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U.S.S.R. Experience in Thermal Design of Building Envelopes with Improved Thermal Properties

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ABSTRACT

This paper deals with the U.S.S.R. experience on improving thermal design of enveloping structures of precast buildings of mass-scale construction. In such buildings, multi-layer enveloping structures with improved thermal properties are becoming increasingly used. They are characterized by non-homogeneity of materials in cross-section and complex butt joints for which methods of computer estimation of temperature fields had been developed. The paper sets forth methods for estimating two- and three-dimensional tasks of heat conduction making it possible to obtain temperature fields of surfaces of envelopes, the distribution of thermal flows, and on that basis to calculate the reduced total thermal resistance of the envelope. For the purpose of codification, based on numerous estimations of temperature fields, simplified design methods of estimation of such structures have been developed. Analytical expressions of thermal characteristics of enveloping structures with the most widely used thermal bridges are given. For design purposes, a data bank has been compiled on typical thermal bridges of enveloping structures in the U.S.S.R.

INTRODUCTION

The analysis of current requirements for thermal properties of enveloping structures, including economic constraints [1], has shown that in the prevailing examples from Soviet building practice, it is necessary to increase their total thermal resistance as compared to the required total thermal resistance, determined in terms of sanitary–hygienic requirements, the larger this increase, the more efficient and cheaper the insulating material is. The increase is the result of a permanently increasing necessity to save, in any possible way, energy resources used in the national economy. The use of such low conduction materials as mineral wool and foam plastics to improve thermal properties of envelopes has not, however, produced the desired effect due to constructional members penetrating the insulating material and diminishing the thermal properties of the envelope as a whole. Such members were termed thermal bridges. The improvement of thermal properties of envelopes with thermal bridges is aimed at reducing their cross-sectional area and at providing connections between structural and insulating layers by increasing their strength and adhesion properties.

Nowadays in the U.S.S.R., three-layer panels with reinforced concrete exterior layers are being increasingly used. Reinforced concrete layers are tied with elements of metal rods. Such flexible ties, owing to their small cross-sectional area, exert substantially less influence than reinforced concrete ribs and keys upon the thermal homogeneity, thus increasing thermal properties of panels on the whole.

The main constructional feature of three-layer reinforced concrete panels with flexible ties is in the fact that the exterior reinforced concrete layer protecting the layer against atmospheric effects is suspended by flexible ties to the interior load-bearing reinforced concrete layer in such a way that it can deform freely with the temperature fluctuation irrespective of the interior layer. The interior layer, which is subject all the year round to the same temperature conditions, does not suffer substantial temperature strains and stresses.

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The total level of thermal properties of the envelope is evaluated by the reduced total thermal resistance which presents numerically the total thermal resistance of such a one-dimensional envelope, the heat losses through which are equal to the heat losses of a two-dimensional non-homogeneous envelope with thermal bridges and of the same square area.

OVERVIEW

The analysis of the investigations conducted in recent decades has shown that the reduced total resistance of three-layer structures in the U.S.S.R. is 50 - 80% of the thermal resistance in the main cross-section, and that of three-layer structures with flexible metal ties is 70 - 90% [2].

Other researchers [3 - 5] had also inferred that thermal bridges were important. In the survey [4] devoted to studies of thermal inhomogeneities in enveloping structures of buildings, numerous works in that field are given.

The research on thermal performance of non-homogeneous enveloping structures was first conducted in the U.S.S.R. in 1960 [6] by means of the electric analogues method [7]. Then with the development of computer techniques in 1972, there followed the estimation method, algorithm and a universal program of estimation of two-dimensional temperature fields of enveloping structures consisting of metals with significantly different thermal parameters [2].

The practical value of the temperature fields of enveloping structures obtained by the estimation method is that they permit the designer to obtain the minimal temperature on the inner surface of the portion in question, characterizing the provision of the Code [8] with regard to conditions of condensate formation on structures, and to determine the reduced total thermal resistance of the field under study required for evaluation of heat losses through the envelope.

METHODS OF MODELLING TEMPERATURE FIELDS

Many works [9 - 13] are devoted to computer estimations of temperature fields of enveloping structures of buildings.

The computation programs for two- and three-dimensional fields [2] developed in the U.S.S.R. are widely used in research and design practice:

— to verify thermal properties of a designed (or existing) structure;

— to choose a better solution in the process of envelope design or development of measures to improve the existing structure;

— to compare survey data on temperature performance of the enveloping structure with the estimation results.

A steady-state two-dimensional temperature field is determined by the finite difference method for a set of partial differential equations of elliptical type. For a flat temperature field, when independent of the temperature, it has the form:

$$\frac{\partial}{\partial x}\left(\lambda_{x,i}\frac{\partial t_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{y,i}\frac{\partial t_i}{\partial y}\right) = 0 \qquad (1)$$

where λ = the heat conduction and t = the required temperature.

Most three-dimensional problems of the thermal analysis of enveloping structures reduce to the problem of a steady-state temperature distribution in a three-dimensional field. The distribution of temperatures is determined by the solution of the system of partial differential equations of Poisson type:

$$\frac{\partial}{\partial x}\left(\lambda_{x,i}\frac{\partial t_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{y,i}\frac{\partial t_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{z,i}\frac{\partial t_i}{\partial z}\right) + Q_i(x, y, z) = 0 \qquad (2)$$

where: Q_i = the heat source intensity for the i region.

On the boundaries of the fields in question, the heat exchange conditions of first, second and third order are assigned

$$t_i = t_{o,k}$$

$$\lambda_i \frac{\partial t_i}{\partial n} = q_{n,k}$$

$$\lambda_i \frac{\partial t_i}{\partial n} + \alpha_k(t_i - t_{o,k}) = 0 \qquad (3)$$

and the mixed conditions, e.g., of second and third order are

$$\lambda_i \frac{\partial t_i}{\partial n} + \alpha_k(t_i - t_{o,k}) + q_{n,k} = 0 \qquad (4)$$

The conditions on the interface boundaries of the regions in the case of the x axis are:

$$t_i = t_j$$

$$-\lambda_{x,i}\frac{\partial t_i}{\partial x} = \lambda_{x,j}\frac{\partial t_j}{\partial x} \qquad (5)$$

The same condition is valid for the y axis.

In the transient heat transfer case, the temperatures are found by solving a set of partial differential equations of a parabolic type: in the case of a flat field

$$c_i\gamma_0\frac{\partial t_i}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_{x,i}\frac{\partial t_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{y,i}\frac{\partial t_i}{\partial y}\right) \qquad (6)$$

Rather complex problems can be solved when the field under study is divided into 5000 - 6000 rectangular meshes for the two-dimensional case and 20 000 - 25 000 parallelepipeds for the three-dimensional case and thermal coefficients can be allowed to range from 0.01 to 200 W/m °C.

The algorithm of the solution is based on the method of equivalent circuits [14] which is a version of the finite difference method. The field under study is divided into small meshes, and we proceed from a medium with continuous-distributed properties to a circuit consisting of thermal conductions connecting the centres of meshes. Using the method of analogues, the scheme of a thermal chain is replaced by a scheme of an equivalent electric circuit of constant current with sources simulating the assigned temperatures on the boundaries or in the medium surrounding the boundaries. The distribution of potentials in such a circuit is similar to that described in eqn. (2), presented in finite differences.

Eventually the estimation of the temperature field reduces to a computer estimation of the electric circuit when matrix coefficients [A] of conductions of the circuit and the value of circuit-feeding currents [B] are calculated, then a system of linear algebraic equations determining the distribution of potentials in the circuit is solved:

$$[A] \times [X] = [B] \qquad (7)$$

To solve eqn. (1) the Gaussian elimination method is used, and to solve eqn. (2) iteration methods are used, namely the Gauss-Zeidel method and conjugation method [2].

ESTIMATION EXAMPLES

The effect of various types of through thermal bridges on the thermal homogeneity of enveloping structures can be discussed for the estimation examples of three-layer wall envelopes used in building practice:

(1) a panel with planking of hard softwood chipboard and an insulating core of mineral wool with a protective cover of corrugated steel sheet on the exterior side fixed on the panel by through metal channels (Fig. 1);

(2) a reinforced concrete panel with mineral wool insulation. Reinforced concrete layers are connected by reinforced concrete ribs 500 mm thick (Fig. 2);

(3) a reinforced concrete panel with an efficient insulation layer. Reinforced concrete layers are connected by metal rod ties of various configuration (flexible ties) (Fig. 3).

The estimation results are presented in Fig. 1. From the graphs of the temperature distribution one can readily see the negative influence of the thermal bridge which in the section II - II results in inadmissible negative temperatures. The thermal resistance of the

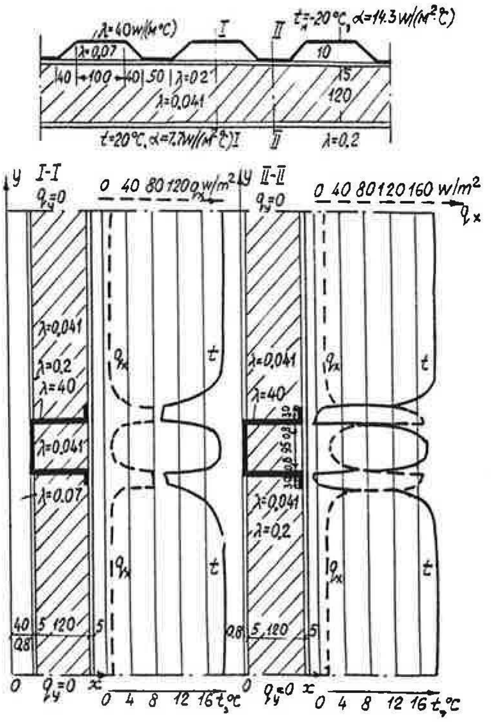


Fig. 1. Estimation results for a wall panel with mineral wool insulation with planking out of softwood chipboard with a protective cover of corrugated steel sheet.

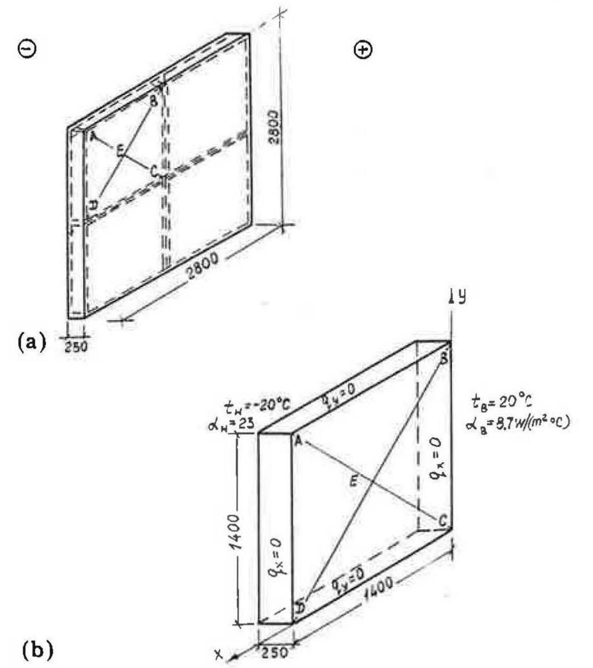


Fig. 2. Formulation of the task of estimating a three-dimensional field of an end wall panel of a building: (a) scheme of the panel, (b) scheme of estimation.

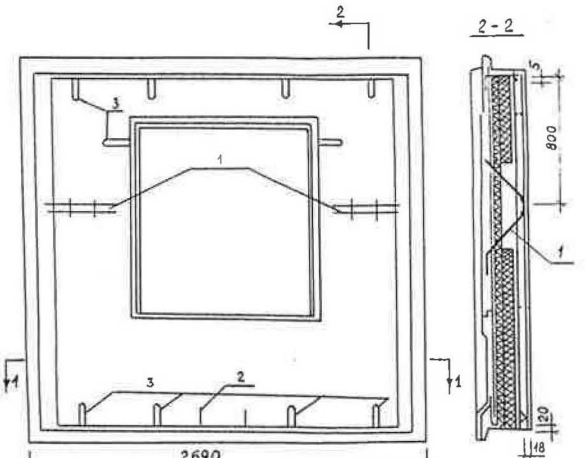


Fig. 3. A three-layer reinforced concrete panel with an efficient insulation on flexible ties (suspensions, struts, cross-bars).

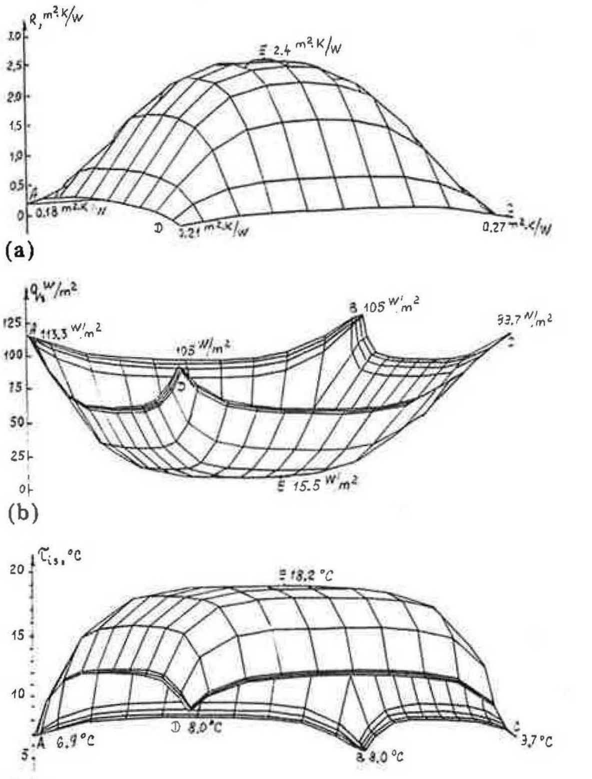


Fig. 4. Axonometric depiction of the estimation results for a three-dimensional temperature field of a three-layer panel: (a) local thermal resistances, (b) density of thermal flows, (c) temperature on the interior surface.

wall in this section is equal to 2.5 m^2 °C/W as compared to 3.3 m^2 °C/W for a wall without any thermal bridge, and the temperatures of the interior surface are −0.8 °C and +18.5 °C respectively.

Figure 4 gives an axonometric presentation of computation results for the second panel in the form of three fields:

(a) temperatures of the interior surface;
(b) density of heat flows;
(c) local thermal resistances.

The reduced thermal resistance of the panel is 1.08 m^2 °C/W as compared to 2.7 m^2 °C/W for the homogeneous part. The distribution of temperatures and densities of the heat flow is extremely non-uniform, e.g., the temperature at the point E is 18.2 °C, at A it is 6.9 °C, while the densities of the heat flow are 15.5 and 113.6 W/m^2 respectively.

The first two estimations show a negative effect of through thermal bridges upon the thermal performance of wall panels under operational conditions: in the first case —

unacceptable reduction of the temperature on the interior surface in the zone of the thermal bridge, in the second case — a multiple increase of the heat flow in the zone of the reinforced concrete rib as compared to the panel portion far from the thermal bridge.

The third panel, with flexible ties as connecting elements of reinforced concrete layers, has a significantly less cross-sectional area of through thermal bridges, while the fastening of metal rods in the reinforced concrete mass levels the temperature of the interior surface in the zone of the thermal bridge. Estimations of three-dimensional temperature fields of the third panel testify to the fact.

The portion of the partition with flexible ties termed suspensions is the most complicated three-dimensional task to solve. It is evidently a three-dimensional process of heat transfer as heat flows distribute intensely along inclined metal rods. Owing to the inclined metal rod, while preparing the task for solution, the object under study should be divided into elementary parallelepipeds in such a way that their total number goes beyond (more than 25 000) the opportunities of the program. That is why there appeared a problem of such an approximation of the inclined rod which allowed researchers to solve the problem by the computers at their disposal and at the same time reflected closely the physical pattern of the heat transfer process.

As a result of the estimations, it was decided to take a multi-step rod having one step in concrete layers and insulating material of the panel (Fig. 5). Figures 6 and 7 present the results of estimation of the temperature field of the interior surface of the panel round the rod. In the area where the rod is nearest to the interior surface, the temperature on it is lower by less than 1 °C than the temperature of the area far from the rod, thus indicating a substantial efficiency of the levelling effect of the concrete layer upon the temperature of the interior surface in the thermal bridge zone, and providing no condensate formation on the interior surface.

SIMPLIFIED ESTIMATION MODELS

Despite the wide development of computer techniques and availability of computer programs for the estimation of temperature fields as the major means of estimating nonhomogeneous enveloping structures, there have been attempts to standardize and simplify the calculation methods and make

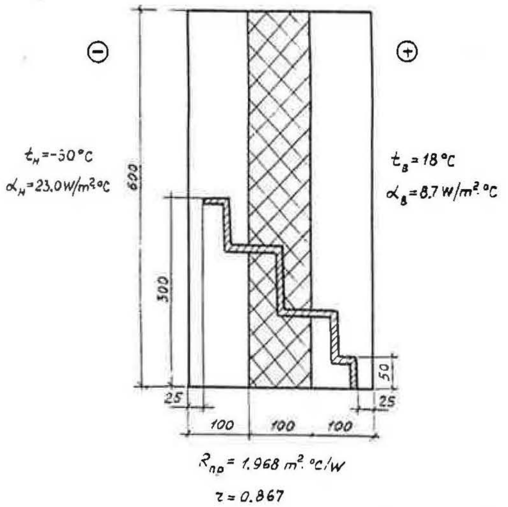


Fig. 5. Approximation of an inclined portion of a suspension by a multi-step rod.

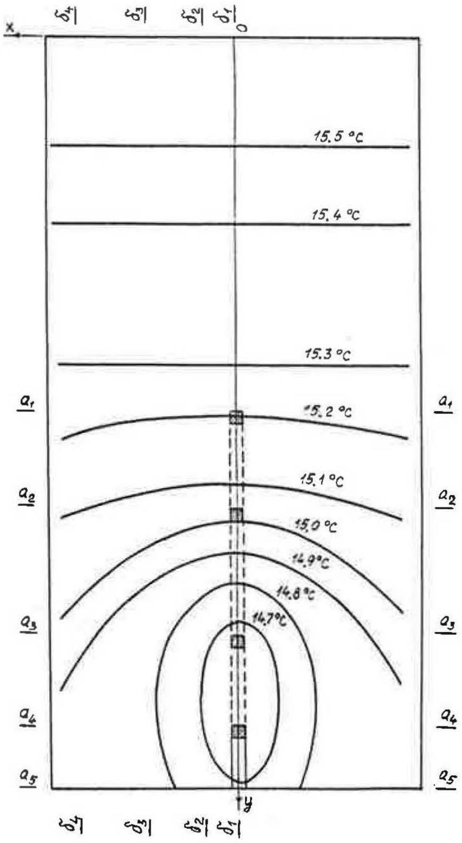


Fig. 6. Temperature field of the interior panel with an inclined rod of the suspension.

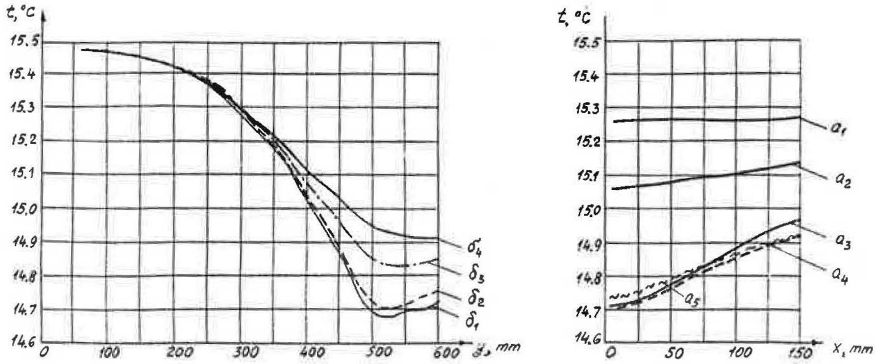
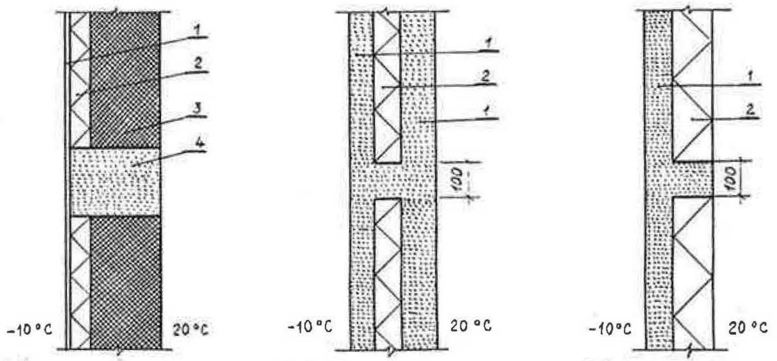


Fig. 7. Distribution curves of temperature on the interior surface of the panel fragment in sections.



(a) (b) (c)

Fig. 8. Schemes of enveloping structures assumed in the estimation in comparing standards 1-reinforced concrete; 2-insulating material; 3-lightweight concrete; 4-plaster.

TABLE 1

Estimation results for three examples of enveloping structures

Example	ISO 6946/2 formulas [15]		SNiPII-3-79^{xx} [8]		Computer program [15]		Computer program [2]	
	τ_{tb}	R_o^r	τ_{tb}	R_o^r	τ_{tb}	R_o^r	τ_{tb}	R_o^r
I	9.02	1.845	8.28	—	8.97	1.859	8.89	1.866
II	11.69	1.022	12.28	1.15	12.54	0.943	12.45	0.971
III	3.69	1.1	—	0.923	3.69	1.099	4.32	1.119

them applicable for codification. Three trends can be distinguished:

(a) standardization of thermal bridges and development of relevant formulas and tables [8, 15];

(b) development of tables of typical structures and determination of thermal properties by the tables [16, 17];

(c) development of simplified methods of estimation based on the division of a non-homogeneous enveloping structure into homogeneous elements and determination of the reduced total thermal resistance [17, 18, 20].

The first two methods are based on the same principle — on the results of computer estimations of two-dimensional temperature fields.

The estimation results of three examples of enveloping structures, given in Fig. 8 and done on the basis of the first method [15], were compared with the computer estimation results [2]. The parameters compared were the temperature of the envelope interior surface in the area of the thermal bridge, τ_{tb} (°C), and the reduced total thermal resistance, R_o^r, (m^2 °C/W). The results are given in Table 1. The comparative analysis of the results shows just a little divergence.

The estimation of the reduced total thermal resistance of a panel can be achieved more easily if the characteristic thermally non-homogeneous zones and the zones influencing the temperature field F_{f_i} and their so-called shape factors f_i are determined beforehand.

Shape factor

The shape factor of a thermally non-homogeneous portion is a dimensionless parameter indicating by how many times the heat flux through the zone area changes in the presence of a thermal non-homogeneity related to the heat flux through the same area in the absence of a thermal non-homogeneity.

$$f_i = \frac{R_{oi}^{\mathrm{cond}}}{R_{oi}^{\mathrm{r}}} \tag{8}$$

where R_{oi}^{cond} = total thermal resistance of a thermally homogeneous ith portion of the panel.

Then the reduced total thermal resistance of the panel can be determined by a simple formula [19, 16]

$$R_o^{\mathrm{r}} = R_o^{\mathrm{cond}}\left[1 + \frac{\sum\limits_{i=1}^{n} F_{f_i}(f_i - 1)}{F_o}\right]^{-1} = rR_o^{\mathrm{cond}} \tag{9}$$

where F_o = the panel area, and n = the number of thermally non-homogeneous portions of the panel, and r = the thermal homogeneity factor of the panel:

$$r = \left[1 + \frac{\sum\limits_{i=1}^{n} F_{f_i}(f_i - 1)}{F_o}\right]^{-1} \tag{10}$$

For thermal bridges of the simplest shape (Fig. 9) crossing the whole or half thickness of the enveloping structure, there are approximation formulas. The numerous computer estimations of temperature fields of enveloping structures with various thermal bridges served as a basis for developing formulas. The results of the estimations were summarized on the basis of characteristic temperatures of the interior surface of the envelope (Fig. 9).

The estimation results of temperature fields have shown that the magnitude of τ_{in}^1 depends mainly upon the ratio of the bridge width to the wall thickness a/δ. With the ultimate magnitudes of the bridge width a the magnitude τ_{in}^1 is equal to:

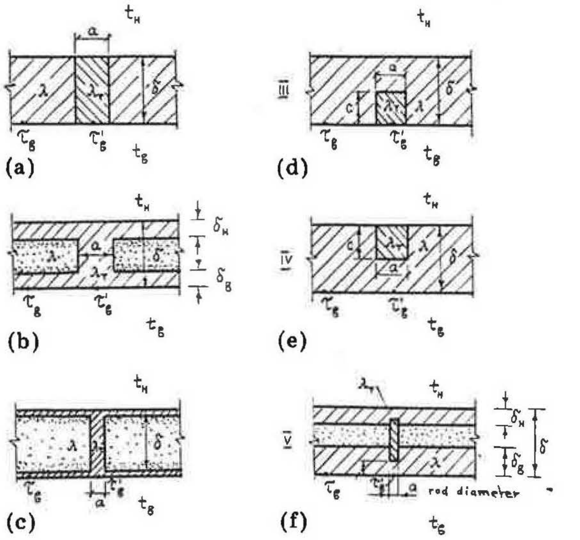


Fig. 9. Schemes of typical thermal bridges. (a) - (e) flat type, (f) symmetric-about-axis type (c_1 not less than 1 cm).

at $a = 0$ $\quad \tau_{\mathrm{in}}^1 = \tau_{\mathrm{in}}$

at $a/\delta > 2$ $\quad \tau_{\mathrm{in}}^1 = \tau_t$

It would be natural to suppose that the difference of temperatures $\tau_{\mathrm{in}} - \tau_{\mathrm{in}}^1$ comprises some part of the difference $\tau_{\mathrm{in}} - \tau_t$, i.e.,

$$\tau_{\mathrm{in}} - \tau_{\mathrm{in}}^1 = \eta(\tau_{\mathrm{in}} - \tau_t) \tag{11}$$

where η = dimensionless coefficient characterizing the intensity of heat transmittance towards the thermal bridge and dependent on its geometrical parameters and location in the envelope.

$$\eta = \frac{\tau_{\mathrm{in}} - \tau_{\mathrm{in}}^1}{\tau_{\mathrm{in}} - \tau_t} \tag{12}$$

Magnitudes of the η coefficient for the most characteristic types of thermal bridges are estimated and given in ref. 8.

Knowing the magnitude of η, it is possible to determine the temperature τ_{in}^1 by the formula:

$$\tau_{\mathrm{in}}^1 = t_{\mathrm{in}} - \frac{t_{\mathrm{in}} - t_{\mathrm{ex}}}{R_o^{\mathrm{cond}}\alpha_{\mathrm{in}}}\left[1 + \eta\left(\frac{R_o^{\mathrm{cond}}}{R_o^{\mathrm{t}}} - 1\right)\right] \tag{13}$$

where R_o^{t} = total thermal resistance in the thermal bridge.

Analytical expressions for thermal characteristics of envelopes with metal thermal bridges are more complex.

Thus the shape factor of the influence zone of a flexible tie in the form of a single metal

TABLE 2

The effect of the diameter of metal rods of the suspension (Fig. 3) upon thermal characteristics (*r*, *f*) of the panel with flexible ties

Diameter of suspension rods d (mm)	Thermal characteristics of the zone of suspension influence			Magnitudes of terms in eqn. (10)		Share of additional heat relevant to the suspension zone	Thermal characteristics of the panel	
	$R^{r}_{o\phi}$ (m^2 °C/W)	r_ϕ	f_ϕ	$F_{f\phi}(f_\phi - 1)$	$\sum_{i=1}^{n} F_{fi}(f_i - 1)$	$\Delta Q_\phi = \frac{F_{f\phi}(f_\phi - 1)}{\Sigma F_{fi}(f_i - 1)} \cdot 100$	r	f
8	1.96	0.86	1.16	0.09	1.15	8.1	0.70	1.43
10	1.87	0.82	1.21	0.13	1.18	10.7	0.69	1.44
12	1.78	0.76	1.31	0.18	1.24	14.8	0.68	1.46
14	1.63	0.71	1.40	0.24	1.30	18.5	0.67	1.48
16	1.52	0.67	1.49	0.29	1.35	21.8	0.66	1.50
18	1.43	0.63	1.59	0.35	1.40	25.0	0.65	1.53
20	1.34	0.59	1.69	0.41	1.47	28.2	0.64	1.55

Note: The index ϕ near the parameters indicates that they refer to suspensions with a certain diameter of rods.

rod (type f, Fig. 9) can be determined from the expression*:

$$f = 1 + \frac{2\eta}{(\beta a_f)^2}\left(\frac{R_o^{\text{cond}}}{R_o^t} - 1\right) \tag{14}$$

where

$$a_f = \frac{1}{\beta}\ln\left[100\eta\left(\frac{R_o^{\text{cond}}}{R_o^t} - 1\right)\right] \tag{15}$$

is the influence zone of the flexible zone, and $\beta = (1.5d + 50)^{-1}$ is the index of the exponential relationship, d = the metal rod diameter, mm.

For thin-wall through thermal bridges (type C, Fig. 9) the thermal homogeneity coefficient of the envelope is equal to**

$$r = \left[1 + \frac{1}{F_o}\sum_{i=1}^{n}\frac{R_o^{\text{cond}}}{R_{oi}^t}F_i^t K_i\right]^{-1} \tag{16}$$

where F_i^t = the square area of the ith metal rib projected on the surface of the envelope;

$$K_i = 1 + \zeta\frac{\delta_i^2}{\lambda_i^t a_i R_o^{\text{cond}}} \tag{17}$$

where ζ = coefficient dependent on the ratio $a\lambda_t/\delta\lambda$, numerical values are given in ref. 8.

The effect of different types of thermal homogeneities on thermal properties of the envelope is considered in the example of estimation of a three-layer reinforced concrete panel with flexible ties (Fig. 3). Depending on the thickness of panels, their load-bearing capacity, operating conditions and other constructional parameters, the diameter of rods of the usual load-bearing flexible tie–suspension can change from 8 mm to 20 mm. The panel with the suspension diameter of 8 mm was assumed as a basic version. There were estimated three-dimensional tasks of heat conduction [2] for the area of the suspension influence, with an increase of its diameter up to 20 mm with a 2-mm distance between them. The obtained data made it possible to investigate the influence of the cross-sectional area of a metal inclusion upon thermal characteristics of a panel with flexible ties, and variation of the contribution share of the suspension among other thermally non-homogeneous elements in additional heat losses through the panel (Table 2).

From the data obtained, it is evident that the increase in the diameter of suspension rods substantially worsens the thermal characteristics of the panel. Thus, with the increase of the rod diameter from 8 mm to 20 mm, the additional heat (i.e., the increment of heat flow due to thermal non-homogeneities) relevant to the suspension area, rose from 8.1% to 28.2%, i.e., by more than 20%, the thermal homogeneity coefficient of the panel dropped from 0.7 to 0.645, i.e., the average reduction was 0.01 per

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*The formula has been derived by E. A. Sidorov, and N. V. Bukharova, MNIITEP, Moscow.

**The formula has been derived by F. V. Kliushnikov, NIISF, Moscow.

TABLE 3

Relationship of thermal characteristics and additional heat losses vs. the type of thermal homogeneities of a three-layer panel with flexible ties, in % (all additional losses are taken as 100%)

Characteristic of significant variable factors affecting thermal homogeneity of a three-layer reinforced concrete panel with flexible ties	Coefficient of thermal homogeneity *r*	Shape factor *f*	Additional % heat losses through							
			Flexible ties			Increase in thickness of the interior r.c. layer in zone of suspension	Increase in thickness of interior r.c. layer in zone of loop	Doors jambs	Vertical junctions	Horizontal junctions
			Suspension	Strut	Crossbar					
Suspensions of 8 mm dia.: connecting ribs over the perimeter of the panel and window are absent	0.70	1.43	8.1	4.9	7.5	17.5	10.7	36.7	14.6	0
Suspensions of 14 mm dia.: connecting ribs over the perimeter of the panel and window are absent	0.67	1.48	18.5	4.3	6.6	15.5	9.5	32.6	13.0	0
Suspensions of 20 mm dia.: connecting ribs over the perimeter of the panel and window are absent	0.64	1.55	28.2	3.8	5.8	13.7	8.4	28.7	11.4	0
Suspensions of 8 mm dia.: there are ribs of cement–sand mixture, 10 mm thick, over the perimeter of the panel and window	0.66	1.50	7.0	4.2	6.4	14.9	9.1	41.3	14.9	2.2
Suspensions of 8 mm dia.: there are ribs of cement–sand mixture, 20 mm thick, over the perimeter of the panel and window	0.63	1.58	6.1	3.6	5.6	13.1	8.0	42.6	14.5	6.5

r.c. = reinforced concrete.

each 2 mm of the increase of the diameter of the suspension rods. Meanwhile, it should be noted that the reduction rate of the thermal homogeneity coefficient of the suspension zone was considerably higher: it was equal to 0.045 per each 2 mm of the increase of the diameter of the suspension rods, i.e., it was 4.5 times that of the panel on the whole.

The share influence of certain types of thermal homogeneities upon additional heat losses through the panel caused by a local reduction of thermal properties of the envelope is of interest. Table 3 presents a percentage distribution of these heat losses according to the types of junctions and thermal bridges of the panel, different parameters of the most serious factors affecting the thermal non-homogeneity of the panel with flexible ties.

It can be seen from the Table that with the increase of the suspension diameter from 8 mm to 20 mm, their share in additional heat losses rises substantially. Heat losses increase and this is characterized by respective changes in parameters r and f. When ribs of cement–sand mixture are arranged over the perimeter of the panel and window aperture to enhance the fire resistance, additional heat losses in horizontal junctions are observed and additional heat losses in door jambs rise significantly (their share rises from 36.7% to 42.6%).

The estimation of the coefficient of thermal homogeneity of the panel by the engineering procedure considering only those thermally non-homogeneous elements that had been taken into account in the estimation of two-dimensional fields by the program [2] made it possible to obtain the magnitude of r equal to 0.745, while estimation by the program gives $r = 0.725$. The divergence of 2.7% confirms that the engineering procedure is quite acceptable for practical calculations.

The data obtained testify that the greatest additional heat losses in three-layer reinforced concrete panels are observed through door jambs, suspensions, increased thickness of the interior panel layer, and vertical junctions.

CONCLUSION

It should be noted in conclusion that:

- the analysis of prefabricated enveloping structures of buildings and their joints has shown that they are rather complicated with regard to their thermal performance, and it would be reasonable to estimate such structures by special computer programs for two- and three-dimensional fields;
- numerous computer estimations of temperature fields of enveloping structures with different types of thermal non-homogeneities can be presented in the form of concrete magnitudes of the shape factor for each type of thermal bridge, complementing the data bank of the shape factor with magnitudes for new types of thermal bridges appearing in the course of development of the design of enveloping structures;
- the data bank of the shape factor allows the designer to assess rather quickly in the course of designing the thermal properties of a version of an enveloping structure employing eqns. (9) and (10) and the current data bank and to introduce relevant constructional changes striving at the wanted thermal properties of the envelope;
- for buildings in general, the present methodology makes it possible to simply assess heat losses of the building shell for the purposes of designing systems of energy conservation and developing measures aimed at the improvement of thermal properties of existing buildings.

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