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Energy performance of buildings made of textile-reinforced concrete (TRC) sandwich panels

N. Vatin [a] ***, S.V. Korniyenko*** [b]

[a] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*
[b] *Volgograd State Technical University, Volgograd, Russia*

svkorn2009@yandex.ru

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Abstract. This research aimed to investigate the energy properties of buildings made of textile-reinforced concrete (TRC) sandwich panels in various humidity-climatic zones. Two configurations of sandwich panel are considered: conventional and advanced. The conventional sandwich panel consists of inner and outer 75 mm thick reinforced concrete layers with separated by a layer of insulation made of extruded 50 mm thick foam polystyrene (XPS) slabs. In the advanced design, due to the use of TRC, the thickness of interior and exterior structural layers is reduced to 40 mm (while maintaining strength), and the thickness of the heat-insulating layer increased to 120 mm. Glass plastic connectors of 10 mm diameter located in nodes of a square grid connect the structural layers. The authors applied an analytical method of research to buildings' energy performance made of TRC sandwich panels based on the investigation of heat and moisture transfer processes in continuous heterogeneous media and analysis of energy indicators of buildings. For the purposes of this research, the element-by-element and complex assessment of building thermal protection was performed. Based on the results of this research, the main thermal advantages of these facade systems are identified. Building component thermal resistance is increased in multiple humidity-climatic zones, providing a high thermal protection level in winter compared to conventional facade systems. Building component heat absorption is increased by 34.4% (compared to conventional facade systems), excluding the risk of overheating of premises in summer. The risks of moisture condensation and deterioration of hydrothermal-protective properties of building components are minimized. The use of TRC sandwich panels allows reducing total heat loss through the building envelope by 26.5%. Simultaneously, the building's specific thermal characteristic is decreased by 16.7%, and the energy-saving class increases to high levels. Construction with advanced facade systems, when the precast sandwich panels with structural layers from textile-reinforced concrete are used, extends the creative boundaries of architecture and allows you to solve the current problem of improving the architectural environment's quality and conserve energy for future generations.

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1. Introduction

Nowadays, there is escalating concern on the sustainable building development around the world [1–3]. One of the major aspects is energy saving in buildings [4]. A significant portion of the energy is consumed by today's buildings in developed and developing countries. For example, about 40% of the total primary energy in Europe is consumed by buildings today, and more than 50% of that energy going toward heating in winter and cooling in summer of the indoor environment [5]. This fact emphasizes on the imperative need for energy conservation in buildings [6, 7].

Building energy efficiency can be improved by implementing either active or passive energy efficient strategies [8]. Improvements to heating, ventilation and air conditioning (HVAC) systems, electrical lighting, etc. can be categorized as active strategies, whereas, improvements to building envelope elements can be classified under passive strategies. Recent years have seen a renewed interest in environmental-friendly passive building energy efficiency strategies. This idea of sustainable buildings encompasses various issues regarding energy, water, land and material conservation, together with environmental pollution and the quality of indoor and outdoor environments [9].

A building envelope is contour that separated the indoor and outdoor environments of a building. It is the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions [10]. Building experts desire to create a durable and esthetic building envelope, adapted to environmental changes with all its potentials [11–13]. Research for new building materials, technological advancement, and structural development are the key targets for achieving this goal. There is a growing trend to use biofibers as fillers and reinforces in composites [14, 15]. Technological advancements in the production of building, structural, and infrastructural components, suggests advanced manufacturing techniques will allow these components to address issues including construction speed, structural performance, combinatorial material efficiencies, and economics of production [16]. A major building element able to benefit from these technological advancements and meet the demands of current urban growth is the development of a more intelligent and responsible building envelope [17–19].

The performance criteria of an effective building envelope is to be the protective layer around a building possessing the qualities of a thermal and moisture break, structural stability, wind and impact resistance, locally acclimated to environmental conditions, and provide the aesthetic expression of the building [21–23]. It is one of the most direct methods to develop a more efficient, sustainable, and economically feasible means to address the pressing needs of rapid urbanization and the performance criteria associated with more intelligent and responsible design. A key component toward developing a more advanced building envelope is the utilization of a precast concrete cladding system, particularly the further advancement of precast concrete sandwich panels. The development of Ultra-High-Performance Fiber-Reinforced-Concrete (UHP-FRC) has made it possible to investigate the extent of a stronger, lighter, and more durable precast concrete sandwich panel [24–26].

Textile-Reinforced Concrete (TRC) is a new composite material made of fine-grained concrete and textile reinforcements with high load-bearing capacities [27]. Due to its material properties, textile reinforced concrete offers a considerable application potential for thin-walled and lightweight facade constructions [20]. For example, sandwich panels, made of two thin TRC facings and a core of polymeric rigid foam present an attractive choice for modern building envelopes. These combine low weight with a high structural capacity, while simultaneously fulfilling structural and physical demands. However, the applicable slenderness is limited because of demands on the load-bearing capacity, deformation, and safety against cracking. Thus, monolithic or metallic bracings are required for large curtain panels. The use of 3D additive technologies is a perspective trend of TRC utilization in modern design [28]. The development of sandwich panels made of TRC has been the subject of several research projects at the Institute for Structural Concrete of RWTH Aachen University in Germany.

It is well known that sandwich panels with facings made of thin metal sheets (less than 1 mm) or reinforced concrete wythes (70–140 mm) have been successfully used in industrial and multistory buildings for decades [29, 30]. Their design principles and structural models are significantly different from each other. Sandwich panels made of TRC with facing thicknesses of 30–70 mm combine the advantages of the aforementioned constructions in terms of weight reduction, great potential for reduction of carbon footprint, and safety against corrosion [20].

Replacing traditional reinforced concrete layers in sandwich panels with thinner TRC structural layers makes it possible to increase the heat insulation layer's thickness at the same thickness of the structure and, therefore, increase the thermal performance of exterior walls. However, the thermal characteristics of TRC type façade are not well researched. There is no data on thermal performance under various humidity-climatic impacts. TRC sandwich sections' thermal stability is practically not studied, which makes it difficult to heat estimate structures in summer, with intense exposure to solar radiation. The processes of heat and moisture transfer in such structures and the influence of these processes on building components' moisture-protective properties are not fully studied. The absence of TRC sandwich panels' thermal characteristics makes it difficult to assess the buildings thermal performance and slows down the implementation of TRC in energy-saving construction. Therefore, it required comprehensive research of the energy performance of buildings made of TRC sandwich panels.

This research aimed to investigate the energy performance of buildings made of TRC sandwich panels in various humidity-climatic zones.

2. Materials and Methods

2.1. Building energy performance calculation concept

The authors applied an analytical method of research on buildings' energy performance made of TRC sandwich panels based on the investigation of heat and moisture transfer processes in continuous heterogeneous media and analysis of energy indicators of buildings.

For this research, the element-by-element and complex assessment of building thermal protection was performed (Fig. 1).

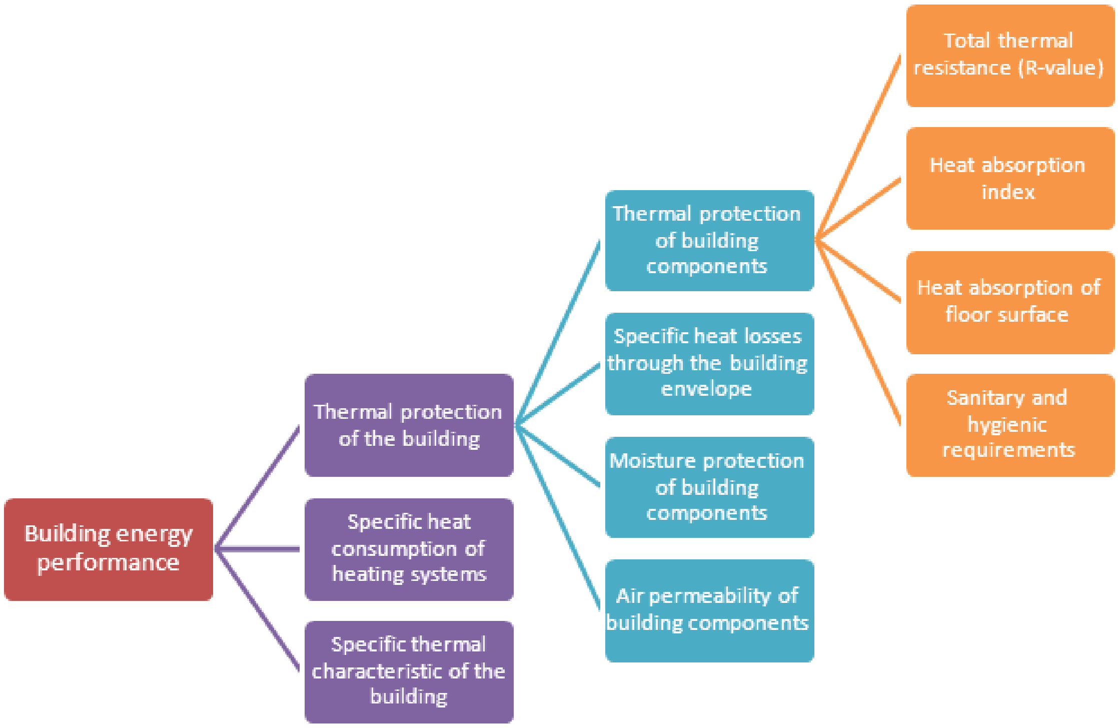


Figure 1. Building energy performance calculation concept according to Russian State Standard GOST 31427–2020 "Residential and public buildings. Composition of energy efficiency indicators."

For element-by-element thermal evaluation, the building envelope should be divided into separate homogeneous building components. The thermal quantities shall be calculated for each building component. The requirements on a building's thermal protection are considered fulfilled if each building component meets the thermal requirements.

A complex assessment of building thermal protection is based on a calculation of energy indicators for the entire building. The advantage of such a method is consideration of not only structural but also space-planning, climatological, engineering, and technical characteristics of building. Results of complex assessment of building thermal protection are the basis for determining the energy-saving class of building.

Generally, the thermal quantities of building components are thermal resistance, heat absorption index, resistance to air permeation, moisture-protective properties. These quantities are calculated as a function of thermal properties, composition, and geometry of element and boundary conditions. The sandwich panel's outer and inner structural layers are made of dense low-porous materials, which practically eliminate through air filtration. Therefore, the calculation of this structure's air permeability in the case that joints of panels are well-sealed is not required.

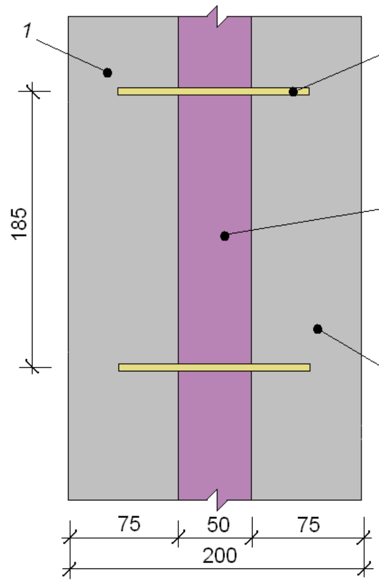
Building energy characteristics calculation is necessary to evaluate it from the point of energy efficiency. Building energy characteristics includes specific heat losses through the building envelope (SHL), specific thermal characteristic of the building (STC) and specific heat consumption of heating systems (SHC).

There are two methods for calculating the thermal quantities of a building component. The detailed calculation method is a numerical simulation carried out on the whole building component or a representative part. The method is valid for any building component. However, the complexity of this method makes it difficult to apply it widely in practice. The simplified calculation method is valid for components consisting of thermally homogenous or inhomogeneous layers. Obviously, this method is less accurate than the detailed calculation method, but it is much simpler and more accessible. Therefore, for the purpose of this research, we use simplified calculation methods.

2.2. Building components

Typical precast concrete sandwich panel consists of two precast reinforced concrete layers (called *wythes*) separated by insulation and joined with connectors penetrate through insulation. Two sandwich panel configurations are considered: conventional (Fig. 2, a) and advanced (Fig. 2, b). The conventional sandwich panel consists of inner and outer reinforced concrete layers with a thickness of 75 mm separated by a layer of insulation made of extruded foam polystyrene (XPS) 50 mm thick slabs. In advanced design, due to the use of TRC, the thickness of interior and exterior structural layers is reduced to 40 mm (while maintaining strength), and the thickness of the heat-insulating layer increased to 120 mm. 10 mm diameter glass plastic connectors located in nodes of a square grid connect structural layers. Grid spacing is 185 mm; the number of connectors is 19 pcs per 1 m^2 of section.

Compared to the conventional product, the use of thinner TRC structural layers allows reducing the mass of the precast sandwich panel by almost half, which contributes to a significant reduction in the entire building's material consumption.



a b

Figure 2. Conventional (a) and advanced (b) sandwich panel configuration: 1 — interior structural layer; 2 — thermal insulation; 3 — exterior structural layer; 4 — connector.

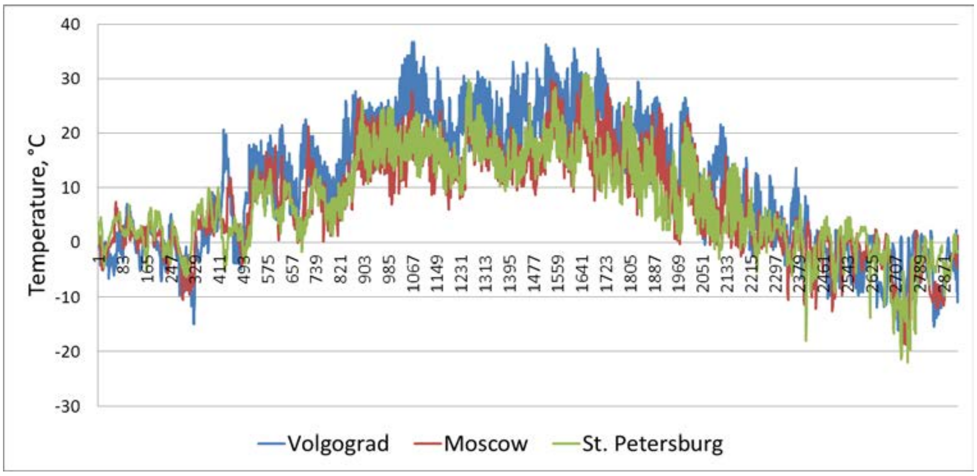
a b

Figure 3. Location of the connectors in the square (a) and hexagonal (b) grid nodes.

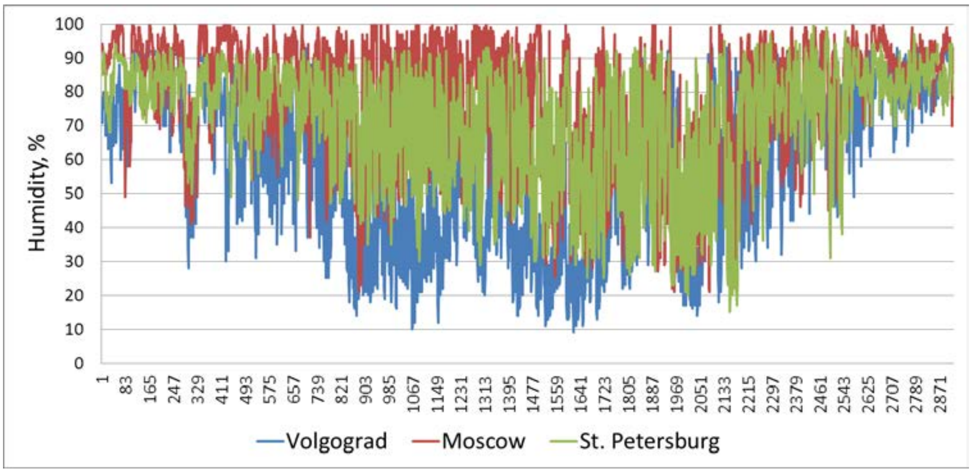
In this research, we use the method of designing building components without thermal bridges. Placing low-thermal conductivity connectors in square or hexagonal grid nodes (Fig. 3) minimizes additional heat loss through the nodes. Sandwich panels in completed form is a continuous heat protection envelope, which practically eliminates additional heat losses through the horizontal and vertical joints of the panels. The use of window blocks with a wide box (frame thickness 80–120 mm), in combination with a relatively small length of assemblies, also contributes to reducing additional heat losses and their insignificant effect on the thermal resistance of building components.

2.3. Environmental conditions

Thermal and hygrothermal performance analysis of outer walls in winter was carried out on the sample locations in various humidity-climatic zones of the European part of Russia: Volgograd (dry zone), Moscow (normal zone), and St. Petersburg (wet zone). Figure 4 shows the external environmental conditions of these locations.



a



b

Figure 4. Temperature (a) and humidity (b) analyze at the locations under consideration.

Parameters of external climate for these points are shown in Table 1.

Table 1. Conditions of the outside air.

	Volgograd (48°42′N, 44°30′E)	Moscow (55°45′N, 37°37′E)	St. Petersburg (59°57′N, 30°19′E)
	Heating period		
Duration of period, day/year	176	205	213
Outside temperature (average value), °C	–2.3	–2.2	–1.3
Humidity, %	75	82	77
	Summer and transition periods		
Duration of period, day/year	189	160	152
Outside temperature (average value), °C	18.6	15.1	14.8
Humidity, %	46	70	64

Thermal stability analysis of outer walls was carried out in the summer period for Volgograd.

Building energy performance of buildings made of TRC sandwich panels was carried out for optimal air parameters (see Table 2).

Table 2. Optimal air parameters in offices (according to Russian State Standard GOST 30494-2011 "Residential and public buildings. Microclimate parameters for indoor enclosures").

Time of the year	Temperature, °C	Humidity, %	Speed, m/s
Cold period	19–21	30–45	0.2
Non-heating period	23–25	30–60	0.15

2.4. Thermal properties of building materials

Thermal properties for sandwich panel materials are adopted depending on the building component's operating conditions (Table 3).

Table 3. Material properties.

Building element	Quantity	Symbol, unit	Design values	
			Conventional configuration	Advanced configuration
Wythe	Density	ρ_c, kg/m^3	2500	2400
	Thermal conductivity	λ_c, W/(m·K)		
	at the moisture content of material is 2% mass by mass		1.92	1.74
	at the moisture content of material is 3% mass by mass		2.04	1.86
	Heat absorption	s_c, W/(m^2·K)		
	at the moisture content of material is 2% mass by mass		17.98	16.77
	at the moisture content of material is 3% mass by mass		18.95	17.88
	Water vapour permeability	μ_c, kg/(m·s·Pa)	$8.33 \cdot 10^{-12}$	$9.72 \cdot 10^{-12}$
Insulation	Density	ρ_{ins}, kg/m^3	30	30
	Thermal conductivity	λ_{ins}^{eq}, W/(m·K)		
	at the moisture content of material is 1% mass by mass		0.030	0.030
	at the moisture content of material is 2% by mass		0.031	0.031
	Heat absorption	s_{ins}, W/(m^2·K)		
	at the moisture content of material is 2% mass by mass		0.3	0.3
	at the moisture content of material is 3% mass by mass		0.31	0.31
	Water vapour permeability	μ_c, kg/(m·s·Pa)	$1.39 \cdot 10^{-12}$	$1.39 \cdot 10^{-12}$
Connector	Density	ρ_{fg}, kg/m^3	1467	1467
	Thermal conductivity	λ_{fg}, W/(m·K)	0.48	0.48
	Heat absorption	s_{fg}, W/(m^2·K)	6.57	6.57
	Water vapour permeability	μ_{fg}, kg/(m·s·Pa)	~0	~0

To take into account the effect of connectors on sandwich panels' thermal characteristics, we used the method of equivalent characteristics based on the addition of thermal transmittance. This method's advantage is the possibility of approximate assessment of impact efficiency of inhomogeneous thermal sections of building components without labor-intensive calculations of temperature fields [20]. Since the influence of connectors is most pronounced concerning the insulation layer, its equivalent characteristics (thermal conductivity and heat absorption) can be calculated by formulas:

$$\lambda_{\text{ins}}^{\text{eq}} = \lambda_{\text{XPS}} + d_{\text{con}}(\lambda_{\text{fg}} - \lambda_{\text{XPS}}),$$

$$s_{\text{ins}}^{\text{eq}} = s_{\text{XPS}} + d_{\text{con}}(s_{\text{fg}} - s_{\text{XPS}}),$$

where λ_{XPS}, λ_{fg} are the thermal conductivity, in W/(m·K), of XPS and fiberglass, respectively;

s_{XPS}, s_{fg} are the heat absorption, in W/(m^2·K), of XPS and fiberglass, respectively;

d_{con} is the fraction occupied by connectors, calculated by the formula:

$$d_{\text{con}} = \frac{\pi}{4} D_{\text{con}}^2 n_{\text{con}},$$

where D_{con} is connector diameter, in m;

n_{con} is a number of connectors per 1 m^2 of panel.

2.5. Thermal properties of building components

Total thermal resistance of building components (from environment to environment) characterizes the heat-protecting properties under steady-state conditions. This thermal quantity is equal to the ratio of temperature difference on different sides of the building component to the density of heat flow rate averaged by area through the building component. In the case of simplified calculation method, the total thermal resistance of a plane building component consisting of thermally homogeneous layers perpendicular to heat flow shall be calculated by the following formula:

$$R_{\text{o}} = \frac{1}{\alpha_{\text{si}}} + \frac{2\delta_{\text{c}}}{\lambda_{\text{c}}} + \frac{\delta_{\text{ins}}}{\lambda_{\text{ins}}^{\text{eq}}} + \frac{1}{\alpha_{\text{se}}},$$

where R_{o} is the total thermal resistance, in m^2·K/W;

α_{si} is the inside surface heat-transfer coefficient, in W/(m^2·K);

δ_{c} is the thickness of the structural layer, in m;

λ_{c} is the thermal conductivity of the structural layer, in W/(m·K);

δ_{ins} is the thickness of insulation, in m;

$\lambda_{\text{ins}}^{\text{eq}}$ is the equivalent thermal conductivity of insulation, in W/(m·K);

α_{se} is the outside surface heat-transfer coefficient, in W/(m^2·K).

Heat absorption index is the property of a building component to maintain relative temperature constancy when thermal effects from external and internal environments of space periodically change. The heat absorption index may be calculated through the well-known heat absorption theory. This theory is characterized by the following main thermal indicators: decrement factor (DF) and time lag (TL).

Building component decrement factor shall be calculated by the formula:

$$v = v_1 v_2 v_3 v_{se},$$

where v is the decrement factor of a component;

v_1, v_2, v_3, v_{se} are the decrement factors in the first, second, third layer and at the outer surface of the wall, calculated by the formulae:

$$v_1 = 0.95\exp\left(\frac{D_1}{\sqrt{2}}\right)\frac{s_1+\alpha_{si}}{s_1+Y_1};$$

$$v_2 = \exp\left(\frac{D_2}{\sqrt{2}}\right)\frac{s_2+Y_1}{s_2+Y_2};$$

$$v_3 = 0.95\exp\left(\frac{D_3}{\sqrt{2}}\right)\frac{s_3+Y_2}{s_3+Y_3};$$

$$v_{se} = 1+\frac{Y_3}{\alpha_{se}},$$

where D_i is the thermal inertia of the i-th layer ($D_i = R_i s_i$);

R_i is the thermal resistance of the i-th layer, in m^2·K/W;

s_i is the design heat absorption of the i-th layer, in W/(m^2·K);

Y_i is the heat absorption at the outer surface of the i-th layer, in W/(m^2·K).

The procedure for calculating the values of Y_i is well known; therefore, it is not considered here.

It is known that the time lag of a building component is given by:

$$\varepsilon = \frac{1}{15}\left(40.5D - \mathrm{arctg}\left(\frac{\alpha_{si}}{\alpha_{si}+Y_{si}\sqrt{2}}\right) + arctg\left(\frac{Y_{se}}{Y_{se}+\alpha_{se}\sqrt{2}}\right)\right),$$

where ε is the time lag, in hours and minutes;

D is the thermal inertia;

Y_{si} is the heat absorption at the inner surface of the component in the direction of the heat wave movement from the inside to the outside, in W/(m^2·K);

Y_{se} is the heat absorption at the inner surface of the component in the opposite direction of the heat wave motion, in W/(m^2·K).

Moisture performance assessment of building components was carried out according to the maximum permissible state of humidification during the annual cycle using the simplified calculation method [23], harmonized with International Standard ISO 13788. Unlike the method for calculating moisture-protective properties adopted in Russian standards, this method allows to analyze the dynamics of moisture accumulation in building components during the year. Compared to International Standard ISO 13788, this method gives a more accurate assessment of humidity conditions of multilayer enclosing structures with a high level of thermal protection.

Thermal quantities calculated for office building. Input data listed in Table 4.

Table 4. Geometric and thermal data.

Name	Unit	Design values
Floors	Number	4
Design area of the building	m^2	2099
Heated volume of the building	m^3	9468
Factor of building compactness	m^{-1}	0,34
Coefficient of glazing	%	17
Share of enclosing structures (walls/windows/roof/basement) in the building envelope	%	44.8/10.6/19.1/25.5

Name	Unit	Design values
Thermal resistance of building components (walls/windows/roof/basement)	$m^2 \cdot K/W$	
using conventional sandwich panels		1.85/0.76/3.11/4.57
using TRC sandwich panels		4.08/0.76/3.11/4.57
Ventilation rate in the building during the heating period (average)	h^{-1}	0.712
Heating heat control efficiency factor	–	0.95

3. Results and Discussion

3.1. Thermal resistance of building components

The design values of the total thermal resistance of the walls are given in Fig. 5.

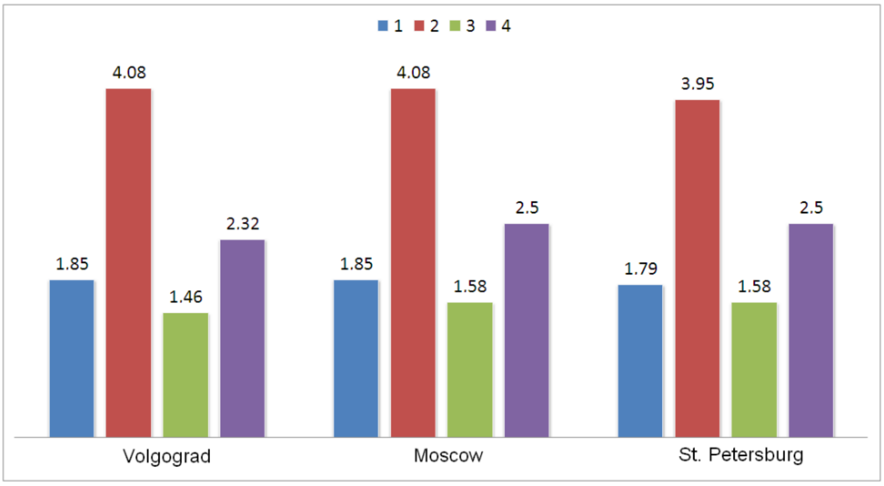


Figure 5. Total thermal resistance of outer walls (R_o, in $m^2 \cdot K/W$): 1 — conventional configuration; 2 — advanced configuration (3 and 4 — respectively minimum and reference values of total thermal resistance according to Russian Standard SP 50.1330.2012).

Fig. 5 demonstrated that the thermal resistance of outer walls made of TRC sandwich panels higher (2.2 times) than the R-value of conventional structures in various humidity-climatic zones. Thus, these façade systems can provide a high level of thermal protection of buildings during the cold period.

3.2. Building components heat absorption

Heat absorption index calculation results for outer walls are given in Table 5.

Table 5. Heat absorption properties of outer wall (Volgograd).

Building element	Conventional sandwich panel			TRC sandwich panel		
	D	Y, $W/(m^2 \cdot K)$	ν	D	Y, $W/(m^2 \cdot K)$	ν
Interior structural layer	0.702	15.9	1.23	0.386	12.6	1.25
Insulation	0.5	0.602	25.3	1.16	0.30	48.8
Exterior structural layer	0.702	12.9	0.939	0.386	6.72	0.907
Outside surface of the wall			1.74			1.39
Building component	1.90		50.8	1.93		76.9

Calculation results analysis demonstrated that the maximum local value of DF is observed in the heat-insulating layer of the outer wall. The minimum value of local DF occurs in the outer structural layer, which can be explained not so much by the low thermal inertia of this layer as by the heat insulation layer located behind it with low heat absorption of the outer surface. In the inner structural layer, the value of DF is slightly greater than in the outer layer, which is due to the higher heat absorption value at the outer surface of the inner layer. Therefore, the decrement factor in the layer depends not only on the properties of its material but also on the layer following it. Therefore, it is possible to increase the heat absorption of these façade systems by different layer combinations.

Based on calculation results, we also established that the value of TL at the inner surface of the conventional structure is 5 hours 12 minutes, for advanced design is 4 hours 18 minutes. The use of structural layers made of TRC in sandwich panels increases external walls heat absorption by 34.4%, reducing the overheating risk of premises in summer.

3.3. Building components hygrothermal-protective properties

Humidity conditions calculation results in outer wall are given in Fig. 6, 7.

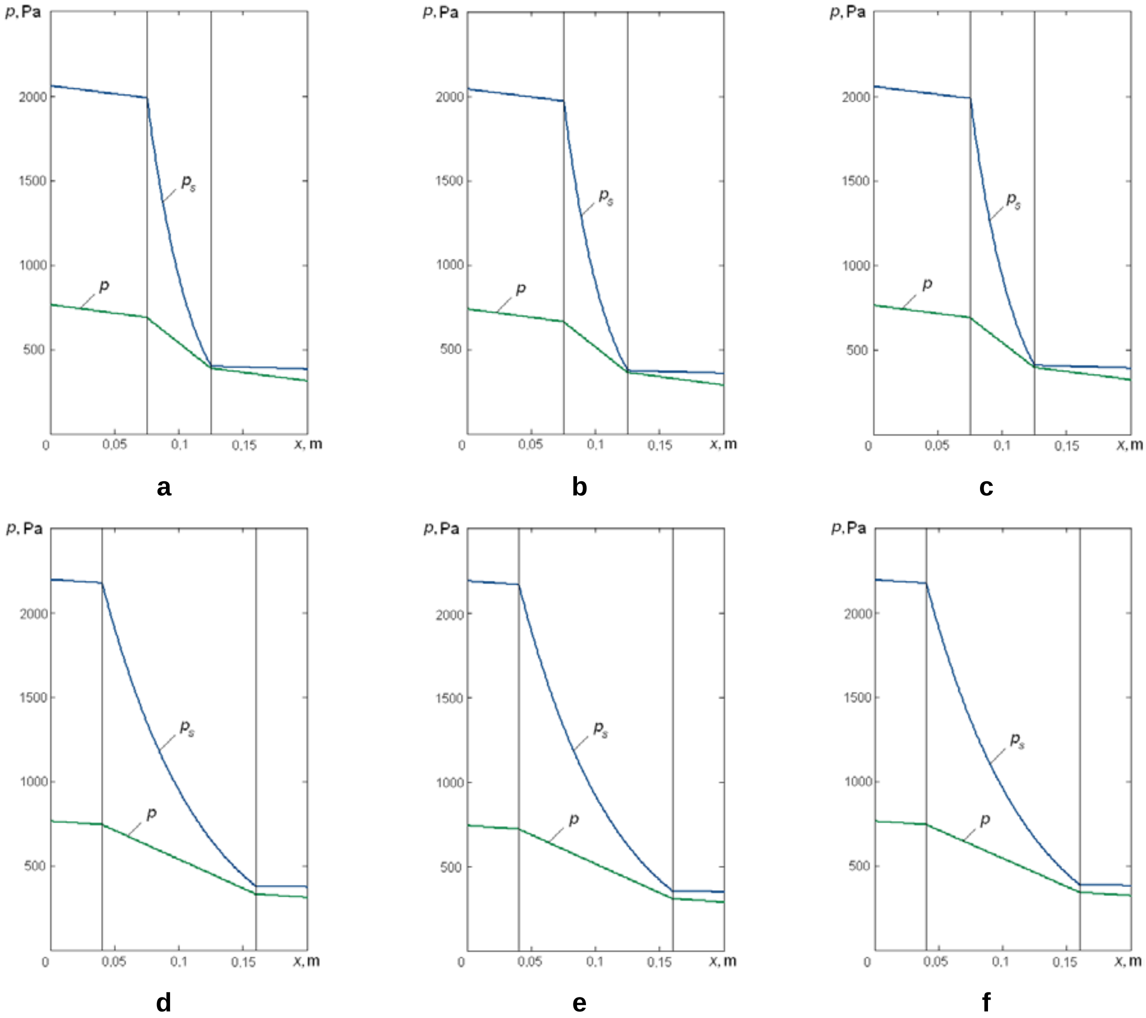


Figure 6. Water vapour diffusion in the multi-layer building components without any interstitial condensation in January (p is the water vapour pressure, in Pa; p_s is the value at saturation, in Pa): a — conventional configuration, Volgograd; b — conventional configuration, Moscow; c — conventional configuration, St. Petersburg; d — advanced configuration, Volgograd; e — advanced configuration, Moscow; f — advanced configuration, St. Petersburg.

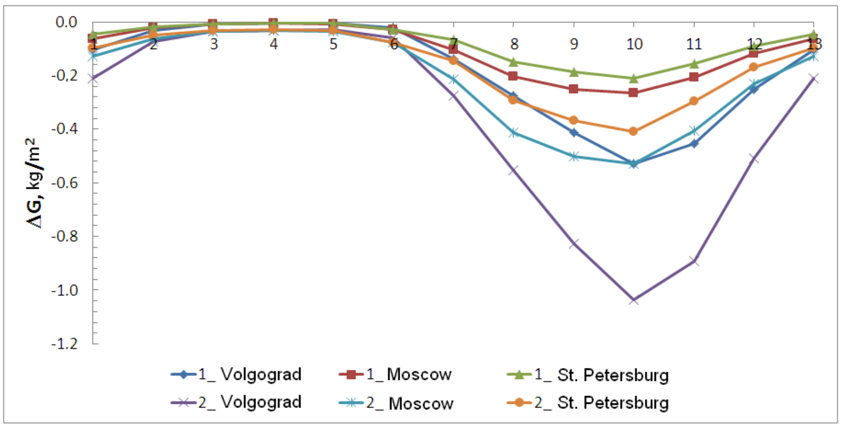


Figure 7. Moisture rate increment in building components during the annual cycle (1 — conventional configuration; 2 — advanced configuration).

In these cases, as shown in Figure 7, there is no condensation at the interface between insulation and exterior structural layer in the coldest month. The maximum convergence of water vapour pressure profile and the value at saturation is noted at the junction of heat insulation and exterior structural layer that increases the risk of moisture condensation, but this effect is characteristic of conventional design. The monthly condensation rate in the building components is negative, indicating no moisture accumulation during the year. Therefore, hygrothermal-protective properties of building components are provided. This conclusion is qualitatively correspondent to the results [29], according to which the risks of moisture condensation and hygrothermal-protective properties deterioration of outer wall made of sandwich panels are minimized.

3.4. Building energy performance

Specific heat losses through the building envelope are demonstrated in Fig. 8.

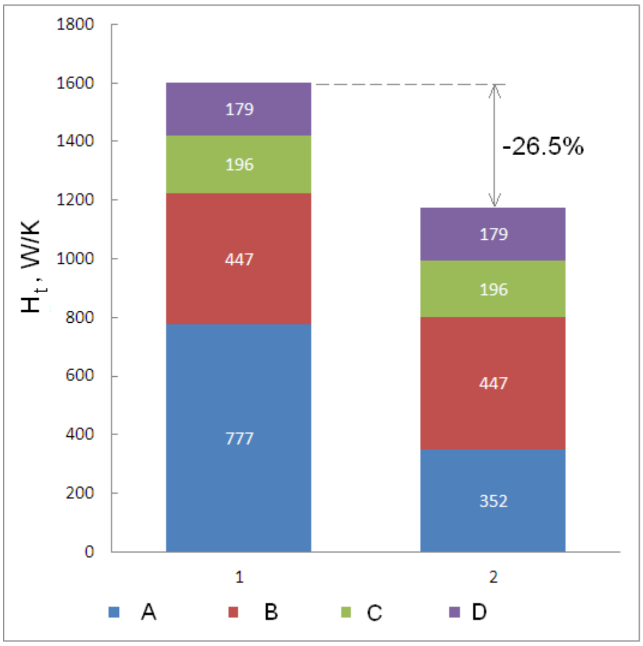


Figure 8. The specific heat losses through the building envelope when applied conventional (1) and advanced (2) sandwich panels: A — outer walls; B — windows; C — roof; D — floor on the ground.

Fig. 8 shows that when using the conventional sandwich panels, maximum heat loss is noted through outer walls (48.6%), minimum heat loss through the floor on the ground (11.2%). The use of advanced sandwich panels makes it possible to balance transmission heat losses, while total heat loss through the building envelope is reduced by 26.5%.

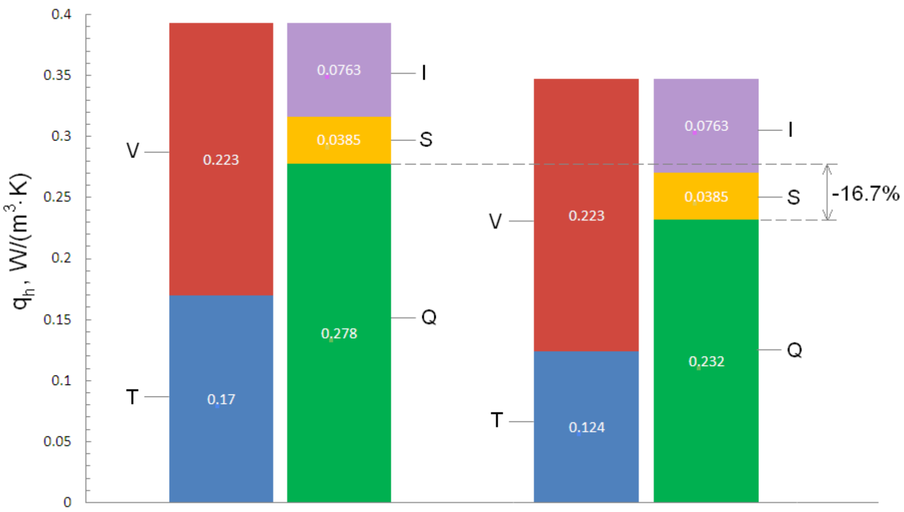


Figure 9. Building thermal balance when used conventional (left) and advanced (right) sandwich panels: T — transmission heat loss; V — ventilation heat loss; I — internal heat gain; S — solar heat gain; Q — heat energy demand for heating and ventilation.

As shown in Figure 9, the specific thermal characteristic of the building when used a conventional façade system is 0.278 W/(m^3·K). The reference value of the specific thermal characteristic of the building is 0.313 W/(m^3·K). The energy-saving class of building is C + (normal). The application of an advanced façade system reduces the specific thermal characteristic of buildings by 16.7%, while the energy-saving class of buildings increases to level B (high).

Based on received results, the values of specific heat consumption of heating systems of the building are given: 25 kWh/(m^3·year) when used conventional façade system and 20.9 kWh/(m^3·year) when used advanced façade system. Then, based on data [26], it is possible to receive values of the total specific consumption of thermal and electric energy for the operation of building during the year, 125 and 121 kWh/(m^3·year), respectively. In this case, the reduction of energy consumption of buildings will be 3.2%, which is well consistent with the calculation data [26] obtained for small office buildings under similar climatic conditions (Fig. 10), and, therefore, confirms the validity of our calculations.

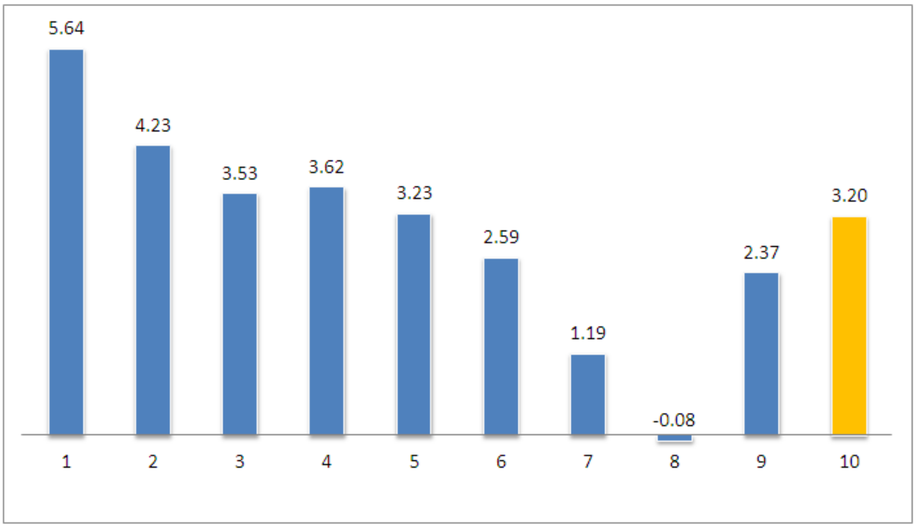


Figure 10. Buildings energy consumption reduction (%) [26]: 1 — Fairbanks; 2 — Duluth; 3 — Helena; 4 — Burlington; 5 — Chicago; 6 — Boise; 7 — Albuquerque; 8 — San Francisco; 9 — Salem McNary; 10 — Russia, Volgograd (our calculations).

Further tasks of research are to refine the actual thermal performance of façade system and analyze the results of the simulation of the thermal conditions of buildings based on detailed calculation methods.

4. Conclusions

This research aimed to investigate the energy properties of buildings made of textile-reinforced concrete (TRC) sandwich panels in various humidity-climatic zones. Two configurations of sandwich panel are considered: conventional and advanced. The conventional sandwich panel consists of inner and outer reinforced concrete layers with a thickness of 75 mm separated by a layer of insulation made of extruded foam polystyrene (XPS) 50 mm thick slabs. In advanced design, due to the use of TRC, the thickness of interior and exterior structural layers is reduced to 40 mm (while maintaining strength), and the thickness of the heat-insulating layer increased to 120 mm. 10 mm diameter glass plastic connectors located in nodes of a square grid connect structural layers. Grid spacing is 185 mm; the number of connectors is 19 pcs per 1 sq. m of section. The analytical method of research was applied to the energy performance of buildings made of TRC sandwich panels based on the investigation of heat and moisture transfer processes in continuous heterogeneous media and analysis of buildings' energy indicators. For this research, the element-by-element and complex assessment of building thermal protection was performed.

Based on the results of this research, the main thermal advantages of these façade systems are identified:

I. Building component thermal resistance is increased in multiple in various humidity-climatic zones, providing a high level of thermal protection in winter compared to conventional facade systems.

II. Building component heat absorption is increased by 34.4 % (compared to conventional facade systems), excluding the risk of overheating of premises in summer.

III. The risks of moisture condensation and deterioration of hygrothermal-protective properties of building components are minimized.

IV. The use of TRC sandwich panels allows reducing total heat loss through the building envelope by 26.5 %. At the same time, specific thermal characteristic of the building is decreased by 16.7 %, and the energy-saving class increases to high levels.

Construction with advanced façade systems, when used the precast sandwich panels with structural layers from textile-reinforced concrete, extends the creative boundaries of architecture and allows you to solve the current problem of improving the quality of the architectural environment and conserve energy for future generations.

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Information about authors:

Nikolai Vatin
Doctor of Technical Science
ORCID: https://orcid.org/0000-0002-1196-8004
E-mail: vatin@mail.ru

Sergey Korniyenko
Doctor of Technical Science
ORCID: https://orcid.org/0000-0002-5156-7352
E-mail: svkorn2009@yandex.ru

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