the manufacture and transport of the building materials and products of Houses 1 and 2 (steel thermo-profiles and roof trusses) diminish relatively the most, which is natural. The largest decrease is in the energy consumption and CO_2 emissions connected with the manufacture and transport of the materials and products used in these houses.

The energy consumption and emissions connected with the use of domestic electricity and heating of the house and its domestic water are considerably greater during the estimated service life of the house than are the energy consumption and emissions connected with the manufacture and transport of building materials and products. The differences in the energy use and emissions during the use of low-energy houses and the "conventional" comparison houses are greater than are the differences in the energy consumption and emissions related to the manufacture and transport of the building materials and products according to different structural solutions.

The Ylöjärvi project has demonstrated that using steel as a structural component does not increase the energy consumption of a building and, furthermore, that the light-gauge steel framed building envelope allows for a good possibility to reduce the environmental impacts caused by the use of a building.

It has been shown in several other low-energy demonstrations that the cost effects of the simple energy saving measures applied in the Ylöjärvi project are minor compared to the price of a standard house. The measures are such, that they can be applied to any kind of building and load bearing system. Steel is evidently not of importance if only the energy saving measures are being looked at. But of utmost importance is the fact that, in this project steel is demonstrated for the first time in Finland in a comprehensive demonstration project and, that steel is used as a structural component in an environmentally friendly housing project.

9. SUMMARY AND DISCUSSION

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 R&D project was to ensure adequate performance and suitability of light-gauge steel framed house for use in a cold climate. Furthermore, the aim was to show that steel can be used economically as load-bearing structures in low-energy buildings. The project included comprehensive research and testing of the steel frame and steel trusses for structural capacity and hygrothermal performance as well as research on the energy performance and environmental impacts of steel buildings.

Structural tests showed that the perforated steel profiles have an adequate capacity in terms of strength and stiffness to be used as structural members in load bearing wall structures. Both roof trusses, one with uniform depth and another pitcher type fulfilled the requirements set for acceptance test and strength test under specified loads.

The results from the demonstration project in Ylöjärvi including comprehensive laboratory testing of the structures and numerical simulations show that there are no major moisture or corrosion risks involved with the structures. Thermal bridging caused by high thermal conductivity of steel can be controlled using perforated steel profiles. The thermal properties of these wall structures compete with typical wooden wall structures. Steel is a non-hygroscopic material, and rapid drying of built-in moisture enables structures to remain dry. The structures can be expected to have a long service life.

The perforated thermoprofiles allow for construction of highly insulated wall structures in an economically viable way. The low-energy demonstration showed that using steel framed building envelope and building services suitable for low heating demand, the heating energy consumption of a building can be reduced by 50%. The pay back time for extra costs of energy saving are recoverable in an acceptable time.

The environmental impacts of the light-gauge steel framed building envelope are very similar to other load bearing systems. According to the result, the energy consumption and related emissions connected with the manufacture and transport of the building materials and products of the low-energy house and the comparison houses differ fairly little from each other. The energy consumption and emissions connected with the use of domestic electricity and heating of the house and its domestic water are considerably greater during the estimated service life of the house than are the energy consumption and emissions connected with the manufacture and transport of building materials and products.

The main environmental, economical and societal benefits of the project are:
- using steel the environmental impacts of construction can be reduced
- steel can be used economically in housing
- moisture safe structures can be built using steel

Environmental impacts of steel buildings are on the same level as any of the competing structural systems. This emphasises the importance of life cycle energy consumption and emissions and reduction of energy consumption in use of the buildings. As the service life of a steel component in an insulated structure is expected to be very long, an energy efficient steel house has low impacts during the whole life cycle of the house, especially when the components can be recycled or reused at the end.

Steel can be used in an economically viable way in housing. The average building price for the Ylöjärvi demonstration houses was roughly 6800 FIM/m^2. This is well below the acceptable costs for e.g. social housing. The project produced practical experience for European countries of using steel for housing in a cold climate. The industrial benefit for building in steel is the high pre-fabrication for both constructing with large elements and site-building of pre-cut members. The possibility for low energy consumption with low extra building costs makes steel attractive for building owners and users.

Service life of buildings and building components has become more and more important in marketing of building products. In Finland, mould and moisture problems have been addressed in the existing building stock. The National Institute of Public Health, based on the results of a field survey /5/, has noted that roughly 50% of all the Finnish detached houses suffer from mould and moisture problems of varying degree. Therefore, new building systems with verified performances are needed. The Ylöjärvi demonstration showed extremely low humidity variations inside the wall structures. The hygrothermal performance of the structures ensures both the durability of steel components and the quality and comfort of living conditions in the house.

Rautaruukki Oy have reached project objectives and effectively proved, that steel can be used attractively, efficiently, economically, environmentally and competitively as frame material for all kinds of houses. With the help of this project, new and significant markets could have been opened to innovative steel products. This demonstration project has been successful.

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