OPTIMIZATION OF STRUCTURAL DETAILS OF WOODEN BUILDINGS, THEIR ASSESSMENT AND INFLUENCE ON THE LIFETIME OF A BUILDING

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Abstract

Wood-base buildings are becoming more common among new buildings. That is why it is necessary to comprehensively perceive the shortcomings that are typical of this type of construction. In general, they can include defects caused by inappropriate design or poor construction. Subsequent deficiencies can thus be a direct consequence of the degradation of the structure, they can affect the quality of the internal environment and the overall service life of a building.

Keywords

Foundation, wood base buildings, timber buildings, foundation on concrete slab, service life, thermal bridges

1 INTRODUCTION

The design of new buildings, as well as the evaluation of existing buildings, must be approached responsibly, with attention to structural details, especially the contact of the foundation structures and the adjoining vertical structures. Therefore, it is necessary to study the shortcomings that are typical of this type of construction.

Among the most fundamental are structural and physical problems, especially thermal and moisture balance, air permeability and airtightness. Subsequent deficiencies can be a direct result of moisture degradation of the structure by biotic pests or leakage of the building envelope and they can affect the quality of the internal environment.

The purpose of this work is to verify these hypotheses using available resources, specific software and practical research, particularly focusing on the possibility of protecting the lower part of the building from the adverse effects of water levels entering the structure and its condensation or evaporation. The work aims to find out the possibilities of optimizing the solution in the following areas: mechanical stress, thermal bridges, waterproofing and airtightness.

Currently, there are several scientific works and professional studies dedicated to the protection of wooden structures. They approach the topic of includeprotecting wooden materials from pests, fungi, moisture, and other external influences in different ways.

Scientific works often focus on research and testing of various protective procedures and materials that can extend the life of wooden structures. These studies examine the effectiveness of different types of surface coatings, and impregnations to provide protection against rot, termites, or other wood pests.

Professional works also include handbooks and manuals that provide instructions and recommendations for the proper protection of wooden structures. They contain information on suitable materials, maintenance, repairs, procedures, and methods to ensure the longevity and durability of these structures.

In general, the standard protection of wooden structures consists not only of prevention and regular maintenance, but also of passive and active protection. Elements of passive protection include placing the foundation of the wooden part of the building sufficiently high above the ground, or the foundation of a "crawlspace" type. The term active protection refers to the construction solutions of structural details and their correct and appropriate design.

Currently, research and published works also focus on ecological and sustainable methods of protecting wooden structures. New methods and materials with a minimal negative impact on the environment are being sought, as well as methods of restoration and repair of old and damaged wooden structures.

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Research issue

This work examines mainly the implementation of frame systems of wooden buildings – a light skeleton of a wooden building (e.g: frame - two by four - TBF) with conventional building envelopes. The researched area of interest is the function of the foundation base frame of the wall structure and its connection to the concrete foundation (slab). This element and its nearby area (joint) in construction separates the structure and has the following functions:

1. preventing the passage of moisture (e.g. soil) into wooden structures and elements.
2. airtightness (between the internal and external environment) and possible penetration of radon from the subsoil.
3. thermal insulation (the junction of the building's horizontal and vertical thermal envelope).
4. bearing (load transfer from the building to the foundations).
5. levelling (unevenness of the concrete base).

When solving a foundation on a concrete slab, the wooden base frame is joined to the foundation slab using mechanical elements. In this way, a relatively extensive perforation of the hydro isolation protection applied to the concrete slab occurs. In general, there are several solutions recommended [1]:

1. using a more durable type of wood (larch, oak) for the base frame, impregnation or an agglomerated board,
2. double concrete slab (base slab, hydro isolation layer, cover slab)

The problem applies to frame wooden buildings as well as panel assembly or traditional timber buildings and log cabins.

In the works available [1], three possible systems of mechanical connection of the basic frame can be studied. The most important requirement is to ensure the stability of the connected element and eliminate the effects of horizontal forces (e. g. wind effects). The principle of connection and the number of mechanical elements are thus directly dependent on the specific requirements of the building. The most common type of elements are threaded rod in combination with a nut and any steel angle element.

This solution is very common in wooden buildings built in the Czech Republic and this work is devoted to its optimization.

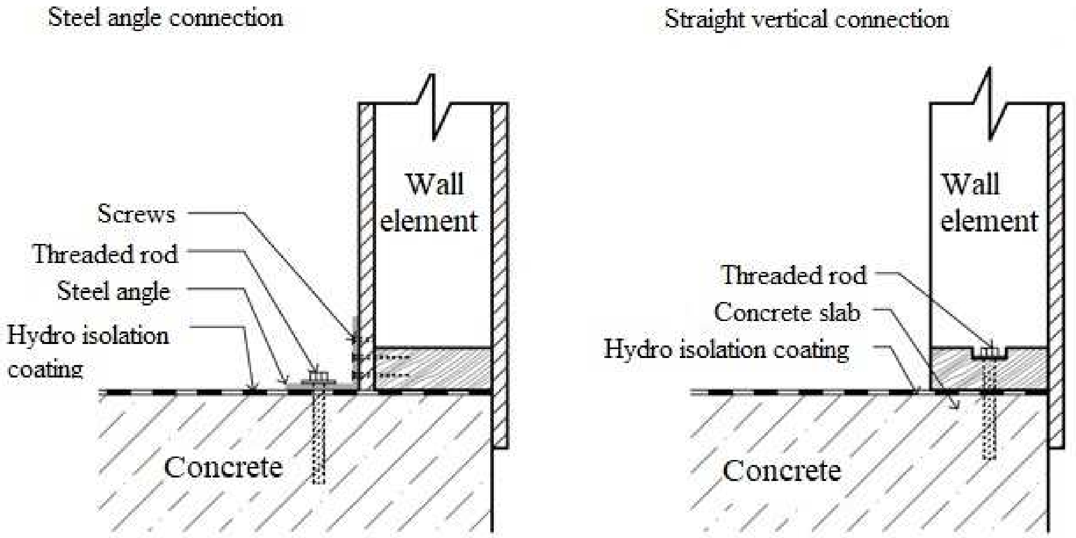

Fig. 1 Basic connection of the foundation beam joist [2], translated.

Summary and description of the assessed variants

Variant 00, current implementation (Fig. 1), typical implementation of these details.

In this variant, vertical threaded rods or steel angles are used. It is also common to use a hammering dowel, in direct contact with the underlying concrete [2]. With this attachment, the coating hydro isolation was perforated in many places. These mechanical violations can have a direct effect on the moisture degradation of wooden elements in the structure. Of course, everything depends on the quality during construction - qualified construction companies use chemical mixtures that improve the tightness of the joint.

Variant 01, a solution with an elevated foundation using prefa-monolithic elements (concrete blocks).

It is a solution based on the first row of concrete blocks filled with concrete mixture, on a hydro isolation layer. The vertical wall structures of the wooden building are then mechanically attached to these blocks from above. Furthermore, the external vertical hydro isolation and thermal insulation of the plinth are pulled above the floor level on the ground floor and the surrounding landscaping. The solution enables better protection of the building against the effects of groundwater, surface runoff/drift water, process water and possibly radon intrusion. The design is particularly suitable for application resistance to wet processes during construction. The considered design is inspired by [3], [4] as a variant of the improvement of log buildings. The specific use of this variant for wooden frame construction is based on the actual design of a detached house in the Czech Republic from 2016.

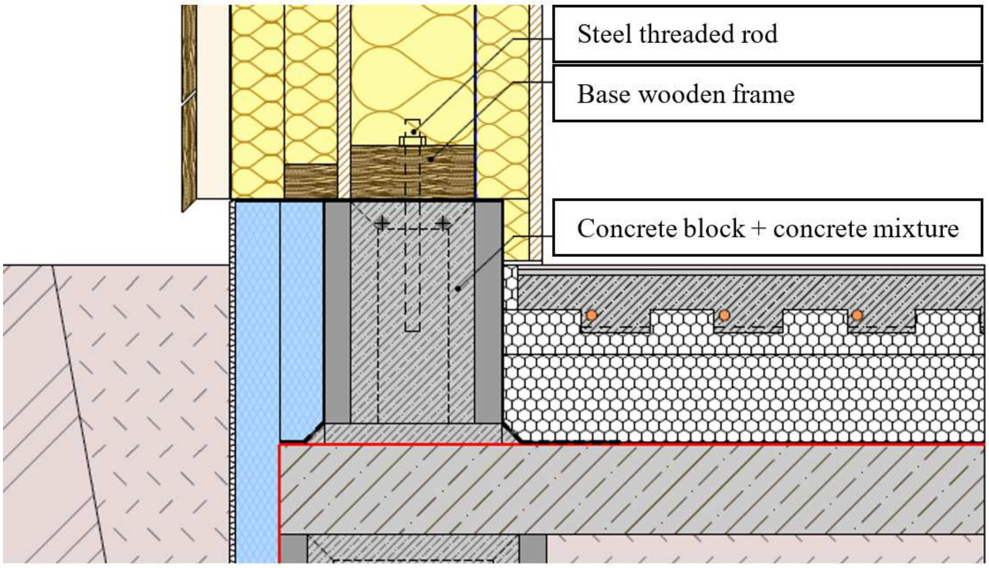

Fig. 2 Variant 01 in a modelled version corresponding to the actual building design in 2016.

Variant 02, a solution with increased foundation when using an element made of solid heat insulator.

A solution with the application of a heat insulating element under the foundation frame of a wooden building. The material can be based on a high-strength insulator: expanded polystyrene (EPS), extruded polystyrene (XPS), foam glass or compacfoam (thermoplastic foam). The stabilization of the element is ensured at the same time as the mechanical attachment of the base frame of the vertical structure. The solution ensures a possible interruption of a potential linear thermal bridge at the point of contact of the horizontal and vertical structure. Water may rise through the steel rod, similar to variant 00. I came across a similar optimization of the solution using insulation (specifically floor EPS 200 kPa) in one company that implements this as its standard know-how [5].

Fig. 3 Variant 02 and its practical solution for a detached house [5].

2 METHODOLOGY

The studied hypotheses were presented above. The results were gradually processed using simulations in professional software for the areas of thermophysical and hydrophysical behaviour in the considered area. Specifically, it evaluated the heat flow (2D temperature area) and condensation risks in the structure (2D humidity area).

The proposed optimization solutions are based on practical knowledge of the current technical expertise in the Czech Republic in the area of design and construction of wooden buildings.

The work thus processes the theoretical results of software simulations, common verification calculations and, scientific results presented in similar works which it is based on or which it follows on from.

1. perception of the current design and implementation of wooden buildings in the Czech Republic
2. determination of verification hypotheses, especially considering potential faults in the structure, or their further technical optimization
3. professional software simulation for hypothesis verification
4. additional calculations
5. evaluation of current results
6. plannedevaluation of currently performed practical measurements on a real house and a physical model

The assessed issue will be the verification of the use of the underlying profile under the basic frame. The work aims to determine the assessment of the optimization possibilities of the solutions described above. The purpose of the work is verification of hypotheses using available resources, software, and research.

Methodologically, the following was assessed:

1) Mechanical strength of the base frame.
    a) Load determination, assessment, and pressure evaluation of the described area.
    b) Mechanical stability of connection elements depending on the building materials used.
2) Linear thermal bridges.
    a) Modelling of 2D structural details, assessment using thermal technology software – 2D temperature field for linear heat transfer factors (ψ) and temperature factor of the inner surface (f_{Rsi}).
    b) Assessing the effect of thermal bonds on the overall energy rating of buildings.
3) Waterproofing and airtightness.
    a) Assessment of details on moisture behaviour in the 2D field.
    b) Possibility of using additional coating waterproofing systems and possibility of using liquid waterproofing systems.
4) Economic assessment and overall feasibility of solution variants.
5) Impact on the overall service life of the building, overall assessment, and recommendations.

3 RESULTS

Tab. 1 Multicriteria analysis.

Variant	Description of subsection	Criterion 1 Mechanical strength 3)	Criterion 2 Thermal connection 2)	Criterion 3 Tightness (air/water)	Criterion 4 Economy of design	Total Criteria Appropriate design
Variant 00	*Common design*	*Y*	*! 1)*	*! 1)*	*Y*	*! 1)*
Variant 01	*Frame on concrete block*	*Y*	*N 2)*	*Y*	*Y*	*N 2)*
Variant 02	*Frame on solid insulation*					
	a) EPS 200	*N 4)*	*Y*	*! 1)*	*Y*	*N 4)*
	b) XPS 300	*! 5)*	*Y*	*! 1)*	*Y*	*! 5)*
	c) XPS 3000 CS	*Y 6)*	*Y*	*! 1)*	*Y*	*Y 6)*
	d) Foam glass, Compacfoam	*Y*	*Y*	*! 1)*	*! 7)*	*! 7)*

Explanation of the main assessment criteria in Tab. 1

Y	Criterion was met positively,
!	Criterion met with proviso,
N	Criterion not met.

Explanatory notes on Tab. 1

1. Waterproofing of the designed detail depends on the quality of the joint sealing performed by the construction contractor. It also depends on the quality of the chemistry (chemical mortar, rubber asphalt, etc.) used, its UV stability, sustainability, technical longevity. A parameter designed in this way is very difficult to evaluate in the case of permanent covering of structures, and it is therefore necessary to rely on the quality of execution. It is also a good idea to equip the structure with sensors with permanent measurement of critical points in the structure to prevent accidents (water seepage). The air tightness parameter can be evaluated most effectively by in-site measurements, for example "blower-door test". The results may vary depending on the quality of the construction.
2. The detail of variant 01 did not meet the assessment of the lowest surface temperature of the structure – temperature factor ($f_{Rsi,min}$), assessed according to the Czech standard [8]. The risk of surface condensation of water vapor and mould growth would be even more pronounced, especially in the corners of the building. This solution is not suitable for the quality of the building's internal environment, nor for guaranteeing the long-term durability of the structure.
   The temperature factor f_{Rsi} is a local property of the structure or the connection of structures, including their heat transfers on the inside and outside (R_{si} and R_{se}) which does not depend on the adjacent temperatures. This is similar to the well-known average property of the entire structure, which is the heat transfer coefficient U. These two properties complement each other when characterizing the behaviour of the structure during heat transfer. The average U-value characterizes the overall energy effect of the structure, the lowest f_{Rsi} values characterize local fluctuations in heat transfer, when usually evaluating a thermal bridge in the structure or a thermal bond between structures, from the point of view of the risk of water vapor condensation or mould growth on the inner surface of the structure [9], [10], [12].

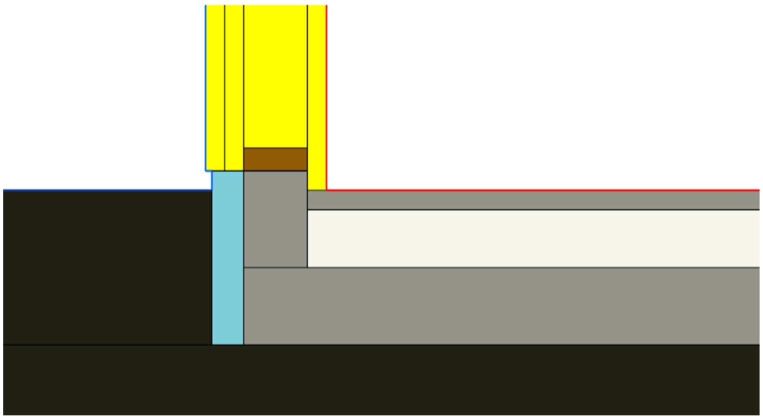

Fig. 4 Variant 01 in the 2D simulation input, figure cropped from the real input.

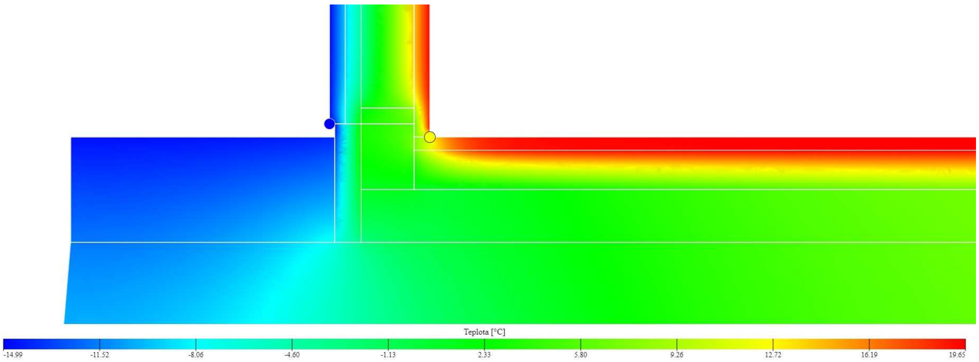

Fig. 5 Variant 01 output of temperature values in the structure and on the surface ($\theta_{si,min}$ = 12,494 °C).

The geometries of the considered 2D scheme of temperature fields have been modified for easier formatting of the visual output in this article. The detail assessed by the software [20] had a set geometric interface of min. three times the width of the wall structure (3d), namely 2.25 m high, 2.5 m long from the zero point and 5 m deep (for the soil boundary condition). Other boundary conditions were chosen as follows: interior – living room: $\theta_{ai} = 20.0$ °C, $\varphi_{i,u} = 50\%$, $R_{si} = 0.13$ m^2.K/W; exterior - Brno $\theta_e = -15$ °C, $\varphi_e = 84\%$, $R_{se} = 0.04$ m^2.K/W. The detail was assessed in the student version of the "Tepelná technika 2D" software by Deksoft [20].

The whole evaluation is based on the equation:

$$f_{Rsi,min}[-] \geq f_{Rsi,cr}\ [-] \tag{1}$$

where $f_{Rsi,min}$ is the lowest temperature factor of the inner surface $[-]$, $f_{Rsi,cr}$ is required critical temperature factor of the inner surface $[-]$ is the value at which the relative humidity on the inner surface will reach the prescribed maximum. The following calculation applies:

$$f_{Rsi,cr} = 1 - \frac{237{,}3+2{,}1\cdot\theta_{ai}}{\theta_{ai}-\theta_e}\cdot\frac{1}{1{,}1-17{,}269/\ln\left(\frac{\varphi_i}{\varphi_{si,cr}}\right)} \tag{2}$$

where θ_{ai} is inner air temperature, in °C, θ_e is exterior temperature, in °C, φ_i is relative humidity of indoor air in %, indoor relative humidity to determine the lowest indoor requirement surface temperature of the structure with a safety margin of 5% and $\varphi_{si,cr}$ is critical internal surface humidity in %; for other structures = 80%.

The required values of the critical temperature factor of the internal surface $f_{Rsi,cr}$ for the relative humidity of the internal air $\varphi_i \leq 50\%$ are according to [8] and calculation (2) for other structures at the design temperature of the internal air $\theta_{ai} = 21$ °C and the design outdoor temperature $\theta_e = -15$ °C on value of $f_{Rsi,cr} = 0.793$. According to the relation (1), the value of the calculated 2D simulation $f_{Rsi,min} = 0.749$ does not meet these requirements.

The spread of heat in porous building materials is closely related to the spread of moisture. The propagation of heat and moisture in porous materials can be characterized in the already mentioned one-dimensional simplification (3) by the equations written in Tab. 2.

Tab. 2 Overview of basic mechanisms of heat and moisture propagation in porous building materials.

Spreading	Mechanism	Controlling magnitude	Equation	
heat	heat conduction	temperature	$q = -\lambda(u)\frac{\partial\theta}{\partial x}$	(3)
water vapour	water vapour diffusion	partial pressure of water vapour	$q_d = -\frac{\delta_{air}}{\mu(u)}\frac{\partial p_d}{\partial x}$	(4)
	water vapour effusion	partial pressure of water vapour		
	thermodiffusion	Temperature	$q_\kappa = -\kappa(u,\theta)\frac{\partial\theta}{\partial x}$	(5)
liquid phase	capillary conduction	capillary pressure	$q_{kap} = -\kappa(u)\frac{\partial u}{\partial x}$	(6)

The models described in Tab. 2 consider moisture propagation under isothermal conditions. This condition is exceptional in practice, and the mentioned models can only be used if there is a small temperature difference in different parts of the structure, and thus the effect of temperature can be neglected. In practical cases, the temperature is not the same in all places, for example, in the perimeter structure during summer days, the temperature difference between the inside and the outside can be as much as *40-50 °K*. Models [13] for the simultaneous description of heat and moisture distributions are available in literature with various advantages and disadvantages for a given application. Among the most common are diffusion models (Krischer [11]) and convective and hybrid models.

In Krischer's model for simultaneous propagation of heat and moisture in building materials, the moisture equation is given in the form:

$$\rho_w\frac{\partial w}{\partial\tau} + \frac{\Pi - w}{R_v\cdot T}\frac{\partial p_d}{\partial\tau} = \rho_w\cdot\kappa\frac{\partial^2 w}{\partial x^2} + \frac{D}{\mu\cdot R_v\cdot T}\frac{p}{p-p_d}\frac{\partial^2 p_d}{\partial x^2} \tag{7}$$

where Π is total open porosity, p_d water vapour pressure in Pa, κ is coefficient of moisture conductivity in m^2·s^{-1}, D is water vapour diffusion coefficient in m^2·s^{-1}, μ is water vapour diffusion resistance factor.

The heat conduction relation is given for one-dimensional propagation in the form:

$$\rho_w \cdot c \frac{\partial T}{\partial \tau} = \lambda \frac{\partial^2 T}{\partial x^2} + L_v \left(\frac{D}{\mu \cdot R_v \cdot T} \frac{p}{p - p_d} \frac{\partial^2 p_d}{\partial x^2} + \frac{\Pi - w}{R_v \cdot T} \frac{\partial p_d}{\partial \tau} \right) \tag{8}$$

where ρ_v is volumetric weight in kg·m^{-3}, c is specific heat capacity in J·kg^{-1}·K^{-1} and L_v is latent heat of vaporization in J·kg^{-1}.

Based on the rules above, it can be concluded that heat conduction also has its own dependence on the spread of moisture in structures (8). In practice, this means that the heat conductor will lead unwanted moisture through its porous mass to a critical point of the structure.

An overall assessment from the point of view of energy and heat savings has evaluated variants met the standard [8] requirements for the Linear heat transfer coefficient (Ψ) when entering the details. Even the thermal bonding requirements for passive houses (Ψ_{pas}).

The evaluation of variants 00 and 02 in terms of Lowest surface temperature of the structure, temperature factor ($f_{Rsi,min}$) resulted in a positive evaluation. The required values of the critical temperature factor of the internal surface $f_{Rsi,cr}$ on value = 0.793. The value achieved for variant 00 was ($f_{Rsi,\,min}$) = 0.871 and for variant 02 the value was ($f_{Rsi,\,min}$) = 0.966.

3. Mechanical strength was assessed for simple pressure (stress in *kPa* passing through the base frame into the underlying concrete slab) per 1 m length and 16 cm width of the element. A total of 6 load cases were determined.
   a) Building with one floor above ground, normal load condition. Calculated value: *108.44 kPa.*
   up to f) Building with three floors above ground, local extreme. Calculated value: *398.02 kPa.*
4. Elements made of ordinary expanded (EPS 200 kPa) polystyrene were found to be unsuitable for the proposed solution. This is due to their mechanical strength, which is determined in the given values for tension at 10% volumetric compression. This deformation would have undesirable effects on the overall deformation of the building (settlement). At an acceptable 2% volume deformation, the EPS product of *200 kPa* achieves a strength of only *36 kPa* [17]. Thus, it is completely unsuitable for the load conditions described above.
5. Elements made of ordinary extruded (XPS 300 kPa) polystyrene were found to be suitable for one-story houses at most. Their strength at an acceptable 2% compression reaches a value of around *130 kPa* [18], which is close to the load conditions mentioned above.
6. High-strength (XPS 5000 CS) polystyrene elements have been found to be suitable for the most common houses of up to 3 stories. Their strength at an acceptable 2% compression reaches a value of around *250 kPa* [19].
7. Elements made from foam glass blocks reach a strength of *1600 kPa*, without change in volume. Elements made from thermoplastic foam (Compacfoam) reach a strength of *560 kPa* at an acceptable 2% compression. In terms of mechanical strength and stability, they are therefore ideal elements. The economic assessment of the proposal primarily offers an evaluation of the simple acquisition costs of the mass of material. Therefore, the only potential disadvantage of the above-mentioned materials is their higher price. For overall comparison, an element of 1 meter in length under the frame made from a suitable XPS 3000 CS normally costs approx. 150 CZK. A similar made from foam stock costs 900 CZK, an element made from thermoplastic foam costs 1770 CZK.

4 DISCUSSION

Summary of results

Variant 00 (*Common design*) is currently the most widespread version of the listed variants. From the practical experience gained during construction preparation, it can be stated that professional companies perform the sealing of perforated areas (using chemical mortar, rubber asphalt, etc.) carefully. It is important that these places are always checked by an authorized person (construction supervisor) before covering. With the correct implementation of this variant, a minimal effect on the overall life of the object can be expected. A research question arises for this variant: What is the lifetime of the mentioned building chemicals in the area in which they are placed?

Variant 01 (*Frame on concrete block*) was based on an actual design of a detached house. It can therefore be stated that this proposal will have a cause in the long-term problem of the formation of mould, in a temperature-varied period. It is also likely to lead to degradation of the wooden structure. The problem is that concrete, as a heat conductor, is placed too close to the inner thermal envelope of the interior. Therefore, option 01 with a concrete block is unsuitable for the long-term service life of a building. However, the solution itself is not closed by new research. There are assessment options: using sand-lime blocks, autoclaved aerated concrete blocks, or similar materials that will be solid and strong and will be more of a heat insulator than a heat conductor.

Variant 02 (*Frame on solid insulation*) was based on a solution that is currently starting to become a trend. The building frame can be sufficiently protected, for example, if it rains during the construction period. However, we see a weak point of this proposal in the chosen thermal insulation material, especially in its mechanical strength. The picture (Fig. 3) shows a photo of the building from practice at the time of construction. A (probably) ordinary floor polystyrene class EPS 100 or EPS 200 was used as a base profile under the frame. However, during the completion of the construction, there will be an increase in the load and this element will be volumetrically compressed. Signs of small defects, such as cracking of cladding elements or failure of board joints, are likely to occur. Of course, there will most likely be no fatal collapse of the structure or degradation of the wooden elements, so the overall service life will probably not be limited. However, the above-mentioned faults are undesirable in new buildings, and their repairs are not cheap. Of course, even this solution considers a high-quality design of the joints, their sealing, and the effect on the service life of the building (as with variant 00). This solution makes sense when making a base profile under a wooden frame while using insulation made from extruded polystyrene with high strength, for one to two-story ordinary detached houses. For multi-storey houses, it is advisable to use this variant with the use of foam glass or thermoplastic foam with high strength.

The presented solutions are only part of the technical details that can be encountered during the construction of wooden structures in the Czech Republic [14], [15]. There are many other and already proven solutions. For example, in the technical manuals of suppliers of building materials [6], solutions similar to those presented in this work can be found. Designs of wooden buildings made of laminated timber (CLT) are treated in a similar way, e. g. Pavlas [7] mentions them in his book. The most effective solutions at present include a double slab (base slab, hydro insulation, cover slab – into which the building is mounted), or an inverted foundation (thermal insulation, hydro insulation, base slab). General requirements for the construction of wooden buildings state that a wooden building should never be founded below ground level or in other conditions that preclude its implementation. In addition, it is always recommended to use monitoring sensors that measure parameters (temperature, air humidity, mass humidity in the wood mass) at critical points in the structure. In this way, it is possible to monitor the decrease/increase in moisture in the structure, or to detect a malfunction (cracked pipe in the wall) effectively and in time.

5 CONCLUSION

The issue of wooden buildings and their design and implementation is dependent on many factors and decisions that must be made correctly and appropriately. There are many different methods and solutions that can be used in the construction of wooden structures, and it is important to choose the right ones. The methods presented in this article are based on general knowledge obtained from manuals, websites, publications, as well as practical experience with non-traditional solutions. A properly designed and executed foundation is essential for the stability and long-term service life of wooden structures. Each type of incorporation has its advantages and disadvantages and there are various factors and demands to consider. When choosing the right method of establishment, it is also necessary to take local conditions into account individually. Individual methods of establishment require different procedures and technologies that must be mastered.

In conclusion, it is necessary to point out the fact that only the evaluation of the 2D temperature field with stationary fields and boundary conditions was used in the work, which can be considered simplified and, in some cases, leads to misleading data. The presented details must be further verified to clarify the results of non-stationary 2D terrain simulations using real data, including climate change and evaluation of the moisture field.

It can be stated that this work brought the generally expected results. Designers and builders of wooden buildings can use these results and apply them in practice.

Future research and studies will help us to better understand the problem of establishing the frame of wooden buildings and provide us with other options and solutions. Timber buildings are an increasingly popular choice for various types of buildings, and it is important that we have enough information and tools to properly design and implement them.

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