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USING THE FINITE ELEMENT METHOD TO PREDICT HEAT DISSIPATION IN A TIMBER FRAME BUILDING CONSTRUCTION

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ABSTRACT

This article focuses on thermal engineering assessment of light building envelope structures using Finite Element Method (FEM). The research was carried out for a particular composition of a lightweight perimeter wall in winter, for which continuous experimental measurements are also carried out. In the preparation of calculation models for numerical simulation, the marginal conditions, which were obtained by experimental measurement, were used. Thus, for simulation purposes, the construction was loaded under the same boundary conditions as the actual structure being monitored within which experimental measurements were performed. The results of the experimental measurement made it possible to compare the actual measured data with the results of the numerical simulation. The difference between calculated and experimentally determined temperatures was in the range from 0.1°C to 1.3°C. This study demonstrated, that with the help of suitable simulation programs, it is possible to predict the thermal-technical behavior of lightweight perimeter constructions.

KEYWORDS: Thermal engineering properties, experimental analysis, temperature field, passive building, timber frame construction, finite elements method.

INTRODUCTION

The development of building construction is today closely associated with the demands for reducing the energy demand of buildings. The energy performance of buildings is influenced by a number of factors relating to both the design of the building, as well as its subsequent use (Sekki et al. 2015). The amount of energy to be delivered to the building in the winter is affected primarily by the heat loss of the building, which is related to the ventilation of the building, the thermal and technical parameters of the heat exchange constructions on the system boundary of the building envelope and the quality of execution of the construction details (Valdiserri et al. 2016).

When designing the composition of constructions of classical masonry structures, contact thermal insulation systems are usually used to reduce the thermal permeability of structures. For example, when designing a perimeter wall that meets the heat transfer coefficients recommended for passive buildings, Upas20 (ČSN 73 0540-2, 2011), today the thickness of the heat insulator itself is typically between 200-300 mm, depending on the type of supporting structure (Pavlik et al. 2014, Yu et al. 2009). An increasing thickness of constructions results either in a decrease of the internal floor area of the building or an increase in built area of the building envelope (Nyers et al. 2015). Therefore, the construction of buildings with light perimeter constructions presents a suitable alternative. The advantage of lightweight perimeter structures is that the thermal insulator becomes part of the supporting layer and thus does not further increase the overall thickness of the construction (Relander et al. 2011). It can be said that the overall thickness of a lightweight perimeter construction compared to a conventional masonry structure is significantly lower, while maintaining the same thermal insulation properties (Sveipe et al. 2011). This article focuses precisely on the analysis of the behavior of lightweight perimeter construction from the point of view of building thermal technology (Liu et al. 2018).

In this study a computational model was created for the monitored lightweight perimeter wall construction, a computational model was created using the selected software, using the boundary conditions affecting the construction structure during the observed period. For this model, a short-term numerical simulation of heat dissipation in the structure was subsequently performed by the FEM. The results of the simulation were compared with data obtained from experimental measurements (Piot et al. 2011). Based on the comparison of the results of the numerical simulation and the experimental measurement, it was then possible to carry out an assessment of the suitability of the FEM for prediction of heat propagation within lightweight perimeter constructions (Guattari et al. 2017).

Heat dissipation in building constructions

In building constructions, heat is propagated based on the temperature gradient (Mendes and Philippi 2005). When calculating heat dissipation in structures, it is necessary to distinguish so-called steady and unstable temperature conditions. At steady (stationary) temperature conditions, the temperature does not change over time (Jones and Jones 1999). This is a simplifying assumption that is used in common building practice for the thermal engineering assessment of building structures and also to evaluate the energy performance of buildings. For the purpose of building practice, the use of steady state temperature is certainly sufficient, but for the purpose of this research, an unstable temperature state was used. A non-stationary temperature state, in contrast to a stable temperature state, more accurately reflects the real response of the structure to the behavior of adjacent environments (Isaev et al. 2005). The results can then be compared with the actual heat dissipation through the structure, wherein the results are compared with the data obtained by the experimental measurement.

Numerical methods for calculation of thermal engineering tasks

Thermal engineering calculations can use analytical and numerical methods. Both methods are applicable for homogeneous and non-homogeneous building constructions, but the analytical methods for the calculation of inhomogeneous structures are considerably simplified (Lorente et al. 1996). In such cases, it is advisable to use numerical methods.

The output of numerical calculations is a temperature field that describes the temperature distribution in the evaluated model of the construction (Deliiski 2009). For the purposes of the research, the FEM was used. The FEM is a variation method, the basic principle of which is the division of a continuous region into a set of separate sub-regions, the so-called finite elements (Pavlik et al. 2014, Liu et al. 2011).

MATERIAL AND METHODS

Experimental building

For the purpose of the research, experimental wooden structures were used, built in the passive building standard (Blatek et al. 2016), see Fig. 1. The official name of this building is the "Research and Innovation Center of the National Wood Cluster", and it is a building which, thanks to its exceptional nature, allows observation of the whole range of thermal moisture parameters of its perimeter constructions. For evaluation and performance of numerical simulations, the data obtained from long-term monitoring was used.

Fig. 1: Experimental building.

The experimental building is structurally designed as a panel wooden structure. From an energy point of view, this building is designed in the passive standard, whose perimeter constructions meet the values of heat transfer coefficient recommended for passive buildings $U_{pas,20}$ according to ČSN 73 0540-2. The perimeter constructions are made up of prefabricated panels that have been manufactured under stable climatic conditions in the production hall.

Composition of the evaluated light building construction

In the context of the research, the construction of a perimeter wall, which is designed as a structure with a ventilated façade with a wooden cladding, was evaluated. The supporting elements are wooden Steico beams, which include Steico fiberboard insulation (Arambakam et al. 2013). Thermal insulation is also executed from the exterior and interior sides of the construction. Cladding of the individual layers of perimeter constructions is executed with Fermacell gypsum fiber boards. Composition of the evaluated construction, including the placement of the measuring devices is evident from Fig. 2.

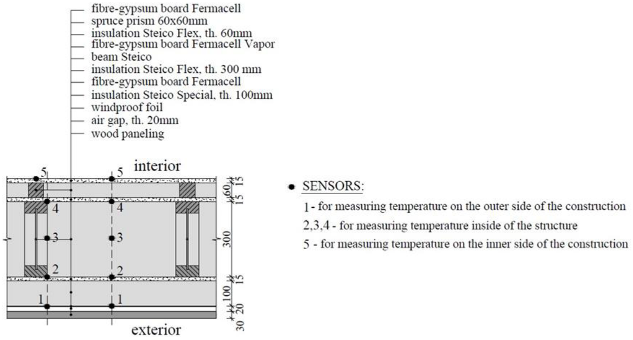

Fig. 2: Composition of the perimeter walls and the position of the built-in measuring sensors.

Placement of measurement devices

As already mentioned above, the research used data obtained from continuous measurements. A large number of physical quantities are measured in the building (Desta et al. 2011). For the purpose of the research, the results of the measurements of temperatures within the construction under consideration, on the external and internal surface of the construction were used, as well as the external and internal air temperatures, which act on the construction. These quantities were measured using a Rotronic sensor, which was installed inside the structure already in the prefabrication phase of the panels in the production hall. The sensors are installed at the level of the axis between the beams and at the beam level where a total of 5 sensors are located in each cut, with 3 sensors located inside the construction and 2 sensors on the surface of the construction. The location of the sensors is shown in Fig. 2.

Theoretical analysis

The subject of this chapter is the description of input data and evaluation of results of numerical calculations of heat conduction under non-stationary boundary conditions. For the non-stationary analysis, a detail of the perimeter wall with a ventilated air gap, and wooden facing with eastward orientation was chosen. This was to make it possible to analyze the temperatures inside the construction in the axis outside the thermal bridge and also at the thermal bridge, as experimental measurements are performed for these sites. Consequently, it is possible to compare the results of the numerical simulation with the measurement results. For the period of evaluation, the days of January 3 – 4, 2016 were selected, during which the temperatures for the given interval approached the standard temperatures, under which the design is standardly evaluated according to ČSN 73 0540-2 (2011). The duration of 48 hours was selected as the length of time of the numerical simulation with a time step of 600 s. The simulation calculation was performed using the ANSYS R16.0 program, which allows non-stationary heat conduction calculations. The output of non-stationary heat conduction calculations is the distribution of temperatures in the construction over time, taking into account the variables of the boundary conditions that affect the construction during the analyzed period.

In the numerical simulation performed, the physical laws of heat propagation through conduction were used, which can be mathematically expressed using Fourier's laws. Heat dissipation through conduction is characterized by a heat flux q that is directly proportional to the temperature gradient. This dependence on stationary heat conduction is expressed mathematically by the first Fourier's law according to Eq. 1 (Hens 2012):

$$q = -\lambda \frac{\delta\theta}{\delta x} = -\lambda \cdot grad\theta \tag{1}$$

where: q - the density of heat flow (W·m^{-2}),
λ - the thermal conductivity coefficient (W·m^{-1}•K^{-1}),
θ - the temperature (°C),
x - the coordinate expressing the position of the point on the construction (m),
$\frac{\delta\theta}{\delta x}$ - the temperature gradient (K·m^{-1}).

In the case of non-stationary problems, according to Fourier's Second Law, is the physical magnitude, which influences the temperature distribution in the construction under the influence of the variable boundary conditions, called the coefficient of thermal conductivity a, which depends on the coefficient of thermal conductivity λ, the density ρ and the specific heat capacity of the substance. For non-stationary calculations, it is therefore necessary to define these material characteristics, and variable boundary conditions, as a function of time and also the initial state of temperature distribution in the construction. This fundamentally affects the results of the calculation itself. The initial state can be set by determining the temperature field by means of a stationary calculation with the input of boundary conditions so that the resulting temperature field closes as closely as possible to the actual temperature distribution in the structure at the beginning of the non-stationary simulation.

Thermal engineering parameters in the calculation model

During the creation of the geometric model, the individual materials were assigned thermal characteristics in accordance with the actual declared properties of the materials used. For the purposes of calculation, these properties were considered as computational, that is, a supplement property was applied taking into account the moisture absorption rate of the materials.

Boundary conditions

Two types of boundary conditions were used for the calculation, which were the Newton (Type III.) and the Dirichlet (Type II.), for further details, see Tab. 1 below.

Tab. 1: Boundary conditions used.

Type	Boundary conditions
I. Dirichlet type	**Surface temperatures** – internal θ_{si} and external θ_{se}
II. Newton type	**Ambient temperature** – temperature of the outside air θ_{ae} and interior air temperature θ_{ai} and the **heat transfer coefficient** h_c on the interior and exterior side of the construction

In the case of Newton boundary conditions, the temperature of the external and internal air was determined as the non-stationary boundary condition, which was determined by experimental measurement. The thermal resistors on the inside and outside of the construction were chosen as stationary according to ČSN 73 0540-3 (2005), which can lead to a certain calculation error as it is a variable quantity. Therefore, the calculation does not take into account the influence of the air temperature and its flow on heat resistance during heat transfer at the surface of the construction on the exterior and interior sides.

In the case of Dirichlet boundary conditions, the construction was loaded with a non-stationary boundary condition in the form of surface temperature of the construction, namely the interior and exterior surface temperature. Both variables were determined by experimental measurements at points 1 (exterior surface) and 5 (interior surface) according to Fig. 3.

As already mentioned above, the temperature distribution is crucial for short-term simulation calculations in the construction at the beginning of the simulation (Li et al. 2018). The temperature distribution in the construction at the beginning of the simulation was determined by numerical calculation under stationary boundary conditions. In order to compare the influence of the initial state of the temperatures in the construction on their further course, in the research, numerical simulations were made for three initial states:

A) Temperature field for boundary conditions at the start of the simulation,
B) Temperature field for boundary conditions of the previous day,
C) Temperature field for boundary conditions of the previous 2 days.

RESULTS AND DISCUSSION

Comparison of the results of experimental measurement and numerical simulations

When evaluating the results of numerical simulations, it was found that the most appropriate starting state was C, where the temperature field was calculated for the average boundary conditions of the previous 2 days. For illustration purposes, see Fig. 3, below, which shows the temperature patterns in the construction for the axis location between the beams using the initial state A and Newton's boundary conditions.

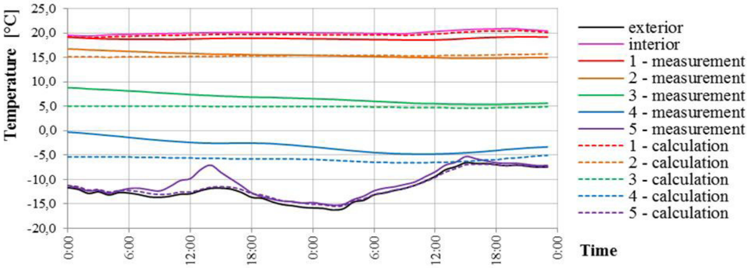

Fig. 3: Courses of temperatures on the axis: Initial state of temperature distribution A Newton boundary conditions.

It can be seen from Fig. 5 that at the beginning of the simulation the temperature inside the structure differs significantly from the results of the experimental measurement.

The initial state A, i.e., the temperature distribution in the construction, determined by the stationary calculation for the boundary conditions at the beginning of the simulation, i.e. for the internal and external temperatures measured on January 3, 2016 at 0:00 am, appears to be incorrect. This simultaneously confirms that the temperature distribution in the construction is significantly affected by the load of the structure before the start of the simulation. At the end of the simulation, the results of the calculation and measurement are very close. Fig. 4 shows the calculated temperature curves for an axis location between beams using C as the starting state and Newton boundary conditions.

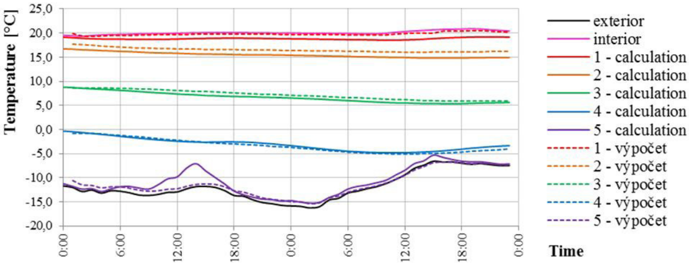

Fig. 4: Courses of temperatures on the axis: Initial state of temperature distribution C, Newton boundary conditions.

From Fig. 4, it is clear that the results of the calculation are very close to the results of the experimental measurement throughout the simulation. This initial state was evaluated as the most appropriate and the further subject of this paper is only the results of numerical simulations for the initial state C. In the short-term simulations of non-stationary heat conduction, it is obvious that the initial distribution of temperatures in the construction fundamentally affects the results of the simulation calculation. Therefore, it is important to get the results as close as possible to suitably select the boundary conditions for calculating the temperature distribution in the construction at the beginning of the simulation. This is different in the case of long-term simulation calculations, such as annual evaluation of structures, when the initial state after temperature equalization does not affect the simulation results further.

Fig. 5 shows simulation and measurement results for the construction site at the thermal bridge site, the simulation was performed for the initial state C. The simulation results are again very close to the experimentally observed temperature patterns in the construction but greater differences were found between the calculated and the measured temperatures.

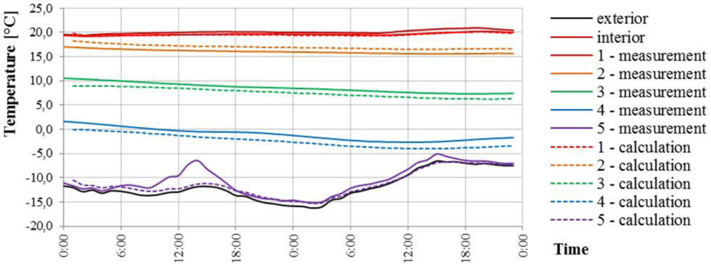

Fig. 5: Course of temperatures at the site of the thermal bridge: the starting state of temperature distribution C, Newton boundary conditions.

When comparing the results of numerical simulation and experimental measurement, the response of the construction to solar radiation, which acts on the construction, is also apparent. Since we are dealing with a ventilated façade construction (Havirova and Kubu 2011), solar radiation does not directly affect the outer surface of the structure, however, due to solar radiation, the air within the air gap is heated, and the subsequent response of the construction is evident by the increasing temperature on the outer surface. Unlike the simulation calculation, which does not take into account this effect, this influence is apparent from the measured temperatures not only on the outer surface of the construction, but also in position 4, where a slight increase in temperature is apparent in the evening, which does not occur in the case of numerical simulation. Also interesting is the phase shift of the temperature oscillation inside the construction where the temperature rise inside the structure occurs with a significant time delay after heating the outer part of the construction.

To make it possible to take into account the influence of solar radiation on the construction, numerical simulations were also performed using the Dirichlet boundary conditions where the construction was directly loaded with the internal and external surface temperature that was experimentally detected. The numerical simulation results are shown in Fig. 6 (for an axis position outside the thermal bridge) and Fig. 7 (for the thermal bridge site), the C state was again used as the starting state.

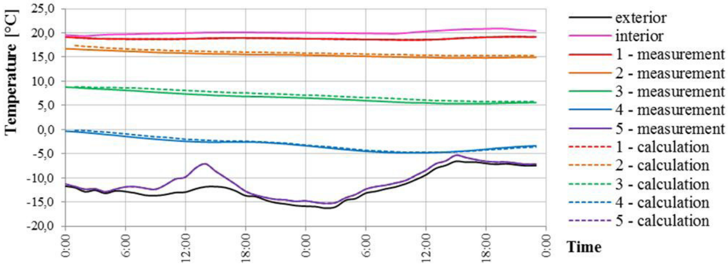

Fig. 6: Courses of temperatures on the axis: beginning state of temperature dissipation C, Dirichlet boundary conditions.

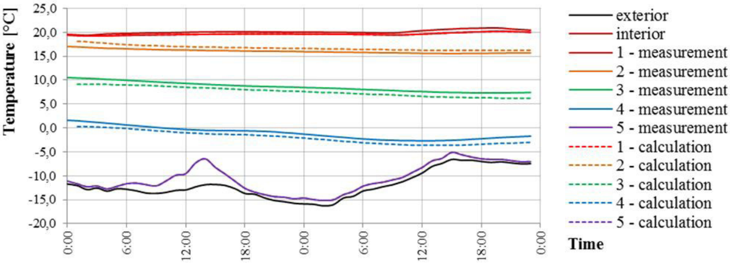

Fig. 7: Courses of temperatures at the site of the thermal bridge: beginning state of dissipation of temperatures C, Dirichlet boundary conditions.

When using the Dirichlet boundary conditions, the results achieved approached the actual temperature states of the construction more frequently than when using the Newton boundary conditions. The following Tab. 2 compares the difference of the calculated temperature results and the actual experimentally observed temperatures in the construction during the monitored period for the stated simulation calculations. Differences are determined for each checkpoint position as the average difference over the duration of the simulation.

Tab. 2 shows that larger differences were achieved in both cases at the site of the thermal bridge. This is mainly due to deformation of the temperature field near the thermal bridge. For higher accuracy of calculations, it would therefore be advisable to increase the concentration of checkpoints at the thermal bridge site. Using Newton's boundary conditions, the maximum mean difference between calculated and experimentally determined temperatures was 1.3°C at the site of the thermal bridge. Larger average differences were obtained using Newton's boundary conditions, primarily due to the effect of solar radiation on the construction, which in this case was neglected. For simulation calculations using Dirichlet boundary conditions, the maximum average difference is only 0.90°C. Finally, it should be noted that the difference is not just a calculation error, but also a possible measurement error, which also depends on the accuracy of the measuring devices, see Tab. 3.

Tab. 2: Average differences in results of numerical simulations and measured data.

Positions (from exterior)	Average difference (°C)			
	Temperatures on the axis		Temperatures at the site of the thermal bridge	
	Newton	Dirichlet	Newton	Dirichlet
1	0.8	-	0.9	-
2	0.3	0.3	1.3	0.9
3	0.6	0.6	1.0	0.9
4	1.1	0.5	1.0	0.7
5	1.0	-	0.1	-

Tab. 3: Measuring equipment used – measurement accuracy.

Equipment	Sensor	Measured variables	Accuracy
ROTRONIC	TG 7 Pt1000, Class A	External and internal surface temperatures	± 0.3 K
	HC2-CO4 RH/T	Temperatures within the constructions	± 0.3 K
	Pt 1000, Class A	Internal air temperature	± 0.1 K

Although an exact match of the results of the simulation calculations and the measured data was not achieved, it can be said that the results of the calculations are very close to the measured temperatures and the curves of the calculated and measured temperatures almost copy each other's course, especially when Dirichlet boundary conditions were used. This, of course, is subject to appropriate input temperature distribution in the construction at the beginning of the simulation. Significantly closer calculation results are also achieved on the axis outside the thermal bridge. The results of the calculation and measured data differ slightly at the thermal bridge site. This error is due to the density of the calculation network in the given section of the construction. When assessing more complex details with elements of very small dimensions, it is necessary to ensure the sufficient density of the network in these places in order to provide the highest possible accuracy of the calculation.

CONCLUSIONS

This article aimed to assess the suitability of numerical methods of thermal engineering calculations, namely FEM, to predict the spread of heat through lightweight perimeter constructions. Within the context of the research, experimental temperature measurements were performed within the studied light building construction, the results of which the results were used for comparison with the results of numerical simulations. Dynamic simulations of heat dissipation through the building construction were performed for non-stationary boundary conditions so as to make it possible to make a comparison with the actually measured data. The boundary conditions that influenced the evaluated construction in the monitored period were used as part of the creation of

a calculation model for dynamic simulations. Two types of boundary conditions were used, and these were the Newton and Dirichlet boundary conditions. In both cases, data obtained by measuring was used. In the case of Newton's boundary conditions (Type III.), the indoor and outdoor air temperature was used. In the case of Dirichlet boundary conditions (Type I.), the internal and external surface temperatures of the construction were used, taking into account the influence of solar radiation, air flow, etc.

Comparing the results of experimental measurements and numerical simulations, it can be stated that the methods of thermo-technical calculations, namely the FEM, under non-stationary boundary conditions are a suitable means for the purpose of research in the design of building structures. Despite the fact that for standard designs of perimeter constructions, thermo-technical calculations under stationary boundary conditions are sufficient, both for the analytical and the numerical methods, for the more detailed thermo-technical analysis of building constructions, it is necessary to perform calculations under non-stationary boundary conditions using numerical simulations. In the framework of the research, it was demonstrated, on the basis of comparison of numerical simulations and results of experimental measurements, that with the help of suitable simulation programs, it is possible to predict the thermal-technical behavior of lightweight perimeter constructions. Numerical calculation methods are therefore a suitable tool for thermo-technical simulation of processes in building constructions. However, a prerequisite for their correct use is the knowledge of factors that can fundamentally affect the results of the calculations. In the absence of knowledge of numerical methods, it is then possible to misinterpret the results of the calculations. Calculations of non-stationary heat conduction using numerical computational tools cannot be considered as a suitable means for the thermo-technical assessment of building constructions by the general professional public. However, these resources can be used to advantage for research purposes.

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