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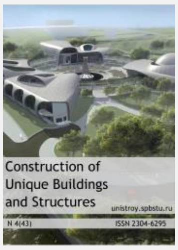

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Assessment of straw construction technologies in terms of thermal efficiency of enclosing structures

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ABSTRACT

Sustainable construction nowadays requires the use of environmental friendly materials with high rate of insulation. Straw construction presents some advantages such as renewability with low energy input, recyclability, CO2 storage, and local availability that implies short distribution cycle. However, before the introduction in the construction industry, attention needs to be paid to the construction technology using such natural materials. In this paper there were developed elements of enclosing structures for two technologies of straw frame building; was done thermal modeling of potentially weak assembles of building envelope; were calculated R-values and then compared with normative indexes; was evaluated efficiency of usability two technologies of low-raise building in cold and wet conditions of St. Petersburg.

Contents

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1. Introduction

Since the early 90-ies of XX century in the world spreads the idea of "green" building. "Green" construction is industry, including the construction and operation of buildings with minimal influence on the environment. Most popular problems of "green" construction in the twenty-first century are:

- reduction in aggregate (for the entire life cycle of the building) harmful effects of construction activities on human health and environment;
- making new industrial products;
- reduce the cost of maintenance of new buildings [1].

Straw has long been used as a construction natural local material. Modern building with straw began from the late 19th century [2-4]. At this time in the United States began to appear steam pressing machines. First straw bale houses, standing more than 100 years in USA, proved durability of the material and reliability of technology.

Applying straw as insulation walling meet the principles of "green" construction. Straw is a natural product, grown by photosynthesis during half or one-year period, fuelled from the sun. Straw is currently produced surplus to requirements, so it is cheap and easily accessible in most of countries. It is product of crops growing, so using it for building purposes is very sustainable and ecological way of recycling [5]. Over the last 20 years, interest in the use of straw in mainstream construction has developed for a number of essential advantages:

- thermal insulation properties;
- sound insulation properties;
- resources saving and healthy microclimate;
- low embodied energy;
- straw sequesters carbon dioxide by photosynthesis, thereby reducing atmospheric CO_2 [6].

Straw is an organic material that carries particular risks with it in the context of living accommodation. The construction of buildings with the use of straw popular in many countries such as Canada, USA, UK, Byelorussia, Germany and Lithuania. The theoretical and practical studies of straw building material were conducted in some of these countries. To meet local building regulations research has been conducted into fire resistance [7–9], vermin resistance [3, 10], structural performance [5, 11–18] and resistance to decay [6, 19-21].

Today the use of straw bales for the construction of buildings in the Russia has to date generally been limited to the self-build fringe sector. In order to bring this form of construction into the mainstream sector, to benefit from its inherent low carbon and high insulation characteristics, it is necessary to know how to use straw in our climatic conditions.

Various techniques exist for straw construction depending whether the straw bales play structural role or not. In our time, used several techniques straw construction. One of them is techniques of load-bearing straw bale wall. But this way has many principal disadvantages:

- prefabrication and wooden façade not possible;
- possible humidity-problem through direct-plaster outside;
- small windows possible;
- missing installation area;
- statics: harder to proof.

So in this paper we have considered the two timber frame construction technology:

- straw bale wall modular system;
- the “GREB” straw bale technique.

These technologies were created in Europe where the climate is less severe than the Russian. The paper has the following goals and objectives of research:

- overview of existing technologies of frame building with straw bale insulation;
- designing of the main nodes of building envelope based on the considered technologies of low-rise building;
- thermal simulation of assemblies for determine their thermal properties;
- calculation of thermal resistance and inside surface temperature in comparison to the normalized values;
- analysis of thermal heterogeneity of constructions and identifying thermal bridges;
- evaluation of the potential use of technologies considered in a climatic region of St. Petersburg.

2. Materials and methods

2.1. Straw bale wall modular system

Straw bale panels have produced at the plant in Europe for a long time. Lithuania straw panels EcoCocon produced successfully for several years. Aaccording to the manufacturer, they are dedicated to create a complete ecological building solution that is able to compete with the mainstream building industry. The company's products have an exceptionally positive impact on the environment – the manufacture of straw panels does not deplete sources of raw materials and demands very little primary energy for production. Energy for heating and cooling is saved thanks to the outstanding insulation of the building over its entire lifetime. The well insulated panels save energy spent on heating and cooling during the entire lifetime of the building. Resulting lower CO_2 emissions do have a beneficial impact on global warming.

EcoCocon panels are modular. Manufacturer can adapt panels to dimensions of project. Assembling the panels on site is quick and precise. Only simple tools and standard screws are needed for assembly. This technology allows to assemble around 100 m^2 of wall per day.

There are some limits presented products:

- all EcoCocon panels (without wood fibre board) are always 400 mm thick;
- minimal width and height are 400 mm;
- maximum width and height is 3000 mm;
- max angle of the top is 45°.

According to the manufacturer, the EcoCocon panels are an ideal element for achieve the passive house standard. Basic rules needed to achieve the passive house standard:

- continuous super-insulation;
- continuous airtight layer;
- eliminating heat bridges;
- correct solar orientation;
- excellent windows and shading;
- include mechanical ventilation.

An airtight layer required serves to achieve the passive house standard. In this case the manufacture point that the airtight layer should always be on the inside, except for the EcoCocon walls. On this technology the straw is plaster directly with clay, therefore achieving airtightness inside is very difficult. Not because of the clay plaster, but all small gaps around light switches, sockets, wooden beams and more. Leakage of air through a gap can lead to condensation in the construction. Through an opening 1mm wide and 1m long as much as 360 g of humidity might pass in 24 h. Manufacturer has verified a solution that is airtight but completely open to vapor. The membrane will let moisture pass from inside to outside without slowing it down. This moisture transfer is only about 2 g per square meter of construction per day, a lot lower than if you would have movement of air passing through. The wood fibre board on the outside is necessary, because it effectively moves the moisture away from the membrane to the outside. Natural materials such as wood fibre or cellulose do transport moisture very well, always from warmer to colder side The membrane also protects the panels from driving rain during the building period. The membrane should be applied to the top and outside of the panels as soon as the walls are put up.

The figure 1 shows the several details that have been designed and thermal bridges calculated.

a) b) c)

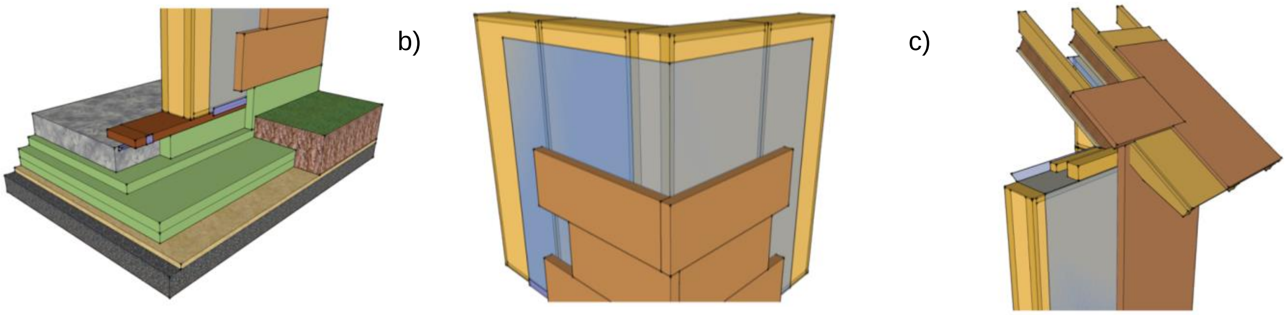

Figure 1. Foundation on XPS (a), wall outside corner (b) and eave (c)

2.2. The "GREB" straw bale technology

Name "GREB" construction technology (Research Group Ecological Construction, Le Groupe de Recherches Ecologigues de la Batture, GREB) comes from the ecological settlement of rural type, located in France, a few kilometers from the district center de La Baie and founded in the 1990-s. The settlement was founded to research and develop methods of ecological and sustainable development of rural areas in terms of the northern regions.

Participants trying to improve quality of rural life by using renewable resources, and reducing sources of pollution and energy consumption. Existence ecovillage confirm global development capabilities with local ecosystems.

The GREB technique is a process in several stages. The first – assembling of a double wooden frame, the second – installation the bale compressed straw width of 60 cm. The third – a lightweight mortar is cast in-between the wooden structure against the straw bales.

A double light timber frame, using a unique section (40 mm x 100 mm) of vertical posts, separated by the width of a straw bale (60 cm, 2 ft average). Posts are screwed directly to a sill plate fixed on the foundations. For each floor, fix an upper rail on the posts to install the floors and ceilings joists. Each upper level and gables can be made with the same construction technique. To support a specific beam or additional load bearing, application a structural column made of 8 posts assembled to each other's, which gives a strong resistance to the work.

A first straw bale layer is slipped inside the double frame; formworks are screwed on the posts, the wood mortar is run between straw bales and formworks.

For straw bale selected healthy and dry cereal straw. Applicable bale must be as identical to the direction of fibers. Bale sizes – 400x500x750 mm.

Straw bales are protected by a light wood mortar, made up of cement – calcic lime – sand and sawdust. The microporous mortar associated with natural lime coating will guarantee a breathing wall and protected from the rain. A lime mortar or other covering will then be depending on the finishing coat need the walls.

The figure 2 shows the several details that have been designed and thermal bridges calculated.

a) b) c)

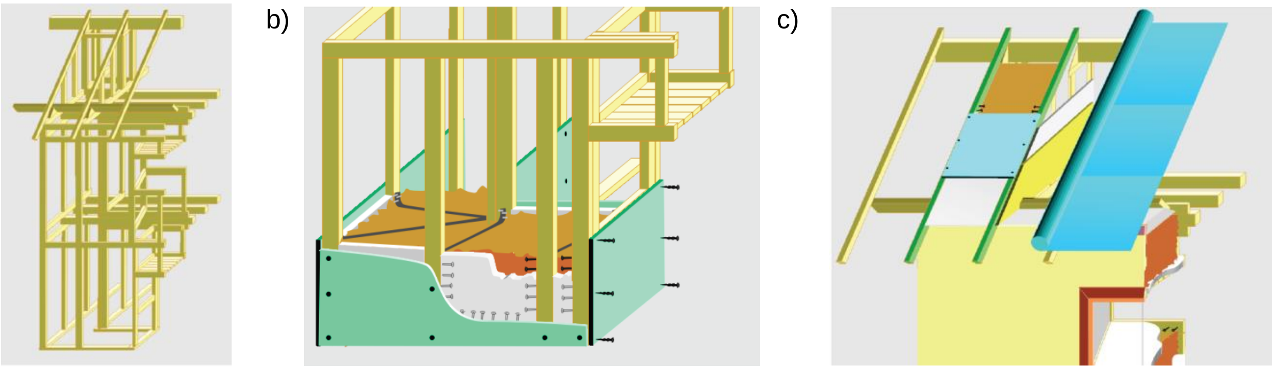

Figure 2. Wooden frame structure straw bales (a), reinforcement with screws, nails and iron strap, lightweight mortar (b), assemble of filling wall and roof (c)

2.3. Numerical thermal analysis

Traditionally, the heat transfer resistance R-value for the multilayer construction is calculated by simply adding a serial resistance of each material. This approach takes into account only one-sided heat exchange mode and assumes the alignment of components and direct thermal contact. Using a two-dimensional simulation tools it is possible to obtain more proper content, which includes all kinds of heat losses.

Applicable two-dimensional conduction heat-transfer analysis is based on the finite-element method (FEM), which can model the complicated geometries of building products. Selected elements have been designed according to the recommendations [22, 23]. Thermal analysis was carried out in WINDOW/THERM 7.4 (LBNL), which is certified to national standard GOST R by "APROK" Association of Russia [24] and meets applicable building code SP 50.13330.2012 «Thermal performance of buildings» [25].

Table 1. Boundary conditions for analysis

Performance	Notation	Unit, [ ]	Value
Heat transfer coefficient of wall surfaces: 1. inside 2. outside	α_{in} α_{out}	[W/(m^2·K)] [W/(m^2·K)]	8.7 23.0
Relative air humidity in cold season: 1. indoor 2. outdoor	W_{in} W_{out}	[%] [%]	55.0 84.0
Optimum indoor air temperature	t_{in}	[°C]	+20.0
Outdoor air temperature (average temperature of the coldest five-day period per year)	t_{out}	[°C]	-24.0
Dew point temperature	t_d	[°C]	+10.7

The modeling focused on the analysis of potential "weak" nodes of building envelope in terms of heat engineering. This paper discusses the junction nodes of different enclosing structure elements:

- section 1 – wall and ground supported floor in a vertical section;
- section 2 – two walls at the corner in plane between supporting elements;
- section 3 – two walls at the corner in plane of supporting frame;
- section 4 – wall and roof slab in a vertical section.

These assemblies are often characterized by the presence of thermal bridges. They have lower thermal resistance and are susceptible to precipitation of condensate on the inside surface.

The main criteria for the analysis of these two technologies and assessment of their compliance with the St. Petersburg climate conditions are defined as follows:

criteria 1: calculated values of thermal resistance should meet the normalized values. According to the national regulation and territorial recommendations [25, 26] required value should be – R_{wall}^{req} = 3.08 $(m^2{\cdot}K)/W$ for walls, R_{floor}^{req} = 4.50 $(m^2{\cdot}K)/W$ for ground supported floors and R_{roof}^{req} = 4.06 $(m^2{\cdot}K)/W$ for attic floors.

criteria 2: minimum temperature of the inside wall surface should not be significantly different from the air temperature. This parameter impacts on the quality of the interior environment and comfort. Maximum difference Δt_{max} should not exceed 4 °C. It is regulated by the national standard GOST R ISO 7730 [27]. Thus the minimum temperature of the inside surfaces of enclosing structures shall conform to the condition $t_{min}^{surf} \geq 16\ °C$.

criteria 3: the susceptibility of materials to the moisture accumulation and condensation resistance is one of the main parameters for the building envelope in St. Petersburg. It is desirable that dew point isotherm positioned inside the insulation layer. This is important to identify potential areas of condensation on the boundary interface [28]. Excessive moisture on the surface of the wooden or concrete elements inevitably leads to the fungal corrosion. The dew point at the insulation surface stimulates moisture absorption and reduces its thermal properties.

criteria 4: on the one hand, availability of heat transfer inclusions reduces the thermal heterogeneity of enclosing construction. On the other hand, it reduces the material-use efficiency. As a result, thermal bridges significantly increase the aggregate heat losses of the building and lead to feelings of discomfort. Analysis of the interface nodes in building envelope allows to detect of potentially "weak" points. In the presence of the local thermal bridges is taking steps to eliminate them.

3. Results of thermal modelling

3.1. Calculation of overall R-values

Required and estimated heat resistance values for elements of enclosing structures (ground supported floor, wall, attic floor), which are designed by two technologies, are compared in the diagram (Figure 3). In this case, the calculated thermal protection characteristics of different elements of building envelope are determined considering their combined influence and placing in a complex structure – interface nodes.

In section 1 ground supported floor is insulated with slabs of polyurethane foam XPS-Carbon (Appendix: figure 8). Complicated heat losses through the floor with consider of increased heat loss intensity at the edge zone of the slab are nearly required R_{floor}^{req} (Figure 3, column 1). In the same section walls have a calculated heat resistance comparable with required R_{wall}^{req} [25]. Not high calculated values in this node are caused by high thermal losses through thermal conductive inclusions – constructive frame elements and reinforced concrete floor slab. Therefore, in section 1 EcoCocon technology in general satisfies requirements of thermal protection. In its turn, GREB technology requires changes of construction scheme: additional insulation of floor slab edge and edge zone of the wall (Figure 3, column 2).

In section 2 and 3 the calculated heat resistance of walls for both technologies satisfies requirements. In section 2 heat resistance that is lower than required is allowed, because this section is “weak” point in terms of thermal engineering (includes through-wall thermal bridges). So total square of this thermal conductive includes is insignificant and does not change average thermal resistance in section 3.

In section 4 values of thermal resistance in both technologies exceed minimal required values. In such a case thermal resistances of walls in this section exceed multiple regulation values. It is caused by absence of wood frame elements which decrease thermal properties of construction.

Summarizing the results of modeling in THERM software, it was determined that the both of technologies satisfy building regulations in terms of thermal protection [25]. It has to be observed that thickness of envelope and material usage for the first technology (EcoCocon) is globally less than for the second technology (GREB) and amounts 545 against 720 mm respectively. In such a way, EcoCocon technology is more preferred than GREB in terms of thermal protection and economical building envelope efficiency.

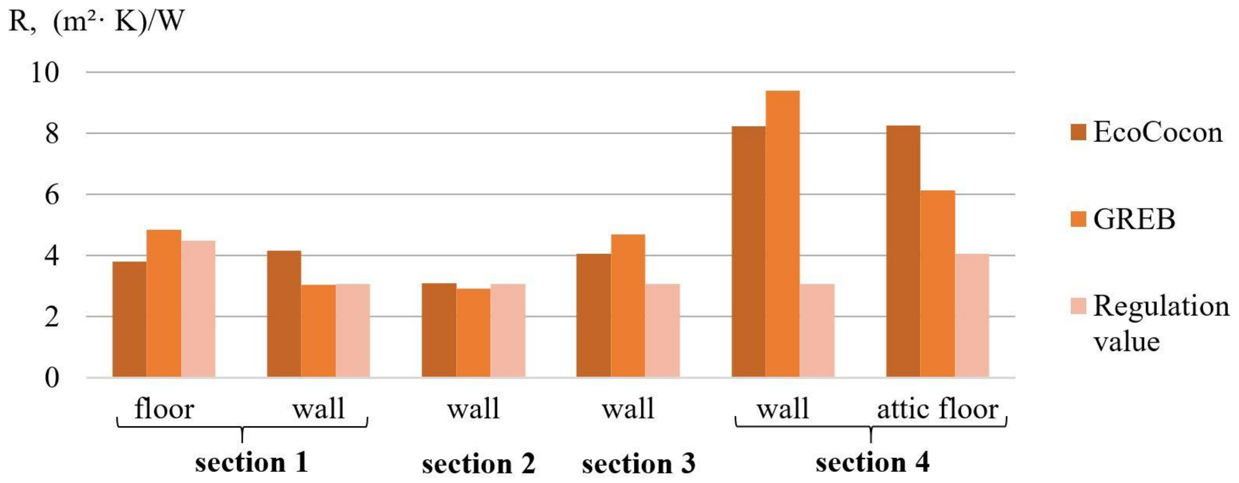

Figure 3. Comparison of the calculated and regulations values of the thermal resistance for the analyzed cross-sections

3.2. Section 1: junction node of wall and ground supported floor

The minimum temperature on the inside surface of construction for “EcoCocon” technology satisfies the normative requirements [27]. But for the GREB temperature is slightly higher than normalized $t_{min}^{surf} \geq 16\ °C$ (Figure 4). During the life cycle the temperature can be reduced further due to moisture accumulation of the wall and formation of micro gaps in nodes [29]. Furthermore, the probability of condensation on the concrete slab surface (Figure 4) and formation of fungi in “GREB” technology higher than in “EcoCocon”.

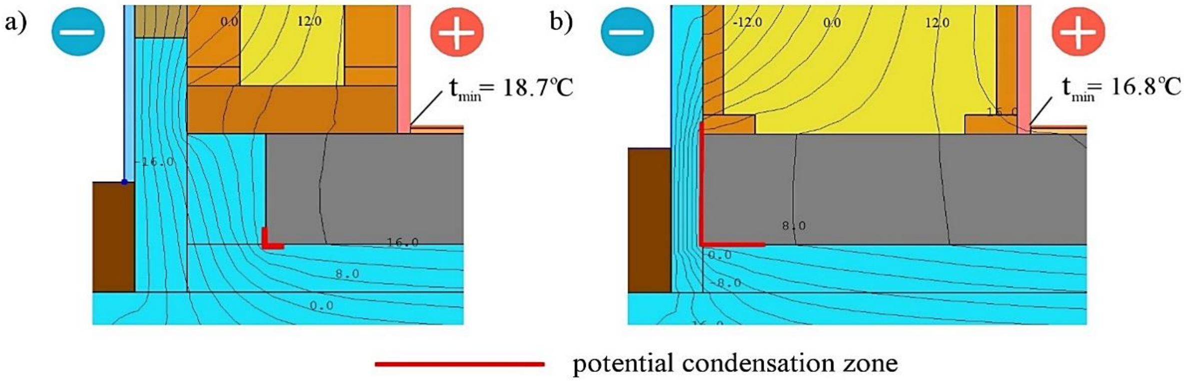

Figure 4. Isotherms of temperatures in section 1 in EcoCocon (a) and GREB (b) technologies

Insufficient heat transfer resistance in the node is associated with the “edge” effect. For selected "GREB" and "EcoCocon" technologies problem of local heat loss is typical. It is caused by weakening of the insulating layer in the end face of massive floor slab. In addition, the wooden framework elements supported by the base plate. The highest heat flow intensity arises precisely at this node (Figure 5).

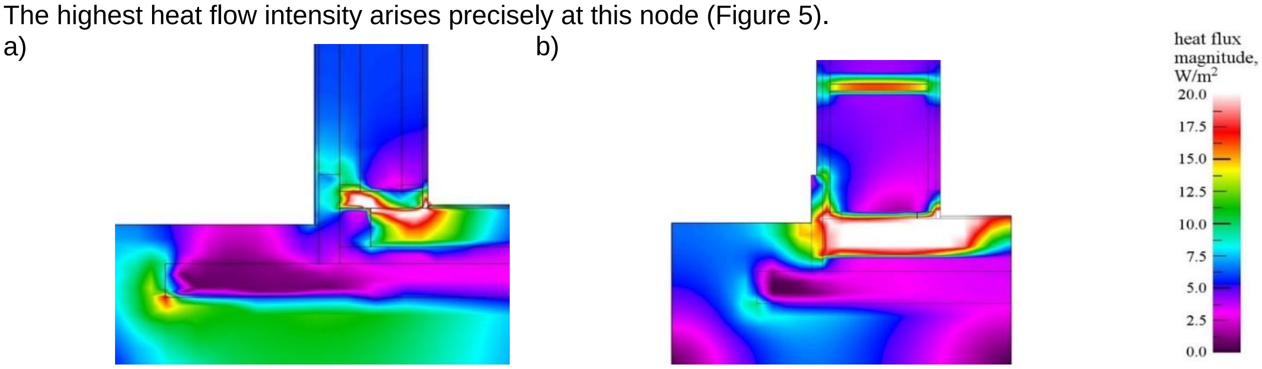

Figure 5. Intensity of heat flux in section 1 in EcoCocon (a) and GREB (b) technologies

Thus, the modified construction for the node in “GREB” technology requires increasing of heat insulating layer in the end face zone of concrete slab. Thermal heterogeneity and influence of heat-conducting inclusions in the building envelope should be reduced for both technologies.

3.3. Section 2-3: junction node of walls at the corner in plane

In the considered node of building envelope, the minimum temperature of the inside surface located in the wall corner. In this case, the temperature varies depending on the height of the measurement point. In section 2 (Figures 6a, 6c) minimum temperatures are 18.7 °C and 19.0 °C for “EcoCocon” and “GREB” technologies respectively. The section 3 of the framework in the plane is unreliable (Figures 6b, 6d). Minimum temperature on the inner corner surface in these section amounted to 18.3 °C and 17.6 °C for “EcoCocon” and “GREB” technologies respectively. Both technologies satisfy the requirements of comfort [27].

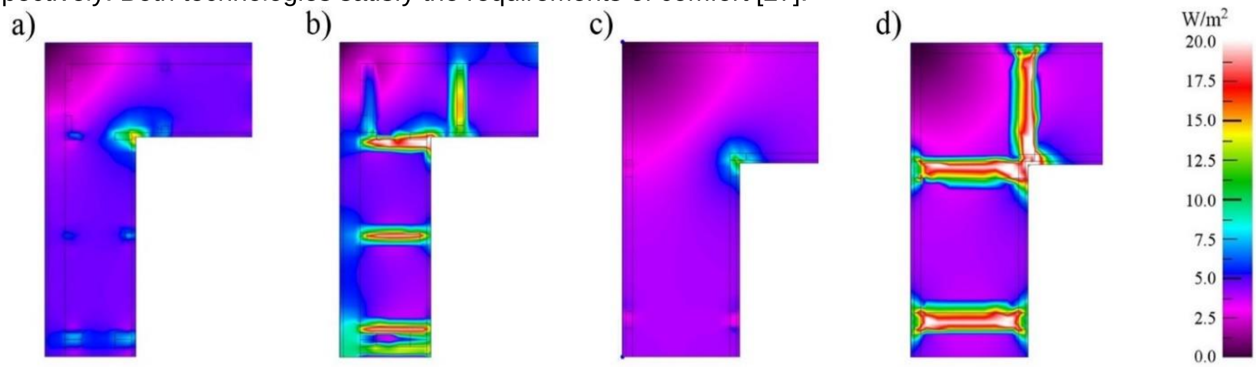

Figure 6. Intensity of heat flux in sections 2 and 3 in EcoCocon (a, b) and GREB (c, d) technologies

Potential condensation areas in the considered nodes are not available. Local transverse thermal bridges are in section 3 for both technologies (Fig. 6b, 6d). This is caused by the presence of wooden bars of frame wall construction. However, their impact on the overall heat loss is negligible. This is so due to the small cross-sectional area of bars and low thermal inertia. Therefore, both of technologies satisfy the climatic conditions and suitable for the construction of buildings with increased thermal resistance of wall in St. Petersburg, Russia.

3.4. Section 4: junction node of wall and roof slab

The lowest temperature, which is the criterion for thermal insulation efficiency is 19.0 °C and 19.1 °C (Figures 7a, 7c) for “EcoCocon” and “GREB” technologies respectively. Thus temperature difference between internal air and wall surface does not exceed 1.0 °C, that satisfies the standard [27].

Obvious condensation zones at the boundary interface does not arise within the building envelope. “EcoCocon” technology has no transverse thermal bridges and has a higher thermal homogeneity in comparison with “GREB” technology (Figures 7b, 7d). However, in both cases the magnitude of the flows through the thermal conductive inclusions does not exceed 13 W/m^2 and 18 W/m^2 for “EcoCocon” and “GREB” technologies respectively. This is so due to a large thickness of insulation in walls and floors.

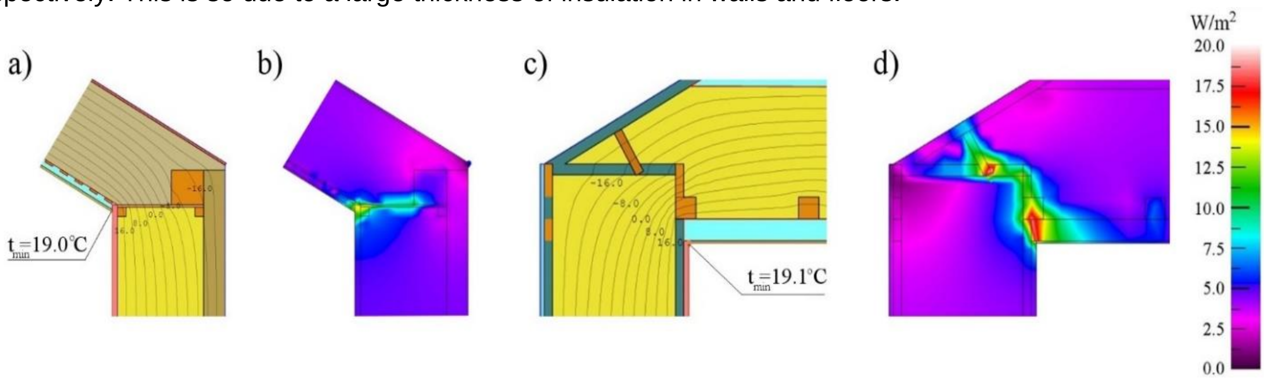

Figure 7. Isotherms of temperatures and intensity of heat flux in section 4 in EcoCocon (a, b) and GREB (c, d) technologies

Summarizing the results of analysis, it has to be concluded that researched constructions in this section satisfy all regulations of thermal protection, sanitary comfort, temperature difference, ecological, economic and energy efficiency aspects. Both technologies can be used in climatic conditions of Saint-Petersburg.

However, building envelope built with EcoCocon technology is more perfect (thermal homogenical) in comparison with GREB technology: temperature gradient between inside surface of construction and indoor air does not exceeds 2 °C, intensity of heat losses through thermal conductive inclusions is less, transparent thermal bridges are almost absent.

4. Discussion and conclusion

This paper presents the results of computer thermal simulation of elements of multilayer heterogenic walling. The analysis revealed that both timber frame construction technology can be used in climatic conditions of St. Petersburg.

All structural building units, which were modeled on the recommendations of technologies, meet the basic criteria:

- excess the required R-value;
- minimum temperature difference between the inner surface and the outer surface of the building;
- absence of potential moisture condensation areas inside structures;
- thermal homogeneity and absence of thermal bridges.

As a result, it may be concluded that the wall frame construction technology with using a straw as insulation can be applied in climatic conditions of St. Petersburg. However, building, that is built using EcoCocon technology, will have large useful square with the same outdoor size, like using GREB technology. Thermal protection properties of both technologies are comparable.

Summarize, it should be noted that the introduction of such technologies requires field-testing and certification in Russia. It needs to do a research on important criteria such as fire and fungi resistance, structural performance and resistance to decay. Moreover, economic comparison with existing technologies of low-rise construction in Russia is needed.

5. Appendix. Composition on enclosure structures

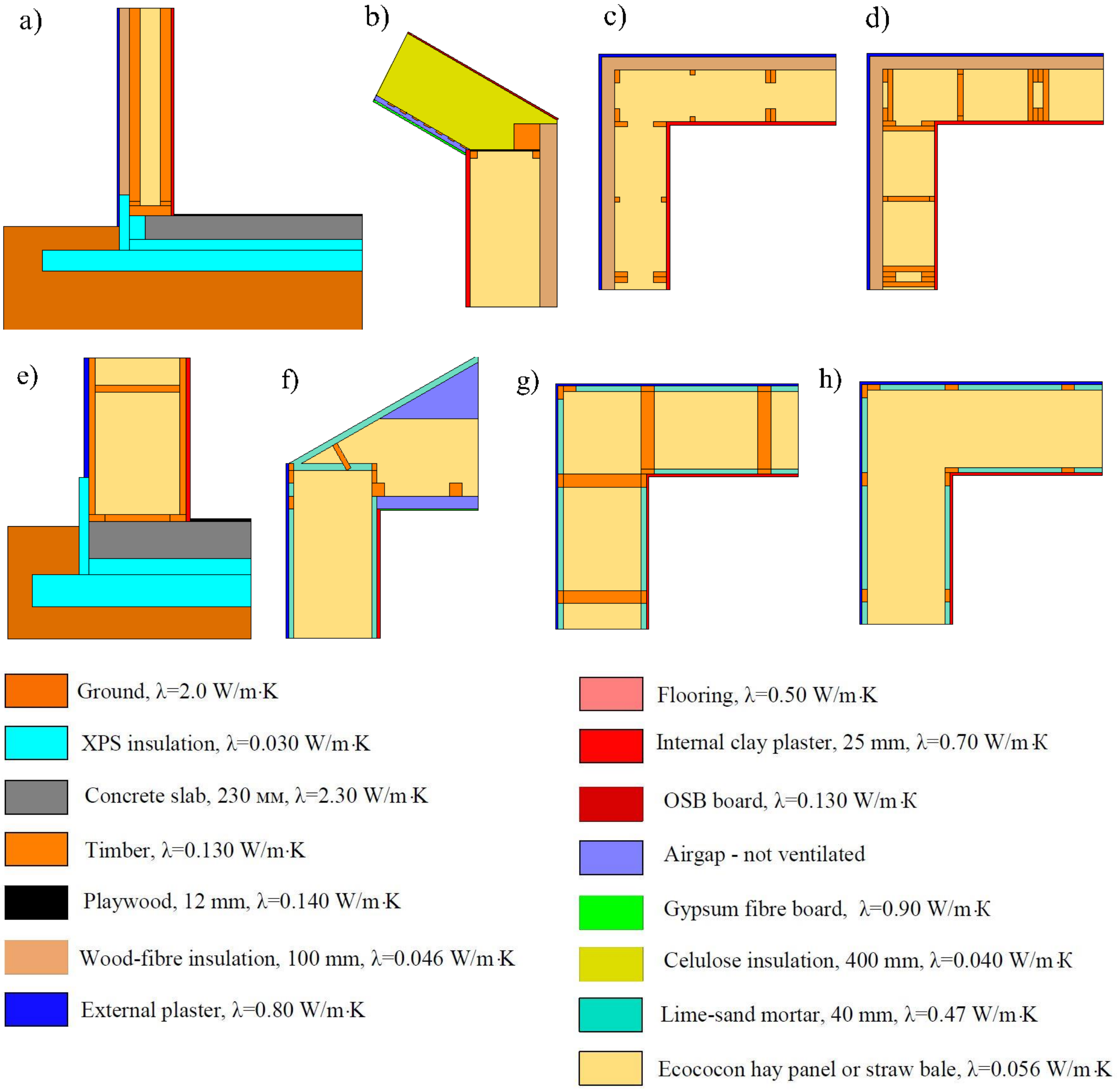

Figure 8. Straw bale wall modular system elements: bottom plate against exterior wall (a), eave (b), corner external (c,d) and the “GREB” straw bale technique elements: bottom plate against exterior wall (e), eave (f) and external corner (g,h)

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Оценка применения технологий соломенного строительства с точки зрения тепловой эффективности ограждающих конструкций

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АННОТАЦИЯ

В настоящее время устойчивое развитие в строительстве подразумевает использование экологических материалов с высоким уровнем изоляции. Строительство с использованием соломы обладает такими преимуществами, как возможность вторичной переработки, сокращение выбросов CO_2 в атмосферу, а также доступность на местах. Тем не менее, до внедрения в строительную отрасль, должно обращаться особое внимание на технологию строительства с использованием подобных природных материалов. В статье разработаны элементы ограждающих конструкций для двух технологий соломенного каркасного строительства; выполнено термическое моделирование потенциально слабых узлов оболочки здания; определены численные значения сопротивления теплопередаче и сопоставлены с нормативными показателями; оценен потенциал использования двух технологий при малоэтажном строительстве в условиях холодного и влажного климата Санкт-Петербурга.

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