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SIMULATION OF THERMALLY STRESSED STATE AND EVALUATION OF THE FIRE-RESISTANCE LIMIT FOR A WALL OF "BESSER" CONCRETE BLOCKS

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We carry out a numerical investigation of the thermally stressed state and make a theoretical evaluation of the fire-resistance limit for a wall of vibrocompressed concrete blocks. We perform calculations on the basis of the method of finite elements. Different variants of thermal loading under ordinary fire conditions are considered. Conclusions are drawn concerning the possibility of using blocks for constructing three-layered walls.

Introduction. The application of new technologies in civil engineering and the use of modern building materials require a comprehensive investigation of the insulating and strength properties of constructions under various maintenance conditions, as well as in the case of extremal situations. In view of this, an important problem is that associated with the fire resistance of building materials under ordinary fire conditions.

In the present work we consider the problems associated with the calculations of fire-resistance of a multilayer wall made of vibrocompressed hollow blocks (produced by the Besser Company technology) on the basis of a numerical finite-element simulation of a thermally stressed state under ordinary fire conditions. The investigations were carried out in accordance with a request from the "Besser–Belarus" Joint Enterprise. The main aim of the work was estimation of the limiting fire resistance on the basis of the carrying capacity of a wall structure made of vibrocompressed blocks for a normalized interval of time.

The physical model of the process of heat conduction in such a structure was based on a model of unsteady heat conduction with allowance for variable thermophysical properties of the structural materials, such as thermal conductivity, heat capacity, and air density of the concrete and mineral-cotton mats. Conceptually, the procedure for theoretical estimation of the carrying capacity-based fire-resistance limit of the wall involved:

- consideration of a fragment of the building wall (the overall dimensions of the structural elements and loading on the floors and ceilings were prescribed to be the maximum possible that ensured the masonry material-based carrying capacity of the wall (without a special frame);
- determination of the needed carrying capacity of the wall (proceeding from the acting normative documents) under normal maintenance conditions and introduction of the strength characteristics of the masonry materials;
- determination of loadings in the most loaded zone of the wall exposed to fire;
- finite-element calculation of the thermally stressed state of the wall model;
- determination of the stressed state at dangerous points of the elements of a block on the basis of the calculated fields of stresses and comparison with the strength criterion of concrete;
- estimation of the carrying capacity of the wall for a prescribed interval of time under fire conditions.

The main requirements and norms that are applied in structural design and used in the present investigation are presented in [1-6].

1. Computational Model of a Wall. For theoretical evaluation and comparison with the results of fire tests of the fire-resistance limit of a wall we considered and modeled a fragment of a building wall consisting of hollow blocks (Fig. 1). According to [7], the height of a storey was assumed to be maximal and not smaller than 3.9 m.

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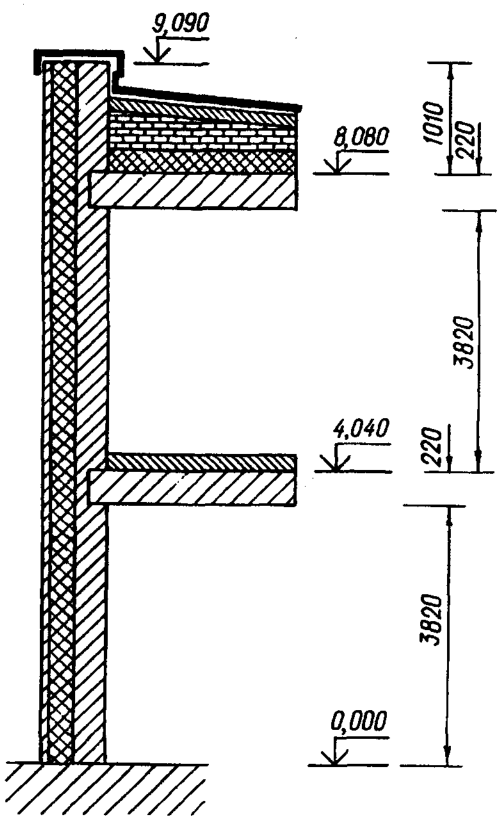

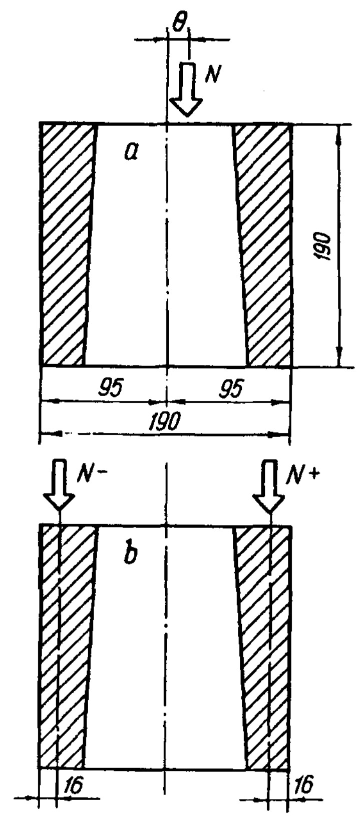

Fig. 1. A fragment of a two-storey building, mm.

Fig. 2. Scheme of application of loads to a block: a) resultant of longitudinal pressure in cross-section of block; d) distribution of longitudinal pressure between heated and unheated edges, mm.

If we used a standard concrete block of height 190 mm and a 220 mm-thick floor slab, the height of the wall was 4.04 m. In addition to the intrinsic mass, the wall experiences the loads from the mass of the ceiling and covering. The spacing between the supporting walls was 9 m. The total normative magnitude of the useful load on the floor was assumed equal to 300 kg/m^2. According to the norms adopted, this corresponds to public catering establishments. We also took into account snow loading (for example, this is the 2nd snow region for the city of Minsk).

Tables 1 and 2 present specific initial data on loadings on floors and coverings. The calculations were carried out with account for both the load reliability index $\gamma_f = 1.0$ and $\gamma_f > 1.0$.

The coefficient of the combination of loads ψ_{A_1} was assumed in the calculations to be equal to 0.7. With a change in the freight area of the place A within the range 25–54 m^2, this is a mean value with a deviation of no more than 10%.

The intrinsic mass of the masonry N_{mas} of a wall of height 9.09 m was 2375 kgf for a the normative value [6] of 2159 kgf. Under normal maintenance conditions the loading on the longitudinal edges of the block was distributed as shown in Fig. 2. In this case, the loadings on the heated and unheated edges (with subscripts + and −, respectively) were 1595 kgf and 950 kgf.

2. Basic Equations and Method of Solution. Numerical integration of the initial equation was carried out by the method of finite elements, which, as is known, is based on a search for the extremum of the functional corresponding to the initial differential equation. For the first time the method was considered in the works of M. J. Turner, R. Clouge, G. Martin, and L. J. Topp. Subsequently, it was extended in the works of O. Zenkevich, L. Sigerlind, G. Streng, D. Norry, et al.

The basic idea of the method is that any value that is continuous in a certain region can be represented by a discrete model, which is constructed on a finite set of piecewise-continuous functions defined on a finite number of subregions. To construct a discrete model, the region is divided into a finite number of elements that, taken

TABLE 1. Loading on a Floor

Loading	Normative loading, kgf/m^2	Calculated at $\gamma_f = 1.0\ kgf/m^2$	Coefficient γ_f	Calculated for $\gamma_f > 1\ kgf/m^2$
Constant:				
multivoid reinforced concrete slab	300	300	1.1	330
concrete-sand covering	18	18	1.3	23.4
inlaid concrete floor, $\delta = 10$ mm	60	60	1.3	78
Temporary:				
useful loading on ceiling with allowance for the coefficient ψ_{A_1}				
sustained	70	70	1.2	84
temporary	140	140	1.2	168
Total				683.4
Including sustained	448.0			515.4

TABLE 2. Loads on Covering

Loading	Normative loading, kgf/m^2	Calculated at $\gamma_f = 1\ kgf/m^2$	Coefficient γ_f	Calculated for $\gamma > 1\ kgf/m^2$
Constant:				
reinforced concrete multivoid slab	300	300	1.1	330
steam insulation (a single layer of prepared roofing paper)	5	5	1.3	6.5
heat insulation (mineral cotton mats)	15	15	1.3	19.5
expanded clay aggregate and gravel fills	90	90	1.3	117
concrete-sand covering	54	54	1.3	70.5
hydroinsulating mat	22	22	1.3	28.5
Temporary:				
snow	70	70	1.4	98
Total				662.8
Including sustained	486.0			571.8

together, approximate the shape of the region. Then, using the nodal values of the unknown quantity, a polynomial is constructed that determines the unknown quantity inside an element. The value of the continuous quantity at each nodal point is considered to be variable and must be determined.

When solving strength problems of elasticity theory by the method of finite elements, an approach is usually used that consists in minimization of the integral quantity associated with the work done by stresses and by the external loading applied. If the problem is solved in permutations, the potential energy of the system must be minimized.

We will write the potential energy of an elastic system as a sum of the energy of deformation and of the potential energy of the forces applied:

$$\Pi = \Lambda + W_{\rm p}, \tag{2.1}$$

where Λ is the energy of deformations; $W_{\rm p}$ is the potential energy of the forces applied. Taking into account that the work is opposite in sign to the potential energy of the forces after the division of the region into elements, equality (2.1) will be presented in the form of a sum:

$$\Pi = \sum_{e=1}^{E} (\Lambda^{(e)} - W^{(e)}). \tag{2.2}$$

The energy of the deformation of an infinitesimal volume dV is

$$d\Lambda = \frac{1}{2}\{\varepsilon\}^T\{\sigma\} - \frac{1}{2}\{\varepsilon_0\}^T\{\sigma\}. \tag{2.3}$$

Performing the usual procedure of finite-element discretization of the region of integration, the energy of deformation for each element can be written in traditional notation as

$$\Lambda^{(e)} = \int_{V^{(e)}} \frac{1}{2}\Big(\{U\}^T [B^{(e)}]^T [D^{(e)}] [B^{(e)}] \{U\} -$$

$$- 2\{U\}^T [B^{(e)}]^T [D^{(e)}] \{\varepsilon_0^{(e)}\} + \{\varepsilon_0^{(e)}\}^T [D^{(e)}] \{\varepsilon_0^{(e)}\}\Big)\, dV. \tag{2.4}$$

The work of the external forces on the system consists of three parts: the work of concentrated forces ($W_{\rm c}$); the work done as a result of the action of the components of stresses on the external surfaces of the region ($W_{\rm p}$); and the work of the body forces ($W_{\rm b}$). Each of these works can be determined by using the components of the permutation vector $\{U\}$ and stress tensor $\{\sigma\}$:

$$W_{\rm c}^{(e)} = \{P\}^T\{U\}, \tag{2.5}$$

$$W_b^{(e)} = \int_{V^{(e)}} \{U\}^T [N^{(e)}]^T \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} dV, \tag{2.6}$$

where x, y, and z are the body forces, which can change inside of an element. And, finally, the work of the surface forces is

$$W_{\rm p}^{(e)} = \int_{S^{(e)}} \{U\}^T \left[N^{(e)}\right]^T \begin{Bmatrix} p_{xx} \\ p_{yy} \\ p_{zz} \end{Bmatrix} dS, \tag{2.7}$$

where p_{xx}, p_{yy}, and p_{zz} are in the general case the components of the stress tensor that are parallel to the coordinate axes x, y, and z.

We will write an expression for the potential energy of the system:

$$\Pi = \sum_{e=1}^{E} \Bigg[\int_{V^{(e)}} \frac{1}{2}\{U\}^T [B^{(e)}]^T [D^{(e)}] [B^{(e)}] \{U\}\, dV -$$

$$- \int_{V^{(e)}} \{U\}^T [B^{(e)}]^T [D^{(e)}] \{\varepsilon_0^{(e)}\} dV - \int_{V^{(e)}} \{U\}^T [N^{(e)}]^T \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} dV -$$

$$- \int_{S^{(e)}} \{U\}^T [N^{(e)}]^T \begin{Bmatrix} p_{xx} \\ p_{yy} \\ p_{zz} \end{Bmatrix} dS \Bigg] - \{U\}^T \{P\}. \tag{2.8}$$

Having differentiated expression (2.8) with respect to $\{U\}$ and equated the result to zero in order to satisfy the minimization condition, we will write a system of algebraic equations for the elements that has the following form in traditional notation:

$$\frac{\partial \Pi^{(e)}}{\partial \{U\}} = [K^{(e)}] \{U\} + \{f^{(e)}\}, \tag{2.9}$$

where

$$[K^{(e)}] = \int_{V^{(e)}} [B^{(e)}]^T [D^{(e)}] [B^{(e)}] dV, \tag{2.10}$$

$$\{f^{(e)}\} = \Bigg[\int_{V^{(e)}} [B^{(e)}]^T [D^{(e)}] [\Delta T^{(e)}] dV - \int_{V^{(e)}} [N^{(e)}]^T \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} dV -$$

$$- \int_{S^{(e)}} [N^{(e)}]^T \begin{Bmatrix} p_{xx} \\ p_{yy} \\ p_{zz} \end{Bmatrix} dS \Bigg] - \{P\}. \tag{2.11}$$

The global matrices of rigidity $[K]$ and the loading vector $\{F\}$ in the matrix equation

$$[K] \{U\} = \{F\} \tag{2.12}$$

are obtained by simple summation over all the elements of expressions (2.10) and (2.11).

The relationship between the permutations and deformations in the case of elastic deformations is expressed by the Hooke law, which in general form is

$$\{\sigma\} = [D] \{\varepsilon\} - [D] \{\varepsilon_0\},$$

where $[D]$ contains the elastic constants of the element, while the vector of the initial deformation caused by thermal effect is determined in the three-dimensional case as

$$\{\varepsilon_0\} = \alpha \Delta T \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{Bmatrix}, \tag{2.13}$$

Here a is the coefficient of thermal expansion and ΔT is the deviation of the temperature from a certain equilibrium value. In the one-dimensional case or in the case of the isotropic material, the elasticity matrix $[D]$ transforms to a constant equal to the elasticity modulus $E = [D]$.

3. Analysis of the Results. The results of a finite-element calculation performed for a model symmetry cell are presented in the form of three-dimensional fields of the basic normal, σ_1, and the greatest tangential, $I_{\max}$,

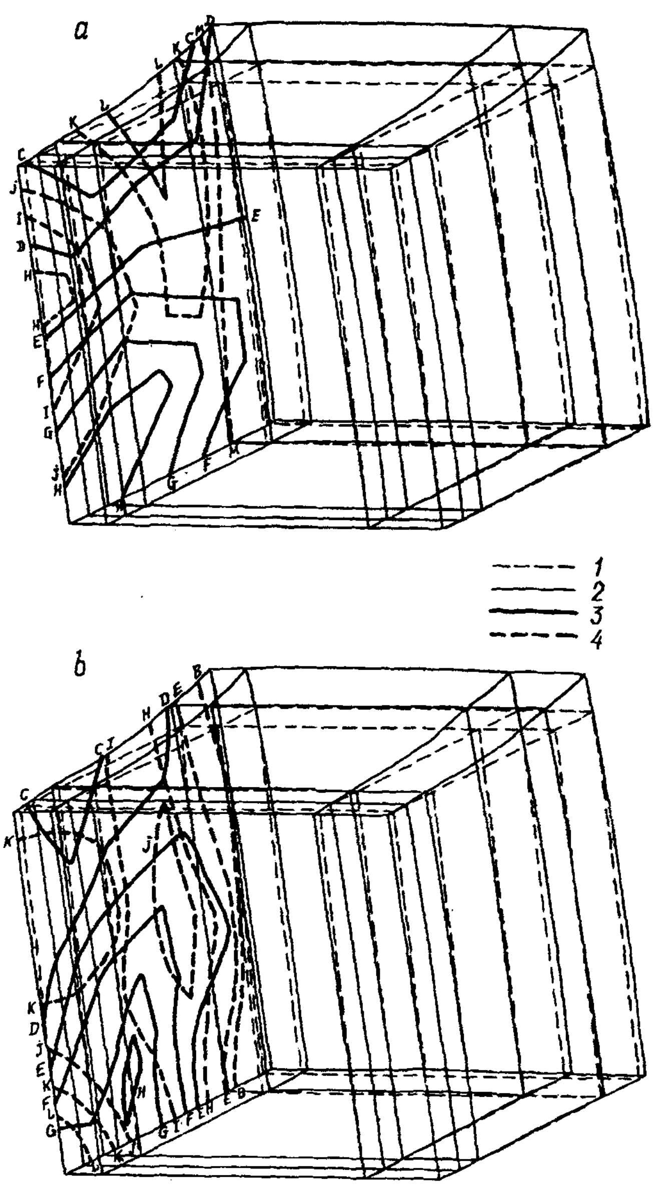

Fig. 3. Stress-strain state of block elements on exposure to fire: a) 30 min; b) 60 min (dashed line), dimensions of block before application of force and temperature loads; solid line, dimensions of block in strained state; bold line, trajectories of main stresses (σ_1); bold dashes, trajectories of maximum tangent stresses (τ_{max}).

stresses that appear under the action of force and heat loadings. Calculations were carried out for 0.5-h and 1.0-h time intervals from the beginning of the fire under standard conditions of its development [7] (Fig. 3). The orientation of the stress vectors shown in the figure is the following: the normal components σ_1 are directed perpendicularly to the lines of equal stresses, and the tangential ones τ_{max} are directed along the tangents to the isolines of total pressures, respectively. The calculations and analysis of the results showed that the thermally stressed state in the transverse edges of a block is virtually identical. Of the greatest interest is the heated edge.

According to the calculations, the considered elements of the block developed a plane-stressed state, in which the stress tensor components σ_{zx} can be neglected due to their smallness. Allowance for both components of main stresses σ_{xy} and σ_{yz} to compare with the strength criterion of concrete was made by the well-known relation: $\tau_{max} = (\sigma_{xy} + \sigma_{yz})/2$, taking account of the algebraic values of σ and τ. Normal stresses were calculated in the most dangerous zones of the block, in which maximum loads were assumed.

TABLE 3. Calculated Resistances and Stresses

Stresses, kgf/cm^2			Temperature at point, °C	Coefficients		Calculation of resistance, kgf/cm^2	
σ_{xy}	σ_{yz}	τ_{max}		γ_{bt}	$\gamma_{b.u}$	$R_{bn}/R_{b.u}$	$R_{btn}/R_{bt.u}$
			$t = 30$ min				
−59	−104	21	360	0.76	0.83	224/205	18.4/16.8
25	−11	18	20	1.0	0.83	224/270	18.4/22.2
			$t = 60$ min				
−19	−37	9	730	0.155	0.83	224/42	18.4/3.4
−20	−48	14	390	0.715	0.83	224/193	18.4/15.9
−20	−56	18	180	0.93	0.83	224/251	18.4/20.6
20	−8	14	115	0.865	0.83	224/233	18.4/19.2

The strength criterion of concrete for loadings of the "extension-compression" type, which characterizes the strain state in the transverse edges of the concrete block, was assumed in accordance with [5] to be

$$\sigma_{mt} \leq \gamma_{b_4} R_{bt.ser} ,$$

and the coefficient of the operational conditions of concrete γ_{b4} was determined from the formula

$$\gamma_{b_4} = (1 - \sigma_{mt}/R_{bt.ser})/(0.2 + 0.01C) ,$$

where C is the numerical value of the compression strength class of the concrete.

The main stresses σ_{xy} and σ_{yz}, determined using the above-described procedure were compared with calculated resistances of concrete in calculations of fire resistance. They were adopted according to the recommendations of [6] (see Table 3).

When we determined the calculated tensile strength $R_{bt.u}$, the coefficient of the operational conditions $\gamma_{b4} = 1.0$ was calculated as if at the actual level of accompanying compression stresses, and the calculated resistances P_{bn} and P_{btn} corresponded to concrete of class C30 (M400), i.e., the maximum one used in production of blocks.

Analysis of the results presented in Table 3 showed that the strength of the longitudinal edge of the block under the conditions of biaxial compression is provided in both cases, despite a considerable difference in the levels of heating of those elements. In transverse edges the limiting tensile state of the concrete is attained in both cases. Moreover, while at $t = 60$ min the excess tensile stress was 4% (the limit of the accuracy of fire-resistance calculation usually amounts to 10%), at $t = 30$ min this excess was equal to 12%.

We should note that the calculated tensile resistance of concrete in the acting norms is determined with allowance for variations in the concrete strength, $\nu = 0.135$, and represents an averaged value for catering establishments of the former USSR. Experience has shown that, provided the requirements of the Construction Specifications and Regulations are observed, the given coefficient usually does not exceed 10% in preparation of concrete. With allowance for this fact, the difference between the calculated tensile stresses and extension resistance was about 5%, which should be regarded as admissible.

CONCLUSIONS

1. A physical model of unsteady heat exchange of a three layer concrete wall made of hollow concrete blocks under the conditions of an ordinary fire is developed, which was implemented in the form of the NIKABT problem-oriented finite-element package.

2. The presented finite-element model of a wall made of hollow concrete blocks describes, within the framework of the assumptions adopted, a thermally stressed state and allows one to carry out parametric investigations of the effect of various factors: thermal and static stresses, dimensions of the construction, thermophysical and strength properties of structural materials.

3. The investigations carried out showed that a three-layer wall made of vibrocompressed concrete blocks with a supporting layer 190 mm thick without a hidden frame can have a carrying-capacity-based fire resistance equal to 1 h.

4. When using three-layer structures as supporting and self-supporting (without a hidden frame) for providing a carrying capacity-based fire resistance limit of no less than 1 h, it is necessary to introduce restrictions on volume-planning and structural-design solutions of the designs of buildings. For buildings with supporting walls it is necessary that the height of the building not exceed two storeys, with a storey being not higher than 4 m, the spacing between the supporting walls not larger than 9 m, and the useful loading on a floor not larger than 300 kg/m^2. For buildings with self-supporting walls, only the height of the building should be limited, i.e., not more than five storeys for a height of a storey of up to 4 m, inclusive.

NOTATION

Π, potential energy of system; $\{\varepsilon\}$, strain tensor; $[N]$, matrix of functions of element shape; $[B]$, matrix of gradients; $V^{(e)}$, volume of element; $\{P\}$, vector-column of nodal forces; $\{U\}$, permutation vector; $[K]$, rigidity matrix; S, surface. Subscripts and superscripts: (e), elements; T, transposed matrix; f, force.

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