Assessment Methods for Fire Durability of Intumescent Fire Protection Coatings

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Abstract. Fire durability of intumescent coatings is their ability to retain their fire-protective properties under fire conditions (under the influence of real temperature conditions of fire). The peculiarities of application of intumescent fire-protective coatings in single-storey buildings on the steel frame with account of fire load are considered. In this study, the fire hazard assessment of single-storey buildings on a steel frame with the use of sandwich panels as enclosing structures is made. The analysis of fire load values has been made. Numerical experiments on estimation of the indoor fire temperature regime have been carried out. For estimation of influence of temperature modes of fire on fire resistance of steel structures the software complex "Fire Dynamics Simulator" was used, which implements the field mathematical model. Various fire temperature modes (temperature-time dependencies) were obtained. Modelling of fire temperature modes was performed without taking into account active fire protection systems. The most critical and unfavourable by their consequences fire scenarios, used later for solving the heat engineering problem, have been chosen by experts. Numerical experiments on heating of steel structures were carried out by solving the heat engineering problem in conditions of non-stationary heat influence at standard temperature conditions according to ISO 834 and at fire temperature conditions obtained by modelling results. The estimation of equivalent fire duration on loss of bearing capacity for steel structures is made. ANSYS mechanical" computing complex was used for modelling the heating of steel structures, which allows us to perform heat engineering calculation of the structure on the basis of its software model.

1. Introduction

In Russia, the history of construction development includes a large number of examples of erecting buildings from steel structures for industrial, agricultural and public purposes. The total number of typical projects of buildings with steel structures now reaches several hundreds, and typologically they are divided in quantitative terms as follows [1]: industrial – 78%; agro-industrial – 5.2% and public – 16.8%. Groups of industrial buildings are divided by types as follows: production – 68.1%; auxiliary – 16.4%; warehouse – 15%; administrative and utility – 0.5%.

With the development of steel construction, intumescent fire protection coatings appeared, which have gained huge popularity over the last decades. Although intumescent fire protection coatings have
long been used as passive fire protection, much is still unknown about changes in their fire protection properties under the influence of different fire temperature regimes and during operation.

At present, the use of intumescent fire protection coatings to increase the fire resistance of steel structures is based on the development of a fire protection project, which, based on the results of fire tests for standard temperature conditions, provides a selection of optimal fire protection means taking into account the specific functioning mode of the protected facility (Figure 1).

![Diagram of fire protection project](image)

**Figure 1.** Approach to fire protection of steel structures with intumescent coatings

When selecting the optimal fire protection agent, a number of criteria are taken into account in project development (Figure 2).

One of the criteria for choosing an intumescent fire protection coating is the required fire resistance limit of building elements. The estimation of fire resistance of steel structures as part of the development of the fire protection project is implemented on the basis of available experimental data on similar structures according to GOST 30247 or on the basis of experimental data on the characteristics of the cladding, obtained according to GOST R 53295-2009.

The results of certification and additional tests are drawn up in the form of tables or nomograms, which indicate the minimum thickness of the fire protection coating required to ensure a given fire resistance limit of steel structures, depending on the given metal thickness and critical temperature obtained from the results of static calculation.

Such an approach in fire protection design, where the thickness of the intumescent fire protection coating is only determined by the calculated critical temperature and the given thickness of the metal, has a significant disadvantage, namely, the calculated thicknesses of the intumescent fire protection coatings are determined on the basis of standard conditions of certification tests, in particular, on the basis of the results achieved under the conditions of exposure to the standard temperature regime in the prescriptive design approach. The results obtained under standard conditions are then extended to all temperature conditions of fires without detailed study of their effect on the behavior of intumescent fire protection coatings. This assumption in the design of fire protection of steel structures assumes that the thermal and technical properties of the intumescent coatings are unchangeable under different fire temperature conditions. However, intumescent coatings are chemically active materials and their...
heat engineering properties not only depend on temperature, but also on heating conditions and the type of fire exposure.

| INTUMESCENT COATING SELECTION CRITERIA |
|----------------------------------------|
| **Determined by normative documents**  |
| 1. The value of the required fire resistance limit of the structure;  
2. Sanitary and epidemiological properties |
| **Determined by the specifics of the protected facility**  |
| 1. Seismic resistance, vibration resistance of the structure with fire protection;  
2. Decontamination possibility (for nuclear power facilities);  
3. Degasification possibility (for the chemical production facilities);  
4. Decorative requirements |
| **Determined by the specifics of carrying out fire protection works**  |
| 1. The type of structure to be protected and the spatial orientation of the surfaces to be protected (columns, posts, beams, joists, connections) as well as the conditions of loading and support;  
2. Temperature and humidity conditions of fire protection works, environmental aggressiveness;  
3. Seasonality of application;  
4. Technology of application of fire protection coating;  
5. The moment of coating application (during construction of the building or during its operation);  
6. Coating shelf-life;  
7. Conditions of storage and transportation;  
8. Cost of fireproof material and of preliminary preparation of structures and application of fire protection coating. |
| **Translated with www.DeepL.com/Translator (free version)** |
| **Determined by the specifics and operation period**  |
| 1. Ability to periodically monitor the coating and restore it after damage;  
2. Temperature and humidity conditions of operation, aggressiveness of environment;  
3. Coating service life. |

**Figure 2.** Intumescent coating choice criteria

2. **Research methods**

Evaluation of fire resistance of steel structures of the building cover was carried out by solving the heat engineering problem of 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 non-linearity was used, which was implemented in the software package "ANSYS mechanical". The software complex "Fire Dynamics Simulator" (FDS), which implements the field mathematical model, was used for modeling the fire temperature modes.
A single-storey building of a typical form with the dimensions 12x12x6.5 m (Figure 3) was chosen as the research object. The following cover beams from solid rolled I-T sections according to STO ASCHM 20-93 have been used as the bearing structures of the cover. 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 cover is a run-flat roof on metal beams and farms of the cover. The building has 2 gates of 4 x 4 m each and an entrance door of 1 x 2 m. There are 32 windows of 0.7 x 1 m in the walls of the building.

Figure 3. General view of the calculation model in the FDS software package

As a fire load according to reference data [2, 3] were accepted: “industrial goods (textile products)”; “rubber products (rubber and its products)”; “linen fiber warehouse”; “plexiglass warehouse”; “ethyl alcohol”; “cables + wires”; “loosened cotton”; “warehouse of paper in rolls”; “containers (wood + cardboard + polystyrene)”; “radio materials”; “industrial oil”; “warehouse of cotton in bales”.

A ventilation opening was accepted as an object simulating fire load in the FDS software package. To estimate the temperature on the surface of steel structures of the upper belt of trusses, sensors (thermocouples) were placed at a pitch of 1 meter (Figure 4), and the average volume temperature at a height of 4.7-6.5 was measured. During the calculations, the building gates were opened and windows closed.

Figure 4. Scheme of the temperature sensors (thermocouples) arrangement
3. Results and discussion

The results of numerical simulation of the fire temperature regime on the basis of reference data [2, 3] are presented in Figure 5.

![Figure 5. Standard temperature mode and average volume temperature at an altitude of 4.7-6.5 m](image)

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

To estimate the equivalent duration of a fire, heat engineering calculations of the steel structures of the warehouse cover (Figure 6) were carried out under the influence of the standard curve temperature regime and under the influence of the fire temperature regime.

![Figure 6. Coating truss](image)
The structural elements of the metal truss are given in Table 1.

**Table 1. Structural elements of the truss**

| №  | Cross-section | Dimensions of the structure, mm | Number of heated sides | Cross-section area, mm² | Perimeter of heated surface, mm | Effective metal thickness, mm |
|----|---------------|---------------------------------|------------------------|-------------------------|---------------------------------|-----------------------------|
| 1  | □ 160x160x5   | 4                               | 3100                   | 640                     | 4,84                            |
| 2  | □ 140x140x5   | 4                               | 2700                   | 560                     | 4,82                            |
| 3  | □ 100x100x5   | 4                               | 1900                   | 400                     | 4,75                            |

Thermal engineering calculation was made under condition of heating medium temperature change with time according to the "standard fire" curve of GOST 30247.0-94. The standard fire curve equation has the form:

\[ t_{vT} = 345 \log(0,133\tau + 1) + t_{ni} \]  \[ (1) \]

where:

- \( t_{vT} \) – heating medium temperature, °K;
- \( \tau \) – time, sec;
- \( t_{ni} \) – heating medium initial temperature, °K.

The heat transfer coefficient \( \alpha \), W/(m²°K), from the heating medium with the temperature of \( t_{vT} \) to the surface with the temperature \( t_0 \) is calculated by the formula (2) [4,5]:

\[ \alpha = \alpha_k + \alpha_l = 29 + 5,77s_{np} \frac{(T_{vT})^4}{(T_0)^4} \]  \[ (2) \]

where:

- \( \alpha_k \) – convective component;
- \( \alpha_l \) – radiant component;
- \( s_{np} \) – effective degree of blackness: "heating medium - construction surface".

In formula (2) the value of the effective degree of blackness is:

\[ s_{np} = \frac{1}{s + \frac{1}{s_0} - 1} \]  \[ (3) \]

where:

- \( s \) – degree of blackness of the furnace fire chamber. \( s=0,85 \);
- \( s_0 \) – degree of blackness of the heated surface of the structure. \( s_0=0,74 \) – for unprotected steel structures.

Calculation of temperature of a metal rod of a structure is made according to the algorithm which represents a number of formulas received on the basis of the solution of an edge problem of heat conductivity by methods of elementary balances (a finite-difference method of the solution of the Fourier equation of heat conductivity at external and internal nonlinearity).

The temperature of steel structures according to the above formulas was calculated sequentially in calculated time intervals \( \Delta \tau \) up to a given critical value. Initial temperature at all points along the cross-section of the structure before the fire and the ambient temperature outside the fire zone was taken 20°C (\( t_{ni} = 293K \)).
The value of the calculated time interval - \( \Delta \tau \) (program step) was chosen so that it would fit an integer number of times in the interval of machine recording of calculation results; at that, the selected value \( \Delta \tau \) would not exceed the value calculated by the formula (4).

Maximal calculated time interval \( \Delta \tau_{\text{max}} \) is calculated according to formula (4):

\[
\Delta \tau_{\text{max}} = \frac{\gamma_{cm} \delta_{\text{np}} (C + D_{cm} t_{cm})}{\alpha}
\]  

(4)

where:
- \( \gamma_{cm} \) – metal specific weight, kg/m\(^3\);
- \( \alpha \) and \( t_{cm} \) – maximum possible values in the calculation;
- \( C \) – coefficient of heat capacity of metal, J/(kg deg);
- \( D_{ct} \) – coefficient of change of heat capacity of metal at heating, J/(kg deg\(^2\));
- \( \delta_{\text{np}} \) – effective thickness of metal, m;

\[
\delta_{\text{np}} = \frac{F}{\Pi},
\]  

(5)

\( F \) – rod cross-section area, m\(^2\);
\( \Pi \) – heated perimeter of the rod section, m.

The algorithm for calculating unprotected metal structures is the formula (6), having the form:

\[
t_{cm,\Delta \tau} = \frac{\Delta \tau}{\gamma_{cm} \delta_{\text{np}} (C + D_{cm} t_{cm})} \alpha t_{w} + t_{n}
\]  

(6)

where:
- \( t_{cm,\Delta \tau} \) – rod temperature in the calculated time interval \( \Delta \tau \), K;
- \( t_{cm} \) – rod temperature at a given time \( \tau \), K;
- \( t_{w} \) – temperature of heating medium at a given time \( \tau \), K;
- \( \alpha \) – coefficient of heat transfer from the heating medium to the construction surface, W/( m\(^2\) deg);
- \( C_{cm} \) – initial coefficient of heat capacity of metal, J/(kg deg);
- \( D_{cm} \) – coefficient of change of heat capacity of metal at heating, J/(kg deg\(^2\));
- \( \gamma \) – specific weight of metal, J/(kg/m\(^3\));
- \( \delta_{np} \) – effective thickness of metal, m.

For heat engineering calculation in the ANSYS Mechanical software package models of the truss elements were built (Figure 7).
The results of calculations are given in Table 2 and Figures 8, 9, 10.

**Table 2. Thermal engineering calculation results**

| Structure name | Temperature, °C | Heating time of the structure, min |
|----------------|----------------|----------------------------------|
| 160x160x5      | 6.6 13.6 7.2 4.6 | 1.7 8.2 5.0 - 11.1 7.4 2.3 |
| 140x140x5      | 6.6 13.6 7.2 4.6 | 1.7 8.2 5.0 - 11.1 7.4 2.3 |
| 100x100x5      | 6.5 13.5 7.1 4.5 | 1.7 8.1 4.9 - 11.0 7.3 2.2 |
| 160x160x5      | 7.4 14.3 7.7 5.2 | 1.9 8.6 5.6 - 11.7 8.1 2.6 |
| 140x140x5      | 7.4 14.3 7.7 5.2 | 1.9 8.6 5.6 - 11.7 8.1 2.6 |
| 100x100x5      | 7.4 14.3 7.7 5.2 | 1.9 8.6 5.5 - 11.7 8.0 2.5 |
| 160x160x5      | 8.4 15.0 8.2 6.0 | 2.2 9.0 6.2 - 12.4 8.9 2.9 |
| 140x140x5      | 8.4 15.0 8.2 6.0 | 2.2 9.0 6.2 - 12.4 8.9 2.9 |
| 100x100x5      | 8.3 15.0 8.2 6.0 | 2.1 9.0 6.2 - 12.4 8.8 2.9 |
| 160x160x5      | 9.5 15.8 8.9 7.0 | 2.4 9.6 7.1 - 13.2 9.8 3.3 |
| 140x140x5      | 9.5 15.8 8.9 7.0 | 2.4 9.6 7.1 - 13.2 9.8 3.3 |
| 100x100x5      | 9.5 15.7 8.9 6.9 | 2.4 9.5 7.0 - 13.1 9.7 3.2 |
| 160x160x5      | 10.9 16.7 9.7 8.4 | 2.7 9.9 8.1 - 14.1 10.8 3.7 |
| 140x140x5      | 10.9 16.7 9.7 8.3 | 2.7 9.9 8.1 - 14.1 10.8 3.6 |
| 100x100x5      | 10.8 16.7 9.7 8.2 | 2.6 9.9 8.1 - 14.0 10.7 3.6 |
| 160x160x5      | 12.7 17.7 10.7 10.7 | 3.0 10.3 9.7 - 15.2 12.2 4.1 |
| 140x140x5      | 12.7 17.7 10.7 10.6 | 3.0 10.3 9.7 - 15.2 12.2 4.1 |
| 100x100x5      | 12.6 17.7 10.7 10.5 | 2.9 10.3 9.6 - 15.1 12.1 4.0 |
| 160x160x5      | 15.2 19.0 12.3 16.7 | 3.3 10.8 12.6 - 17.0 14.4 4.6 |
| 140x140x5      | 15.2 19.0 12.2 16.7 | 3.3 10.8 12.6 - 17.0 14.4 4.6 |
| 100x100x5      | 15.1 19.0 12.2 16.7 | 3.2 10.8 12.5 - 16.9 14.3 4.5 |

* Positions in the table: 1 - Standard temperature mode; 2 - Industrial goods; 3 - Rubber products; 4 - Warehouse of flax fiber; 5 - Warehouse of plexiglass; 6 - Ethyl alcohol; 7 - Cables + wires; 8 - Cotton loosened; 9 - Warehouse of paper in rolls; 10 - Packaging (wood + cardboard); 11 - Radio materials; 12 - Industrial oil; 13 - Warehouse of cotton in bales. ** The sign "*" in the table means that the specified temperature in the table does not occur during the calculation period.

The results of numerical experiments show that the heating time of warehouse building cover truss structures up to 400-700°C for the fire loads under consideration are significantly different and in some cases less than under standard temperature conditions. Figure 11 shows the dependence of the equivalent fire duration on the fire load.

Figure 8 shows that the values of equivalent duration of the fire for fire loads: "flax fiber warehouse", "ethyl alcohol", "loosened cotton", "industrial oil", "rubber products" are higher than the duration of the fire, which indicates the underestimation of the thermal impact of "real" fires on steel structures of warehouse buildings cover under the influence of standard temperature regime.

In normal operation, steel structures last for many years until their service life ends. It is known that the mechanism of fire-protective action of polymeric coating depends on the composition and physical and chemical interaction between components, which provides fire-protective efficiency of the coating at elevated temperatures during a fire. Under the influence of external factors in the polymeric coating there are physical and chemical, biochemical, photochemical, electrochemical processes in the polymer matrix with the loss of technological, strength, performance, adhesion and fire protection characteristics. The analysis of applied methods of research of physicochemical and mechanical properties of polymeric materials has shown that in recent years dielectric methods are widely used for their evaluation and control [6,7], thus allowing us to assess the fire safety of the intumescent coatings in the process of continuous operation of structures.
Figure 8. Curves of heating of a rectangular pipe of the size 160x160x5 mm in conditions of varying temperature influence.

Figure 9. Curves of heating of a rectangular pipe of the size 140x140x5 mm in conditions of varying temperature influence.
Figure 10. Curves of heating of a rectangular pipe of the size 100x100x5 mm in conditions of varying temperature influence.

Figure 11. Dependence of the equivalent duration of a fire on the type of fire load

The results of the experiments of fire resistant intumescent coatings confirmed their ability to remain the properties in different temperature regimes under fire conditions. Investigation of physical and chemical processes in intumescent coatings taking into account real fire load allows to evaluate fire safety for single-storey buildings with steel frame and sandwich panels as enclosing structures.
Real fire load parameters demonstrate the variety of temperature regimes. Authors considered fire scenarios which were used for thermotechnical problem solution. Thermotechnical calculation was realized with construction models in ANSYS software. Results of steel construction investigation under fire conditions have practical significance.

4. Conclusions
To improve the safety of buildings and structures with a steel frame it is necessary to assess the fire safety of the intumescent coatings both at the design stage and during operation.

The results of the numerical experiments mentioned above show that the evaluation of fire resistance limit of the cover of steel structures of a building with a steel frame according to the standard temperature regime of fire tests without taking into account either the specifics of the fire load, or fire durability control of the intumescent coatings can lead to the understatement of the actual fire resistance limit, which has a negative impact on the safety of the whole building. This is particularly true for cover structures that have a fire resistance requirement of 15 minutes and can be used without fire protection with their own fire resistance limit of more than 8 minutes.

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