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The effect of temperature difference on bending of external panel walls

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Abstract. One of the most common structural systems of buildings intended for various purposes is a prefabricated panel system of factory-made elements assembled on-site. Single-layer structures made of lightweight concrete are widely used as envelopes of these buildings. In buildings operated under various climatic conditions, exterior wall panels, as well as other envelopes, are exposed to thermal deformations and, accordingly, changes in the stress-strain state. As the temperature changes, corresponding stresses and deformations occur across the thickness of the exterior panels. To analyze their values, the bending moments and support reactions of single-layer lightweight concrete panels of different length and thickness in the range of temperature differences from 0 °C to 65 °C have been calculated. It was found that the bending moments and support reactions of 1,500 mm long panels decrease as the thickness of the panels increases over the entire temperature gradient. The values of bending moments and support reactions of panels with length of 3,000, 4,500 and 6,000 mm decrease only when the temperature rises from 0 to 10 °C, in the rest of the range 15–65 °C – increase as the thickness of the panel increases due to the bending stiffness.
Keywords: exterior wall panels, stress-strain state, temperature difference, thermal deformations

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1. INTRODUCTION

The construction of buildings made of large panels can significantly increase the degree of industrialization of construction and labor productivity, reduce the cost of construction and decrease the construction time of buildings. According to the design scheme, they are frameless with longitudinal and transverse load-bearing walls and frame. Frameless buildings consist of a smaller number of prefabricated elements, are easy to install, and are preferentially used in mass housing construction. In these buildings, the external and internal walls perceive all the loads acting on the

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building. Spatial rigidity and stability are provided by the mutual connection between the panels of walls and overlaps [5, 6].

In this case, there can be four constructive options for supporting the plates: on longitudinal load-bearing walls; along the contour (on longitudinal and transverse walls); on internal transverse walls; on three sides (on longitudinal load-bearing and internal transverse walls).

In frame panel buildings, the loads acting on them perceive by the crossbars and frame posts, and the panels most often perform only enclosing functions. At the same time, the following design schemes distinguish:

– with a full transverse frame;
– with a full longitudinal frame;
– with a spatial frame;
– with an incomplete transverse frame and load-bearing external walls;
– with the support of the floor slabs at four corners directly on the columns (a non-stick version); with the support of panels on the outer panels and on two racks along the inner row.

The adoption of a particular structural scheme depends on the type of building being design, its number of floors and other factors. Therefore, large-panel residential buildings design, as a rule, frameless. These houses, in comparison with frame ones, allow to reduce the number of standard sizes of prefabricated elements, reduce metal consumption, simplify the installation process, reduce labor costs, avoid the appearance of protruding elements (columns and crossbars) in the interior of premises, etc. However, frame buildings, compared with frameless ones, have less material consumption per 1 m2 of living space, greater rigidity and stability of the building, which is especially important for high-rise buildings. These schemes are particularly effective for public buildings [5, 6].

An important stage in the design of large-panel buildings is the choice of a wall-cutting scheme, which depends on the design structural scheme, installation conditions, type of building and its size.

The structures of large-panel buildings are a complex combination of concrete and reinforced concrete elements, which, in addition to temperature deformations caused by fluctuations in air temperature and the action of solar radiation, also experience deformations associated with changes in their humidity (periodic sorption deformations and shrinkage) [5, 6].

With fluctuations in air temperature, radiation, humidity and shrinkage, large forces and deformations can occur in the walls and overlaps of large-panel buildings, which often cause various kinds of damage (cracks, gaps of panels and ties, chipped supports, etc.). These damages may cause a decrease in the load-bearing capacity, durability and operational qualities of large-panel building structures. In order to prevent these damages, the current regulations recommend cutting long buildings with expansion seams into separate temperature blocks (compartments), the length of which, in the absence of a special calculation, should not exceed the maximum permissible length for concrete, reinforced concrete and stone structures. At the same time, it is considered that the cutting of buildings with seams completely eliminates the harmful effects of temperature and humidity effects and a special calculation of buildings for these effects is not require.

Cutting buildings with thermal seams often worsens architectural planning and structural solutions of buildings, increases the number of standard sizes of structures and increases the cost of construction. This often forces engineers to construct buildings without expansion seams.

Field studies have shown that cutting buildings with expansion seams without calculation does not always save them from serious temperature damage and cracks. In this regard, there is a need to calculate panel buildings for temperature and humidity effects, regardless of their length, number of floors and construction area.

The calculation makes it possible, by choosing the right design temperatures, schemes and rigid characteristics of structures and their connections, significantly to reduce temperature forces and damage to wall panels and joints, increase their operational qualities, reliability and durability [5, 6].

Walls and overlaps of panel buildings under fluctuations in temperature and humidity experience alternating forces and deformations (stretching and compression). It’s known that the tensile strength of concrete is significantly less than that of compression.

Therefore, it is a difficult task - completely to eliminate the possibility of temperature-shrinkage cracks in panels and joints of prefabricated buildings without pre-voltage.

In this regard, the main purpose of the temperature calculation of buildings is not to completely eliminate the possibility of cracks appearing in structures, but to limit, in accordance with the requirements of their disclosure standards, to a value safe for strength, durability and operational suitability of buildings.

The calculation makes it possible to erect panel buildings without expansion seams in any climatic conditions of almost unlimited length. However, for some extreme conditions, the construction of long-length buildings without expansion seams may be economically impractical due to a more significant expenditure of funds and materials than when cutting them with expansion seams [5, 6].

Constructions of large-panel buildings in connection with the typification and unification of building parts are regular (approximately equal division in length and height) statically indeterminate spatial systems consisting of precast reinforced concrete elements such as plates (panels, plates) interconnected by point or continuous connections. With changes in temperature, humidity and shrinkage in building structures due to the embedding of walls into the base, as well as due to the interaction of external and internal structures having different temperature and humidity deformations, temperature forces and deformations arise both in the plane (axial) and from the plane of structures. Longitudinal temperature forces and deformations that occur in the plane of the supporting and enclosing structures are caused by a change in the reduced average temperature of the section Δt. Temperature forces and deformations from the plane of structures arise when the difference in the reduced temperature changes along the thickness $\Delta\theta$. The calculation of buildings for temperatures Δt and $\Delta\theta$ is carried out separately. With the combined action of these temperatures (the outer walls of heated buildings), the temperature forces and deformations are summed up based on the principle of independence of the action of forces. The given temperature is a conditional temperature that takes into account the combined effect of annual and daily fluctuations in outdoor and indoor air and equivalent temperatures of solar radiation, annual fluctuations in relative humidity and shrinkage. During the construction period, the calculation makes as for unheated buildings without taking into account the effect of shrinkage. During operation, the calculation carries out for the combined effect of the reduced temperatures and shrinkage with their most unfavorable combination in winter (lowering the temperature plus shrinkage) [5, 6].

Exterior wall panels, like other building envelopes, are prone to thermal deformations. Exterior walls of panel buildings are formed of load-bearing or curtain wall panels with bonded joints in which, in addition to longitudinal thermal stresses and deformations, there are stresses and deformations resulting from temperature difference across the thickness $\Delta\theta$ and eccentricity of normal force eN. The panels are fixed to the internal structures (walls, ceilings, columns) by means of cross bracing, in which the temperature difference across the thickness $\Delta\theta$ and eccentricity eN can cause stresses that cause displacements, and in the panels themselves – bending moments [1-5].

The size of the temperature difference across the thickness of the panel directly depends on the time of year and the climatic zone of the facility. The greatest temperature differences are typical of regions with an extreme continental climate, where average winter temperatures are 30–45 °C below zero [1-6].

The authors of a number of guidance papers suggest to determine the stresses in bracings, bending moments in the panels, as well as the deflection of the panels, the angles of rotation of the panel sections and the opening of the joints by considering the panel wall as a statically indeterminate continuous beam of variable stiffness [5, 6].

Research in this area is mainly aimed at predicting and determining bending moments, as well as developing design models of non-standard reinforced concrete structures in a particular region of construction [1-3].

This paper investigates numerically the effect of temperature difference on the bending moments and support reactions of wall panels of different length and thickness over a wide temperature range.

2. METHODS AND MATERIALS

The following assumptions are made when performing numerical investigation:

1) bonded joints of the panels take bending moment as reinforced beams on two supports;

2) the effective length of the joint lj is taken equal to the width of the supporting structure (wall, frame, etc.);

3) the effective length of the panel lp, respectively, equals:

$$lp = li - lj, \tag{1}$$

where li is the distance between the axes of the supporting structures that support the panels (cross walls, columns) [5, 6].

The flexural stiffness of panels Bp and joints Bj is determined as for reinforced single-layer concrete sections, taking into account the plastic properties of concrete with cracks. The supporting structures and cross bracing adjacent to the walls have a certain elasticity, which should be taken into account in the calculations.

In the most general case, i.e., when the supports of a continuous beam have different flexibility, the temperature stresses arising from a temperature difference across the thickness Δθ are obtained by solving a system of k equations of the form (for the n-th support):

$$\frac{c_{n-1}}{l_{n-1}l_n}M_{n-2}+\left[\frac{l_n}{6B_n}-\frac{c_{n-1}}{l_n}\left(\frac{1}{l_{n-1}}+\frac{1}{l_n}\right)-\frac{c_n}{l_n}\cdot\left(\frac{1}{l_n}+\frac{1}{l_{n+1}}\right)\right]M_{n-1} +\left[\frac{l_n}{3B_n}+\frac{l_{n+1}}{3B_{n+1}}+\frac{c_{n-1}}{l_n^2}+c_n\left(\frac{1}{l_n}+\frac{1}{l_{n+1}}\right)^2+\frac{c_{n+1}}{l_{n+1}^2}\right]M_n+\left[\frac{l_{n+1}}{6B_{n+1}}-\frac{c_{n+1}}{l_{n+1}}\cdot\left(\frac{1}{l_{n+1}}+\frac{1}{l_{n+2}}\right)\right]\cdot M_{n+1} +\frac{c_{n+1}}{l_{n+1}l_{n+2}}M_{n+2}=-\frac{1}{2}\left(\frac{\alpha_n\Delta\theta^{(n)}}{h_n}l_n+\frac{\alpha_{n+1}\Delta\theta^{(n+1)}}{h_{n+1}}l_{n+1}\right), \tag{2}$$

where cn-1; cn; cn+1 are the compliance of supports determined from generalized experimental data; αn; αn+i; hn; hn+1 are the thermal expansion coefficients and beam thickness in n and n+1 spans; Mn-i; Mn-1; Mn; Mn+1; Mn+2 are the unknown support moments [5, 6].

In the case of rigid supports, the temperature moments are determined by solving the system of equations (2), assuming cn-1, cn etc. equal to zero, which leads to the solution of the system of trinomial equations:

$$l'_n M_{n-1}+2\left(l'_n+l'_{n+1}\right)M_n+l'_{n+1}M_{n+1}=-3\left(M_{\theta,n}l'_n+M_{\theta,n+1}l'_{n+1}\right), \tag{3}$$

where l'_n, l'_{n+1} are the adjusted spans, equal to:

$$l'_n=l_n/B_n;\ l'_{n+1}=l_{n+1}/B_{n+1}, \tag{4}$$

$M_{\theta,n}, M_{\theta,n+1}$ are the equivalent temperature moments of n and n+1 spans, equal to:

$$M_{\theta,n}=\frac{\alpha_n\Delta\theta_n}{h_n}B_n;\ M_{\theta,n+1}=\frac{\alpha_{n+1}\Delta\theta_{n+1}}{h_{n+1}}. \tag{5}$$

The shear forces Q and support reactions R are determined by the formulas:

$$Q_n=\frac{M_n-M_{n-1}}{l_n};\ R_n=Q_{n+1}-Q_n. \tag{6}$$

The walls of buildings with a regular structural scheme consist of panels of the same geometric dimensions and stiffness. The temperature gradients of such panels and joints are about the same, which allows us to take an approximation:

$$M_{\theta,p}=\frac{\alpha_p\Delta\theta_p}{h_p}B_p;\ M_{\theta,j}=\frac{\alpha_j\Delta\theta_p}{h_p}B_j \tag{7}$$

The temperature deflections in the middle of the panel υn and the rotation angles on the supports ψn in the temperature difference across the thickness are found by the formulas:

$$\upsilon_n = \left(\frac{\alpha_n \Delta\theta_n}{h_n} + \frac{M_{n-1}+M_n}{2B_n}\right)\frac{l_n^2}{8}; \quad (8)$$

$$\psi_{n-1} = \frac{\alpha_n \Delta\theta_n l_n}{2h_n} + \frac{l_n}{6B_n}(2M_{n-1} + M_n); \quad (9)$$

$$\psi_n = \frac{\alpha_n \Delta\theta_n l_n}{2h_n} + \frac{l_n}{6B_n}(M_{n-1} + 2M_n); \quad (10)$$

where Mn-1 and Mn are determined from the solution of the system of equations (2), (3).

The stresses, deflections and angles of rotation occurring in panels and joints in the presence of eccentricity of normal force eN are determined by formulas (2-10) by replacing the expression of the equivalent temperature moment at the temperature difference across the thickness Mθ with the expression of the bending moment at the eccentricity:

$$M_N = -N_p e_N, \quad (11)$$

where Np is the longitudinal force in the panel, kN; eN is the eccentricity of the longitudinal force Np which is assumed to be equal to the distance between the centers of gravity of the areas of reinforced sections of the panel and the joint, taking into account the presence of cracks.

When the temperature difference Δθp and the longitudinal force Np with eccentricity eN affect the walls together, the stresses, deflections and rotation angles of the panels and joints on the supports are summarized based on the principle of independent action of forces. In this case, there are two possible cases of vertical joints of panels in tensile bending:

1st case, when no through cracks are formed in the concrete of the joint bonding (there is a compression area);

2nd case, when through cracks occur (no compression area of concrete).

The case of tensile bending of joints is defined according to the conditions:

1st case:

$$|c_j N_p| \le (h_j - a_j)\psi_{j,2}. \quad (12)$$

2nd case:

$$|c_j N_p| \ge (h_j - a_j)\psi_{j,2}. \quad (13)$$

For practical calculations of panel walls on the above effects the three most typical ways of fixing exterior wall panels to the internal structures of buildings (walls, columns, floors) are of interest [5, 6].

Below are formulas for calculating the total values of moments Mi, support reactions Ri and rotation angles of panels on elastic supports ϕi under the joint effect of temperature difference Δθ and eccentricity of normal force eN for the second case of tensile bending of joints and the specified methods of panels attachment.

Moments $M_i = M_i^{\theta} + M_i^{N}$ are calculated using the following formulas:

$$M_{n-1,j} = 0; \quad (14)$$

$$M_{n-1,p} = M_N; \quad (15)$$

$$M_{n,p} = -(M_\theta + M_N)\left[\frac{m_2 - m_5}{m_1 + m_5} + 1\right] + M_N; \quad (16)$$

where: $M_{n-1,j}$ is the bending moment in the joint on support n-1; $M_{n-1,p}, M_{n,p}$ are the same in the panel on supports n-1 and n, respectively.

The support reactions $R_i = R_i^{\theta} + R_i^{N}$ are calculated by formula (17):

$$R_{n-1,j} = -R_n = -(M_\theta + M_N)\frac{m_3}{l_п(m_1 + m_5)}; \quad (17)$$

where R_{n-1}, R_n are the support reactions of the panels (stresses in cross bracing) on supports n-1 and n.

Angles of rotation on the supports $\varphi_i = \varphi_i^{\theta} + \varphi_i^{N}$ are calculated by the following formulas:

$$\varphi_{n-1} = (M_{\theta} + M_N)\frac{l_p}{2B_p} \cdot \frac{m_5+1}{m_1+m_5}; \quad (18)$$

$$\varphi_n = -(M_{\theta} + M_N)\frac{l_p}{2B_p} - \frac{(1-2s)(m_2-m_5)}{m_1+m_5}, \quad (19)$$

where: φ_{n-1}, φ_n are the angles of rotation of the panels on supports n-1 and n.

M_{θ}, M_N are the equivalent and bending moments at the temperature difference across the thickness and eccentricity of the normal force determined by formulas (7) and (11); s is nondimensional coefficient, taken to be: for panels without intermediate supports in the span s = 1; with one or two intermediate supports s = 0.5.

$$0 < s = \frac{l_s}{l_p} < 0.5,$$

where: ls is the distance from the end support to the intermediate support of the panel; ξ,ζ,η are the relative values of thermal expansion coefficients, bending stiffness and length of panels and joints, respectively, calculated by formulas:

$$\xi = \alpha_j/\alpha_p; \zeta = B_p/B_j; \eta = l_j/l_p, \quad (20)$$

where: B_p, B_j are the bending stiffness of panels and joints, respectively; α_j, α_p are thermal expansion coefficients of panels and joints; m1, m2, m3, m5 are the nondimensional coefficients, calculated by formulas:

$$m_1 = \frac{3-4s}{s(2-3s)}; \quad (21)$$

$$m_2 = \frac{1}{2-3s}; \quad (22)$$

$$m_3 = \frac{3(1-s)}{s^2(2-3s)}; \quad (23)$$

$$m_5 = \frac{6\varepsilon}{s^3(2-3s)}, \quad (24)$$

where ε is the coefficient that takes into account the influence of the compliance of the panel supports, calculated by the formula:

$$\varepsilon = \frac{(c_0 + c_1)B_p}{l_p^3}, \quad (25)$$

where c0, c1 are the coefficients of compliance of the end and intermediate supports, respectively [5, 6].

For rigid supports (c0 = c1= 0) the coefficients ε and m5 equal zero. For this case, formulas (26-31) for calculating the total values of Mi, Ri and ϕi of the panels on rigid supports are given below. These formulas can also be used for approximate analysis of panels on elastic supports.

Moments $M_i = M_i^{\theta} + M_i^{N}$ are calculated using the following formulas:

$$M_{n-1,j} = 0; \quad (26)$$

$$M_{n-1,p} = M_N; \quad (27)$$

$$M_{n,p} = -(M_{\theta} + M_N)\left[\frac{m_2}{m_1} + 1\right] + M_N. \quad (28)$$

The support reactions $R_i = R_i^{\theta} + R_i^{N}$ are calculated by following formulas:

$$R_{n-1,j} = -R_n = -(M_{\theta} + M_N)\frac{m_3}{l_p m_1}. \quad (29)$$

Angles of rotation on the supports $\varphi_i = \varphi_i^{\theta} + \varphi_i^{N}$ are calculated by the following formulas:

$$\varphi_{n-1} = (M_{\theta} + M_N)\frac{l_p}{2m_1 B_p}; \quad (30)$$

$$\varphi_n = -(M_{\theta} + M_N)\frac{l_p}{2m_1 B_p} - \frac{1-2s}{2-3s}. \quad (31)$$

For panels with unbonded joints or if the joint has no cross bracing, bending stiffness of the joint Bj can be equal to zero. The corresponding values of bending moments, support reactions and angles of rotation of the panels on the supports in such cases are determined by formulas (14-31) [5, 6].

3. RESULTS AND DISCUSSION

To obtain lightweight silicate bricks at different parameters of hydrothermal synthesis, substandard clay rock from the KMA region was used as the main active component. The used rock has plasticity number 6 and belongs to loamy sand. Its composition is dominated by mixed-layer minerals, finely dispersed quartz, and X-ray amorphous phase, which is confirmed by the data of X-ray phase analysis (Fig. 1). Rocks of similar composition are widespread not only in the KMA region, but also in other regions of Russia.

The bending moments and support reactions of single-layered light concrete panels (ρ = 1,600 kg/m3) of 1,500, 3,000, 4,500 and 6,000 mm length and 250, 300, 350, 400 and 450 mm thickness on elastic supports with one intermediate support in the middle of the span (s=0.5) at temperature difference Δθ from 0 °C to 65 °C with 5 °C step are calculated. The panels are supported by a reinforced concrete slab of heavy concrete (ρ = 2,500 kg/m3), 160 mm thick, 6,000 mm long. The eccentricity of normal force eN is assumed to be 10 cm, the bending stiffness of joints Bj = 0.1 MPa·m4, the reduced cross bracing compliance coefficient of a joint Cj = 10-8 m/N; the longitudinal bracing compliance factor: end C0 = 5·10-8 m/N; intermediate C1 = 10-8 m/N. The values of the normal force Np, and the bending stiffness of the panels Bp are presented in Table 1.

Table 1. The values of the normal force and the bending stiffness of the panels.

Panel length, mm	Longitudinal force N_p, kN	Flexural rigidity of the panel B_p, MPa·m^4				
		Panel thickness, mm				
		250	300	350	400	450
1,500	-17.65	3.1	4.8	6.9	9.5	12.5
3,000	-35.30	3.4	5.3	7.6	10.3	13.5
4,500	-52.96	3.6	5.5	7.9	10.7	14.0
6,000	-70.61	3.7	5.7	8.1	11.0	14.3

Fig. 1 and 2 show the results of calculations of bending moments ($M_{n.p}$) and support reactions (Rn-1). At the same time the bending moments in the panels of length 1,500, 3,000, 4,500 and 6,000 mm on the end supports (Mn-1,p) are equal to 1.77; 3.53; 5.30; 7.06 kN·m, and at the joint Mn-1,j = 0 for all panels, respectively. The bending moments $M_{n.p}$ and support reactions Rn-1 of a 1,500 mm long panel decrease as the panel thickness increases across the entire temperature range (0–65 °C). The values of bending moments and support reactions of panels with length of 3,000, 4,500 and 6,000 mm decrease only when the temperature rises from 0 to 10 °C, in the rest of the range 15–65 °C – increase as the thickness of the panel increases due to the bending stiffness.

Table 2. Formulas for bending moment's calculation.

Panel length, mm	Panel thickness, mm				
	250	300	350	400	450
Bending moment Mn.p					
1,500	$M_{n.p} = -0.0641\Delta\theta - 2.9074$	$M_{n.p} = -0.063\Delta\theta - 2.632$	$M_{n.p} = -0.0598\Delta\theta - 2.4411$	$M_{n.p} = -0.0564\Delta\theta - 2.2894$	$M_{n.p} = -0.0526\Delta\theta - 2.1843$
3,000	$M_{n.p} = -0.138\Delta\theta - 8.01$	$M_{n.p} = -0.1652\Delta\theta - 7.6609$	$M_{n.p} = -0.1854\Delta\theta - 7.3$	$M_{n.p} = -0.1993\Delta\theta - 6.9471$	$M_{n.p} = -0.2093\Delta\theta - 6.6094$
4,500	$M_{n.p} = -0.1634\Delta\theta - 12.809$	$M_{n.p} = -0.2023\Delta\theta - 12.6$	$M_{n.p} = -0.2407\Delta\theta - 12.359$	$M_{n.p} = -0.2749\Delta\theta - 12.1$	$M_{n.p} = -0.306\Delta\theta - 11.81$
6,000	$M_{n.p} = -0.0641\Delta\theta - 2.9074$	$M_{n.p} = -0.063\Delta\theta - 2.632$	$M_{n.p} = -0.0598\Delta\theta - 2.4411$	$M_{n.p} = -0.0564\Delta\theta - 2.2894$	$M_{n.p} = -0.0526\Delta\theta - 2.1843$
Support reaction Rn-1					
1,500	$R_{n-1} = -0.0854\Delta\theta - 1.52$	$R_{n-1} = -0.084\Delta\theta - 1.16$	$R_{n-1} = -0.08\Delta\theta - 0.89$	$R_{n-1} = -0.0753\Delta\theta - 0.6971$	$R_{n-1} = -0.0702\Delta\theta - 0.5571$
3,000	$R_{n-1} = -0.092\Delta\theta - 2.99$	$R_{n-1} = -0.1102\Delta\theta - 2.752$	$R_{n-1} = -0.1236\Delta\theta - 2.5129$	$R_{n-1} = -0.1329\Delta\theta - 2.278$	$R_{n-1} = -0.1395\Delta\theta - 2.0531$
4,500	$R_{n-1} = -0.0727\Delta\theta - 3.3371$	$R_{n-1} = -0.0898\Delta\theta - 3.2486$	$R_{n-1} = -0.107\Delta\theta - 3.138$	$R_{n-1} = 0.1222\Delta\theta - 3.0249$	$R_{n-1} = -0.136\Delta\theta - 2.89$
6,000	$R_{n-1} = -0.0578\Delta\theta - 3.4426$	$R_{n-1} = -0.0732\Delta\theta - 3.4031$	$R_{n-1} = -0.0877\Delta\theta - 3.3477$	$R_{n-1} = -0.1023\Delta\theta - 3.2843$	$R_{n-1} = -0.1161\Delta\theta - 3.2231$

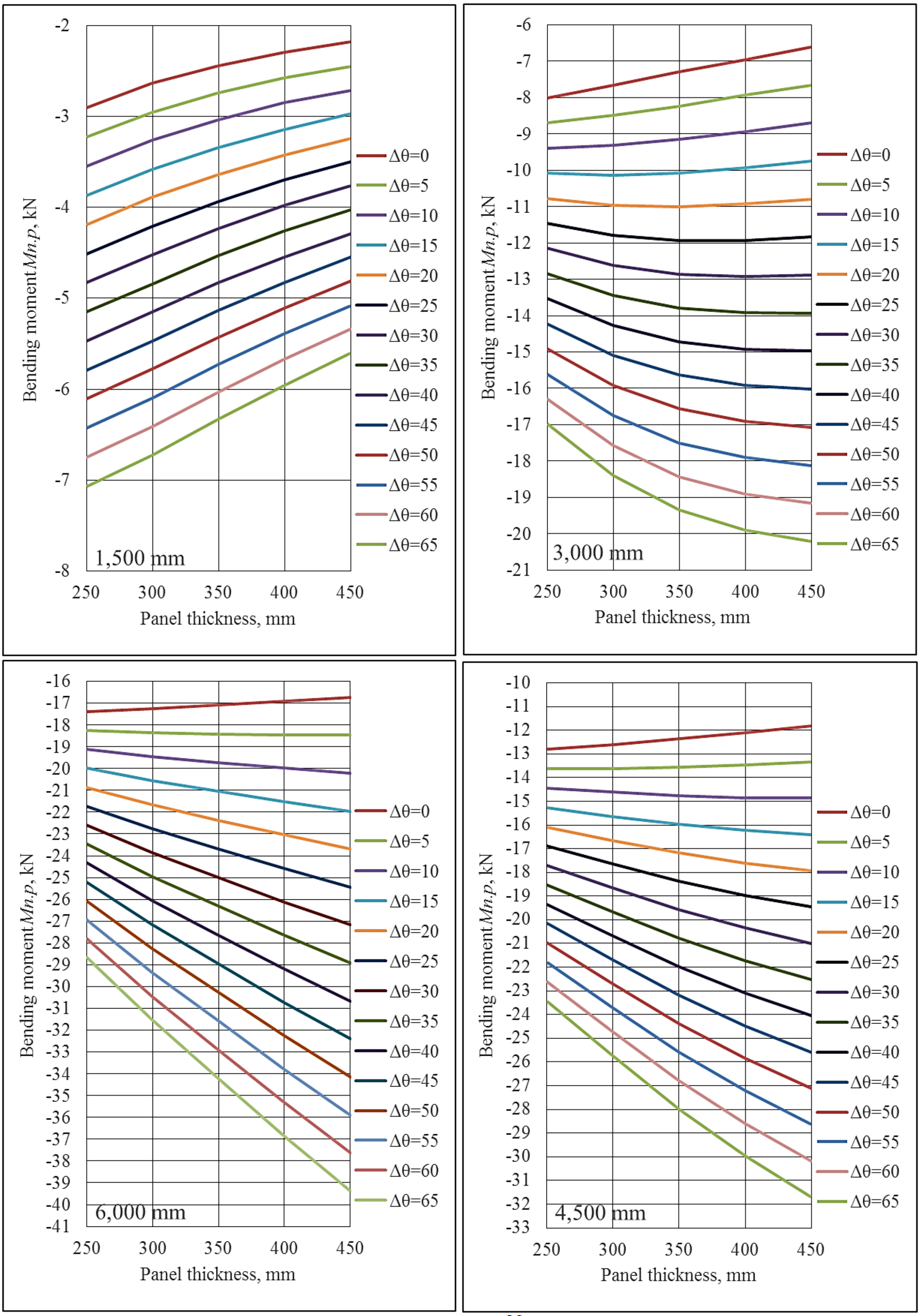

Fig. 1. The relationship between the bending moments $M_{n.p}$ of single-layered wall panels with length of 1,500, 3,000, 4,500 and 6,000 mm and the thickness of the panels at a temperature difference of 0–65 °C.

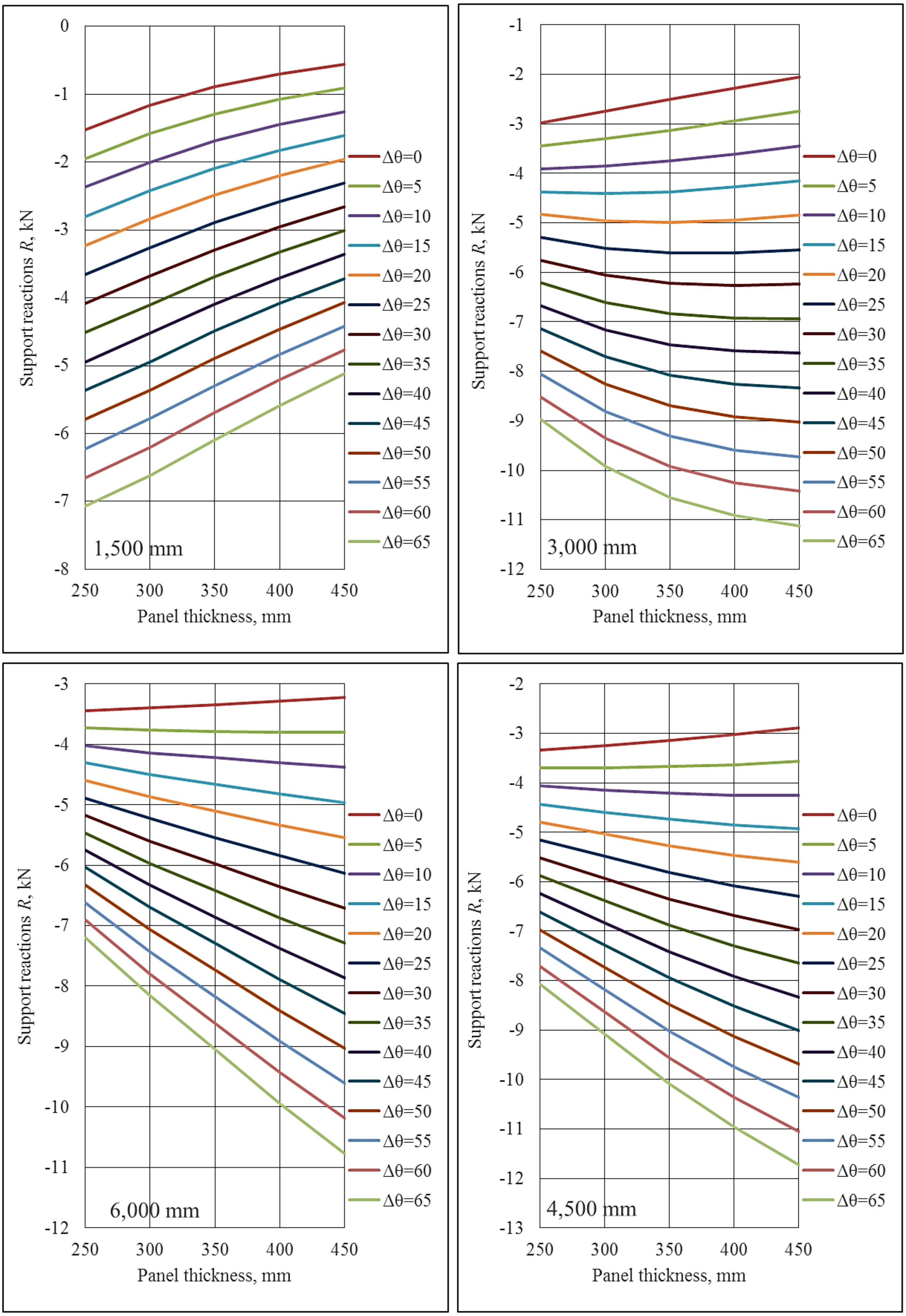

Fig. 2. The relationship between the support reactions R of single-layered wall panels with length of 1,500, 3,000, 4,500 and 6,000 mm and the thickness of the panels at a temperature difference of 0–65°C.

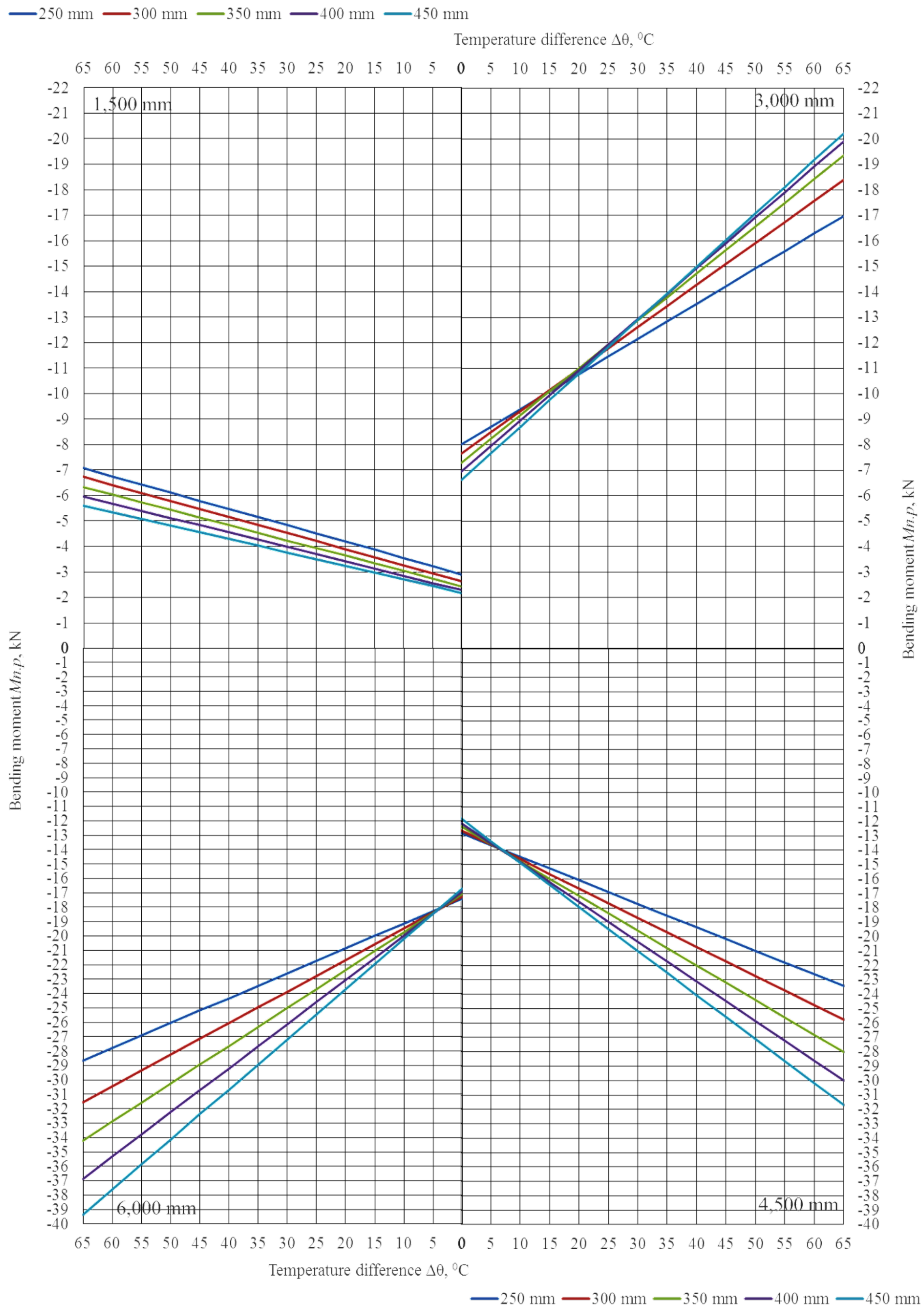

Fig. 3. The design chart for determining the bending moments $M_{n.p}$ of single-layer wall panels with a length of 1,500, 3,000, 4,500 and 6,000 mm, depending on the thickness.

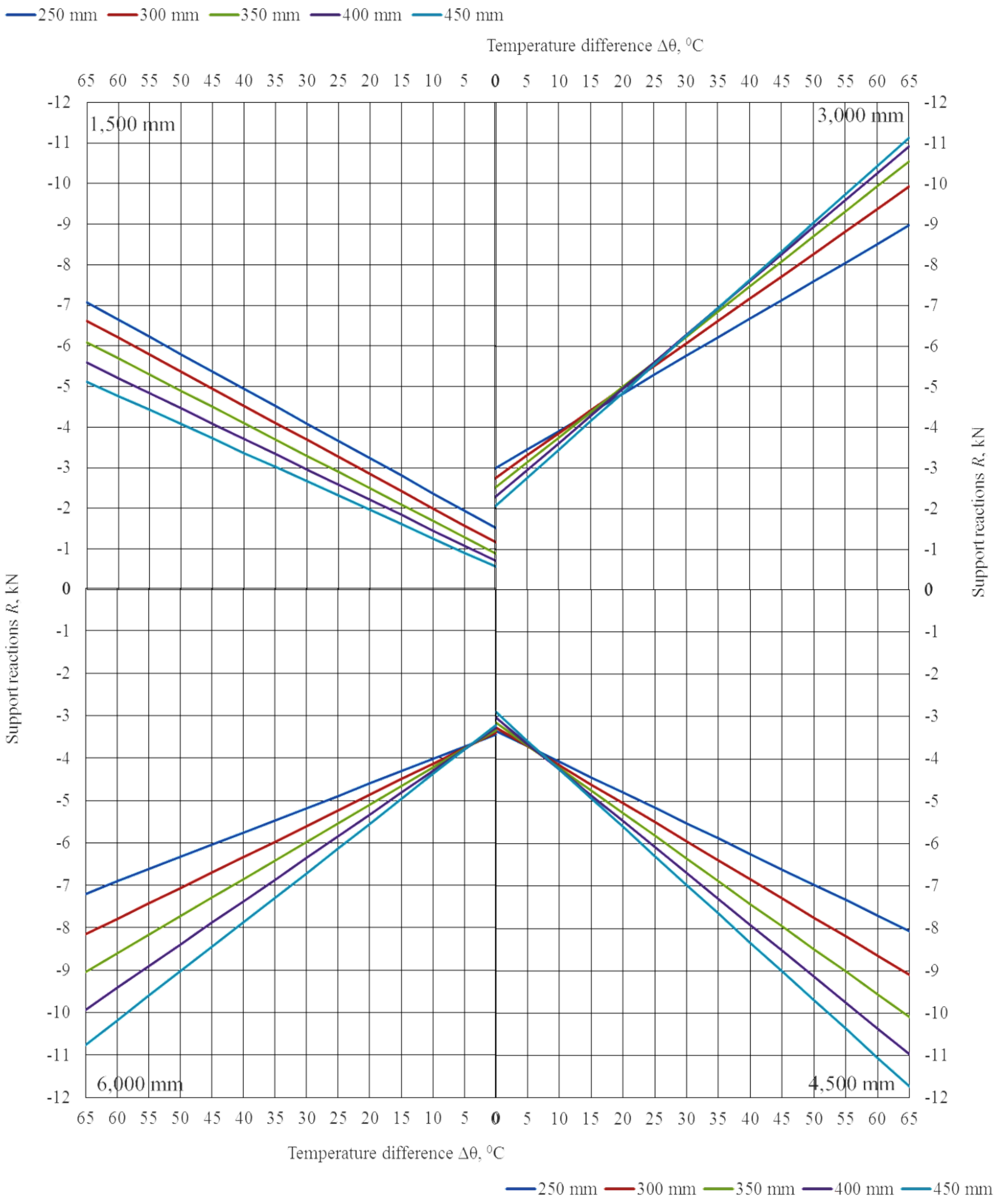

Fig. 4. The design chart for determining the support reactions R_{n-1} of single-layer wall panels with a length of 1,500, 3,000, 4,500 and 6,000 mm, depending on the thickness.

To reduce the complexity of determining bending moments $M_{n.p}$ and support reactions Rn-1 design charts were developed (Figures 3 and 4) for panels with a length of 1,500, 3,000, 4,500 and 6,000 mm and a thickness of 250, 300, 350, 400 and 450 mm, which allow to determine them graphically and if necessary, to select a rational geometric dimensions (length, thickness) of the outer wall panels [7-11].

To determine the bending moments or support reactions, a vertical line is drawn from the X axis (or X') to the graph, which is in the area corresponding to the length of the panel. From the point of intersection of the desired graph, a horizontal line is drawn to the Y axis (or Y'), which will indicate the value of the bending moment Mn.p or the support reaction Rn-1 for the desired panel with a given temperature difference. The accuracy of the design chart is due to its scales. To determine the bending moments of temperature differences not a multiple of 5 °C, one must use the method of interpolation of known intermediate values or the formulas in Table 2 [12-19].

Deformations caused by temperature differences are a common problem of reinforced concrete wall panels. The reference point for the beginning of studies of the influence of temperature differences on the bending moments of reinforced concrete structures is the widespread use of large-panel construction in the 1960s. In 1960, Leabu researched common problems affecting the characteristics of prefabricated wall panels. It reveals that the temperature difference affects the bending moments of both single-layer and multi-layer reinforced concrete wall panels. He suggested calculating the curvature of the panel using classical mechanics, taking into account two reference conditions. Full-scale tests did not carry out; however, recommendations were given when designing to take into account the connections of wall panels, their plasticity and strength [4].

In 1984, Leung conducted full-scale tests of multilayer reinforced concrete wall panels, subjecting them to various temperature conditions. He revealed that the full-scale data is 25% higher than the theoretical calculations obtained by Leabu in 1960. In 1992, Einea examined the temperature deformations of reinforced concrete wall panels of various lengths. In 2002, in the studies of Gali, Favre and Elbadri, it was noted that deformations depend on many variables, such as cross-sectional geometry, thermal conductivity, specific heat capacity, material density, surface character and color, convection, orientation of the axis of the structure and its location, time of day and season, changes in air temperature and wind speed, etc. They also pointed out those sections with cracks exhibit less bending moment than a section without cracks and, consequently, less deflection due to temperature differences. In 2018, tests conducted at the University of Utah, the purpose of which was to verify the assumptions made by various researchers about the behavior of multilayer reinforced concrete wall panels under temperature changes [4]. The following conclusions were:

1) The change in the temperature of the unheated room is insignificant;
2) The change in the temperature between the two cross-section points has no effect;
3) There is a linear dependence between the bending moment and the temperature differences in the panel [4].

4. CONCLUSIONS

The bending moments and support reactions of single-layer lightweight concrete panels of different lengths and thicknesses for temperature differences Δθ from 0 °C to 65 °C have been calculated.

It was found that the bending moments and support reactions of the 1,500 mm panels decrease as the thickness of the panels increases across the entire temperature range. The values of bending moments and support reactions of panels with length of 3,000, 4,500 and 6,000 mm decrease only when the temperature rises from 0 to 10 °C, in the rest of the range 15–65 °C – increase as the thickness of the panel increases due to the bending stiffness.

In order to determine bending moments $M_{n,p}$ and support reactions Rn-1 for panels with a length of 1,500, 3,000, 4,500, 6,000 mm and thickness of 250, 300, 350, 400 and 450 mm by means of graphical method, the design charts are designed to intensify the process of deciding on the choice of rational geometric parameters of exterior wall panels operated in different climatic conditions.

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