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Formation of a software calculation model for restoring building structures after a fire

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Abstract. The collapse of building structures after a fire is not uncommon. Taking into account the parameters that affect the elements of the building exposed to extreme temperatures of fire and extinguishing allows assessment of the durability of the entire structure. The analysis of regulatory documents on the survey of buildings and structures after a fire allowed us to establish they lack consideration of such parameters, including the Code of Practice 329.1325800.2017 “Buildings and constructions. Examination rules after a fire”. The decision on the appropriateness of the further operation of buildings after the occurrence of both single and multiple fires is possible based on mathematical modelling of this process, and its software and algorithmic support. The technical objective of the study is to create a universal model for the software calculation of the restoration of structures after fire and fire extinguishing. The object of the study is the fire-related damage and destruction of building structures due to thermal effects. The research method consists in developing a cellular model of a thermally insulated plate based on the localization of the heat source in a certain position above the plate and characterized by the temperature distribution in the cells. The evolution of this distribution is a transition probability matrix that describes the change in thermal conductivity along with the plate in two directions and by the functions of the sources. One of the sources describes the supply of heat to a particular cell (a localized moving source), and the other describes the removal of heat due to heat emission to the environment. As a result of the study, a universal model for the formation of a software calculation for the restoration of structures after fire and fire extinguishing has been developed. The purpose of this model is to establish the residual fire resistance of a building structure after a fire with a minimum calculation time and receive recommendations on the possibility of further operation of the building.

1. Introduction

The heat-resistant properties of structural materials are always a significant component in deciding on their use in the design of various buildings and structures. The influence of temperature effects on the structure during the fire and the results of studies of the heat-resistant properties of materials of building structures have always worried designers. Indeed, without information on heat resistance and an index of fire resistance, it is impossible to make a decision on the use of this material for the design and subsequent construction of buildings and structures for various functional purposes. In addition, sudden cooling during fire extinguishing of materials or double heating of building structures during irregular or periodic fire extinguishing, both by fire departments and sprinkler and deluge fire extinguishing systems, will lead to a change in the structural characteristics and will affect its bearing capacity.

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The object of the study is damage and destruction of building structures caused by thermal effects due to fire.

There is a large amount of methodological literature on the diagnosis of damage and destruction of buildings and structures [1–5]. Various approaches and methods for assessing the technical condition of structures after a fire when modeling fire resistance are presented in the publications: A. Krivtcov, M. Gravit, S. Zimin, O. Nedryshkin, V. Pershakov (2016), J. Schmid, M. Klippel, A. Just, A. Frangi, M. Tiso. (2018), M.B. Dwaikat, V.K.R. Kodur (2009), Y.J. Kwon, D.J. Kim, S.G. Kang, B.C. Kim, B.C. Han, J.Y. Leesp, H. Kazunori. (2013), M. Cvetkovska., M. Knezevic., Q. Xu, C. Chifliganec, M. Lazarevska., A.T. Gavriloska (2018), W.Y. Gao, J.G. Dai, J.G. Teng, G.M. Chen (2013) [6–11] and others too.

The technical task of our study was to create a universal model for the software calculation of the restoration of structures after fire and fire extinguishing.

Existing requirements for water supply to the structure by fire departments in order to extinguish a fire do not regulate the direction of the stream (extinguishing point or points on the structure). Water can be supplied to any point in the structure, but at the same time its characteristics will vary unevenly from where the water is supplied.

You can divide the water supply into the structure in the following ways up, in the middle, down the structure or into the corners of the structure, both in the upper and lower. With a different choice of the cooling location of the structure heated during a fire, its fire resistance limit will change, which can significantly affect the further operational characteristics of the structure.

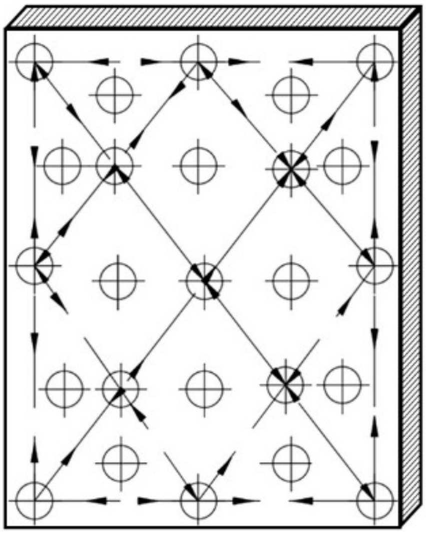

Figure 1. Possible cooling points when extinguishing a fire.

According to the nature of the same type of damage and destruction of building structures, the volume of a building (structure) exposed to fire is divided according to Code of Rules 329.1325800.2017 “Buildings and Structures. Inspection rules after a fire”, in three (in the absence of collapse) or four (in the presence of collapse of structures) the main areas of fire exposure on building structures (the tables B.1-B.5 of the appendix B) [1]:

- zone of emergency degree of fire exposure (fire exposure);
- zone of a high degree of fire exposure (fire exposure);
- a zone of moderate fire exposure (fire or heat);
- zone of low degree of fire exposure (thermal effect or smoke).

In the zone of emergency degree of fire exposure, all defective structures must be dismantled and replaced with new structures.

In areas of severe and moderate fire exposure, a visual and instrumental examination of building structures is necessary.

In the zone of low degree of fire impact, an instrumental examination of building structures after a fire is not required according to the set of rules, but at the same time, thermal radiation affected the structure and requires an assessment of its condition.

Defects and damage to building structures (cracks, deflections, deformations, discoloration of the material of the structure, the presence of metal fusion, exposure and buckling of reinforcing bars, etc. are significant signs of determining the further operation of the structure.

After the fire, to make a decision on the further operation of the structure, it is necessary to carry out verification calculations of the building structure, and the automation and simplification of such calculations by modern informatization methods by compiling the software are dictated by time.

The actual design of the building (structure) is determined by the results of the inspection after the fire and should reflect:

- the actual conditions of abutment or conjugation of adjacent structures;
- the actual geometric dimensions of the cross sections, the values of spans, eccentricities;
- the type and nature of the actual (or required) loads;
- the presence of damage and structural defects.

The actual duration of intense burning of materials and structures in the fire is set without taking into account the duration of its initial stage of ignition and the final stage of attenuation. The initial stage of ignition can be 5-40 minutes and is characterized by the ignition of materials with a slight increase in the temperature of the environment in the room (150 °C–200 °C). The stage of intense combustion is characterized by a rapid increase in temperature (up to 1200 °C–1500 °C, sometimes up to 2000 °C), stabilization of maximum fire temperatures and subsequent sharp decrease in temperature to 600 °C–400 °C.

According to indirect signs remaining after the fire, it is possible to establish the values of temperatures that were in effect during the fire, namely:

- by changing the appearance and shape of individual objects and materials remaining after the fire;
- to change the structure and condition of heavy concrete;
- by changing the color of concrete;
- by the fusion temperature of various metals;
- color discolouration (color of oxides on the surface) of steel;
- on the color change of polymer coatings and paints;
- the presence of soot and soot, the condition of paper and wood;
- on a change in the state of metal structures;
- by changing the state of masonry;
- by changing the state of gypsum plaster;
- by changing the state of cement-sand plaster.

However, at the same time, the formation of cracks and changes in the properties inside the structures, which cannot be visualized without the use of special equipment and sampling for laboratory studies, are possible.

The relevance of the study lies in the adoption of very quick decisions on the further operation of the building and structure after the fire, since people who live in buildings may live on a permanent basis and may not be able to live in another place until the end of a long study of structures for their bearing capacity after fire and fire extinguishing.

When structures are heated during a fire and during the process of extinguishing, various processes occur, these processes have restrictions on the speed and uniformity of heating, in most fires the size of the heat source is less than the heated surfaces of the structures.

In a fire, heat sources cannot be fixed local, they are constantly increasing, and thermal energy is moving along the surfaces of structures. It is also impossible to exclude delays of sources in different zones due to the presence of a greater fire load in these areas, while the areas that were previously heated and the combustion process in these areas stopped, have time to cool significantly.

The conditions for such heating depend on the materials of the structures, heat transfer from the heat source to the product, from heat transfer from the product to the environment, and from the thermophysical properties of the material from which the product is made.

Under the conditions of the diversity of these parameters and their combinations, the empirical search for the optimal paths and velocities of the source along the heated product is a laborious and lengthy task. The choice of rational warm-up conditions can be greatly simplified and facilitated using mathematical models of this process and its software and algorithmic support, especially since the current level of development of building thermo-physics already contains mathematical descriptions of the individual components of this process, allowing their sufficiently reliable forecasting for timely identification of the need restoration of structures damaged by fire and the possibility of their further safe operation.

The purpose model is to establish the residual fire resistance of a building after a fire (with rapid cooling) to minimize the time to obtain accurate results on the further operation of buildings. The tasks are:

– selection of a management solution for extinguishing, to maintain the bearing capacity of the building structure;
– reduction of damage during fire extinguishing;
– establishing the possibility of further operation of buildings exposed to fire;
– development of a universal model for the formation of a software calculation for the restoration of structures after fire and fire extinguishing.

2. Methods

As a theoretical basis for constructing mathematical models of heat transfer processes, the Markov chain theory method was chosen [12, 13], which has proven itself in solving a number of practical engineering problems [14].

We give an example of modeling a process with constructing a cellular model of a thermally insulated plate, a diagram of which is shown in Fig. 2. Let the heat source be localized in a certain position above the plate. The thermal state of the plate is characterized by the temperature distribution over the cells, and the evolution of this distribution is characterized by a transition probability matrix describing the thermal conductivity of the plate in two directions and by the functions of the sources, one of which describes the heat supply to a particular cell (localized moving source), and the other heat removal due to heat transfer to the environment.

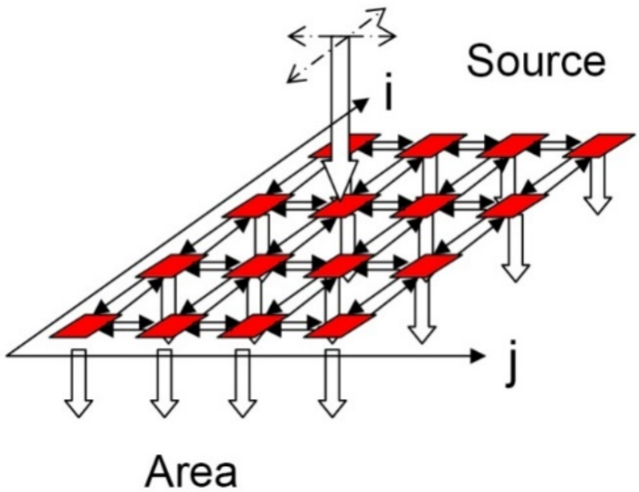

Figure 2. The cell model of the plate and the heat flow diagram in it.

In particular, the transition matrix (thermal conductivity matrix) for a grid of 4×4 cells in the most common case of modeling with square cells has the form

$$P=\begin{bmatrix} 1-2d & d & 0 & d & 0 & 0 & 0 & 0 & 0 \\ d & 1-3d & d & 0 & d & 0 & 0 & 0 & 0 \\ 0 & d & 1-2d & 0 & 0 & d & 0 & 0 & 0 \\ d & 0 & 0 & 1-3d & d & 0 & d & 0 & 0 \\ 0 & d & 0 & d & 1-4d & d & 0 & d & 0 \\ 0 & 0 & d & 0 & d & 1-3d & 0 & 0 & d \\ 0 & 0 & 0 & d & 0 & 0 & 1-2d & d & 0 \\ 0 & 0 & 0 & 0 & d & 0 & d & 1-3d & d \\ 0 & 0 & 0 & 0 & 0 & d & 0 & d & 1-d \end{bmatrix}, \quad (1)$$

where

$$d = \alpha \frac{\Delta t}{\Delta x^2}, \tag{2}$$

α is coefficient of heat diffusivity of material; Δx is side length of a square cell.

Since no more than four transitions are possible from this cell, the smallest probability of staying is 1 – 4d, which implies the stability condition of the computational procedure $d \leq 1/4$, since, in accordance with the physical meaning, the probabilities cannot be negative.

Thus, temperature redistribution over a fully thermally insulated plate can be described by recurrence matrix equality

$$T^{k+1} = PT^{k}, \tag{3}$$

where initial distribution of temperature of T^0 has to be set.

As the sum of elements of matrix P (1) is equal in every line to unit (normalization in the lines), asymptotic distribution of temperature at $k \to \infty$ will be uniform that corresponds to physical essence of process.

With a moving source, the cell number to which heat is supplied changes, that is, i = i (k) and j = j (k). In the heating procedure for the same type of recording operations, it is advisable to introduce the temperature matrix of the sources T_s (k) is a matrix where all elements are zeros, except for element ij, where i = i (k) and j = j (k), and which is equal to T_s. Then the transfer of heat to the cell ij at the kth transition can also be described by the matrix equality

$$T^{/} = T + a_2 \left(T_s(k) - T \right), \tag{4}$$

in which the program and the speed (delay in the cell) of the source movement are given by the equalities i = i (k) and j = j (k).

Thus, equality (4), which describes the heat transfer to the plate cell, together with equality (3), which describes the propagation of heat through the plate through heat conduction, completely describes the heating of a heat-insulated plate both stationary (i, j = const) and mobile (i = i (k) and j = j (k)) by a local heat source.

Heating a fully insulated plate leads to an asymptotically uniform temperature distribution, and this temperature is equal to the temperature of the source. However, the uniformity of distribution in the transitional stages of heating for a stationary and moving source is significantly different. In Fig. 3 the source motion program is defined by the radius vector rs (k) with projections is (k) and js (k), the law of change of which is the motion program

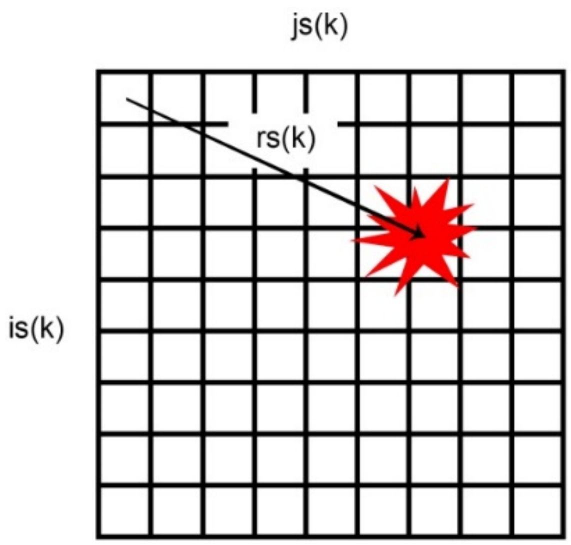

Figure 3. To the program of the movement of source.

In Fig. 4 shows the influence of the program of movement along the contour: first along its two points, then along four, and then along the same contour with an increasingly dense coating of its points.

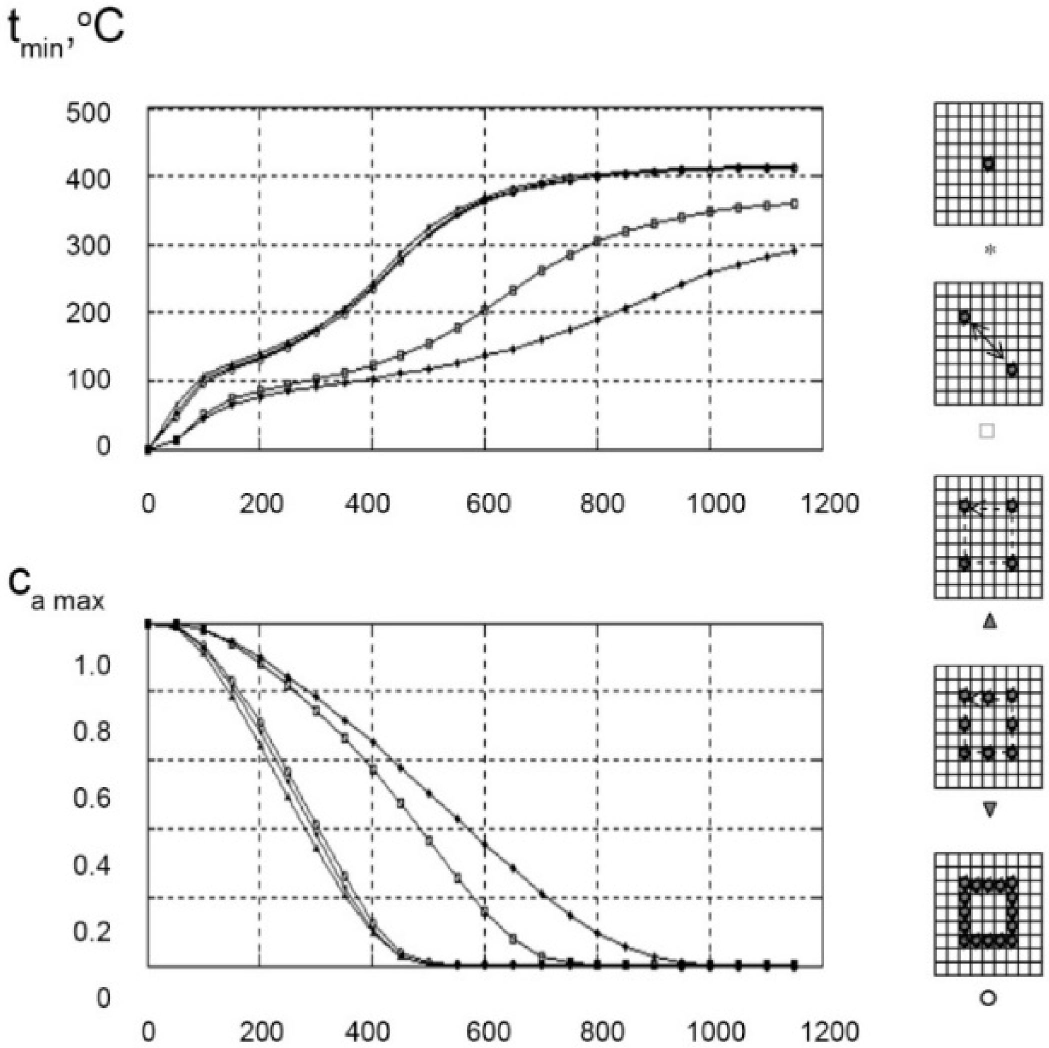

Figure 4. Change in minimum plate temperature and maximum concentration with various source movement programs.

3. Results and Discussion

If the above simulation of the process of constructing a cellular model of a thermally insulated plate is shifted to a real fire, then will see that in the initial stage any fire is characterized by a focal zone (temperature effect at one point in the room). In the initial stage, a local temperature effect occurs on the structure, with increasing temperature, the fire area increases and, accordingly, the source moves along the surface of the structure according to various movement programs, while the areas where the combustible load is contained in a smaller amount cool down. Because of which there is an uneven heating of the structure and its more rapid destruction. In this case, heat transfer to the external environment takes place not without taking into account the possibility of the origin of fires in different climatic zones and at different environmental temperatures, which affect the uneven change in the characteristics of structures. This circumstance necessitates the development of a universal fire extinguishing model, which will lead to the least destruction of the structure in different environmental conditions. In view of the foregoing, we described in Fig. 5 universal model for the formation of a software calculation of the restoration of structures after fire and fire extinguishing.

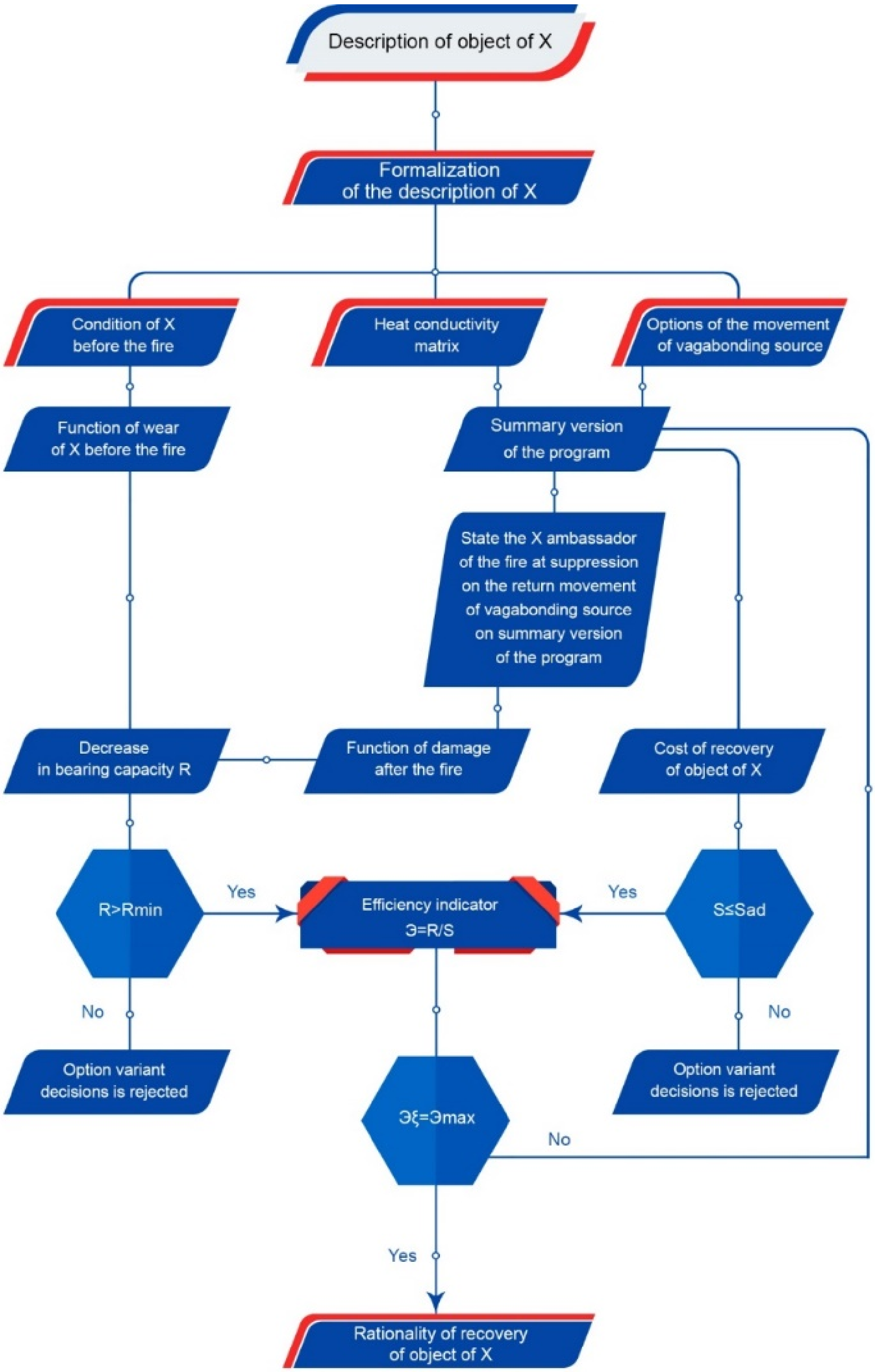

Figure 5. Universal model for the formation of software calculation of restoration of structures after fire and fire extinguishing.

The description of the model is as follows: the description of the object X are includes subsystems (x1...x15) of structures subjected to thermal action. The state of the subsystem is characterized by an indicator of possible structural failure, which (the remainder R is bearing capacity) can be caused as a result of a fire.

The content of the structures is characterized, firstly, by the list of objects on which the fire occurred. Secondly, the type of destruction, which is reflected by the thermal conductivity matrix. The totality of the proposed movement of the stray source forms a variant of accepting the proposed model of motion of the stray source, with the worst result of the remainder (R) adopted for this design. The elements of the object X are the amount of expenditure of various resources for the most complete restoration of bearing capacity.

The difference between the proposed model and other models of program calculation, for example, W.Y. Gao, J.G. Dai, J.G. Teng, G.M. Chen, consists in assessing the recovery after sudden cooling of the structure during fire extinguishing by fire departments using a heat conduction matrix [11].

Here is one of the possible algorithms for the program to work according to the model have described.

B1 – wall with probability r1 remained intact as a result of fire. B2 – the wall after the fire does not meet the required fire resistance limit, but it can be fixed. We apply the probability r2 to this event. B3 – the wall with probability r3 after the fire is hopelessly damaged and cannot be restored. C1 – after the fire, the house with probability ρ1 remained suitable for further operation. C2 – As a result of the fire, the house with probability ρ 2 became unsuitable for further operation. Obviously, the first three and the last two events form complete groups: $r1 + r2 + r3 = 1$, $\rho 1 + \rho 2 = 1$.

For the sake of simplicity, the main event options are listed here. In real conditions, there may, of course, be more complex situations, however, they can easily be reduced to the cases listed above.

As a result of the onset of these events, the "house-wall" system is in one of the following six states (Fig. 6).

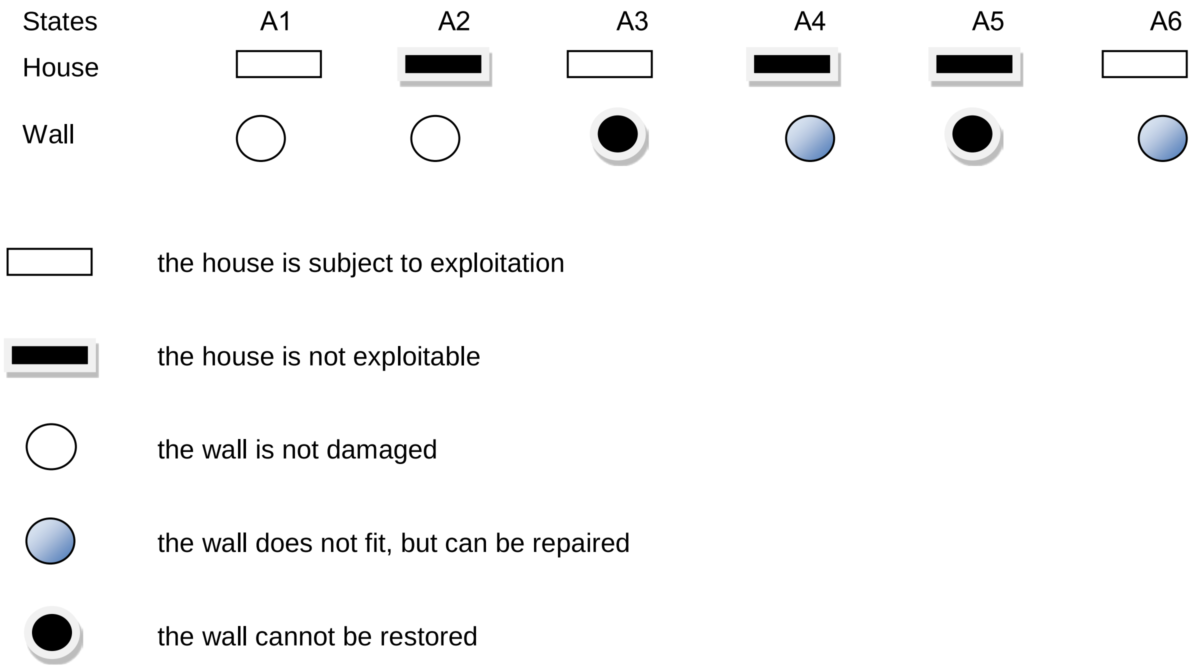

Figure 6. System event status.

According to the classification adopted above, the states A1 and A2 will be absorbing, as in either case, in the indicated state, the goal is achieved. True, the possibility of getting into the A2 state, i.e. receiving an undamaged wall with an unused house. The house may be emergency, its maximum wear has occurred as a whole, and a separately taken wall has not yet reached its maximum wear and tear and a fire has occurred in the house.

One more remark should be made. In this model, the states with an intact and damaged wall, but which can be restored, are considered the same, although this is not entirely true.

Obviously, state A6 should appear as the initial state in this example.

The transition probabilities are determined very simply here.

Since the states A1 and A2 are absorbing, then P11 = 1 and P22 = 1, and the probabilities of transition from the first and second to all subsequent states are equal to zero. If you get into the A3-A5 states, it will be necessary to repeat the operation (with the replacement of the wall, repair of the house, or with the replacement and repair at the same time), i.e., they will return to the initial state A6. Therefore, the corresponding transition probabilities P36, P46, P56 will be equal to 1.

Since the events B1-B3 and C1-C2 are compatible, the probabilities of transition from the initial state to all subsequent states are determined as the product of the probabilities of the corresponding events. The easiest way to find these works is using the event tree shown in Fig. 7.

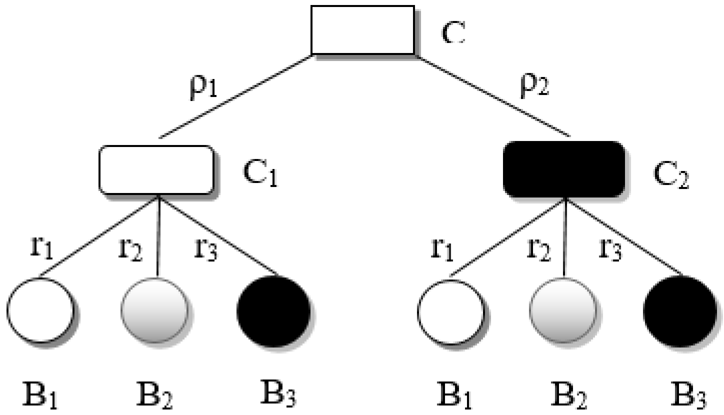

Figure 7. Transient probabilities event tree.

For example, from the initial state A6 to the absorbing A1, we will pass with the simultaneous occurrence of events B1 and C1. Consequently, the total probability of a common event will be equal to the product of private events:

P61 = r1 ρ1

Arguing similarly, we obtained

P62 = r1 ρ2; P63 = r3 ρ1; P64 = r2 ρ2; P65 = r3 ρ2; P66 = r2 ρ1.

If we assume that in each trial (operation) the transition probabilities do not change, then the process can be described by a simple homogeneous Markov chain. The graph that visually displays possible transitions in the system is shown in (Fig. 8).

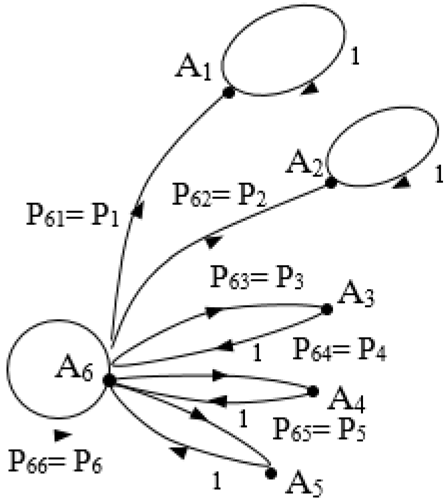

Figure 8. Possible transitions in the system.

The transition probabilities are designated hereinafter for the multiplicity P1, P2, P3, P4, P5, P6. Now the transition matrix can be represented, as before, in canonical and fundamental forms. But first of all, it would be necessary to answer the question: what can be obtained in practice?

First, let us pay attention to the fact that getting into any state is accompanied by certain expenditures of material resources and time.

For example, getting into the A3-A5 state entails costs associated with repairing a house or building a new house, etc.

If the wall is damaged, when its fire resistance limit is reduced, you also have to pay for its partial restoration. In short, along with the transition matrix, a cost (or damage) matrix must be compiled. It will have the same form as the transition matrix, but its elements are costs, P61 = r1 ρ1 corresponding to transitions in a certain state (Fig. 8). In the conditions associated with the restoration of the wall, one must take into account the loss of time, etc. and in cases of failure or impossible restoration of the wall – the cost of buying the whole house.

Timely restoration of the wall after a fire will reduce the likelihood of scrap collapse and the time that the house will not be used, which will extend the life of the house.

We will assume that during the period of time we are observing, the house can be in three states:

A1 – normal operation;

A2 – collapse repair;

A3 – repairs after each fire.

We will serve the house according to the following scheme. Let's assume that at time t0 the operation of an absolutely serviceable wall begins. If the wall plaster does not collapse during the planned period of time T, at t = T it is replaced with a new one (re-plastered) (preventive replacement).

If the operation continues without plastering, a fire still occurs, it destroys the wall itself, while the house is evicted and emergency repairs are carried out. For any type of repair, the destroyed element is replaced with a new one of equal quality. Of course, full equality will not be achieved. There are always some differences that lead to variances in uptime.

As a result, the time of trouble-free operation will be a random value, obeying some law of probability distribution F (t).

The intervals of time during which one or another type of repair occurs – emergency ta and preventive tpr, i.e. random process. Let us depict one of its implementations graphically (Fig. 9).

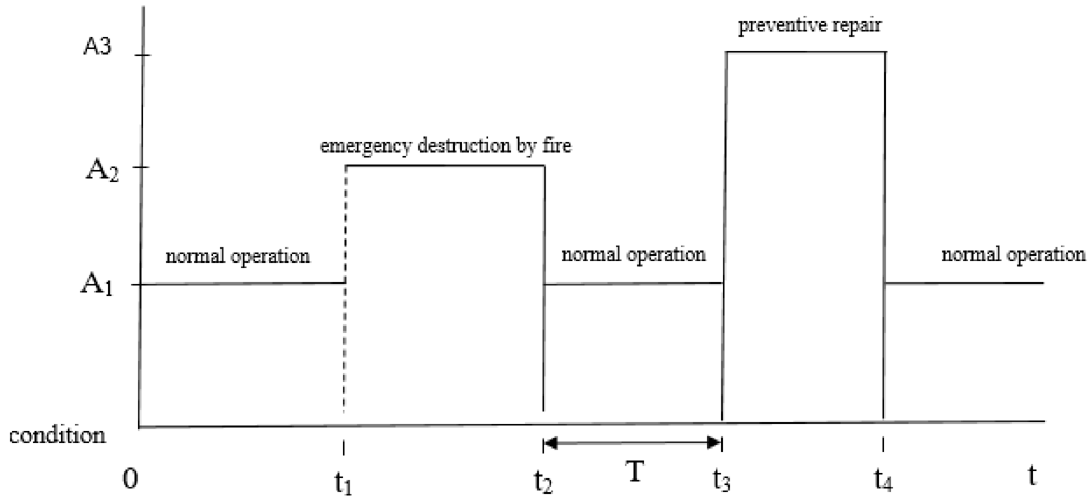

Figure 9. State graph over time intervals.

Here, the segment 0 – t_1 corresponds to the state of normal operation. At the moment t1, the wall collapses, and the system jumps into state A2 – emergency repair. In the interval t_1 – t_2, the element (wall) is restored, and from the moment t_2 it is normally operated again. Further, the section (t_2 – t_3) = T ends favorably. The wall is in operation, a fire occurs, the plaster is destroyed, and at time t_3, preventive maintenance begins, which lasts until time t_4. Then again in normal operation, etc. Consider now the likely picture of the process. Since the residence times in the states A1-A3 are random and not necessarily subject to the exponential law. An exception is the transition from state A1 to state A3, which always occurs after a certain time equal to T. Such processes were previously called semi-Markov processes, the transition matrix in this case will have the form:

$$P_{[3]} = \begin{bmatrix} 0 & 1-F(t) & F(t) \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}. \quad (5)$$

There are zeros on the diagonal of the matrix. This means that transitions within the same states are impossible. The units in the first column follow from our adopted preventive maintenance scheme. It is believed that after this or that type of repair, normal operation of the premises will begin. To assess the correctness of our actions, a matrix of expenses is compiled. Here the main task is to minimize the cost of operation, then the matrix elements will be the losses associated with the stay of the wall in a particular state. For example, during the transition from state A1 to A2 – emergency repair – the losses are equal C_{ac}

If we update the plaster prophylactically, then the costs will be less indicated C_{pr}($C_{pr} < C_{ac}$). We write them in the form of a matrix:

$$U_{ij} = \begin{cases} C_{ac},\ if\ \ a\ A_1 \to A_2 \\ C_{pr},\ if\ \ a\ A_1 \to A_3 \\ 0,\ in\ all\ other\ cases \end{cases}. \quad (6)$$

If the goal is to assess the effectiveness of preventive repairs after a fire. Then you need to take into account the income from the normal operation of the house. It can be written like this

$$U_{ij} = \begin{cases} C_{ac},\ if\ a\ A_1 \to A_2 \\ C_{n.e},\ if\ a\ A_1 \to A_3 \\ C_{n.e,t},\ if\ a\ A_1 \end{cases}. \quad (7)$$

4. Conclusions

1. Monitoring existing approaches to analyzing the problem of restoring building materials, products and structures after a fire confirms the importance of this problem. This, in turn, allows us to state that the existing engineering methodologies for forecasting, mathematical and software allow the researcher and designer to determine rational directions for searching for new promising and original ways to restore construction objects.

2. A management decision has been found that, when applied, will cause the least damage when extinguishing a fire in accordance with the selected conditions, and determine the remaining strength of the structure, as well as the possibility or impossibility of its further restoration, taking into account previous fires, climatic zone and operating time designs.

3. Given the complexity of establishing the further operation of buildings after a fire and the direct impact on the bearing capacity, reducing the fire resistance when cooling structures as a result of extinguishing a fire. A universal model has been developed for the formation of a software calculation for the restoration of structures after fire and fire extinguishing, to establish the residual fire resistance of a building structure after a fire in order to minimize time, which will lead to accurate results on the further operation of the building (s).

4. An option is proposed for taking into account the sharp cooling of the structure during the formation of the program calculation of decision making on the long-term operation of buildings and structures exposed to fire.

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