Superinsulated Strip Foundation for a Single-Family House

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SUPERINSULATED STRIP FOUNDATION FOR A SINGLE-FAMILY HOUSE

by

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ABSTRACT:
A new principle for making superinsulated strip foundations of prefabricated lightweight elements were introduced and demonstrated. The principle was demonstrated on a single-family house with an exterior wall constructed as a traditional wood-stud wall with mineral fiber insulation. The elements made of expanded polystyrene were designed to be handled on site by one man. The base of the house was cast in one working operation and completed within two working days. The element was placed on the stable surface beneath the top-soil layer, only 0.25 m beneath the finished ground surface. Non-freezing ground beneath the house was established by means of insulation material placed at the outer plinth. Elements were integrated into the insulation material placed beneath the concrete floor slab; this constitutes a foundation system allowing very little energy to be lost through the joint between the concrete floor slab and the outer wall. This strip foundation constitutes a full and continuous insulation cover against the heated part of the building. Temperatures were measured at measurement points located at the outer plinth and onwards from these points beneath the building. In addition, measurements were made of the soil temperature, the temperature within the concrete floor slab and outdoor temperatures and relative humidity.

1. INTRODUCTION
In 2005 the Danish Government presented an action plan with the aim of promoting significant results in the energy field. This action plan will have an impact on Danish energy-saving initiatives in the years to come (Ministry of Transport 2005). The action plan includes a description of the Danish energy sector in the years leading up to 2025. The strategy covers the climate policy related to the Kyoto Protocol, United Nations (1998), which entered into force on 16 February 2005. As part of the internal distribution of obligations within the EU, Denmark must reduce its emissions of greenhouse gases by 21% compared with 1990 emissions (Olesen, *et al.* 2004).
The plan focuses particularly on energy consumption in buildings, where the largest and most cost-effective potential for energy savings lies. The most important initiative is a tightening of the energy provisions in the Danish Building Regulations (Danish Enterprise and Construction Authority 1995). The tightening of these energy provisions will apply both to new and existing buildings. Besides a strengthening of current regulations in 2006, the plan paves the way for further strengthening in 2010 and in 2015. The tightened energy provisions came into force on 1 April 2006, and they are expected to result in an energy reduction of 25 % for new buildings compared with the former building regulations. The new energy provisions were incorporated in the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008) that came into force on 1 August 2008 and have had an impact on energy consumption in buildings, in

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that the regulations focus on the building envelope as well as individual building components. One focus area has been heat loss through the strip foundation of a building. In order to meet the new energy consumption requirements and the need to improve innovation and efficiency in the built environment, a new strip foundation principle was developed. The principle was an alternative solution to the strip foundation built 0.9 m beneath the finished ground surface traditionally used in Denmark. The new principle for making superinsulated strip foundations of prefabricated lightweight elements was introduced and demonstrated on site. The new principle paves the way for a further strengthening of the energy consumption requirements relating to heat loss through the strip foundation of a building.

The alternative solution was a prefabricated element made of expanded polystyrene that was demonstrated used as strip foundation and the base of a single-family house with an exterior wall constructed as a traditional wood-stud wall with mineral fiber insulation. The prefabricated element should meet the same performance requirements as traditional solutions.

Methods for establishing stable non-freezing ground beneath the building by taking advantage of natural geothermal energy were described and instructions were drafted of how to handle prefabricated elements on site.

2. Temperature Measurements

The temperature was measured with a type T thermocouples and a data logger, type 605. The junction of the thermocouples was covered with epoxy. Data from the data logger were transferred to a PC and a computer program processed the results. The data logger was placed outdoors in a waterproof plastic container positioned over and above the finished ground surface. The plastic containor was sealed to ensure a dry clean location for the data logger. The plastic container included an electrical supply for the data logger as well as a 10 W heating element. Measurement points were placed on site beneath the strip foundation, at the outer plinth and beneath the insulation layer in the ground deck as well as cast in the concrete floor slab of the building. In addition one measurement point was placed in the soil, approximately 0.4 m beneath the ground level. Measurement points were not exposed to direct sunlight and were well away from any heat-producing appliances. The temperature was recorded every two hours.

3. Meters for Measuring Outdoor Climate

The outdoor climate (temperature and relative humidity) was measured by means of a small data logger. Data from the data logger were transferred to a PC and a computer program processed the results. The data logger was positioned at approximately 3 m above ground level, not exposed to direct sunlight and away from any heat or moisture producing appliances. The climate was determined by temperature and relative humidity and was recorded every hour. The foundation for the house was completed in the late fall of 2007 and the construction site was abandoned for the winter. Construction was to be continued in the summer of 2008.

4. Materials Used for the Strip Foundation

The prefabricated elements were made of expanded polystyrene that was used to form an element, which could be used as strip foundation of a house of up to two storeys. Elements were produced as one coherently shaped element in a production process that included an injection molding process. 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 foam by means of heat, usually steam. The polystyrene is filled with trapped air, which gives it low thermal conductivity. This makes it ideal as a construction material used for insulation in building systems. In the following the expanded polystyrene will be referred to as EPS. The chemical structure 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 °C and a melting point of 240 °C. The calculated thermal conductance is 0.034 W/mK. The prefabricated element consisted of units measuring 1200 mm in length and 600 mm in width. The prefabricated element is approximately 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.

The EPS element was specially designed to form a strip foundation that could be integrated into the insulation material located beneath the concrete floor slab. By integrating the insulation material beneath the concrete floor slab through the strip foundation to the insulation material in the exterior wall, the strip foundation thus constitutes a full and continuous insulation cover against the heated part of the building. Furthermore, by applying a principle that results in a full and continuous insulation cover against the heated part of the building will provide a foundation system that allows very little energy to be lost through the joint between the concrete floor slab and the exterior wall.

The EPS element was specially designed to form the strip foundation that together with the ground deck represent the base of a single-family house with an exterior wall constructed as a traditional wood-stud wall with mineral fiber insulation, see Figure 1a).

5. Performance-based Criteria for the Design of Strip-foundation Elements

The prefabricated EPS element was designed to comply with the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008), which allow very little heat to be lost through the strip foundation between the ground deck and the exterior wall. Furthermore, it was the objective to show how to establish superinsulated strip foundations for single-family houses by following the new principle. The principle of how to reduce the heat loss through the strip foundation of a traditionally constructed single-family house paves the way for a further strengthening of the energy consumption requirements. Reducing the energy consumption for heating and comfort and improving energy efficiency by eliminating thermal bridges in the building envelope lead to more sustainable buildings. In the following heat loss through the strip foundation will be referred to as the surplus heat loss, [W/mK]. The surplus heat loss is defined as the heat loss that can be attributed neither to the one-dimensional heat loss through the ground deck nor to the exterior wall. Surplus heat loss through the joint between the ground deck and the exterior wall is closely related to the design of the strip foundation.

To comply with the new energy provisions of 1 January 2006, which came into force on 1 April 2006 and are incorporated in the Danish Building Regulations (Danish Enterprise and Construction Authority 2008), in practice strip foundation of buildings must normally not exceed a surplus heat loss of 0.12 W/mK, when using heating in the concrete floor slab. The surplus heat loss must not exceed 0.15 W/mK in practice when using conventional heating in the building. Danish Building Regulations require the overall coefficient of heat transmission of the ground deck and the exterior wall to be equal to or less than 0.12 W/m^{2}K and 0.2 W/m^{2}K respectively.

Calculations of the surplus heat loss through the prefabricated element were carried out by 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 2.

Figure 1b) shows the prefabricated EPS element used as strip foundation for a traditional wood-stud wall with mineral fiber insulation. The exterior wall has 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 cracking reinforcement is 1.6 W/mK. Stainless steel rods 5 mm in diameter were put through the EPS at every 600 mm, thus 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 with 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 0.09 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 still calculated to be 0.09 W/mK. Calculations were carried out with a temperature of the concrete floor slab of 30 °C and with an interim insulation to the soil of 1.5 m^2K/W, which allowed the overall coefficient of heat transmission of the ground deck to be 0.1 W/m^2K.

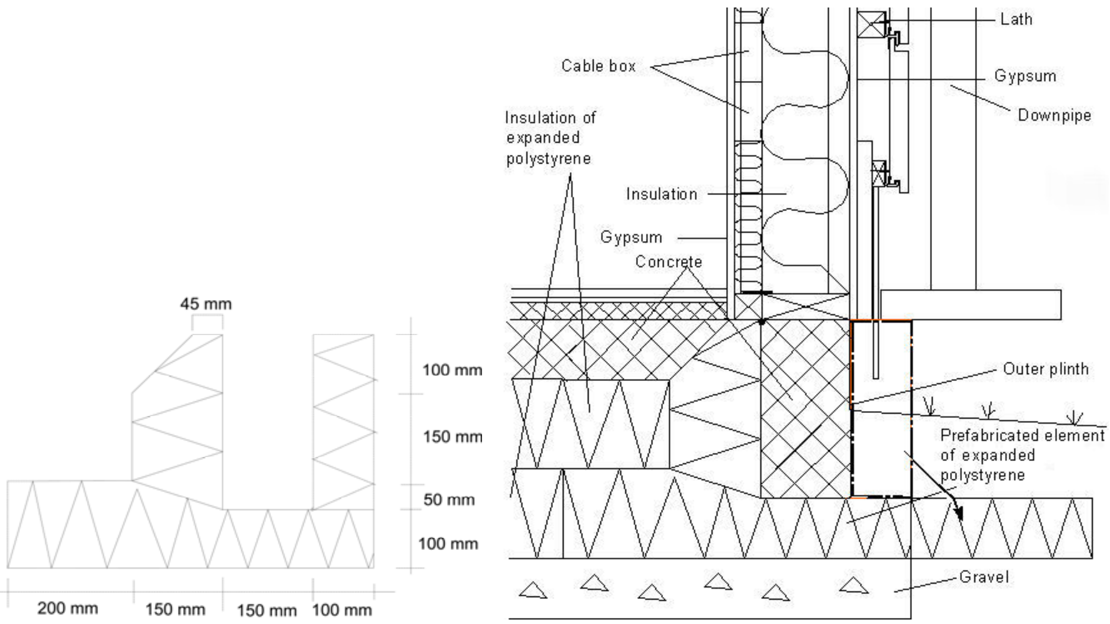

Figure 1 a): left, the prefabricated EPS element, b): right, the EPS element used as the strip foundation of a traditional wood-stud wall with mineral fiber insulation.

In a building using conventional heating with the traditional wood-stud wall with mineral fiber insulation and with the overall coefficient of heat transmission of the exterior wall equal to 0.2 W/m^2K, the surplus heat loss was calculated to be 0.09 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 0.09 W/mK. For the calculations, the temperature towards the concrete floor slab was 20 °C with an interim insulation to the ground deck and soil of 1.67 m^2K/W, which allows the 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.

6. Ensuring Stable Non-freezing Ground Beneath the EPS Element

Ensuring stable non-freezing ground beneath the building is necessary for maintaining the stability of the structure and avoiding settling cracks. To ensure stability of the strip foundation, it is important that temperatures below -1 °C do not occur in any layer beneath the building susceptible to frost during a cold winter (Danish Standards 2001). Temperatures below -1°C beneath the capillary breaking layer during a cold winter could cause frost deformations of the soil beneath, and this would increase the risk of settling of the strip foundation. EPS boards from the outer plinth of the strip foundation were used to form the part of the prefabricated element called the outer insulation. Taking advantage of natural geothermal energy, (Steiner 2004) stable non-freezing ground underneath the building was established by outer insulation. At the vicinity of a corner of the building, the necessary outer insulation was designed on the basis of the experience gained from 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 at equal depths. 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 2. Figure 2 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).

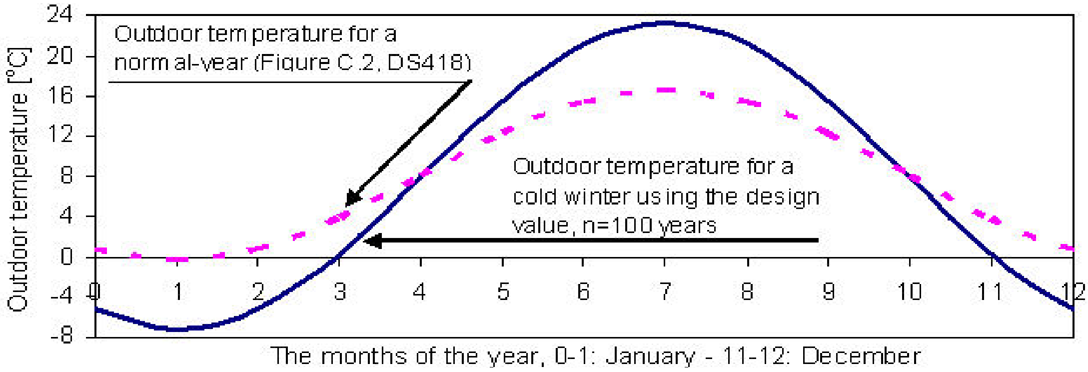

Figure 2. Variation of the monthly outdoor mean temperature for a normal year and for a cold year in Denmark

Outer insulation was designed for three different cases describing the indoor temperatures, 1) an indoor temperature of 20 °C, 2) an indoor temperature equalling the outdoor temperature but not lower than 5 °C, and 3) an indoor temperature equalling the outdoor temperature.
Along the facade of a building, calculations showed that an outer EPS insulation, 0.1 m thick and extending 0.4 m in front of the outer plinth of a building facade only 0.15 m under the finished ground surface, was sufficient to keep the soil immediately beneath the gravel layer from freezing during a cold winter, while keeping an indoor temperature equal to the outdoor temperature.
In addition calculations showed that the outer insulation needed to be extended at the vicinity of a corner of a building. Calculations showed that by keeping the indoor temperature at 20 °C, it was sufficient with an outer EPS insulation, 0.1 m thick and extending 0.42 m in front of the outer plinth only 0.15 m under the finished ground surface in order to keep the soil immediately beneath the gravel layer in the vicinity of a corner of a building from freezing during a cold winter. If the indoor temperature was kept equal to the outdoor temperature but not lower than 5 °C, it was sufficient with an outer EPS insulation, 0.1 m thick and extending 0.7 m in front of the outer plinth only 0.15 m under the finished ground surface, in order to keep the soil immediately beneath the gravel layer in the vicinity of a corner of the building from freezing during a cold winter. However, if an indoor temperature equal to the outdoor temperature was maintained, an outer EPS insulation (0.1 m thick and extending 0.9 m in front of the outer plinth and only 0.15 m under the finished ground surface) was able to keep the soil immediately beneath the gravel layer in the vicinity of a corner of a building from freezing during a cold winter. It is recommended that the vicinity of the corner should include the area in the ground in front of the corner and the area along the facade of a building, at least covering the extra length of outer insulation along the outer plinth around the corner.

7. PERFORMANCE ON SITE

In most locations in Denmark a stable ground of glacial deposits (moraine) is found beneath a top-soil layer approximately 0.2 to 0.4 m thick. The top-soil layer was removed from an area covering the area of the building. Material at least up to a depth of 0.35 m beneath the top-soil surface had to be dug up. The excavated area was then covered with a 0.1 m capillary breaking layer of gravel, which was stamped in order to form the stable base for the building. Temperature measurement points were mounted on top of the gravel layer and the prefabricated elements were mounted on top as the strip foundation, see Figure 3a). Mounting the strip foundation, held together with large staple-shaped pieces of plastic and outer support, 0.3 m of EPS in two layers was mounted inside the strip foundation serving as insulation beneath the concrete floor slab, see Figure 3b). Before casting the concrete, iron was mounted as a net that prevented the development of shrinkage cracking inside the strip foundation, and as wires along the moat formed by the two vertical EPS boards in the prefabricated elements. Wires of stainless steel rods, 5 mm in diameter were put through the inner vertical boards of the prefabricated EPS elements every 0.6 m, in order to attach the concrete in the moat to the concrete floor slab. Concrete was cast and leveled. After a few hours, when the concrete was stable in shape, the outer vertical EPS boards of the prefabricated EPS elements were removed, thus exposing the outer surface of the concrete moat as the outer plinth. The removed outer vertical EPS boards were used as the outer insulation on the ground around the outer plinth.

FIG. 3 a): left, prefabricated EPS elements mounted as the strip foundation and held together with large staple-shaped pieces of plastic, b): right, 300 mm EPS, mounted as two layers on top of the base of stamped gravel bordered by the strip foundation, serving as the insulation layer beneath the concrete slab.

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

8. OUTDOOR CLIMATE

The outdoor climate was measured at a location in the shadow. The reason for making these measurements was to observe outdoor exposure and to be able to explain possible extraordinary results of the temperature measurements made on site, at measurement points located beneath the strip foundation, beneath the insulation of the ground deck and within the concrete floor slab of the building. Results of the temperature and relative humidity measurements are shown in Figure 4. Measurements are shown as mean values of measurements made over a 6-hour period.

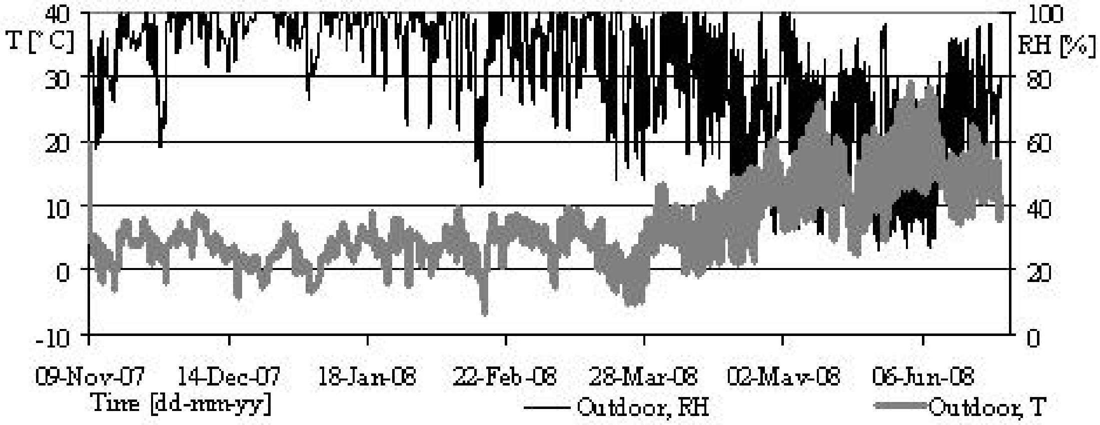

Figure 4: Temperature and relative humidity measured outdoors at a shady locations. Measurements are shown as mean values of measurements made over a 6-hour period.

9. HEAT FLOW AND TEMPERATURE IN THE STRIP-FOUNDATION ELEMENT

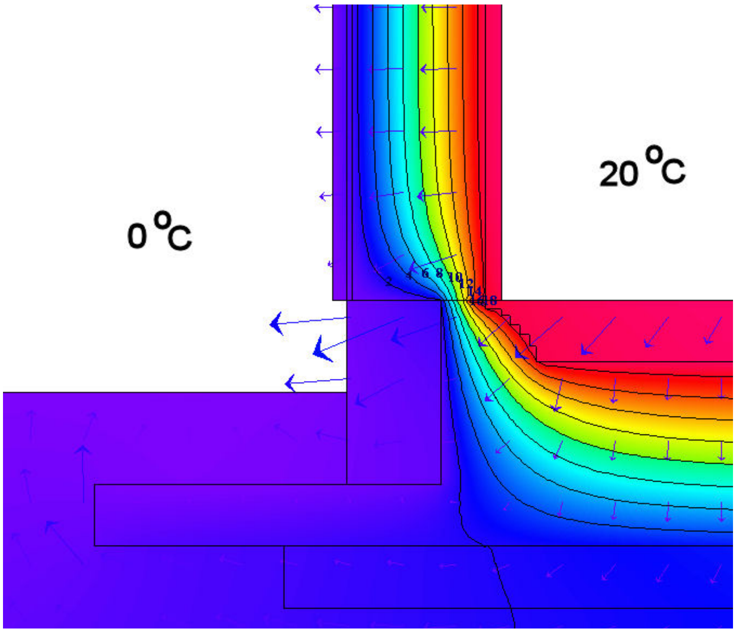

Figure 5. Temperature, isotherm curves and the heat flow through the prefabricated lightweight element used as strip foundation and the base of a building with a traditional wood-stud wall with mineral fiber insulation as the exterior wall.

Figure 5 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 wood-stud wall with mineral fiber insulation as the 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 °C and an indoor temperature of 20 °C. The calculation was carried out using the 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 are used to visualize the temperatures, the blue colors visualize lower temperatures and the red colors visualize higher temperatures.

10.TEMPERATURES CALCULATED AT MEASUREMENT POINTS

The outdoor temperature has an impact on the temperature at the measurement points between the capillary breaking layer of gravel and the layer of EPS beneath the building. Table 1 shows the lowest temperatures calculated at the measurements points facing the west-facing facade. Calculations were carried out for i) a constant indoor temperature of 20 ^{o}C, ii) a lowest indoor temperature of 5 ^{o}C and iii) 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 wood-stud wall with mineral fiber insulation as the exterior wall.

TABLE. 1: Lowest temperatures calculated at measurement points facing the west-facing facade. Measurement points were located under the strip foundation from under the outer plinth and onwards from these points beneath the house at a 90^{o} angle, along a straight line 0, 1 and 2 m referred to as Facade #1, Facade #2, Facade #3, respectively.

Measurement points	Facade #1	Façade #2	Facade #3	Inside
Normal year	4.9 ^{o}C	8.3 ^{o}C	9.8 ^{o}C	20 ^{o}C
Normal year	4.0 ^{o}C	6.4 ^{o}C	7.5 ^{o}C	$\geq$5 ^{o}C
Normal year	3.8 ^{o}C	5.9 ^{o}C	6.9 ^{o}C	Outdoor
Cold year	1.5 ^{o}C	6.8 ^{o}C	9.2 ^{o}C	20 ^{o}C
Cold year	0.7 ^{o}C	5.0 ^{o}C	7.0 ^{o}C	$\geq$5 ^{o}C
Cold year	0.2 ^{o}C	3.9 ^{o}C	5.7 ^{o}C	Outdoor

10.RESULTS

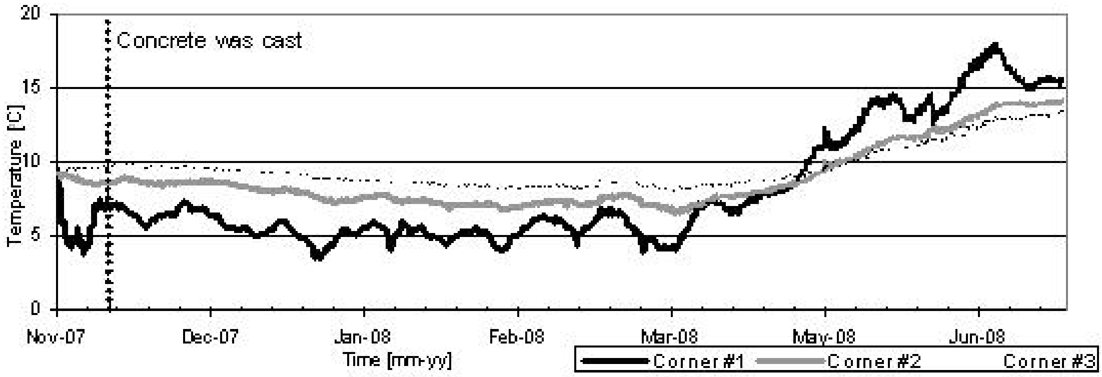

Figure 6. Temperature measurements at 3 locations along the line that starts at the north/western corner, from under the strip foundation at the outer plinth and onwards from this point at a 45^{o} angle.

Results from temperature measurements on site between the capillary break layer of gravel and the layer of EPS beneath the building are shown in Figures 6 and 7. Figure 6 shows temperature measurements at 3 locations along the line that starts at the north/western 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, and Corner #3 respectively, located along the straight line

$\sqrt{2}$ * (0, 1 and 2) m from the outer plinth. Figure 7 shows temperature measurements at 3 locations along a line that starts 3 m from the north/western corner along the west-facing side of the building, 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, and Facade #3 respectively, located along the straight line 0, 1 and 2 m from the outer plinth. Measurements are shown as mean values of measurements made over a 6-hour period.

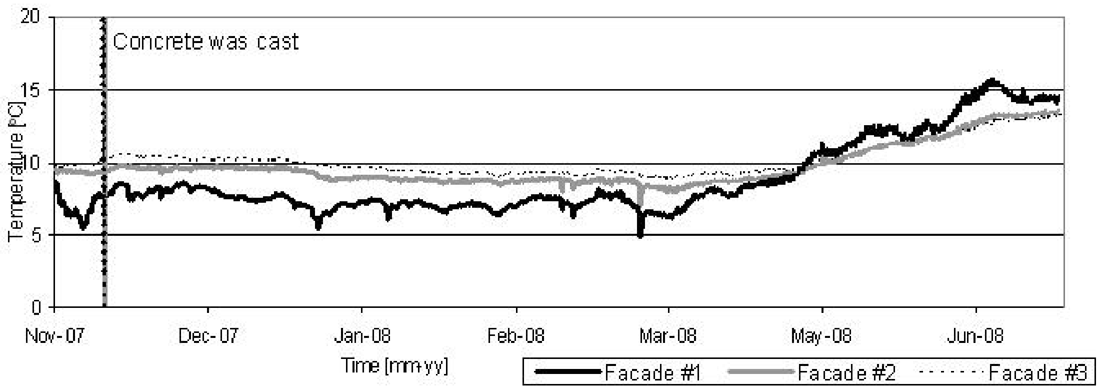

Figure 7. Temperature measurements at 3 locations along a line that starts 3 m from the north/western corner along the west-facing side of the building, from under the strip foundation at the outer plinth and onwards from this point at a 90^o angle.

Results from temperature measurements on site within the concrete floor slab of the building and within the soil are shown in Figure 8. In the following the measurements at the 2 locations within the concrete floor slab vertically above the two lines, one located $\sqrt{2}$ *0.5 m from the outer plinth above the first line and the other located above the measurement point referred to as Facade #3, are referred to as Corner concrete and Facade #3 concrete; measurement of the soil temperature is referred to as Soil. Measurements are shown as mean values of measurements made over a 6-hour period.

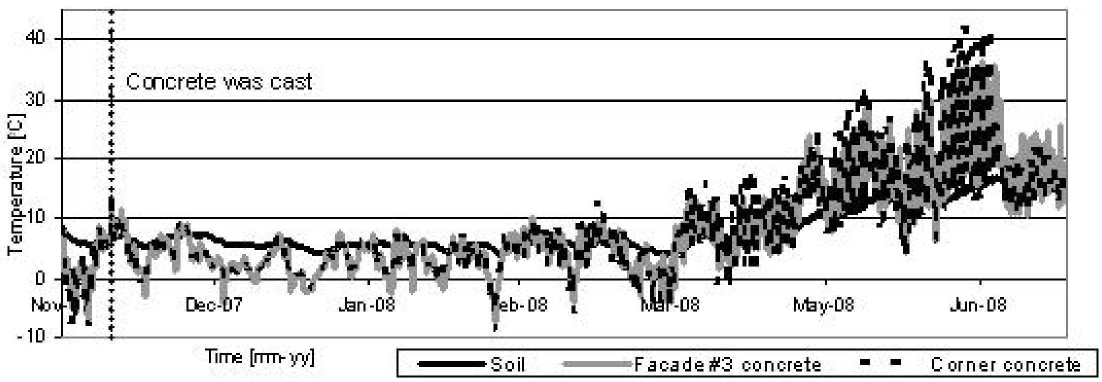

Figure 8. Temperature measurements within the concrete floor slab of the building and in the soil.

11. SUMMARY AND CONCLUSION

This study investigated the performance of the design of a new prefabricated lightweight element used as the strip foundation of a traditional wood-stud wall with mineral fiber insulation as the exterior wall. The element was designed for low energy consumption and it was shown to be even lower in practice, than what is required in order to comply with the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008). Furthermore, it was demonstrated that outer insulation is needed to ensure stable non-freezing ground beneath the building, which is necessary for maintaining the stability of the structure and for preventing settling cracks during a cold winter by taking advantage of natural geothermal energy. The designed element was then used in a real-life situation, where the construction of a building and normal weather conditions affected the working operation and the handling of the lightweight element used as strip foundation of a traditional wood-stud wall with mineral fiber insulation as the exterior wall.

The element was designed as a strip foundation to support a traditional wood-stud single-family house. It was shown that the element could be built on stable ground beneath the top-soil layer, only 0.25 m beneath the finished ground surface. Stable non-freezing ground beneath 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 expanded polystyrene, was handled on site by one man.

The method outlined for determining temperatures in the ground beneath a building combined with experience to ensure stable non-freezing ground beneath a building was shown to be in agreement with temperature measurements carried out on site. Temperature measurements on site, Figure 4 to Figure 7 indicate temperature conditions referred to as iii), a house with an indoor temperature equalling the outdoor temperature exposed to outdoor temperature for a normal-year. As listed in TABLE 1, iii) normal-year shows that the method for calculating the temperatures under the strip foundation, outlined by Danish Standards (Danish Standards 2001 & 2002), was calculated to be comparable with the measurements on site. However, by using the PC finite difference program HEAT2 for 2D and 3D, calculations were shown to provide conservative results that would ensure a stable non-freezing ground beneath the strip foundation used as the base of a single-family house.

In conclusion, this study has demonstrated that by using the EPS element a full and continuous cover of the heated part of a building can be established at the joint between the exterior wall and the ground deck. The strip-foundation element was shown to provide an efficient and less energy consuming solution for the strip foundation of traditional wood-stud single-family houses.

12. Acknowledgement

Sundolitt A/S, Denmark has supported this field study.

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