Prefabricated Elements Used as Strip Foundation of Single-Family Housing

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ABSTRACT

A new prefabricated lightweight element was designed for a strip foundation that was used on site as the base of a single-family house. The element was placed on the stable surface underneath the top soil layer, just 0.4 meters underneath the finished ground surface. The prefabricated element was designed to fulfill the requirements of low energy consumption required by the new Danish Building Regulations. The base of the house was cast in one working operation and completed within two working days. The element, made of expanded polystyrene boards, was designed to be handled on site by one man. A non-freezing ground was established by using outer insulation located at the outer plinth. Temperatures were measured at measurement points located at the outer plinth and onwards from these points underneath the building. In addition the soil temperature, the temperature within the concrete floor slab and outdoor temperature and outdoor relative humidity were measured.

INTRODUCTION

In 2005 the Danish Government presented an action plan that aimed to promote significant results in the energy field. This action plan will have an impact on Danish energy-saving initiatives in the years to come (Transport- og Energiministeriet 2005). The action plan includes a description of the Danish energy sector in the years up to 2025. One subject in the strategy is the climate policy related to the Kyoto Protocol, United Nations (1998), which entered into force on 16 February 2005. Signatory industrialized countries to the Protocol are obliged to limit their emissions of greenhouse gases in the period between 2008 and 2012. As part of the internal distribution of obligations within the EU, Denmark must reduce its emissions by 21% compared with 1990 (Olesen, *et al.* 2004). Furthermore the draft action plan contains energy saving initiatives which from 2006 to 2012 are intended to reduce consumer energy consumption by an average of 1% per annum. In addition, the action plan also signals that long-term efforts must be made to keep energy consumption at current levels in the run-up to 2025.

The draft plan in particular focuses on energy consumption in buildings, where the largest and most cost-effective potential for energy savings lies. The most important initiatives are a tightening of energy provisions in the Danish Building Regulations (National Agency for Enterprise and Construction 1995), a new and improved energy-labeling scheme, enhanced supervision of boilers and ventilation installation regulations, and finally a number of energy-saving initiatives within the public sector.

The tightening of energy provisions in the Building Regulations will apply both to new and existing buildings. Besides the strengthening of current regulations from 2006, the plan paves the way for a further strengthening in 2010 and in 2015. The newly tightened energy provisions in building regulations of 1 January 2006 came into force on 1 April 2006, and will result in an energy reduction of 25% for new buildings compared with the former building regulations. The new building regulations have had an impact on energy consumption in buildings, in that the regulations focus on the thermal envelope as well as individual building components. One area of focus has been heat loss through the strip foundation of a

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building. In order to meet the new energy consumption requirements, alternative solutions were needed to the strip foundation of concrete traditionally used in Denmark. These traditional foundations are built 0.9 m below the finished ground surface in order to reach non-freezing ground with adequate bearing capacity.

Therefore, a new prefabricated lightweight element was designed and tested on site. The prefabricated element was used as strip foundation placed on the stable ground underneath the top soil layer, just 0.4 m underneath the surface. The prefabricated element was introduced as an alternative to the traditionally used solution and was to meet the same performance requirements as traditional solutions. However, when using the prefabricated element, there was no need to dig to a depth of 0.9 m below the surface and the base of the house was cast in one working operation. The base of the building was completed within two working days. The prefabricated element was made of expanded polystyrene (EPS) boards glued together and forming an element. The prefabricated element was designed to be handled on site by one man and to be used as the strip foundation of a house of up to two storeys. The prefabricated element was specially designed to form the base of a house with an exterior wall of either a traditional double-brick wall, a traditional wood-stud wall, or combinations of lightweight concrete, brick and wood-stud walls with insulation. Furthermore, the prefabricated element was designed to fulfill the new Danish Building Regulations by minimizing the heat loss through the strip foundation between the ground deck and the exterior wall.

In the design phase, the design criteria were outlined, the methods to establish stable non-freezing ground underneath the building were described and instructions were drafted on how to handle the prefabricated element on site. To increase knowledge of the temperatures underneath the building, temperature measurement points were located along lines under the strip foundation at the outer plinth and onwards from these points underneath the building. In addition the soil temperature, the temperature in the concrete floor slab and the temperature and the relative humidity outdoors were measured.

Temperature Measurements

The temperature was measured using type T thermocouples and a datalogger, type DT80. The junction of the thermocouples was covered with epoxy. Data from the datalogger were transferred to a PC and a computer program processed the results. The datalogger was placed outdoors at a dry clean location underneath the ground in a well, 300 mm in diameter and 500 mm deep, with an approximately 200 mm thick base of stones serving as a drain layer. The well was covered and included an electrical supply for the datalogger. The datalogger was placed in the well on a stand approximately 200 mm underneath the ground level. Measurement points were located on site underneath the strip foundation, at the outer plinth and underneath the insulation layer in the ground deck, and cast in the concrete floor slab of a building. In addition one measurement point was located in the soil, approximately 400 mm underneath the ground level. Measurement points were not exposed to direct sunlight and were away from any heat producing appliances. The temperature was recorded every hour.

Meters for Measurement of Outdoor Climate

The outdoor climate (temperature and relative humidity) was measured using small dataloggers. Data from the individual dataloggers were transferred to a PC and a computer program processed the results. Dataloggers were placed outdoors at locations approximately 2.5 m above the ground level, not exposed to direct sunlight and away from any heat or moisture producing appliances. The outdoor climate was recorded every hour. The climate was determined by the outdoor temperature, together with the outdoor relative humidity.

Materials Used for Strip Foundation of a House

The prefabricated elements were made of expanded polystyrene boards glued together to form an element that could be used as strip foundation of a house of up to two storeys. The expanded polystyrene is produced from a mixture of about 5-10% gaseous blowing agent (most commonly pentane or carbon dioxide) and 90-95% polystyrene by weight. The solid plastic is expanded into a foam through the use of heat, usually from steam. The voids filled with trapped air give it low thermal conductivity. This makes it ideal as a construction material and it is used as structural insulated panels in building systems. The expanded polystyrene will in the following be referred to as EPS. The prefabricated element is made from EPS boards. However, the element can be produced as one coherently shaped element through a production including an injection molding process. The chemical makeup of polystyrene is a long chain hydrocarbon with every other carbon connected to a phenyl group (an aromatic ring similar to benzene). The EPS has a Glass temperature of 95^{o}C and a melting point of 240^{o}C. The calculated thermal conductance is 0.034 W/mK.

The EPS element was specially designed to form the strip foundation that together with the ground deck represents the base of a traditional double-brick wall, a traditional wood-stud wall, or combinations of lightweight concrete, brick and wood-stud walls with insulation, see Figure 1. The prefabricated element was produced as units of 1200 mm in length and 600 mm in width. The prefabricated element is 98% air by volume and has a density of 33.0 kg/m^3. The EPS has a characteristic short-term compressive strength equal to 250.0 kPa and long-term compressive strength equal to 75.0 kPa with a 2% strain.

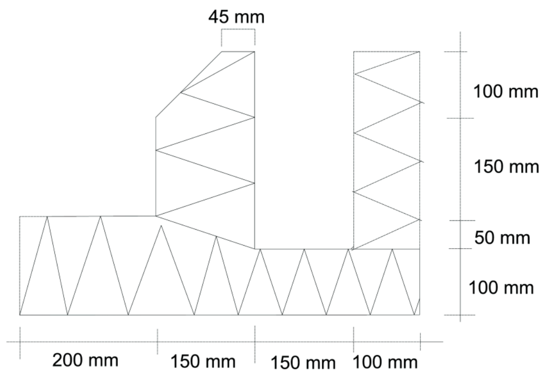


Figure 1 *The prefabricated element, made of expanded polystyrene (EPS) boards glued together to form an element used as the strip foundation of a building.*

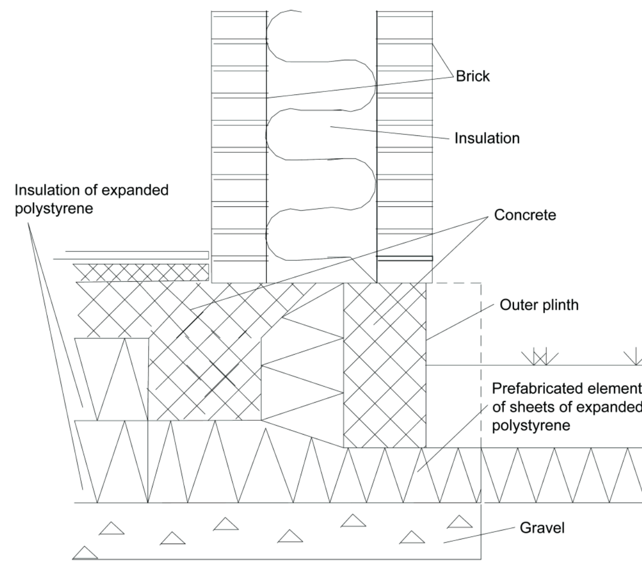


Figure 2 *Prefabricated element made of expanded polystyrene boards used as the strip foundation of a traditional double-brick wall separated by mineral based insulation.*

Performance-Based Criteria for the Design of Strip-Foundation Element

The prefabricated element of EPS has been designed to comply with the new Danish Building Regulations which allow very little heat to be lost through the strip foundation between the ground deck and the exterior wall. The heat loss through the strip foundation will in the following be referred to as the surplus heat loss, [W/mK]. The surplus heat loss is defined as the heat loss that can not be attributed to the one-dimensional heat loss through the ground deck and the exterior wall, individually. Surplus heat loss through the joint between the ground deck and the exterior wall is to a great extent related to the design of the strip foundation.

Buildings that meet the new energy regulations of 1 January 2006, which came into force on 1 April 2006, must in practice, when using heating in the concrete floor slab, normally not exceed a surplus heat loss of 0.12 W/mK. When using conventional heating in the building, the surplus heat loss must not exceed 0.15 W/mK. Danish Building Regulations require that the overall coefficient of heat transmission of the ground deck and the exterior wall are equal to or less than 0.12 W/m^{2}K and 0.2 W/m^{2}K respectively.

Calculations on the surplus heat loss through the prefabricated element were carried out using a PC and the finite difference program HEAT2 version 5.0 in accordance with the method described in Danish Standards 2002. Calculations are dynamic with the outdoor temperature changing throughout the year, see Figure 4.

Figure 2 shows the prefabricated element, made of EPS boards and used as the strip foundation of a traditional double-brick wall separated by mineral fiber insulation. The thermal conductivity of the exterior wall is 0.78 W/mK, 0.037 W/mK, 0.68 W/mK for the exterior brick wall, mineral fiber insulation and interior brick wall, respectively with an interim insulation of 0.17 m^{2}K/W. The thermal conductivity of the ground deck is 2.2 W/mK, 0.034 W/mK, 0.80 W/mK for the reinforced concrete floor slab, EPS insulation and the stamped gravel layer, respectively. The thermal conductivity of concrete, without shrinkage crack reinforcement, is 1.6 W/mK. Stainless steel rods 5 mm in diameter were put through the EPS, every 600 mm, forming the mechanical fastening point of the concrete for the outer plinth and the concrete floor slab. The contribution of the mechanical fastening to the surplus heat loss through the strip-foundation element is 0.002 W/mK (Danish Standards 2002, Table A.3.2).

The following calculations were made for a building using heating in the concrete floor slab. The exterior wall was designed to meet the limit on the overall coefficient of heat transmission equal to 0.2 W/m^{2}K. The surplus heat loss was calculated to be 0.14 W/mK. When the warm side of the exterior brick wall was replaced with a lightweight concrete wall, with the thermal conductivity of 0.45 W/mK, in the calculations, the surplus heat loss was calculated to be 0.14 W/mK. When a calculation was made to assess the effect of increasing the thickness of the insulation within the exterior wall so that the overall coefficient of heat transmission of the exterior wall was equal to 0.18 W/m^{2}K, the surplus heat loss was calculated to still be 0.14 W/mK. Calculations were carried out with a temperature of the concrete floor slab of 30^{o}C and with an interim insulation to the soil of 1.5 m^{2}K/W which allow the overall coefficient of heat transmission of the ground deck to be 0.1 W/m^{2}K.

Using conventional heating in the building with the traditional double-brick wall, with the overall coefficient of heat transmission of the exterior wall equal to 0.2 W/m^{2}K, the surplus heat loss was calculated to be 0.13 W/mK. When the brick wall was replaced, at the warm side of the exterior wall, with a lightweight concrete wall with the thermal conductivity 0.45 W/mK the surplus heat loss was calculated to be 0.13 W/mK. For an exterior wall that was less energy consuming, with an overall coefficient of heat transmission equal to 0.18 W/m^2K, the surplus heat loss was calculated to be 0.13 W/mK. For the calculations the temperature towards the concrete floor slab was 20^{o}C with an interim insulation to the ground deck and soil of 1.67 m^2K/W, which allow overall coefficient of heat transmission of the ground deck to be 0.09 W/m^2K.

Calculations were carried out with the specific heat capacity of the soil and the thermal conductivity of the soil set to 2.0 MJ/m^3K and 2.0 W/mK, respectively.

Strip Foundation Supporting a Traditional Wood-Stud Wall

Figure 3 shows the prefabricated element, made of EPS used as the strip foundation of a traditional wood-stud wall with mineral fiber insulation. When supporting a wood-stud wall, the insulation underneath the concrete floor slab can be of the same thickness throughout the concrete floor slab. Hence the need for a concrete beam supporting the inner wall of the exterior wall is not necessary when building with a traditional wood-stud wall. The exterior wood-stud wall is supported by the concrete beam behind the outer plinth. As for the prefabricated element to be used as the base of a traditional double brick wall, stainless steel rods 5 mm in diameter were put through the EPS at every 600 mm forming the mechanical fastening point of the concrete for the outer plinth and the concrete floor slab. The contribution of the mechanical fastening to the surplus heat loss through the strip-foundation element is 0.002 W/mK (Danish Standards 2002, Table A.3.2). For a design of the exterior wall to meet the limit on the overall coefficient of heat transmission equal to 0.2 W/m^2K of a building using heating in the concrete floor slab the surplus heat loss was calculated to be 0.09 W/mK.

Using conventional heating in the building, the surplus heat loss was calculated to be 0.09 W/mK.

Ensuring Stable Non-Freezing Ground Underneath the EPS Element

Ensuring stable non-freezing ground underneath the building is necessary for maintaining the stability of the structure and avoids settling cracks. To ensure stability of the strip foundation, it is important that temperatures lower than -1°C do not occur in any layer sensitive to frost underneath the building during a cold winter (Danish Standards 2001). Temperatures below –1°C underneath the capillary breaking layer during a cold winter could cause frost deformations of the soil underneath, which would increase the risk of the strip foundation settling. Boards of EPS from the outer plinth of the strip foundation were used to form the prefabricated element called the outer insulation. At the vicinity of a corner of a building the necessary outer insulation was designed on the

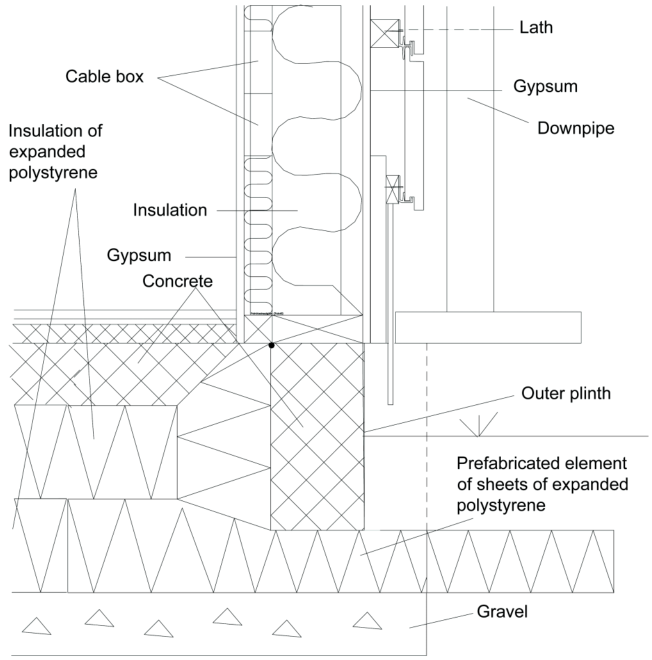


Figure 3 *Prefabricated element made of expanded polystyrene boards used as the strip foundation of a traditional wood-stud wall.*

basis of the experience using the PC finite difference program HEAT2 for 2D and 3D calculations. Calculations showed that if the temperature was determined to be +1.6°C along the facade of the building this was equal to -1°C at the vicinity of a corner of the building. Experience was gained from calculations on different types of foundation all dug at lower depth. Temperature characteristics for a cold winter were fed into the model using a design value of 100 years, based on the descriptions given in the Danish Standards 2001, see Figure 4. Figure 4 shows the outdoor temperature for a cold winter. The lowest average temperature of a month was decreased from -0.5°C in a normal year to -7.3°C in a cold year (Rose 2006).

Outer insulation was designed for three different cases describing the indoor temperatures, 1) an indoor temperature of 20°C, 2) an indoor temperature equal to the outdoor temperature but not lower than 5°C and 3) an indoor temperature equal to the outdoor temperature.

Along the facade of a building, calculations showed that an outer insulation of EPS, 100 mm in thickness and extending 400 mm in front of the outer plinth of a building facade just 150 mm under the finished ground surface, was adequate to hold the soil just underneath the gravel layer above freezing during a cold winter, while keeping an indoor temperature equal to the outdoor temperature.

At the vicinity of a corner of a building there was a need for extending the outer insulation if not keeping an indoor temperature at 20°C. For a building keeping an indoor temperature at 20°C it was calculated that an outer insulation of EPS,

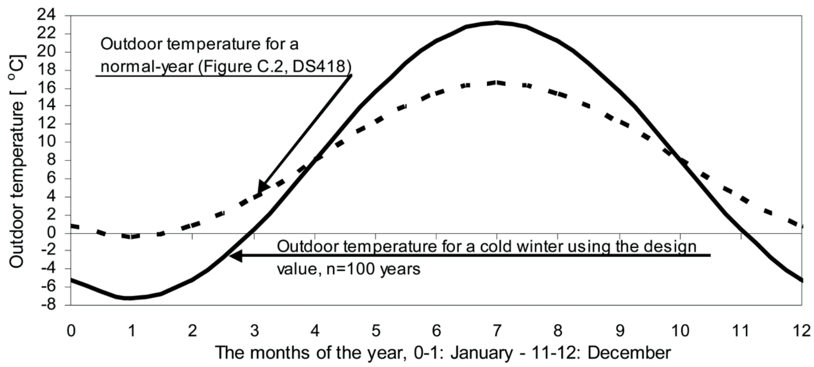


Figure 4 *Variation of the outdoor mean month temperature for a normal year and for a cold year in Denmark.*

100 mm in thickness and extending 400 mm in front of the plinth just 150 mm under the finished ground surface was adequate to hold the soil just underneath the gravel layer at the vicinity of a corner of a building above freezing during a cold winter. If kept an indoor temperature equal to the outdoor temperature but not lower than 5°C, an outer insulation of EPS, 100 mm in thickness and extending 700 mm in front of the plinth just 150 mm under the finished ground surface, was adequate to hold the soil just underneath the gravel layer at the vicinity of a corner of a building above freezing during a cold winter. However, in order to maintain an indoor temperature equal to the outdoor temperature, an outer insulation of EPS (100 mm in thickness and extending 900 mm in front of the plinth and just 150 mm under the finished ground surface) was able to keep the soil just underneath the gravel layer at the vicinity of a corner of a building non-freezing during a cold winter. It was recommended that vicinity of the corner includes the area in the ground front of the corner and the area along the facade of a building, at least covering the extra length of outer insulation along the plinth around the corner.

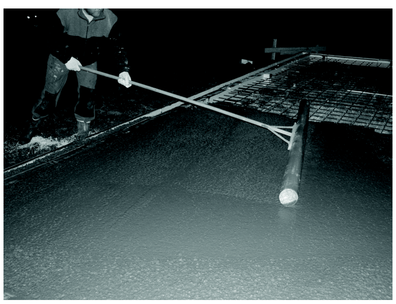
Building a Strip Foundation

In most locations in Denmark a stable ground of glacial deposit (moraine) is present underneath a top soil layer of approximately 0.2 to 0.4 m in thickness. The top soil layer was removed in an area covering the ground of the building. At least material up to a depth 0.35 m underneath the top soil surface had to be dug up. The excavated area was then covered with a capillary breaking layer of gravel which was stamped in order to form the stable base for the building. Temperature measurement points were mounted and the prefabricated elements were mounted as the strip foundation, see Figure 5a). Mounting the strip foundation, fixed together with comb-shaped pieces of plastic and outer support of stamped gravel, 0.3 m of EPS in two layers was mounted inside the strip foundation working as insulation underneath the concrete floor slab, see Figure 5b). Before casting the concrete, iron was mounted, as a net, preventing shrinkage crack development, inside the strip foundation and as wires along the moat formed by the two vertical boards of EPS in the prefabricated elements. Wires of stainless steel rods, 5 mm in diameter were put through the inner vertical boards of the prefabricated elements of EPS every 0.6 m, in order to attach the concrete in the moat to the concrete floor slab. Concrete was cast and leveled, see Figure 5c). After a few hours, when the concrete was stable in shape, the outer vertical boards of the prefabricated elements of EPS were removed exposing the outer surface of the concrete moat as the outer plinth. The removed outer vertical boards of EPS were used as the outer insulation on the ground around the plinth.

On site, temperatures were observed at locations in the zone in between the capillary break layer of gravel and the layer of EPS. Temperature measurements were made at measurement points located along two lines. Firstly, along a line taking its starting point at the north/eastern corner, under the strip foundation at the outer plinth and onwards from this point at a 45^{o} angle horizontally, underneath the building. Temperature measurement points were located along the straight line $\sqrt{2}$ *(0, 0.2, 0.5, 1 and 2) meter from the outer plinth. Secondly, along a line taking its starting point 3 m from the north/eastern corner along the side of the building facing east, under the strip foundation at the outer plinth and onwards from this point along a straight line at a 90^{o} angle horizontally, underneath the building. Temperature measurement points were located along the straight line 0, 0.2, 0.5, 1 and 2 m from the outer plinth. In addition the temperature of the concrete floor slab of the building was observed at four points along the two straight lines where temperatures were measured, just above the measurement point located $\sqrt{2}$ *0.5 m and $\sqrt{2}$ *2 m from the outer plinth on the first line and above the measurement point located 0.5 and 2 m from the outer plinth on the second line. Temperature measurements along the two lines located horizontally and temperature measurements within the concrete floor slab were carried out underneath the same room of the building. Furthermore the soil temperature were measured 2 m from the north/eastern corner along the side of the building facing east in front of the strip foundation 0.2 m from the outer plinth 0.4 m below the ground level.

(a)

(b)



(c)

Figure 5 *(a) Prefabricated elements, made of EPS boards glued together and forming an element, were mounted as the strip foundation, fixed together with comb-shaped pieces of plastic; (b) 300 mm EPS, mounted as two layers on top of the base of stamped gravel bordered by the strip foundation, working as the insulation layer underneath the concrete slab; (c) iron was mounted, as a net inside the strip foundation and as wires along the moat formed by the two vertical boards of EPS in the prefabricated elements before concrete was cast and leveled.*

Outdoor Climate

The outdoor climate was measured at locations outdoors in the shadow. The reason for making these measurements was to observe and be able to explain possible extraordinary results from the temperature measurements taken on site, at measurement points located under the strip foundation, under the insulation of the ground deck and within the concrete floor slab of

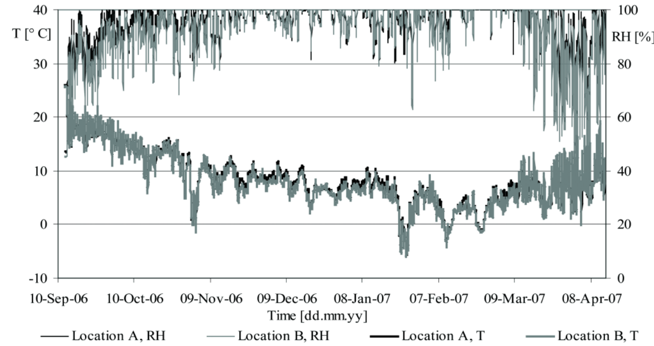


Figure 6 *Temperature and relative humidity measured at two different shady locations. Measurements are shown as mean values of measurements made over a period of six hours.*

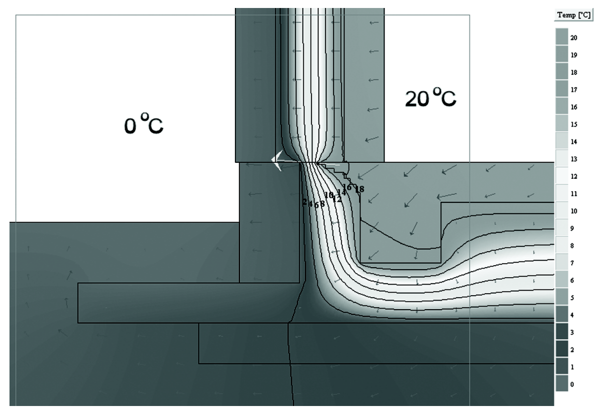


Figure 7 *Temperature, isotherm curves and the heat flow through the prefabricated lightweight element used as strip foundation and the base of a building with a traditional double brick exterior wall.*

the building. Results from the temperature and relative humidity measurements outdoors at two different shady locations (Location A and Location B) are shown in Figure 6. Measurements are shown as mean values of measurements made over a period of six hours.

Heat Flow and Temperature in the Strip-Foundation Element

Figure 7 shows the temperature, isotherm curves and the heat flow calculated for the prefabricated lightweight element used as the strip foundation and the base of a building with a traditional double-brick exterior wall. The overall coefficient of heat transmission of the exterior wall was equal to 0.2 W/m^{2}K. Calculations were made for a building with conventional heating and for an outdoor temperature of 0^{o}C and an indoor temperature of 20^{o}C. The calculation was carried out using the

Table 1. Lowest temperatures Calculated At Measurement Points Facing the Facade to the East*

Measurement points	Facade #1	Facade #2	Facade #3	Facade #4	Facade #5	Inside
Normal year	5.0°C	6.0°C	7.2°C	8.4°C	9.9°C	20°C
Normal year	4.0°C	4.7°C	5.5°C	6.4°C	7.5°C	≥5°C
Normal year	3.8°C	4.4°C	5.1°C	5.9°C	6.9°C	Outdoor
Cold year	1.7°C	3.2°C	4.1°C	6.9°C	9.3°C	20°C
Cold year	0.7°C	1.9°C	3.4°C	5.1°C	7.0°C	≥5°C
Cold year	0.2°C	1.2°C	2.4°C	3.9°C	5.7°C	Outdoor

* Measurement points were located under the strip foundation from under the outer plinth and onward from these points underneath the house at a 90° angle, along a straight line 0, 0.2, 0.5, 1, and 2 m referred to as Facade #1, Facade #2, Facade #3, Facade #4, and Facade #5, respectively.

PC program HEAT2 version 5.0 as a stationary calculation reaching thermal equilibrium between indoor and outdoor temperature. Arrows show the heat flow and the length of the arrows visualizes the size of the heat flow relatively. Isotherm curves are drawn as continuous lines with fixed indications of the temperature of the individual curve. Colors/grayscale are used to visualize the temperatures which are given in the column to the right.

Temperatures Calculated at Measurement Points

The outdoor temperature has an impact on the temperature at the measurement points in between the capillary break layer of gravel and the layer of EPS underneath the building. Table 1 shows the lowest temperatures calculated at the measurements points facing the facade facing east. Calculations were carried out for a constant indoor temperature of 20^{o}C, lowest indoor temperature of 5^{o}C and for an indoor temperature equal to the outdoor temperature. The calculated lowest temperature at the measurement points had a time delay of approximately two months from the time of the lowest outdoor temperature. Calculations were carried out for a building with a traditional double-brick exterior wall.

RESULTS

Results from temperature measurements on site in between the capillary break layer of gravel and the layer of EPS underneath the building are shown in Figures 8 and 9. Figure 8 shows temperature measurements at 5 locations along the line that starts at the north/eastern corner, from under the strip foundation at the outer plinth and onwards from this point at a 45^{o} angle, in the following referred to as Corner #1, Corner #2, Corner #3, Corner #4 and Corner #5 respectively, located along the straight line 0, $\sqrt{2}$ * (0, 0.2, 0.5, 1 and 2) m from the outer plinth. Figure 9 shows temperature measurements at 5 locations along a line that starts 3 m from the north/eastern corner along the side of the building facing east, from under the strip foundation at the outer plinth and onwards from this point at a 90^{o} angle, in the following referred to as Facade #1, Facade #2, Facade #3, Facade #4, Facade #5 respectively, located along the straight line 0, 0.2, 0.5, 1 and 2 m from the outer plinth. Results from temperature measurements on site within the concrete floor slab of the building and within the soil are shown in Figure 10. The measurements at the 4 locations within the concrete floor slab vertically above the locations Corner #2, Corner #5, Facade #2 and Facade #5, are in the following referred to as Corner #1 concrete, Corner #2 concrete, Facade #1 concrete and Facade #2 concrete. In the following, measurement of the soil temperature is referred to as Soil. Measurements are shown as mean values of measurements made over a period of six hours. Unfortunately the datalogger broke down and was not able to make temperature measurements in the period from 24 October to 27 November 2006 and again in the period from 21 January to 9 February 2007.

SUMMARY AND DISCUSSION

The performance of a new prefabricated lightweight element to be used as a strip foundation forming the base of a single-family house was assessed on site. The lightweight elements were made of expanded polystyrene boards. The elements were produced as units 1200 mm in length and 600 mm in width. The assessment of performance was based on observations of the handling of the element on site as well as measurements of temperature conditions at measurement points located at the outer plinth and onwards from these points underneath the building. In addition the soil temperature, the temperature within the concrete floor slab and outdoor temperature and moisture conditions were measured. Recording of outdoor climate at locations in shadow showed "normal" Danish weather conditions when recording the relative humidity and the temperature. However the mean temperatures in November and December were in the high range in Danish climate records. The building was under construction throughout the period of investigation.

Design of Elements

The prefabricated element was designed to comply with the requirements of low energy consumption required in the new Danish Building Regulations. In order to meet the new requirements, buildings that use heating in the concrete floor slab must minimize the heat loss through the foundation element and in practice, normally not exceed a surplus heat

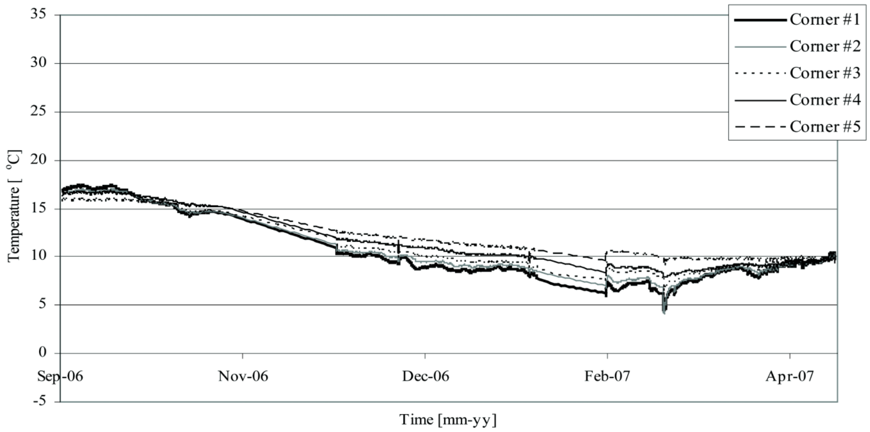


Figure 8 *Temperature measurements at 5 locations along the line that starts at the north/eastern corner, from under the strip foundation at the outer plinth and onwards from this point at a 45^o angle. Corner #1, Corner #2, Corner #3, Corner #4 and Corner #5 are located along the straight line $\sqrt{2}$ *(0, 0.2, 0.5, 1 and 2) m from the outer plinth. Measurements are shown as mean values of measurements made over a period of six hours.*

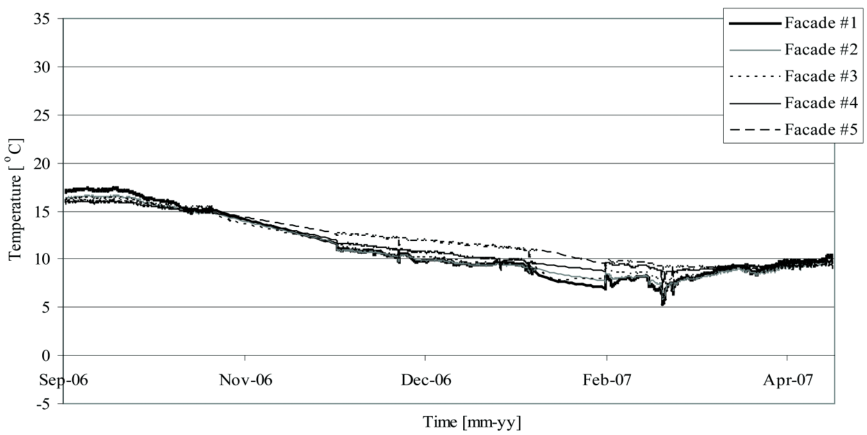


Figure 9 *Temperature measurements at 5 locations along a line that starts 3 m from the north/eastern corner along the side of the building facing east, from under the strip foundation at the outer plinth and onwards from this point at a 90^o angle. Facade #1, Facade #2, Facade #3, Facade #4, Facade #5 are located along the straight line 0, 0.2, 0.5, 1 and 2 m from the outer plinth. Measurements are shown as mean values of measurements made over a period of six hours.*

loss of 0.12 W/mK. When using conventional heating in the building, the surplus heat loss must not exceed 0.15 W/mK. Within these parameters, the overall coefficient of heat transmission of the ground deck and the exterior wall must be equal to or less than 0.12 W/m^{2}K and 0.2 W/m^{2}K respectively. The element used as the strip foundation of the single-family house met the heat-loss requirements when using conventional heating in the building. The surplus heat loss through the foundation element was calculated to be 0.13 W/mK increasing to 0.14 W/mK when using heating in the concrete floor slab. The surplus heat loss through the foundation element increased as the temperature in the block of concrete underneath the exterior wall increased and hence increased the heat flow, especially at the less insulated areas towards the exterior wall, see Figure 7. By eliminating the block of concrete underneath the exterior wall and allowing the strip foundation to support a wood-stud wall, the surplus heat loss through the foundation element was lowered to 0.09 W/mK.

Ensuring that there is stable, non-freezing ground underneath a building is necessary for maintaining structural stability and avoiding settling cracks during cold winters. In order to ensure stability of the strip foundation, temperatures below -1°C must not occur in any layer sensitive to frost underneath the building (Danish Standards 2001). Along the facade outer insulation of EPS, 100 mm in thickness and extending 400 mm in front of the outer plinth and just 150 mm under the ground

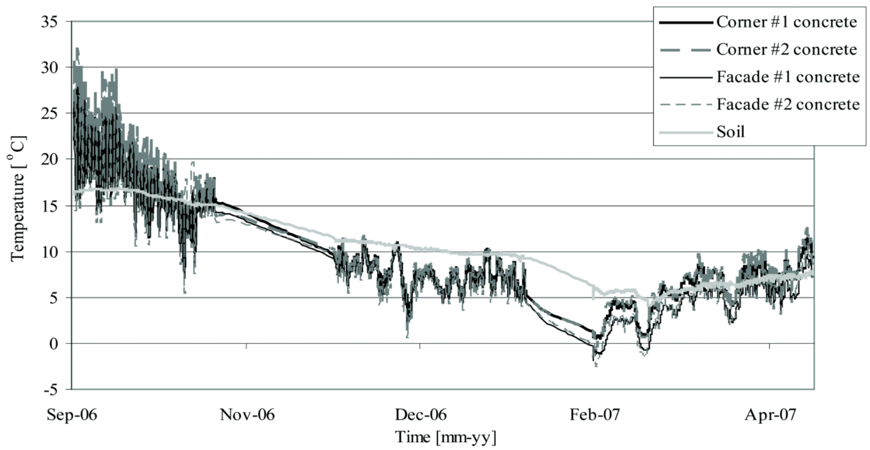


Figure 10 *Temperature measurements within the concrete floor slab of the building and in the soil. Measurements at 4 locations within the concrete floor slab vertically above the locations Corner #2, Corner #5, Façade #2 and Facade #5 referred to as Corner #1 concrete, Corner #2 concrete, Facade #1 concrete and Facade #2 concrete. Measurement of the soil temperature is referred to as Soil. Measurements are shown as mean values of measurements made over a period of six hours.*

level, proved sufficient to keep the soil just underneath the gravel layer non-freezing. In the vicinity of the corners of the building, no extra insulation was needed when keeping the indoor temperature at 20°C. However, when decreasing, the required indoor temperature to a minimum of 5°C, it was necessary to use outer EPS insulation that was 100 mm in thickness and extended 700 mm in front of the plinth and just 150 mm under the ground level. Keeping an indoor temperature equal to the outdoor temperature it was necessary to use outer EPS insulation that was 100 mm in thickness and extended 900 mm in front of the plinth and just 150 mm below the ground level.

For the strip-foundation element to meet the normal requirement of 0.12 W/mK, to be used as shown in Figure 2, for the surplus heat loss for buildings using heating in the concrete floor slab, the prefabricated element must for instance have thicker insulation (170 mm instead of 150 mm) between the concrete floor slab and the concrete acting as the outer plinth, in turn decreasing the thickness of the outer plinth of concrete from 150 mm to 130 mm. Alternatively, by increasing the thickness of the EPS element at the surface facing the insulation of the outer wall from 45 mm to 110 mm. This will provide a strip-foundation element less flexible towards the overall thickness of a wall.

Performance on Site

The investigation covered a real life situation and use of a newly designed element to be used as the strip foundation of a single-family house. The performance of the element was observed and recorded on site. Ground conditions at the building site consisted of a stable ground of glacial deposit (moraine) underneath the top soil layer. The top soil layer was removed with a mechanical mini-excavator in an area comprising the base of the building, including the area for the outer insulation. The area of the base of the building was excavated to a depth of 0.35 m below the top soil surface. The excavated area was then covered with a 0.1 m capillary break layer of gravel and stamped to obtain a stable base for the building. Hereafter the prefabricated elements were mounted on top of the gravel as the strip foundation and fixed together with comb-shaped pieces of plastic and an outer support was established. A layer of insulation was mounted inside the strip foundation serving as insulation underneath the concrete floor slab. The elements were designed to be able to be handled on site by one man, and proved to be so. At the end of the first day concrete iron was mounted inside the strip foundation, as a net, preventing shrinkage crack development, and mounted as wires along the moat formed by the two vertical boards of EPS in the prefabricated elements. Wires of stainless steel rods were placed to form the mechanical fastening point of the concrete for the outer plinth and the concrete floor slab. At the beginning of the second day concrete was cast and leveled. After a few hours, when the concrete was stable in shape, the outer vertical boards of the prefabricated elements of EPS were removed, exposing the outer surface of the concrete moat as the outer plinth. The removed outer vertical boards of EPS were mounted as the outer insulation and covered to protect them from being damaged during the later construction phases of the building. The base of the house was cast in one working operation and completed within two working days.

Measured Temperatures

Temperatures were measured at measurement points located at the outer plinth and onwards from these points underneath the building. In addition the soil temperature, the temperature within the concrete floor slab and temperature outdoors were measured.

The outdoor temperature measured at shady locations is shown in Figure 6. Temperature measurements were found to vary a lot from day to day. However, temperature measurements showed a period with a fairly stable outdoor temperature of -1.2°C in late February. The temperature measured during the same period of time was 5°C at the outer plinth under the strip foundation of the facade. This results in a mean temperature difference of 6.2°C between the outdoor temperature and the temperature under the strip foundation at the outer plinth. Calculations of the lowest temperature under the strip foundation of the facade are shown in Table 1. The calculated difference between the temperature under the strip foundation at the outer plinth and the outdoor temperature was 4.3°C for a normal year when the indoor temperature is equal to the outdoor temperature. The method outlined to determine the temperature in the ground underneath a building was calculated to be 1.9°C lower than measured on site. The method outlined follows the principles stipulated by Danish Standard (Danish Standards 2001 & 2002). From experience calculating on different types of foundation dug at lower depth, the difference in temperature along the facade of a building and at the vicinity of a corner of a building was 2.6°C. The temperature was calculated to be higher along the facade of a building compared with temperatures calculated at the vicinity of a corner of a building. Temperature measurements showed that the difference in temperature along the facade of the building and at the vicinity of the corner of the building was 1.2°C. The temperature was measured to be higher along the facade of the building compared with temperatures measured at the vicinity of the corner of the building.

The method outlined for determining temperatures in the ground underneath a building by using the method outlined by Danish Standard (Danish Standards 2001 & 2002) was shown to be in agreement with temperature measurements carried out on site. However, using the PC finite difference program HEAT2 for 2D and 3D, calculations were shown to produce conservative results that would ensure a stable non-freezing ground underneath the strip foundation used as the base of a single-family house. Ensuring stable non-freezing ground underneath the building is necessary for maintaining the stability of the structure and avoids settling cracks.

Thermal Bridges in the Building Envelope

Thermal bridges in the building envelope cause unnecessary energy loss and a risk of mould growth. The water vapor content in the outdoor air is low in winter. When the cold air enters the heated rooms indoors, it will be heated up and the relative humidity (RH) of the air indoors will decrease as a consequence (Andersen et al. 1993). The indoor air will be altered by water vapor from occupants, plants and from activities included in daily life such as cooking and washing. In this case the air in a heated occupied room will contain more water vapor than the outdoor air. By ventilating, water vapor will be removed from the room. A certain amount air change is necessary to keep the RH of the air at an acceptably low level.

Previous investigations of a real life situation in a community of 24 dwellings, which included thermographic observations of the building envelope, identified a number of thermal bridges (Rasmussen and Nicolajsen 2004, Rasmussen and Hansen 2004). The most important thermal bridges were related to the architectural design of the building. Observations revealed lower temperature than seen for the overall wall, towards the floor panels just above the strip foundation (Rasmussen et al. 2006). In the worst case 12°C along the foot panel (Rasmussen and Nicolajsen 2007) above the strip foundation inside at a room temperature of 20°C and a temperature of -1°C saturated air outside. Assuming that 12°C/75% RH can provide suitable conditions for mould growth, these areas are in danger of mould growth if the foot panel is covered behind curtains, a closet or bookcase indoors. The 24 dwellings investigated were built with a traditional strip foundation used in Denmark before the new stricter energy provisions in the Danish Building Regulations were introduced (Rasmussen and Nicolajsen 2004). Calculations of the temperature, shown as isotherm curves and the heat flow through the strip foundation and the base of a building with a traditional double-brick exterior wall, showed almost identical temperatures at the inner overall wall surface towards the floor panel for a building meeting the new building regulations.

CONCLUSION

This study investigated the performance of the design of a new prefabricated lightweight element to be used as strip foundation for the base of a single-family house. The element was designed to meet the requirements of low energy consumption required in the new Danish Building Regulations. Furthermore, the need of outer insulation to ensuring stable non-freezing ground underneath the building necessary for maintaining the stability of the structure and avoids settling cracks during a cold winter was demonstrated. The designed element was then used in a real-life situation where the construction of a building and normal weather conditions influenced the working operation and the handling of the lightweight element to be used as strip foundation of a single-family house.

The element was designed as a strip foundation to support a single-family house and was shown to be able to be built on the stable ground underneath the top soil layer, just 0.4 m underneath the finished ground surface. Stable non-freezing ground underneath the building was ensured by using insulation located at the outer plinth. The base of the house was cast in one working operation and completed within two working days. The element, made of boards of expanded polystyrene, was handled on site by one man.

The method outlined for determining temperatures in the ground underneath a building combined with experience ensure stable non-freezing ground underneath a building was shown to be in agreement with temperature measurements carried out on site. By using the method, outlined by Danish Standard (Danish Standards 2001 & 2002), temperatures under the strip foundation was calculated to be comparable with measurements on site exposed to normal weather conditions. However, using the PC finite difference program HEAT2 for 2D and 3D, calculations were shown to produce conservative results that would ensure a stable non-freezing ground underneath the strip foundation used as the base of a single-family house.

In conclusion, this study has shown that the EPS and the insulation within the wall must provide full and continuous cover to the heated part of a building in order for the strip-foundation element to provide an efficient and less energy consuming solution for the strip foundation of single-family houses.

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