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CASE STUDY OF COST-SAVING AND ENERGY-EFFICIENT HOUSES WITH INTERNAL INSULATION SYSTEMS

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Abstract

The paper aims to assess the suitability of a foreign construction technique for use in the climatic conditions of the Czech Republic. The internal insulation of the investigated houses is combined with shell block masonry manufactured on vibrating presses imported from France. The evaluation of measurements taken at selected construction sites demonstrates the safety of such houses from moisture condensation on interior surfaces and inside insulation layers. Any defects and leaks in the envelope of the houses were determined using infrared imaging, while air tightness was measured by a blower door. The thermal comfort level in critical rooms in relation to intermittent heating is also significant. In this contribution, the results obtained in the evaluated houses are compared to data from computer simulations. The construction costs are compared to the costs of similar buildings made of materials commonly used in the Czech Republic. Costs were calculated using Czech costing software. Environmental impacts are evaluated using methods for the life cycle assessment of buildings.

Key words

Concrete shell blocks; internal insulation; humidity of external walls; thermal comfort; environmental impacts; costs of chosen constructions

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1 INTRODUCTION

The paper presents the results of research carried out at houses built according to a French technique in the climatic conditions at different locations in the Czech Republic. It primarily involved the implementation of a building envelope whose walls consisted of internal thermal insulation and load-bearing masonry constructed from concrete shell blocks. The use of the "French" shell blocks in comparison with burned clay hollow bricks is especially advantageous in terms of the lower greenhouse gas emissions arising during their production. The construction of houses with internal thermal insulation requires a certain composition of external walls to be built as a whole to avoid the risk of the condensation on internal surfaces and to meet the limits of the vapour condensation within the structure, which must be lower than subsequent evaporation during the annual cycle. The research is long-term in nature, being conducted since 2008. The evaluation of its outcomes, including the subsequent development and modification of the building technology processes by Czech designers and contractors, conformed to the directive [1].

Within the scope of the research programme at the Institute of Technology, Mechanization and Construction Management [2], this type of building has been investigated in the climatic conditions of the Czech Republic from different points of view:

1/ Evaluation of the continuous measurements made with temperature sensors in order to assess the thermal comfort of users and the thermal stability of the critical rooms in winter

2/ Verification of the thermal properties of external wall structures according to ČSN 73 0540-2 (2011) "Thermal protection of buildings – Requirements" valid for the Czech Republic:

- the lowest internal surface temperature
- the heat transfer coefficient
- the condensation of water vapour within the structure
- the annual balance of condensation and evaporation of water vapour within the structure
- the air tightness of the envelope structure

3/ Detection of the incidence of thermal bridges and any defect in the building envelope with thermal imaging camera

4/ Measurements of the air permeability of the building envelope due to the pressure gradient using a blower door device; this was carried out in accordance with ČSN EN 13829 "Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method".

5/ Estimation of the environmental impact of the implemented masonry technique and the subsequent use of the buildings was performed in accordance with the French "Life Cycle Assessment" certificate [3]. For the overall evaluation of external walls with internal insulation, the LCA data [4] often used in Czech Republic were applied.

6/ The evaluation of this method of constructing external walls was accompanied by an economic assessment of the structure.

2 RESULTS OF THE MEASUREMENTS WITH TEMPERATURE SENSORES

In the context of the research, two houses situated in climatically different localities in the Czech Republic were selected. This section presents the results of measurement at a typical detached house with ground floor and attic in the Moravian-Silesian Beskydy Mountains in the village of Pržno. A schematic view of the south façade is shown in Fig. 1.

Fig. 1: Schematic view of the south façade

The house is covered by a hipped roof and was constructed without a basement. The supporting parts of the 200 mm thick external walls were built of Betong hollow blocks. These masonry units, known as concrete shell building blocks, are manufactured on vibro-presses which Adler imported from France. The concrete mixture determined for the production plant at Ratiškovice near Hodonín contains: dolomitic limestone of fractions 0-4 mm and 4-8 mm, a cement dose of 6-8 % and mixing water. Automated production control ensures precise adherence to mix recipes and that all blocks of one type have exactly the same dimensions. The shell is usually up to 18 mm thick. For blocks kinds – see Fig. 2:

Continuous *Corner* *Dividing* *Moulding* *Ceiling*

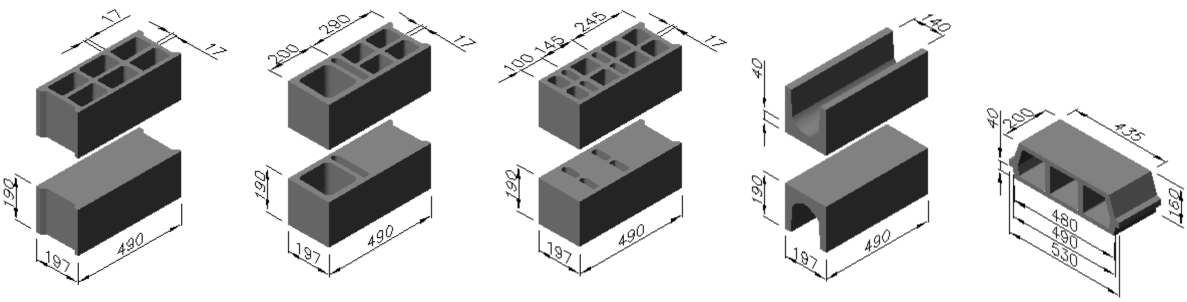


Fig. 2: Main production range of concrete blocks

An internal insulation system was used for heat insulation of external walls. It is based on a sandwich panel made up of gypsum drywall board and a thermal insulation layer of stabilized expanded polystyrene. The thickness of the thermal insulation material, within the used Rigitherm panels (12.5+140 mm [5]), was 140 mm. The panels were fully glued on interior surfaces of the walls built of Betong blocks.

The ceiling structures above the ground floor were created as composite steel and concrete ceilings with suspended false ceilings assembled from gypsum boards. As for the insulation, it is formed from blown mineral wool with a thickness of 140 mm. Thermal insulation of the floor on the ground is made of expanded polystyrene with high compressive strength. The thickness of the layer is 100 mm. Wooden floors and carpets are laid in habitable rooms. Bearing and non-bearing walls are separated by insulation at places where they connect with outer walls, thus avoiding thermal bridges and linear thermal bindings. The frames of windows and entrance doors have been properly inserted into the layer of internal thermal insulation. The continuous measurement was carried out in a north-facing room during the period from 12th to 20th December. Fig. 3 and 4 illustrate the distribution of sensors.

Fig. 3: View of the measurement setup – the image was taken, along with the related Figs. 4 and 5, from a document by the authors Hrazdil et al. available in Design Materials section of the company Be-Tong Hodonín's, web pages at http://be-tong.cz

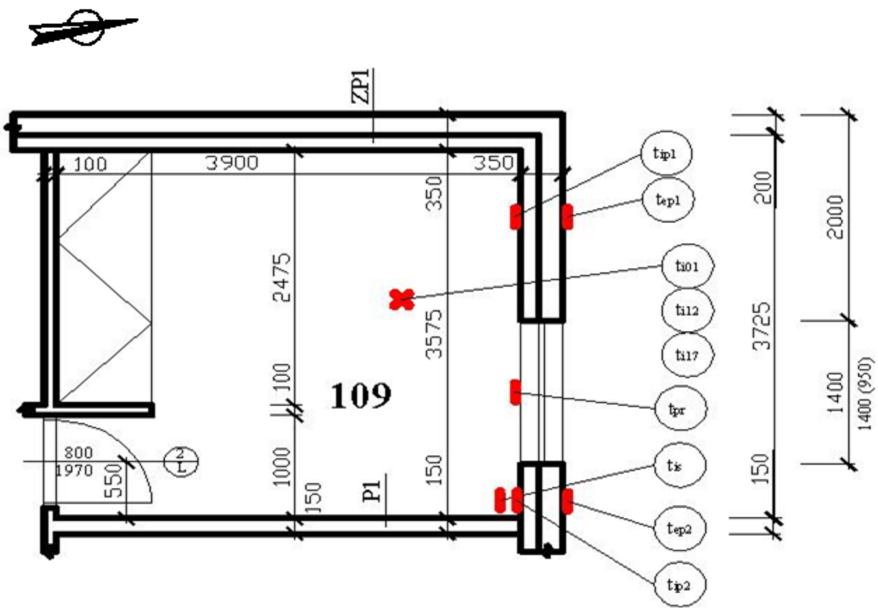


Fig. 4: Deployment of sensors in the north- facing room on the ground floor

The given room is separated from adjoining, similarly used, spaces of the ground floor by Betong 150 and 100 mm partitions. Both partition walls are plastered with a thickness of 15 mm. The room was heated with a low-temperature radiator. The water used for heating is prepared in a condensing gas boiler. During heating, the temperature of the surface of radiator usually fluctuates around 35 ˚C (measured by the sensor t_{pr}).

The heating mode was set to intermittent. The heating of the house was switched off every night from 10 pm to 6 am. At the time of the experiment, the attic of the house was neither inhabited nor heated. It should be noted that no habitable rooms had been completed in the attic at the time of measurement; thermal insulation of the roof would be desirable, but it was missing at that time. A description of sensor locations in the room and on the surfaces of the north peripheral wall and the ceiling is provided in Tab. 1. The measurements were performed with the sensors shielded against radiation from surrounding areas, and direct solar radiation.

Tab. 1: Placement of sensors

Sensor	**Description**	**Placement**
	Air temperature in the vertical	Height above flooring
t_{i01}	at the level of a person's ankle	0.1 m
t_{i02}	at the level of a person's abdomen	1.1 m
t_{i03}	at the level of a person's head	1.7 m
	Surface and ambient temperatures	Interior/Exterior
t_{pr}	surface temperature of the radiator	interior
t_{is}	temperature of the ceiling	interior
t_{ip1}	surface temperature of the peripheral wall	interior
t_{ep1}	surface temperature of the peripheral wall	exterior
t_{ip2}	surface temperature of the peripheral wall	interior
t_{ep2}	surface temperature of the peripheral wall	exterior
t_e	air temperature	exterior

The measurements and their accuracy comply with legal regulations and technical standards. A measurement data logger and sensors with a sensitivity of 0.1 ˚C were used for digital measurement and value recording. The results were checked by separate, single-point measurements, which also complement the data on air humidity and air movement in the room.

The air temperatures at different vertical levels demonstrate compliance with the standard. The maximum difference between the temperatures at the height of the ankle and head of a standing person was only 0.9 ˚C during the entire nine-day measurement period. The interior surface temperatures of the external wall were measured at a height of 1.1 m with sensors t_{ip1} and t_{ip2}. The second sensor was placed near the join between the inner and outer construction. The differences in the recorded values were inconclusive, being a maximum of 0.4 ˚C. Also, the deviations of the values measured on the inner surface in comparison with the indoor air temperature were very low. The surface temperature dropped only once during the entire period of measurement, with a decrease of 1.9 ˚C compared to the air temperature. Appreciable results were also provided by ceiling sensor t_{is}, which was placed in the corner of the room, and in addition, close to the window. The expected reduction in surface temperature was not recorded. Conversely, the measured values were obviously higher than the results from the sensor t_{ip2} positioned below (1.5 ˚C on average). Analysis of the continuous measurement confirmed thermal stability within the definition of cited standard ČSN 73 0540-2 (2011), which requires that the temperature in the critical room of a house does not decline more than the limits allow. This condition was met.

Fig. 5 shows a typical part of the periodically fluctuating temperatures that was selected from the tabular outputs from the time when measurements were taken during the winter. The graphical representation starts at 10 o'clock in the evening, when a drop of the temperature of the radiator occurs. It then illustrates the next 16 hours of controlled heating (from 6 am to 10 pm) and, thereafter, periodically continues.

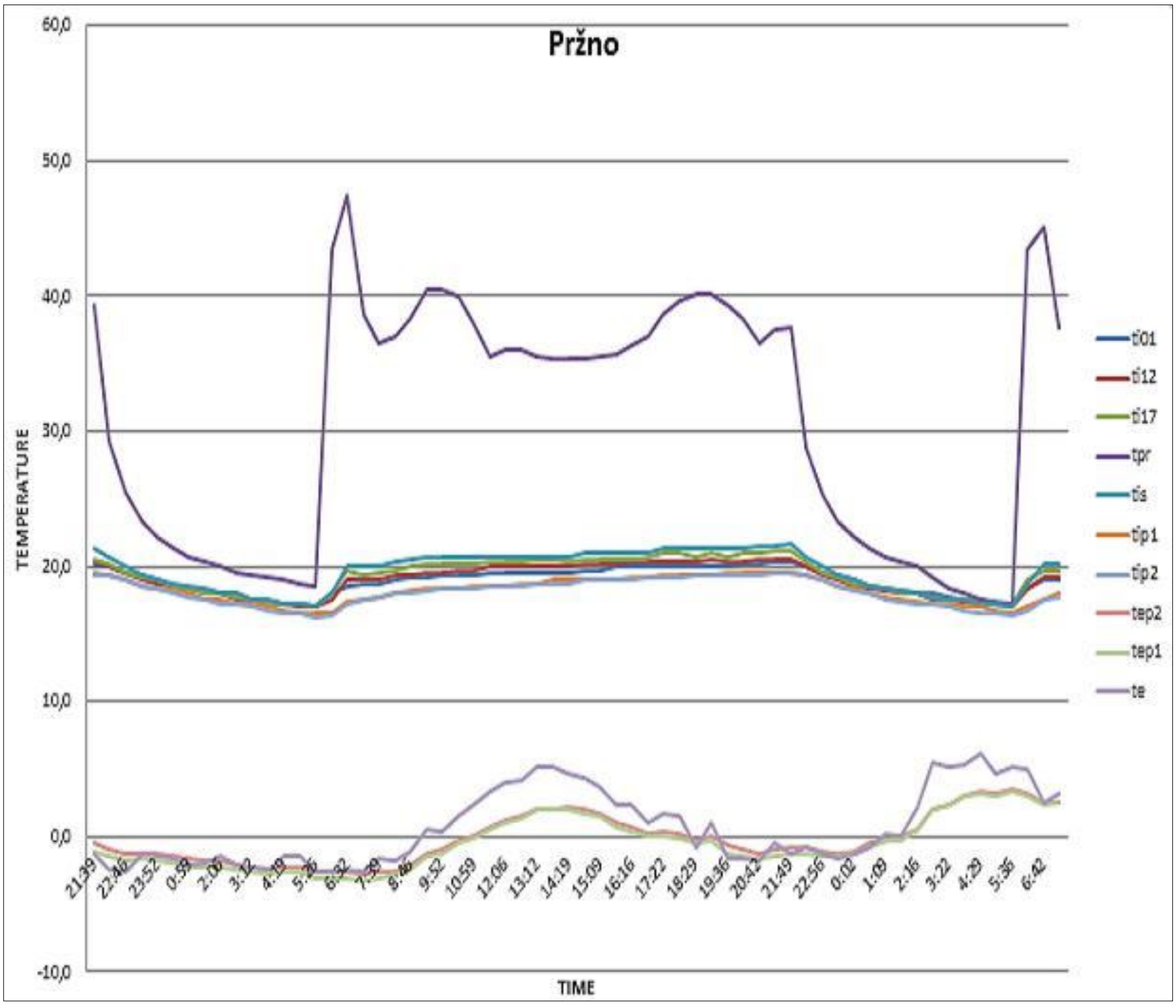


Fig. 5: Temperature curves in the interior of the critical room

On the basis of the measurements in the north-oriented room, which had a significant proportion of external walls, we can draw the following conclusions: The persons inhabiting the room and the whole house did not experience any thermal discomfort in winter. They were not disturbed by greater vertical differences in temperature or by asymmetric radiation from surfaces. A noticeable advantage of the internal insulation is the instantaneous rise in air temperature in the interior of the house once the heating is resumed.

The occupants of the house were also asked about their subjective feeling of thermal comfort during the hottest days of summer. They evaluate the internal environment of the house as “thermally neutral and comfortable”.

3 VERIFICATION OF THERMAL AND HUMIDITY CHARACTERISTICS BY USING SOFTWARE MODELLING

The characteristics of the external wall structure of the examined house at Pržno were entered into a calculation process (in “Teplo” software for one-dimensional heat losses [6]); see Tab. 2. When determining the characteristics of the concrete blocks and their air cavities, the influence of the shell block floors, walls and masonry mortar were calculated as thermal bridges.

Tab. 2: Composition of layers (from the interior)

Nº	Designation	Thickness	Thermal conductivity	Specific heat capacity	Bulk density
		D [m]	λ [W/(m.K)]	C [J/(kg.K)]	ρ [kg/m^3]
1	Gypsum plasterboard	0.0125	0.22	1060.0	750.0
2	Expand. polystyrene	0.14	0.033	1270.0	35.0
3	Construct. adhesive	0.004	0.22	1300.0	1500.0
4	Shell wall of blocks	0.02	1.01	830.0	2000.0
5	Air cavities	0.07	0.422*	967.7	470.9
6	Shell wall of blocks	0.02	1.01	830.0	2000.0
7	Air cavities	0.07	0.422*	967.7	470.9
8	Shell wall of blocks	0.02	1.01	830.0	2000.0

The calculated lowest indoor surface temperature was higher than the required values for winter. The reason for this is to prevent condensation and mould growth. Therefore, determining the minimum temperature factor value of inner surfaces f_{Rsi} is important. The calculation conditions contain a design outdoor temperature and relative humidity of outdoor air: - 15 ˚C and 84 % respectively. For the indoor air: 20 ˚C, 50 %. The critical temperature factor of the inner surface is stated by the standard ČSN 73 0540-2 and the amendment ČSN 73 0540-2 Z1 (2012). The value takes into account the air humidity safety margin of + 5 % and the factor for wall surfaces was applied: $f_{Rsi,cr} = 0.744$. The value calculated in accordance with the design conditions was: $f_{Rsi} = 0.950$.

The temperature factor values of the in critical structural details of the houses designed using the investigated French construction technique have also been stated in a PhD thesis by Čech [7]: The calculated minimum value of $f_{Rsi} = 0.928$, and thus the condition below (1) was met. The fulfilment of this requirement confirms that the conditions for mould growth on wall surfaces are not present.

$$f_{Rsi} > f_{Rsi,cr} \quad (1)$$

Based on our research, another requirement concerning the potentially harmful spreading of moisture in structures was also fulfilled: In the case of the external walls, the output of the modelling of the temperature and moisture behaviour of the tested structure validates their advantageous physical properties - see Fig. 6.

In addition to the one-dimensional solution, critical details were examined via two and three–dimensional modelling (in 2D Area and 3D Cube programs, respectively). Also, in the case of critical design details, the conditions of the standard relating to moisture distribution in structures have been met. The values calculated using software simulation were compared to the values measured on site. It should be noted that the house in Pržno had insulating layer fully glued to the wall. This layer is more frequently laid on the so-called targets of adhesive, thus creating unventilated air gap of 10 mm between the masonry and insulation. This method of construction causes further reduction in existing low condensation.

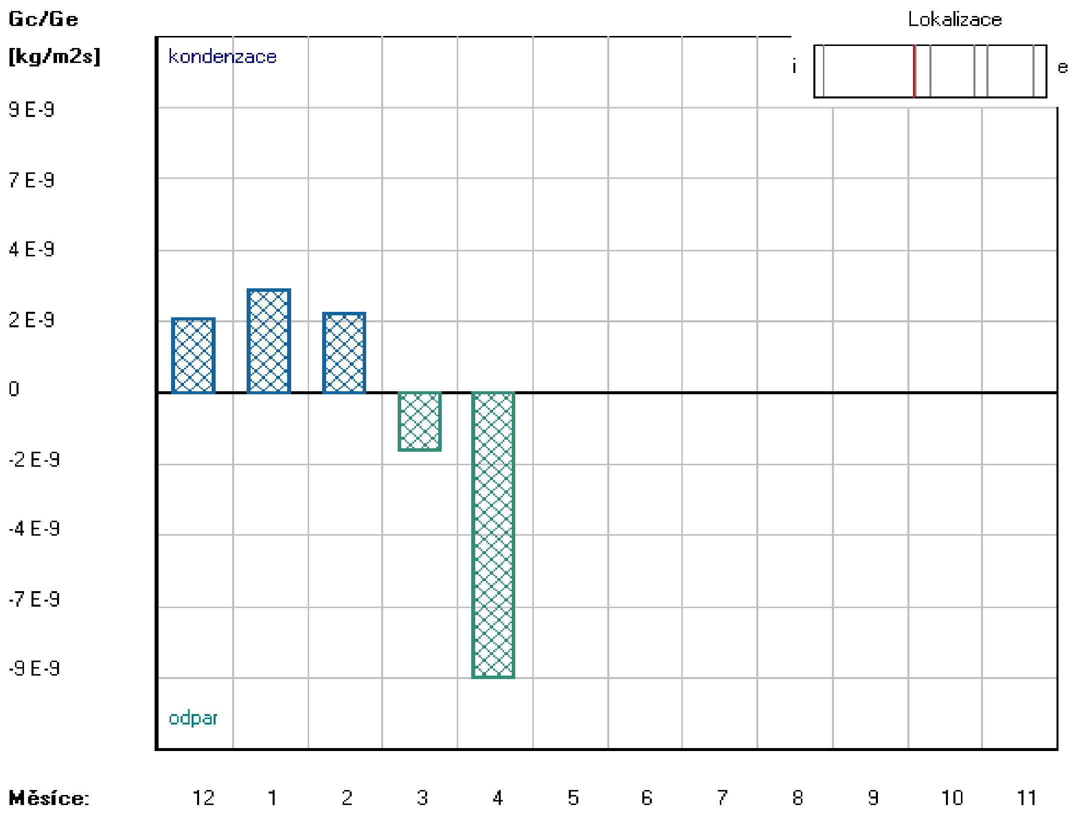


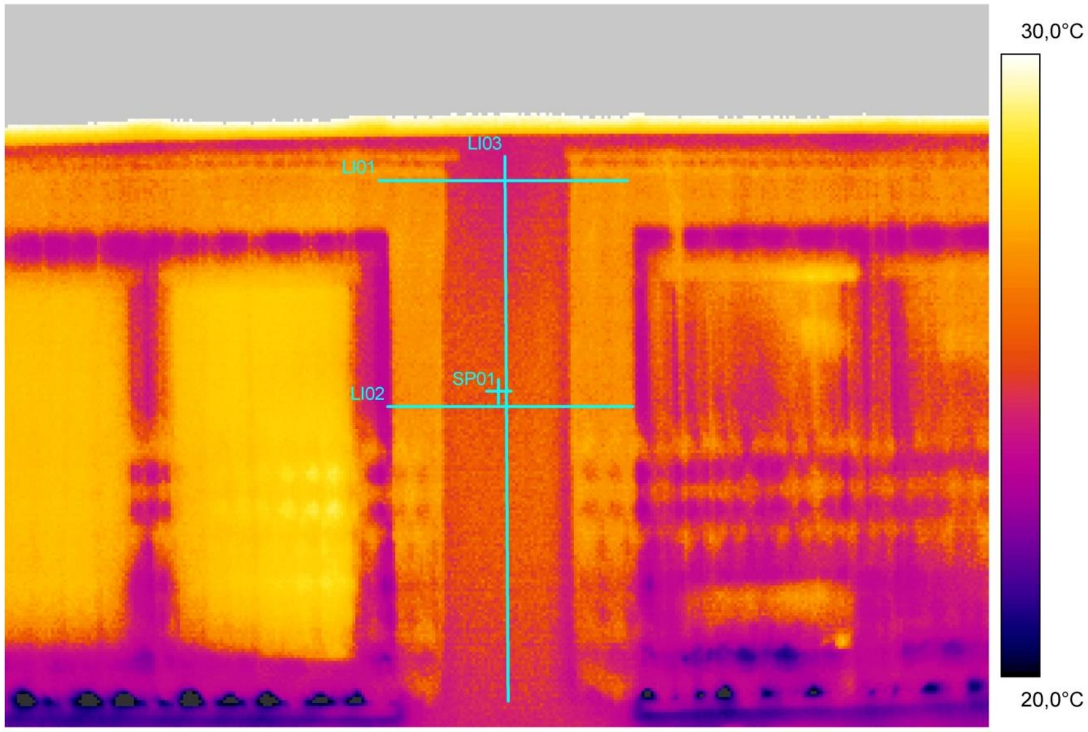
Fig. 6: Software graphical output showing a prevailing evaporation (odpar Ge) over condensation (kondenzace Gc) in months (Měsíce) of annual cycle and localization of calculations within the structure (Lokalizace)

4 DETECTION OF THERMAL IRREGULARITIES USING INFRARED IMAGING, AND TESTING THE AIR TIGHTNESS OF THE BUILDING ENVELOPE

The purpose of infrared imaging was to find possible thermal bridges and irregularities in the external walls of the house in Pržno. The tests disproved worries that reinforcing elements in the walls could result in an unacceptable decrease of internal surface temperature during winter. Infrared photographs were taken by a Thermacam PM 695 thermal imager. An Amir 7814 infrared pyrometer was used for non-contact temperature monitoring.

These tests were performed during the winter in January 2009. It was in the following winter after measuring in the critical room with temperature sensors. During the previous winter, measuring had taken place in the critical room with temperature sensors. Between these two periods, the building of the house had been completed and a fireplace installed on the ground floor.

A thermographic picture of the western wall of the largest habitable room, containing a reinforcing pillar between the windows, is shown in Fig. 7. The display features these measured values: “SPO1” – surface temperature at the centre of the image: 25.8 ˚C; “LI01 max-min” – temperature difference along the horizontal line containing the reinforcing element: 1.2 ˚C; “LI02 max-min” – temperature difference along the lower horizontal line: 1.9 ˚C; “LI03 max-min” – difference along the vertical line: 1.0 ˚C.



Object parameter	Value
Emissivity	0,90
Object distance	4,0 m
Ambient temperature	27,0°C
Atmospheric temperature	27,0°C
Relative humidity	0,18
Label	**Value**
IR : max	37,3°C
IR : min	18,2°C
SP01	25,8°C
LI01 : max	26,3°C
LI01 : min	25,1°C
LI01 : max-min	1,2°C
LI02 : max	26,4°C
LI02 : min	24,5°C
LI02 : max-min	1,9°C
LI03 : max	25,9°C
LI03 : min	24,9°C
LI03 : max-min	1,0°C

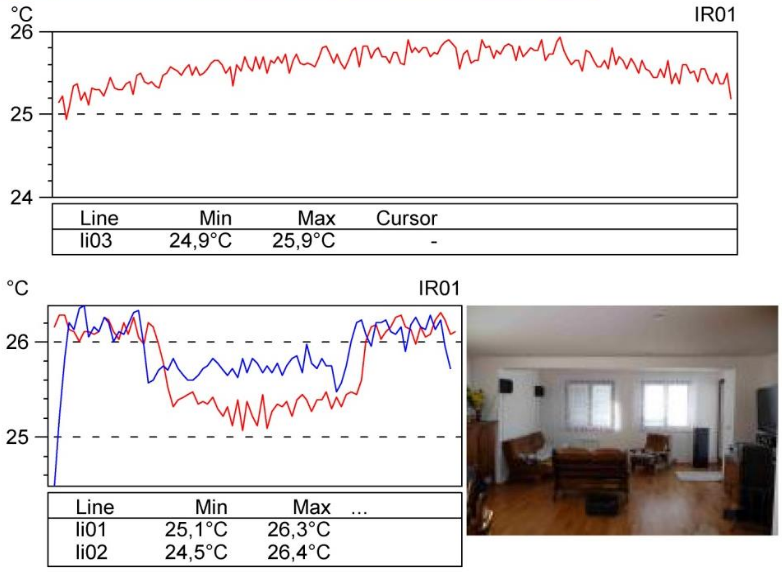


Fig. 7: Detection of the internal surface temperature differences across an internal pillar viewed from the interior. The results can be accepted (taken from [2])

Specified conditions for the validity of infrared examination were met. First of all, the temperature difference between the inside and outside of the tested walls in relation to the theoretical heat transfer coefficient U_j [W/(m^2.K)] was determined: According to the calculation on the basis of the design characteristics, we obtained $U_j = 0.20$. The required difference for external walls should be greater than the numerical value $3/U_j = 15$ ˚C. The outdoor air temperature by the west side of the house equalled – 5 ˚C, and therefore this condition was fulfilled. At the same time, the hygrothermal performance of the house was monitored by using air temperature and humidity sensors, contact sensors for surface temperatures, transducers for heat flux through external walls and instruments for monitoring outdoor weather conditions. Obtaining accurate heat flux in unstable conditions demanded an extensive set of data. Long-term measurement is demanded by the manufacturer, Almemo (heat flux density measuring plates, q [W/m^2]). The transducers were stuck on the inner surface near the outer corner reinforced by an internal concrete pillar. The heat flux density determines the local heat transfer coefficient. Based on long-term monitoring, we can determine the average value 0.210 W/(m^{2}K) and the median value 0.200 W/(m^{2}K).

4.1 The most current state of development of the efficient construction technique, and the air permeability of the envelope of a house in Veselí nad Moravou

The internal thermal insulation of another examined house (in Veselí nad Moravou) consisted of two layers. The first, thicker, layer was attached to the wall of Betong blocks in the usual way. The insulation was stuck on the adhesive targets. After bonding the first insulating layer, internal installations, electrical wiring, water distribution pipes but also windows and doors should be mounted. Only when the installation works had been completed, the second fully glued insulating layer was added. Finally, the second layer was covered with plasterboards. The total thickness of the stabilized polystyrene insulation (EPS 50 S) was 140 mm. The overall air permeability of the building envelope was measured with a Blower Door Model 4.1. device. Data was obtained for the total air exchange rate n_{50} [h^{-1}] with an air pressure difference between the interior and exterior (over- or underpressure) $\Delta p = \pm 50$ Pa. The determined value $n_{50} = 2.71$ met the recommended value of the standard ČSN 73 0540-2 (at a better level, II) for natural or combined ventilation in a building. The constant development of this building technique has also been observed abroad, especially with regard to the connection of ceilings to external walls as stipulated in guidelines [8], see Fig. 8.

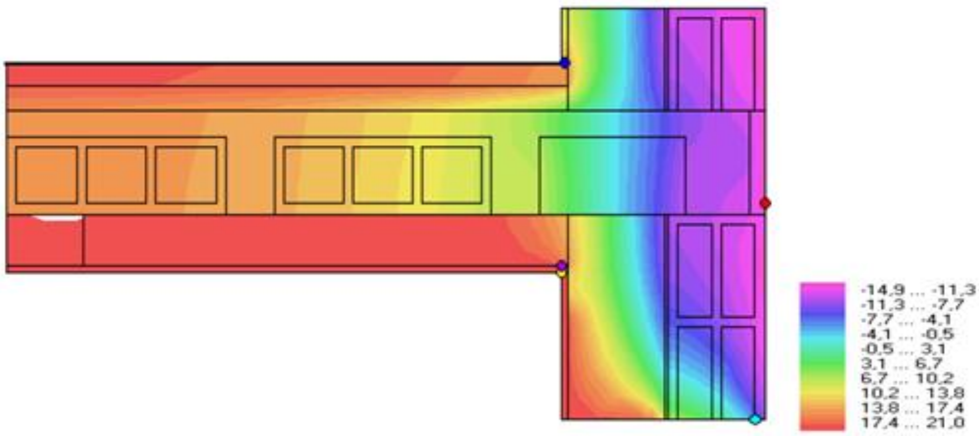


Fig. 8: Diagram of the connection between the ceiling and the outer wall

The diagram above depicts a ceiling made of prestressed concrete beams and concrete ceiling blocks where thermal bridges created by its connection to an external wall are interrupted with insulation blocks known in France as “Thermorupteur” system (see the quoted guidelines [8]).

It is also necessary to note the internal thermoacoustic wall insulation of mineral wool covered with aluminium foil of low emissivity ε - technological prescription is provided in the French technical guide [9].

5 ENVIRONMENTAL AND ECONOMIC COMPARISON WITH CONVENTIONAL STRUCTURES – DISCUSSION

The relative items (in Tab. 3.) have been taken from KROS plus and BUILDpower softwares.

Tab. 3: Budgetary items for outer walls of Betong with internal insulation at the house in Pržno

N°	Divis.	Item code	Short description	Unit	Volume	Unit price, CZK	Total price, CZK
		3	**Vertical & complete constructions**				**103,297**
1	011	311271511	Bearing masonry Betong 200	m^3	25.80	3,370	86,946
2	011	311361821	Reinforcing steel – pillars, 10 505	t	0.327	38,800	12,688
3	011	317351109	Shuttering supports	m^2	15.9	27.2	432
4	011	317351512	Lost formwork – moulding units	m	15.9	134.0	2,131
5	011	317361821	Reinforcing steel – lintels, 10 505	t	0.028	38,800	1,100
		6	**Finishing works**				**20,511**
6	011	622381021	Thin-layer mineral plasters	m^2	129.00	159	20,511
		99	**Site material movement**				**6,958**
7	011	998011001	Material movement up to 6 m height	t	36.62	190	6,958
		713	**Thermal insulation**				**69,210**
8	713	713131131	Thermal insulation bonding - *Rifix*	m^2	129.00	91.50	11,804
9	*595*	*595920352*	*Rigitherm A 1200x2600x153 mm*	m^2	*131.58*	*420*	*56,006*
10	713	998713101	Material movement up to 6 m height	t	1.939	722	1,400
		763	**Dry constructions**				**32,926**
11	763	763121211	Gypsum construct.– sealing, spatula	m^2	129.00	247	31,863
12	763	998763301	Material movement up to 6 m height	t	1.489	714	1,063
		784	**Paintings**				**1,961**
13	784	784453601	Paintings Primalex - double	m^2	129.00	15.20	1,961

The sum of the basic budgetary costs amounted to 234,845 CZK. If we were to build outer walls of the same surfaces but using the Porotherm 40 EKO (Profi Dryfix) masonry system without any thermal insulation, the price increases to 298,070 CZK, thus the saving using the French method is 63,225 CZK.

The results of environmental impact evaluation – conducted according to the “Life Cycle Assessment” method, as defined in section 1, are significant. For example, the production of greenhouse gases per 1 m^2 of external walls (Betong 20 and Rigitherm 15.3) amounts to 38 $kgCO_{2,eq.}/m^2$, while for the compared Porotherm masonry system, it equals 84 $kgCO_{2,eq.}/m^2$.

As a result of an analysis of experiments in Pržno, a computer program was also developed for calculating heat transfers on exterior surfaces of the building. Research by Mirsadeghi et al. [10] is concerned with components of this heat balance. Our software, available online [11], is a contribution needed to determine the thermal balance of buildings with internal insulation.

6 CONCLUSION

The outcomes of the research referred to in section 2 are extraordinarily important. They are the first to demonstrate the applicability of the French building technique in the climatic conditions of the Czech Republic. The construction method is based on the use of Betong blocks produced using imported manufacturing equipment. The assessment of environmental impacts of this type of structure in section 5 is also extremely important. The results of this research demonstrate there is a significant decrease in the volume of greenhouse gas emissions in comparison with conventional brick constructions.

The presented results of the measurements taken on site confirm that the internal insulation system can enable the temperature inside the house to rise quickly after heating is re-started and thereby improves the building's energy performance.

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