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An analysis of methods for determining the fire resistance of building structures

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ABSTRACT:
The article presents the method of using materials that increases fire resistancy in metal and wooden structures. Analytical dependencies of the structure's resistance to high-temperature loads resulting from fire are discussed. Recommendations for structural designers to increase fire resistancy are presented, including an analytical method for determining fire resistance in wooden structures by determining the loss of load-bearing capacity.

KEYWORDS:
fire resistance; metal structures; timber structures; estimating of the fire resistance

1. Introduction

More and more frequent construction disasters resulting from fire is encouraging the use of educational and methodological prevention.

An important requirement in the field of fire safety in buildings is to ensure that the load-bearing capacity of the structure is maintained for the assumed period of time in the event of a fire. Technical and construction regulations [1-7] specify the requirements regarding the fire resistance class of various structural elements, depending on the required function of the analyzed building. In practice, this means that individual structural elements must be designed or protected in a way that ensures that they achieve fire resistance based on a number of technical conditions.

The aim of this work is to analyze fire protection for constructors and construction managers.

2. Ways to increase the fire resistance of metal structures

In practice, metal structures are made of steel, cast iron and aluminum alloys. The most popular structures are constructed from steel of various classes and grades. Steel structures are much lighter and easier to assemble than reinforced concrete structures with the same load-bearing capacity. However, in a fire, under the influence of high temperatures, steel structures often collapse. The consequences of fires, as well as fire resistance tests, have shown that most steel structures deform, losing stability and load-bearing capacity after 15 minutes of intense fire exposure. Thick-walled steel structures, as well as structures with a large margin due to the security methods employed are fire-resistant [8-11].

Unprotected steel columns, trusses and beams are at risk of losing load-bearing capacity during fires. Deformations and the loss of load-bearing capacity of steel columns generally result in the collapse of buildings and contribute to further fire development.

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In cases where fire initiation lasting longer than 15 minutes is possible in the designed building, ongoing maintenance of the structure and its protection against the effects of fire are planned.

Table 1 shows the values of the cross-sectional temperature of uninsulated steel elements depending on the heating time according to the standard curve and the section index A_m/V, where A_m – circumference of the heated element [m], V – area of the cross-sectional element [m^2]. The relationship is often called the massiveness index, where the higher the value of this index, the lower the "massivity" and the increase in temperature.

Table 1

Temperature Θ_s of steel elements according to the standard relationship where: Θ_s – steel temperature $\Theta_s = f(A_m/(V))$ [9]

Time [min]	Θ_s	A_m/V [m^{-1}]					
		20	30	50	100	150	200
0	20	20	20	20	20	20	20
15	739	171	236	347	534	632	700
30	842	375	493	684			

The A_m/V, indicators of steel structures range from 100-250 m^{-1} (in trusses they reach 400 m^{-1}). Uninsulated steel structures already reach a relatively high temperature within the first 15 minutes. Only lightly loaded, non-insulated elements with an A_m/V, index less than 100 m^{-1} can maintain their load-bearing capacity for 15 minutes.

Assuming a uniform temperature field of the cross-section, the critical temperature can be determined, i.e. the temperature at which the load-bearing capacity is exhausted, as illustrated by the relationships shown in Figure 1 [9]. The time it takes to reach this temperature determines the fire resistance of the element.

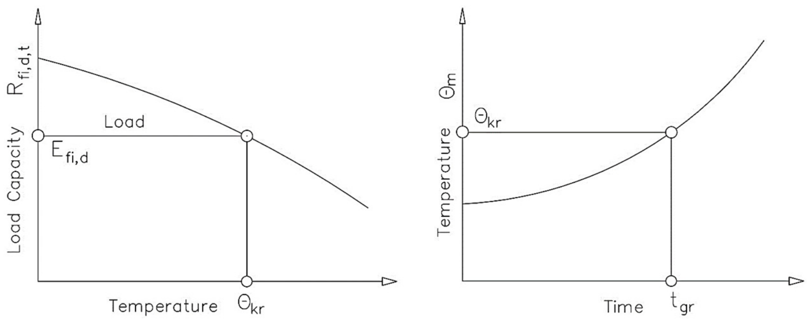

Fig. 1. Principle of determining the critical temperature and fire resistance according to [9]

In construction practice, the most common way to protect steel structures against fire is to cover them with fire-resistant building material. In this case, it becomes necessary to choose the most suitable material for this purpose. Determining the required thickness of the protective cladding and finding a reliable way to attach it to the surface of the steel structure is widely discussed in sources [10, 12].

Lightweight concrete, prefabricated lightweight concrete slabs, ceramic bricks, ceramic blocks, gypsum, asbestos-cement blocks, gypsum, fiberglass and other composite mineral boards are used for protective cladding of steel columns. The effectiveness of the use of protective coverings depends on the physical and chemical properties of the materials from which they are made. Fire resistance decreases with increasing temperature, where the structure of the material changes, loses strength and cracks appear. This accelerates the loss of fire resistancy.

The required thickness of the protective lining is determined computationally, based on the thermal properties of the lining material, and verified experimentally, if necessary.

By examining steel columns made of C-sections or I-sections and protected with various cladding materials, a comparative characterization of the thermal insulation properties of protective materials was obtained.

A layer of 25 mm thick plaster reinforced with metal mesh increases the fire resistance of the steel column for up to 50 minutes. Increasing the plaster thickness to 50 mm increases the fire resistance of the columns to 2 hours. Cracks may form on the plaster surface, individual sections of the surface may peel off, and as a result, parts of the plaster may collapse.

Unlike plaster, cladding of steel columns made of half bricks preserves and protects the column for 5 hours during all fire tests. Columns clad with quarter bricks have a fire resistance of 2 hours 10 minutes. However, if in such cases the space between the cladding and the steel core is filled with concrete, brick, cinder block or other non-combustible material, the fire resistance limit of such a structure can be increased to 3 hours.

The cost of plate cladding for a steel column is approximately 15% of its base cost. Plaster reinforced with mesh is already 20% of its base costs. The fire resistance limit of a steel column protected with 30 mm thick plasterboards and a 20 mm thick plaster layer can increase the fire resistance to 2 hours, and increasing the thickness of the plasterboards to 60 mm will increase the fire resistance limit to 4 hours 30 minutes. The disadvantage of such protection is the shrinkage of gypsum boards and their localised collapse under the influence of the fire. The cause of shrinkage in gypsum boards is the physico-chemical processes occurring in the gypsum during heating.

40 mm thick expanded clay boards with 20 mm thick plaster protects the steel pole for 2 hours, and 65 mm thick boards with the same plaster layer increases the fire resistance to 3.5 hours. 40 mm thick asbestos-cement boards with 20 mm thick plaster protects the steel pole for 2 hours. Filling the free space between the plates and the steel structure's core with a material, e.g. perlite, increases the fire resistance of such a steel pole to 2.5 hours.

It is much more difficult to protect steel beams and trusses from the effects of fire. Cladding the surfaces of such structures with board materials is practically impossible. Applying a layer of plaster is also very difficult, especially on steel truss elements.

Currently, spray technologies are being proposed to protect metal structures against fire. Various solutions of chemical composites applied by spraying are particularly interesting. Such composites are materials containing asbestos, vermiculite and perlite.

Good results were obtained when testing samples with a 60 mm thick lining consisting of perlite, C50 cement, asbestos and liquid water glass. Poles with this cladding reached a fire resistance limit of up to 3 hours. The same fire resistance limit was achieved for poles protected with a 55 mm thick cladding in which vermiculite was used instead of perlite. If ordinary heavy concrete reinforced with steel mesh is used as a cladding, then the cladding thickness should be 70 mm.

Thermal insulation consisting of asbestos, perlite, vermiculite and building plaster can be made according to the material composition recipe in weight proportions that determine the relationship 2: 1: 2: 3; such a composite has high fire-resistancy properties. Steel columns, protected with 40 mm thick thermal insulation, achieve a fire resistance limit of 3 hours.

Methods of using coatings to protect steel structures from swelling under the influence of high temperatures is currently considered very promising: These coatings can be used in closed, heated rooms with a relative humidity not higher than 80%. The coatings are applied several times to the surface of the metal structure cleaned of rust, these are coatings with a thickness of 2.5 to 3 mm. Under the influence of fire, the thickness of the coating layer swells, where the thickness of the applied protective coating increases to 70 mm. The fire resistance limit of metal structures increases from 15 to 45 minutes. The cost of fire-resistant treatment of metal structures with intumescent coatings ranges from 20 to 25% of the cost of the protected structure [13, 14]. In recent years, buildings with metal frames that are filled with water have been experimentally constructed to increase their fire resistance limit.

Water fills the columns of the building frame, or in some cases the ceiling beams, increasing resistance to fire. For this purpose, water with anti-corrosion additives is used, and antifreeze is used for unheated buildings. These systems are permanently filled with water via natural or forced circulation. The fire resistance limit of such structures, depending on their thickness and the speed of water movement, can achieve fire resistance of up to 2 hours.

3. Ways to protect timber structures against fire

The production of new structures in the construction of prefabricated buildings is developing dynamically. However, the flammability of timber structures and their protection remains a current engineering issue that often limits the use of wood in construction. Therefore, many research centers around the world carry out research aimed at developing means and methods of protecting wood against the destructive effects of fire [12, 15, 16]. Technically, it is possible to protect wood against fire by impregnation with an aqueous solution of flame retardants. The impregnation process is carried out in pressurized autoclaves; practice shows that 1 m^3 of wood should absorb 50-75 kg of dry salts in the form of ammonium sulfate and phosphorus.

Plastering and cladding with non-flammable materials should be considered the most effective means of protection. Typically, lime-alabaster or lime-cement plasters provide fire protection to wooden structures for a period of 15-30 minutes, depending on the thickness of the plaster layer and the method of its application.

The protective effectiveness of plasters is determined by the time after which the wooden structure catches fire as a result of cracking, peeling or partial disintegration of the protective layers of plaster and the heating of the surface of wooden structures to the self-ignition temperature. Ordinary plaster collapses or cracks before the plaster layer heats up to the spontaneous combustion temperature of the wood. Plaster cracks may also appear before a fire as a result of wood shrinkage, building settlement, or the use of excessively greasy plaster mortars. The use of stucco solutions on a reinforcing mesh, e.g. metal, reduces the possibility of cracks and peeling of the plaster in fire conditions.

Plasterboards are used as fireproof cladding materials, gypsum-fiber boards are used instead of plaster for finishing walls and partitions inside dry rooms. Such boards are attached using special nails protected against corrosion, or the cladding is glued to the base using mastic mortars or adhesive masses.

One of the features of wooden structures are empty spaces left in the walls and ceilings for better ventilation of the wood and to prevent it from rotting. In some cases, such empty spaces during a fire create favorable conditions for the hidden and very rapid spread of fire. Similar cases have been reported many times during fires in buildings with wooden partitions and ceilings. When designing empty spaces in wooden walls, partitions and ceilings, their surface and volume should be limited by installing board diaphragms or filling them with a light fire-resistant material, e.g. perlite. To protect the surface of wooden structures against fire, various types of coatings and impregnations are also used. These agents reduce flammability and prevent the surfaces of wooden structures from igniting under the influence of heat sources, such as flames, short circuits in electrical wires, etc. A much greater effect is achieved by using intumescent coatings on the surfaces of wooden structures. The fire resistance limit of timber structures coated with intumescent coatings generally increases the fire resistance to 45 minutes.

4. An analytical method for determining the fire resistance of timber structures

The loss of load-bearing capacity of timber structures occurs as a result of the burning of the load-bearing elements, which ultimately leads to a reduction in their working area and an increase in stresses. The limit state of a structure in terms of strength occurs when the stresses in the working section of the structure are equal to the normal stresses. In this case, the calculated resistances are multiplied by the fire coefficient w_0 = 1.24 and are treated as the tensile strength coefficient of wood.

The fire resistance limit of timber bar elements is determined taking into account the reduction in their cross-section due to its charring as a result of fire. The charring rate is assumed to be 0.7 mm/min for elements with a cross-section of 120 x 120 mm or larger, and for smaller elements with a cross-section this value is 1 mm/min.

The task of determining the fire resistance limit comes down to determining the time during which, as a result of reducing the cross-sectional area, the stresses equal the standard stress. These values are most often determined by determining the amount of stress in the structure at time intervals (15, 30, 45 min), plotting the stress change curve over time and the standard stress value in the form of a straight line as in Figure 1. The normal from the point of intersection of these lines to the time ordinate gives the value of the redistribution of the fire resistance of the structure.

5. Conclusions

The growing responsibility of specialists involved in the process of preparing construction documentation and technical managers of construction facilities, including reporting when assessing threats and their elimination, is supported by a descriptive analysis of ways and methods of determining fire resistance.

In analytical methods of determining fire resistance through thermal engineering calculations of analyzed metal and timber structures, it allows the determination of the safe range of fire resistance without the need to conduct costly and time-consuming laboratory tests.

The specificity of the analysis in the field of fire resistance, in particular in terms of the multitude of assessment methods, increases the safety of buildings with metal structures and timber structures or reinforced concrete structures.

Designing structures taking into account the analysis of ways to increase fire resistance is one of the fundamental aspects of ensuring fire safety and protection of human life and property in buildings.

Traditional design methods are most often used to meet the fire resistance requirements of steel and timber structures. Limiting ourselves to these selection of fireproofing measures.

In the case of metal and timber structures, new intumescent coating materials for fire protection are constantly appearing on the market.

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Analiza sposobów określenia odporności ogniowej konstrukcji budowlanych

STRESZCZENIE:
Przedstawiono działania technologiczne wraz z opisem sposobu wykorzystania materiałów zwiększających odporność ogniową konstrukcji metalowych oraz konstrukcji drewnianych. Omówiono analityczne zależności wytrzymałości konstrukcji na działanie obciążeń wysokich temperatur powstałych w wyniku pożaru. Przedstawiono rekomendacje dla projektantów konstrukcji w celu zwiększenia odporności ogniowej, w tym analityczny sposób określenia odporności ogniowej dla konstrukcji drewnianych poprzez określenie utraty nośności.

SŁOWA KLUCZOWE:
odporność ogniowa; konstrukcje metalowe; konstrukcje drewniane; sposób szacowania odporności ogniowej