Empirical studies of structural material with given parameters at various fire factors

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Abstract. The results are given of numerical experiments on heating of steel structures of buildings roofing by solving a heat engineering problem in conditions of non-stationary heat influence at standard temperature mode according to GOST 30247.0 and at fire temperature mode. The estimation of equivalent duration of fire for steel roofing structures is made. For modeling of heating of steel structures the computational system allowing to carry out thermal engineering calculation of a structure on the basis of its program model was used. For estimation of fire temperature modes the software package "Fire Dynamics Simulator" (FDS) was used, which implements the field mathematical model.

1. Introduction
Evaluation of fire resistance of steel structures of the building roofing was carried out by solving the heat engineering problem for heating in conditions of non-stationary heat influence at the standard temperature regime and in conditions of fire temperature regime. For modeling the process of steel structures heating the finite-difference method of solving the Fourier heat conductivity equation at external and internal nonlinearity was used, which was implemented in the software package "ANSYS mechanical". For modeling of fire temperature modes the software package "Fire Dynamics Simulator" (FDS) was used, which implements the field mathematical model.

A building with dimensions of 12 x 12 x 6.5 m was chosen as an object of research. Steel structures were used as bearing elements of the building. The bearing structures of the roofing are beams made of solid rolled I-T sections according to STO ASCHM 20-93 (standard of iron industry association). Farms are made of bent-welded profiles in accordance with GOST 30245-2003, horizontal links - of bent-welded profiles in accordance with GOST 30245-2003. The plating is a continuous flat roof on metal beams and roofing trusses. The building has 2 gates of 4 x 4 m and the entrance door of 1 x 2 m. In the walls of the building there are 32 windows measuring 0.7 x 1 m.

As a fire load according to reference data [1,2] were accepted: industrial goods (textile products); rubber products (rubber and its products); flax fiber storage; plexiglass storage; ethyl alcohol; cables + wires (0.75 (vinyl-insulated flexible aluminum power cable in vinyl sheathing, polyethylene-insulated aluminum power cable in polyvinylchloride sheathing, thermoplastic volcanizite) + 0.25 (rubber-insulated wire in rubber sheathing, rubber-insulated wire)); loosened cotton; paper in rolls; packaging (wood + cardboard + polystyrene); radio materials; industrial oil; cotton in bales.
2. Experimental part
In the software package "FDS" the object, simulating the fire load, was the ventilation opening. To assess the temperature on the surface of steel structures of the upper belt of trusses sensors (thermocouples) were placed with a pitch of 1 m, also the average volume temperature at an altitude of 4.7-6.5 m was measured. During the calculations, the gates of the building were open, the windows were closed.

The results of numerical simulation of the fire temperature regime based on reference data [1,2] are presented in Figure. 1.

![Figure 1. Standard temperature and average volume temperature at an altitude of 4.7-6.5 m.](image)

The received temperature modes for cables + wires, industrial oil, ethyl alcohol fire loads show that the standard temperature mode has lower maximum temperature values. For the rest of the fire loads, given above, the values of maximum temperatures, obtained by numerical experiment, are lower than in the standard temperature regime.

For an estimation of equivalent fire duration the heat engineering calculations have been carried out for steel structures of a roofing (figure 2) of a building when exposed to the temperature regime of standard curve and at exposure to the temperature regime of a fire

![Figure 2. Roofing truss.](image)

Structural elements of a metal truss:
1. rectangular cross-section; construction dimensions: \(a = 160\ mm, b = 160\ mm, h = 5\ mm\); cross-section area \(S = 3100\ mm^2\); perimeter of heated surface \(p = 640\ mm\), effective metal thickness \(d = 4.84\ mm\);

2. rectangular cross-section; construction dimensions: \(a = 140\ mm, b = 140\ mm, h = 5\ mm\); cross-section area \(S = 2700\ mm^2\); perimeter of heated surface \(p = 560\ mm\), effective metal thickness \(d = 4.82\ mm\);

3. rectangular cross-section; dimensions of construction: \(a = 100\ mm, b = 100\ mm, h = 5\ mm\); cross-section area \(S = 1900\ mm^2\); perimeter of heated surface \(p = 400\ mm\), effective metal thickness \(d = 4.75\ mm\).

Heat engineering calculation was performed under condition of temperature change of heating medium in time along the "standard fire" curve, according to GOST 30247.0-94 [3,4]. The equation of the standard fire curve has the form:

\[
t_{B,\tau} = 345 \cdot \lg(0,133 \cdot \tau + 1) + t_h,
\]

where:
- \(t_{B,\tau}\) – temperature of heating medium, °K;
- \(\tau\) – time in seconds;
- \(t_h\) – initial temperature of heating medium, °K.

Coefficient of heat transfer \(\alpha, \text{W/(m}^2\text{deg)}\), from heating medium with temperature \(t_{B,\tau}\) to surface with temperature \(t_\theta\) is calculated by formula (2):

\[
\alpha = \alpha_c + 29 + 5.77 \cdot S_r \cdot \frac{(T_B)^{100} - (T_\theta)^{100}}{T_B - T_\theta}.
\]

where:
- \(\alpha_c\) – convective component;
- \(\alpha_r\) – radiant component;
- \(S_r\) – reduced power of blackness: "heating medium - structure surface".

In formula (2) the reduced power of blackness is

\[
S_r = \frac{1}{3^s s_0^{-1}}
\]

where:
- \(s\) – power of blackness of the furnace fire chamber. \(s = 0.85\);
- \(s_0\) – power of blackness of the heated surface of the structure. \(s_0 = 0.74\) – for unprotected steel structures.

Calculation of the temperature of a metal rod of a structure is performed according to the algorithm, which represents a number of formulae obtained on the basis of solving the boundary problem of heat conductivity of elementary balance methods (finite-difference method of solving the Fourier heat conductivity equation at external and internal non-linearity).

The temperature of steel structures using the above formulae was calculated sequentially in calculated time intervals \(\Delta\tau\) up to a given critical value. Initial temperature at all points of the structure cross-section before the fire and ambient temperature outside the fire zone were taken equal to 20°C (\(t_m = 293\ °K\)).

The value of the calculated time interval \(\Delta\tau\) (program pitch) was chosen so that it would fit an integer number of times in the interval of the machine record of calculation results; the selected value \(\Delta\tau\) would not exceed the value calculated by formula (4).

The maximum calculated time interval \(\Delta\tau_{\text{max}}\) is calculated using the formula:

\[
\Delta\tau_{\text{max}} = \frac{\gamma_{\text{sw}} \delta_{\text{ef}} (C + D_{\text{cm}} e_{\text{cm}})}{\alpha},
\]

where:
- \(\gamma_{\text{sw}}\) – metal specific weight, kg/m³;
\[ \delta_{ef} = \frac{\rho}{\delta} \]

Where:
- \( \delta_{cm,\Delta t} \) – rod temperature in the calculated time interval \( \Delta t \), 0K,
- \( t_{cm} \) – rod temperature at a given time \( \tau \), 0K,
- \( t_{w,\tau} \) – temperature of heating medium at a given time \( \tau \), 0K,
- \( \alpha \) – heat transfer coefficient from the heating medium to the structure surface, W/(m2deg);
- \( C_{cm} \) – initial coefficient of heat capacity of metal, J/(kg deg);
- \( D_{cm} \) – coefficient of change of heat capacity of metal at heating, J/(kg deg2);
- \( \gamma \) – specific weight of metal, J/(kg/m3);
- \( \delta_{ef} \) – effective thickness of metal, m.

For thermal engineering calculation in the "ANSYS mechanical" software package models of farm elements were built.

The results of the calculations are given in Table 1 and on Figures 4, 5, 6.

Table 1. Thermal engineering calculation results.

| Structure Type | Temperature, °C | Heating time of the structure, min. |
|----------------|-----------------|-------------------------------------|
|                | 1°              | 2°                                  | 3°       | 4°       | 5°       | 6°       | 7°       | 8°       | 9°       | 10°      | 11°      | 12°      | 13°      |
| 160x160x 5    | 400             | 6.6                                 | 13.6     | 7.2      | 4.6      | 1.7      | 8.2      | 5.0      | 11.1     | 7.4      | 2.3      | 3.1      | 24.9     |
| 140x140x 5    | 450             | 7.4                                 | 14.3     | 7.7      | 5.2      | 1.9      | 8.6      | 5.6      | 11.7     | 8.1      | 2.6      | 6.8      | 25.6     |
| 100x100x 5    | 500             | 8.4                                 | 15.0     | 8.2      | 6.0      | 2.2      | 9.0      | 6.2      | 12.4     | 8.9      | 2.9      | 9.9      | 27.9     |
The results of numerical experiments show that the heating time for building roofing truss structures up to 400-700°C for the considered fire loads vary significantly and in some cases are less than in the standard temperature regime. Figure 6 shows the dependence of equivalent duration of fire on fire load.

Figure 6 demonstrates that the values of equivalent duration of fire for such fire loadings as flax fiber storage, ethyl alcohol, loosened cotton, industrial oil, rubber goods are higher than the duration of fire, which indicates underestimation of thermal influence of "real" fires on steel structures of warehouse roofing under the influence of standard temperature regime.
**Figure 3.** Heating curves of a rectangular 160 x 160 x 5 mm pipe under various temperature conditions.

**Figure 4.** Heating curves of a rectangular 140 x 140 x 5 mm pipe under various temperature conditions.
Figure 5. Heating curves of a rectangular 100 x 100 x 5 mm pipe under various temperature conditions.

Figure 6. Dependence of equivalent fire duration on the type of fire load.

3. Conclusions
The results of the above numerical experiments show that assessment of the fire resistance limit of steel structures of the building roofing by the standard temperature regime of fire tests without taking into account the nature of the fire load can lead to underestimation of the actual limit of fire resistance,
which adversely affects the safety of the entire building. This is especially true for roofing structures, which have requirements for fire resistance of 15 minutes and can be used without fire protection when its own fire resistance limit is more than 8 minutes.

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References
[1] Yu. A. Koshmarov. Prediction of hazardous factors in the room fire: A manual. - Moscow: Academy of State Fire Service of the Ministry of Internal Affairs of Russia, 2000. 118 c. ISBN -59229-0011-0;
[2] A.A. Abashkin, A.V. Karpov, D.V. Ushakov, M.V. Fomin, A.N. Giletich, P.M. Komkov. Manual on Application of "Methods of Determining Calculated Values of Fire Risk in Buildings, Structures and Constructions of Various Classes of Functional Fire Hazard" - M.: VNIIPo, 2014;
[3] A.I. Yakovlev Calculation of Fire Resistance of Building Structures. - M. Stroyizdat, 1988. - 143 p. - BN 5-274-00178-5;
[4] Roitman V.M. Engineering Solutions for Assessment of Fire Resistance of Projected and Renovated Buildings. Fire Safety and Science Association, 2001 - 382 p.
[5] Federal Law No.123-FZ dated July 22, 2008 "Technical Regulations on Fire Safety Requirements" (ed. 13.07.2015).
[6] GOST 30247.0-94 "Structures construction. Methods of fire resistance tests. General requirements".
[7] SP 2.13130.2012 Fire protection systems. Providing fire resistance of protection objects.
[8] Peacock R. D., Reneke P. A., Jones W. W., Bukowski R. W. And Forney G. P., 2000, "User's Guide for Fast: Engineering Tools for Stimating Fire Growth and Smoke Transport", NIST-SP 921
[9] Portier R. W., Reneke P. A., Jones W. W and Peacock R. D, 1992, "User's Guide for Cfast Version 1.6", NISTIR-4985
[10] Peacock R. D., Reneke P. A., Jones W. W. and Forney G. P, 2000, "Tecnical References for Cfast: An Engineering Tool for Stimating Fire Growth and Smoke Transport", NIST-1431
[11] Peacock R. D., Jones W. W. and Bukowski R. W., 1993, "Verification of a model of fire and smoke transport", Fire Safety Jaournal Vol. 21
[12] Deal S., 1990, "A review of four compartment fires with four compartment fire models", Fire Safety Developments and Safety, Proceedings of the annual meeting of Fire Retardant Chemicals Association
[13] Duong D. Q., 1990, "The accuracy of Computer Fire models: some comparison with experimental data from Australia", Fire safety Journal Vol. 16
[14] Davis W. D., Notarianni K. A., and McGrattan K.B., 1996, "Comparison of fire model predictions with experiments conducted in a hangar with a 15 m ceiling", NISTIR-5927
[15] Cadorin J. F., Franssen J. M., and Pintea D., 2001, "The design Fire Tool Ozone V2.0 – Theoretical Description and Validation On experimental Fire tests", Rapport interne SPEC/2001_01 University of Liege
[16] Sleich J. B., Cajot L. G., Pierre M., Joyeux D., Au tenetxe G., Unanu Ja., Pastorino S., Heise F. J., Salomon R., Twilt L. and Van Oerle J., 2002. "Competitive steel buildings through natural fire safety concepts" Final Report EUR 20360 EN
[17] Cadorin J. F., 2002, " On the application field of Ozone V2", Rapport interne N°
M&S/2002-003 University of Liege

[18] Cadorin J. F., 2003, "Compartment fire models for structural engineering", Doctoral Thesis of J.F. Cadorin, University of Liege

[19] Sleich J. B., Cajot L. G., Pierre M., Joyceux D., Moore D., Lennon T., Kruppa J., Hüller V., Hosser D., Dobbernack R., Kirchner U., Eger U., Twilt L., Van Oerle J., Kokkala M. And Hostikka S., 2002, "Natural Fire Safety Concepts – Full Scale Tests, Implementation in the Eurocodes and Development of an user friendly design tool" Final Report EUR 20580 EN

[20] McGrattan K. B., Forney G. P., Floyd J. E., Hostikka S. And Prasad K., 2002, "Fire Dynamics Simulator (Version 3) – User’s Guide", NISTIR-6784

[21] Forney G. P. and McGrattan K. B., 2003, "User’s Guide for Smokeview Version 3.1 – A Tool for Visualizing Fire Dynamics Simulation Data", NISTIR-6980

[22] McGrattan K. B., Baum H. R., Hamins A., Forney G. P., Floyd J. E., Hostikka S. And Prasad K., 2002, "Fire Dynamics Simulator (Version 3) – Technical Reference Guide", NISTIR-6783

[23] Hurley M. J. and Madrzykowsky D., 2002, "Evaluation of the computer fire model DETECT-QS", Performance-Based Codes and Fire Safety Design Methods, 4th International Conference.Proceedings

[24] Davis W. D., 1999, "The Zone Fire model JET: A Model for the prediction of detector activation and gas temperature in presence of a smoke layer", NISTIR-6324

[25] F. Morente; J. de la Quintana; F. Wald. Software for Fire Design