Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Programme in Civil and Construction Engineering

Iuliia Petukhovskaia

Passive fire protection methods of load-bearing structures in case of hydrocarbon fire

Thesis 2018

Abstract
Iuliia Petukhovskaia
Passive fire protection methods of load-bearing structures in case of hydrocarbon fire, 36 pages, 1 appendix
Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Programme in Civil and Construction Engineering
Thesis 2018
Instructors: Lecturer Heikki Vehmas, Saimaa University of Applied Sciences
Manager, Civil & Structural Engineering, Sergei Lemetti, Neste Jacobs.

The work was commissioned by Neste Jacobs. The first objective of the thesis was to study a procedure of passive fire protection design for structures and to create a guide and a scheme for civil engineers containing steps of the fire protection design process. The second objective was to figure out what passive fire protection methods are used for load-bearing structures in case of hydrocarbon fire, to study and to compare them.

The data for this study was gathered from codes, articles taken from the Internet and by interviewing civil engineers working in the relevant field. Websites and brochures of some manufacturing companies were a very useful tool in understanding the composition and the protection mechanism of fireproofing materials.

The final result of this thesis was the work instruction designed for civil engineers which describes the procedure of the passive fire protection design. As a result of the thesis, an important conclusion was drawn that the choice of a fire protection method depends on many factors, of which the most significant are the type, the material, and the shape complexity of a structural member, acting load, the type of a fire and the environmental conditions. Composite structures have a good behavior under a fire situation and deserve further thorough study.

Keywords: fire protection, hydrocarbon fire, ceramic fibre, vermiculite, intumescent, fire protection blanket

Table of contents

1 Introduction

Fire safety is the set of practices intended to reduce the destruction caused by fire. Fire safety is often a component of building safety. Nowadays the regulations in many countries require that structures have to fulfil not only the basic requirements related to bearing capacity, stability, and serviceability of the structures but also the requirements concerning the structures' fire safety. Passive fire protection is widely used in oil and gas industry as a method to avoid or delay a collapse of installations.

The purposes of the thesis are:

- to study a procedure of passive fire protection design of structures;
- to create a guide and a scheme for civil engineers, which contains the steps of the passive fire protection design process;
- to study and compare different passive fire protection methods used for structures (for a hydrocarbon fire case).

1.1 Difference between passive and active fire protection

Fire protection is the complex of measures designed to reduce or eliminate the possibility of the contact of open fire with a material of a structure. There are two groups of fire protection means used in the construction field. The first group comprises means related to active fire protection (AFP). The active fire protection purposes are to detect, alert about, and seek to eliminate a fire hazard. So, when fire or smoke are detected somewhere, the fire or smoke alarm alerts those who are inside or near the building (or the structure). Active fire protection systems include fire detection and alarm systems and automatic fire-extinguishing systems.

Passive fire protection systems work in a different way. They do not need any external activation nor they try to extinguish fires. Passive fire protection (PFP) aims to limit or slow down fire propagation for a certain period of time, regulated by relevant standards (more information in chapter 1.4) by means of the use of fire barriers and insulation materials.

In high-risk facilities, PFP systems and materials are used in conjunction with AFP systems. Their common goals are to ensure that people can be evacuated out of a dangerous area, to localize the fire, to save structural integrity and to prevent toxic gas emission. Active fire protection uses systems that take action in putting out a fire, while passive fire protection uses systems that help to prevent the spread of fire and smoke and to save structural integrity. This combination enhances the overall safety by reducing dependence on a single protection system that could be rendered inoperable in the event of a fire. To ensure total fire protection of a structure, both AFP and PFP should be working together in unison.

1.2 Hydrocarbon fire and its impact on structures

A hydrocarbon fire is the most dangerous type of a fire. It occurs when the ignition of petrochemicals, petroleum or oil gas takes place. Hydrocarbon fire is characterized by rapid growth of temperature accompanied by impact action of fire to a fireproofing coating. Figure 1 shows temperature – time curves typical for two types of a fire – cellulosic fire (a blue line) and hydrocarbon fire (a red line).

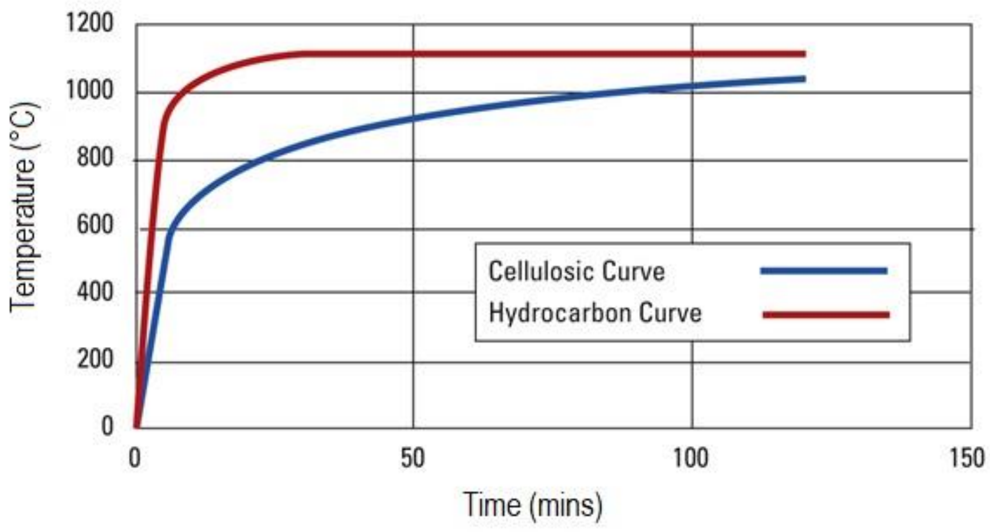

Figure 1. Temperature – time curves (43)

The significant difference between two types of a fire is the time it takes to reach its maximum temperature value. Hydrocarbon fire reaches the temperature of 900°C in 8 minutes, whilst cellulosic fire takes 60 minutes to reach the same level.

In such conditions, standard fireproofing materials do not provide sufficient level of fire protection.

1.3 Structures to be protected

Whatever the reason of ignition, any fire more often than not causes dire consequences both material damages and death of people. A collapse of support structures leads to the most catastrophic consequences. Therefore, these structures have to be protected against fire.

In oil and gas industry where the hydrocarbon fire may take place, load-bearing structures support tanks, pipelines and different equipment installed on them. Concrete structures are typically used as supports of vessels and process units. Steel structures also support different equipment and process pipes containing flammable liquids and gases.

Two types of the hydrocarbon fire may occur at factories – a pool fire and a jet fire. It depends on the equipment that will be installed. A pool fire is caused by fire burning above a horizontal pool of vaporizing hydrocarbon fuel where the fuel has zero or low initial momentum (see Figure 2).

Figure 2. Pool fire (2)

A jet fire is caused by the combustion of a fuel continuously released with significant momentum in a particular direction (see Figure 3).

Figure 3. Jet fire (28)

Three main types of fire protection products used in hydrocarbon-processing complexes can be identified:

- intumescent coatings generally epoxy based, spray or hand applied;
- blanket systems made from man-made fibres;
- cementitious products.

1.4 Fire-resistance of structural elements

Building regulations require certain elements of a structure to be fire resistant. Fire-resistance is the ability of structures to maintain its primary structural functions under the influence of fire. Resistance to fire is measured in minutes 15, 30, 45, 60, 90, 120, 180, 240 and 360. (32) Fire resistance of the structure, or structural member, is measured by the ability to resist fire retaining its loadbearing capacity (classification R), integrity (classification E), and insulating properties (classification I).

For bearing bar elements (beams and columns) only loadbearing capacity is required. Loadbearing capacity is the ability of a structural member to withstand the fire exposure during a certain period of time without loss of stability.

2 Passive fire protection design process

Structural fire engineering involves analysing the thermal effects of fire on structures and designing structural members for adequate load bearing resistance. A structural engineer should be aware of all requirements relating to fire safety contained in building regulations.

The process of passive fire protection design always starts with a preliminary report on necessary passive fire protection methods which should be used for structures in flammable areas. Flammable areas are defined on the basis of a fire scenario. When fire resistance time required for structures is specified, the structural fire design starts. Design of structures for fire situation is based on load combinations that are different from those considered at room temperatures. (10, 11) Structural fire design is performed in accordance with Eurocode 2 – for concrete structures, with Eurocode 3 – for steel structures.

In order to calculate a thickness of fireproofing material, it is necessary to know not only the required fire-resistance but also:

- the section (profile) and the critical temperature of the structural member – in case of steel structures;
- the cross-section dimensions and the axis distance of the element – in case of concrete structures.

As used herein the term “axis distance” means the distance between the center of main reinforcement and the closest exposed concrete surface.

In fire design of steel structures, one of the main things that have to be done is the determination of the critical temperature for steel member. EN 1993-1-2 (13) contains the recommendations for calculating the critical temperature of the structural steel member. In accordance with (13) “critical temperature of structural steel member for a given load level is the temperature at which failure is expected to occur in a structural steel element for a uniform temperature distribution.” In other words, it is the temperature at which a steel member reaches its ultimate limit state. The critical temperature of steel members without instability phenomenon may be obtained according to the formula (1) or the table given in (13):

$$\theta_{a,cr} = 39{,}19 \ln\left[\frac{1}{0{,}9674\mu_0^{3{,}833}} - 1\right] + 482 \qquad (1)$$

where μ_0 – the degree of utilization. The degree of utilization is determined as the ratio between the design effect of actions in fire and the design resistance in fire for time t=0. In practice, the critical temperature of a steel member can be obtained by means of software Autodesk Robot Structural Analysis.

For structural fire design of concrete structures, EN 1992-1-2 provides different methods. Each method has restrictions. A designer is entitled to choose any of the design methods if terms and conditions of use set for the method are met.

A calculation of the required thickness of a fire protection material is carried out by the manufacturer of the protection material. A structural engineer has to provide a manufacturer of fireproofing material with the following information: the type of a fire, the required fire resistance, the cross-section dimensions of the structural member to be protected or the profile (for steel member), the axis distance (in case of concrete structures) and the critical temperature (in case of steel structures).

3 Fire protection of steel structures

It is impossible today to imagine a construction industry without a usage of steel structures. Their reinforcing and loadbearing functions provide constructions with operational reliability, durability, and strength.

3.1 High-temperature exposure to steel

Steel, being a non-flammable material, however, loses most of its properties and becomes a plastic material when the temperature exceeds critical values. Figure 4 shows the variation of reduction factors with temperature. Reduction factors are introduced to represent the change in mechanical properties with temperature.

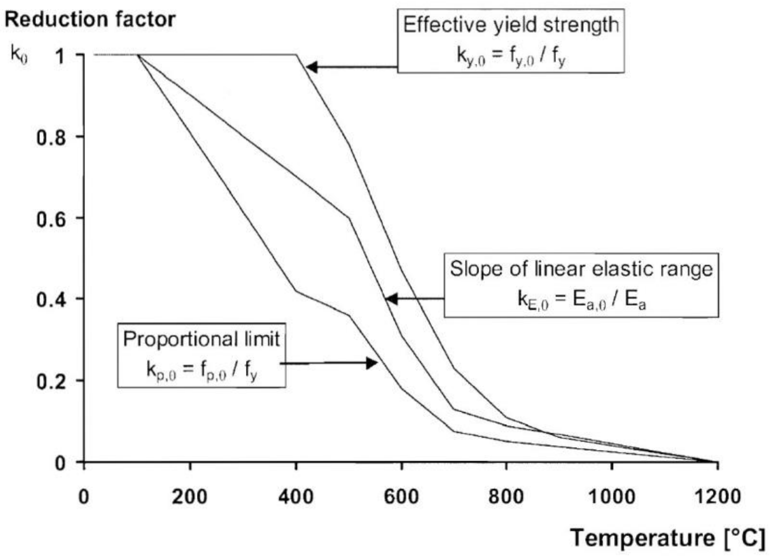

Figure 4. Reduction factors for stress-strain relationship of carbon steel at elevated temperatures (13)

Table 1 shows how effective yield strength of steel changes with rising temperature. Two steel grades were chosen for the analysis – S355 and S235. Reduction factor at temperature θ_a is defined as effective yield strength $f_{y,\theta}$, relative to yield strength at 20°C f_y.

Table 1. The variation of steel effective yield strength with the temperature

Steel temperature θ_a	Reduction factor $k_{y,\theta} = f_{y,\theta} / f_y$	Value of effective yield strength $f_{y,\theta}$ [N/mm^2]	
		S355	S235
20°C	1,000	355,0	235,0
200°C	1,000	355,0	235,0
400°C	1,000	355,0	235,0
500°C	0,780	276,9	183,3
600°C	0,470	166,85	110,45
700°C	0,230	81,65	54,05
800°C	0,110	39,05	25,85
900°C	0,060	21,3	14,1
1000°C	0,040	14,2	9,4

1100°C	0,020	7,1	4,7
1200°C	0,000	0,0	0,0

The following factors influence the increase of steel temperature in a fire situation: the thermal properties (specific heat, the thermal conductivity) and the thickness of a fire protection material and section factor.

The rate at which a structural member responds to heating in fire depends on the volume of steel member and its surface area exposed to heat. Therefore, the factor used in structural fire design is A_m/V (for unprotected steel member) or A_p/V (for steel members insulated by fire protection material) called section factor. "A_m" is defined as the exposed surface of the steel member; "V" is the volume of steel; "A_p" is defined as the internal surface area of the exposed encasement. (13)

In case of steel member with a constant cross-section, its section factor can be defined as follows:

- the ratio between the exposed perimeter of the cross-section and the area of this cross-section – for unprotected steel member;
- the ratio between the internal perimeter of the encasement and the steel cross-section area – for fire-protected steel member.

Figure 5 illustrates the above. An I-section steel member is considered here. The protection material is marked in green and the perimeter taken into account in calculating the section factor for both cases is marked with a yellow line.

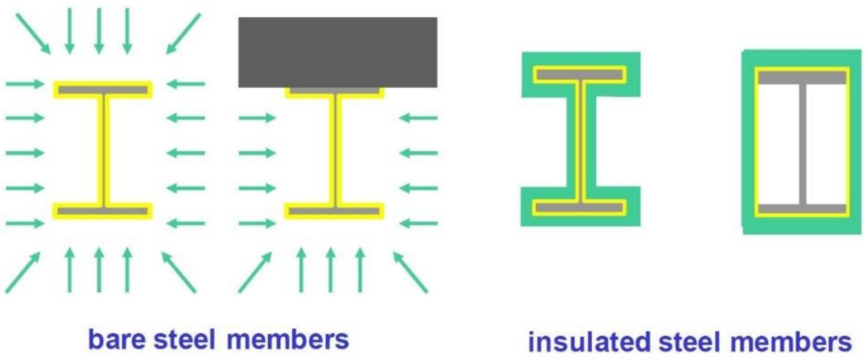

Figure 5. Definition of the section factor (40)

The lower the section factor, the slower a structural member will heat up in a fire.

The main role of protecting coatings is to prevent or delay the collapse of the structure by reducing the rate of steel temperature rise.

3.2 Overall overview of applicable fire protection methods

A wide range of coatings and insulation can be used to make a structure more fire-resistant. Generally, all fire protentional methods used for steel structures can be divided as follows:

- concrete encasement and brick facings (see Figure 6);

Figure 6. Brick facing (36)

- board facings and sheet materials (see Figure 7);

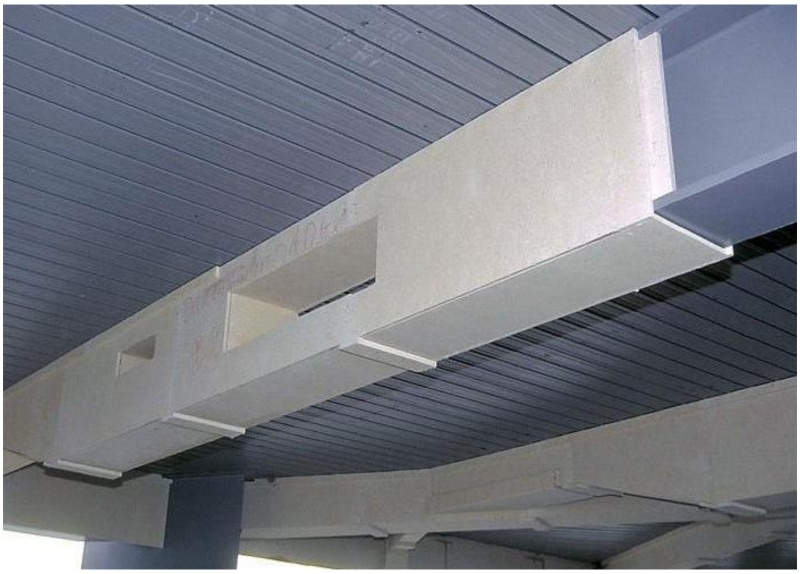

Figure 7. Board fire protection (4)

- spray protection (e.g. plasters) (see Figure 8);

Figure 8. Spray fire protection (4)

- flexible blanket systems (see Figure 9);

Figure 9. Flexible blanket systems (25)

- intumescent coatings (see Figure 10).

Figure 10. Intumescent coating (5)

Advantages, disadvantages and application features of the above-mentioned methods are summarized in the table in Appendix 1.

Taking into account the features of hydrocarbon fire, the inference should be drawn that not all of the above-mentioned methods can be applied. The use of intumescent coatings is the preferred solution to protect a steel structure from a hydrocarbon fire. Further consideration would be given to that type of passive fire protection. An alternative to the intumescents is flexible blanket systems. They are described below as well.

3.3 Intumescent coatings

One of the most effective ways of passive fire protection is the use of intumescent compositions. These materials increase their volume under the influence of fire and create a thermo-insulating barrier with low thermal conductivity on the surface of a structure. The barrier separates flame from metal and significantly retards its heating up that allows saving structural integrity for a necessary period of time. Three stages of protection process are shown in Figure 11. During the first stage, steel is heating up monotonically up to 200±50°C. Coating being in solid form works as isolation. Then intumescence process starts. Stage II continues until the temperature is 400°C. The process is endothermic. Outer layers to be more heated are gradually “moving away” from the steel surface. At the third stage, the intumescent coating works as isolation. The heating rate of steel is rising. (3, 19, 23)

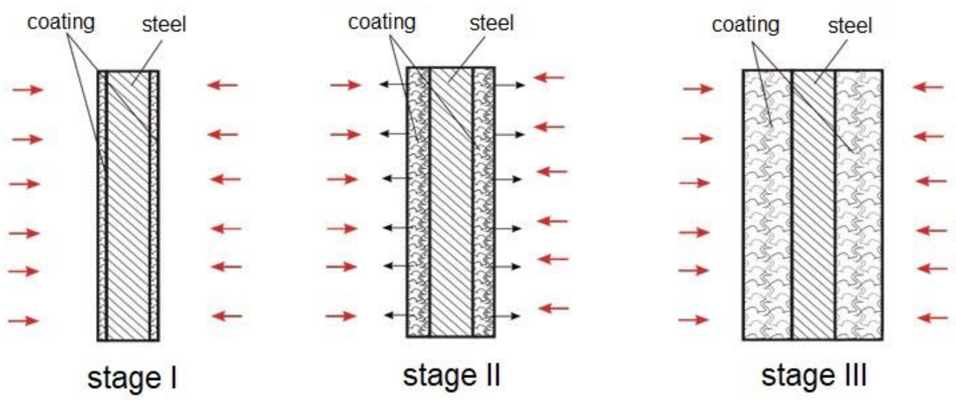

Figure 11. Stages of the process of protection by intumescent coatings (3)

Under the intense pressure and heat from a fire, intumescent coatings work by producing a foam-like substance from the chemicals in it reacting and releasing a vapour. Upon carbonization, the foam will solidify to a black material – a char (see Figure 12) (6). The char is a bad conductor of heat, and it does not allow the heat to pass through the coating layer and reach the structural member. It potentially prevents the temperature of steel reaching the critical temperature of 500°C. Many intumescents require a corresponding primer to ensure proper adhesion to the steel surface. The primer is important to the performance of the intumescent (33).

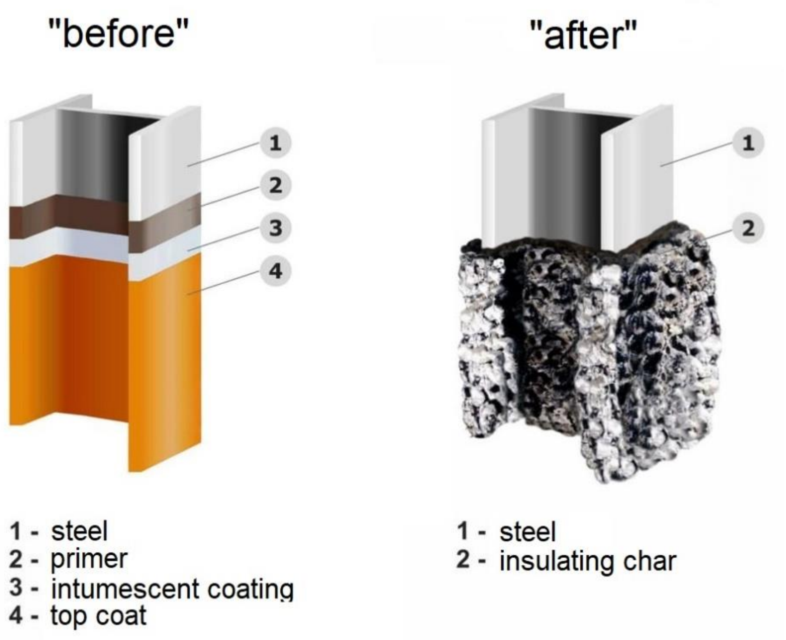

Figure 12. Fire-protected steel member before and after fire exposure (15)

All intumescent coatings can be divided into two groups – thin film and thick film (31). Thin film materials may be solvent- or water-based. They are mainly used for building fires (35) and are not taken into consideration in this case.

Thick film intumescent coatings are usually epoxy-based and typically have a much higher dry film thickness than thin film alternatives. They were originally developed for use with hydrocarbon fires. Epoxy-based intumescent coatings provide resistance to very high temperatures, flame erosion, and char sagging. Two types of epoxy-based coatings are considered and compared in this section.

The first type is the coatings requiring an additional reinforcement mesh. To promote the requisite level of fire protection some protective compositions shall have quite high thickness. That is the reason to use the reinforcement mesh. It provides reinforcing of the char once it starts to form and prevents its cracking or collapse. Figure 13 illustrates the basic idea of application of a mesh-containing epoxy coating. The process of the application contains the following steps:

1. Application of primer.
2. Application of the first layer of protective mixture accurately to the correct thickness.
3. Application of the mesh. The mesh can be applied manually or mechanically by pressing. The mesh is contacted to the first layer and embedded into it.
4. Application of the second protective layer.
5. Application of a top coat. The top coat provides additional durability to physical or environmental challenges.

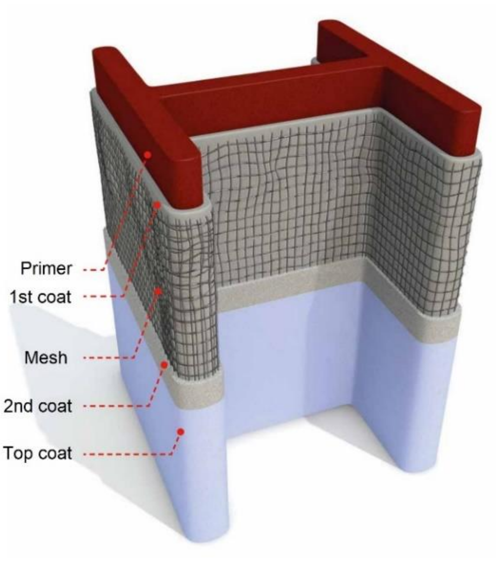

Figure 13. Mesh containing epoxy passive fire protection (21)

All procedures have to be carried out in accordance with related certification rules.

Keeping in mind all the benefits of using mesh containing coatings, it is important to understand the disadvantages they have. To avoid any risk of failure when exposed to fire, the reinforcement mesh must be installed correctly. Incorrect installation of a mesh will result in unpredictable fire performance. Mistakes may be committed during the following procedures:

- Installing the reinforcement mesh at a specific depth within the coating. The incorrectly installed mesh can reduce the cohesive properties between the mesh and the final coat and lead to its detachment and system failure.
- Creating mesh joints. If the overlapping mesh is not correctly installed, the upper layer will lift. This causes delays and reworkings.

In addition, the use of reinforcement mesh leads to the increase of the weight of fire protection coating, thereby increasing dead loads on the structure.

Therefore, another type of epoxy coatings is worth consideration. This is about epoxy coatings that do not require mesh for their application (see Figure 14). That is a new development in intumescent coating technology. Some manufacturers offer such intumescent coatings as the alternative to traditional mesh-containing coatings.

Without the need for additional mesh reinforcement, installation time is significantly reduced, because there is no stopping for mesh application. Repair and maintenance processes take less time and labour.

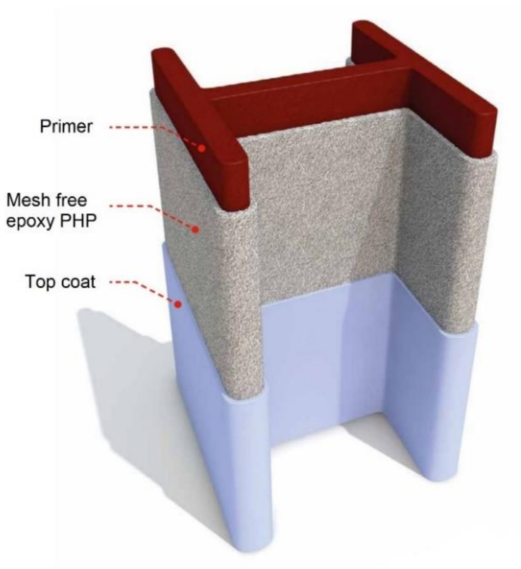

Figure 14. Mesh free epoxy passive fire protection (21)

Before the application of a primer, the protected surface should be carefully prepared. Surface preparation is a very crucial stage not only for steel members which have already been in operation but also for new structural members. Improper surface treatment or the lack of preparation measures can cause a failure of protecting coating. There are two methods of surface cleaning – chemical and mechanical. Chemical methods include the use of rust penetrating solvents, paint removers etc. Mechanical cleaning may be manual as well as cleaning by means of mechanical equipment. The latter involves sandblast cleaning, abrasive blasting, and wire brushing. The important procedure in the surface preparation process is degreasing. It is carried out by the use of degreasing agents. The procedure is done immediately before the application of primer and often comes with dedusting a surface. (15)

The advantages of the intumescent fire protection system are durability, ability to cover complex shapes and details easily, the ease of maintenance and reparation. However, their disadvantages include:

- high cost;
- implementation of a good quality coating requires great attention and efforts;
- intumescent coating can be damaged if it is applied offsite.

3.4 Flexible blanket systems

The use of ceramic fiber and ceramic fiber products for insulation has become very popular nowadays. Ceramic fiber products have many advantages, including high-temperature stability, light weight, excellent insulation, and ease of application.

Ceramic fibers are amorphous fibres, which are produced by melting a combination of two oxides: aluminum oxide (Al_2O_3) and silicon oxide (SiO_2). Alumino silicate wool (ASW) is also known as “refractory ceramic fibre” (RCF). Products made of ASW are generally used at application temperatures of greater than 900°C (41).

The scheme of the manufacturing process of ceramic fiber products is shown in Figure 15. A mixture of raw materials – Al_2O_3 and SiO_2 – is melted at about 2000°C. After that, the melted mass undergoes spun or blow forming. The produced fiber is then used for manufacturing the ceramic fiber products. Ceramic fiber is a highly versatile material. It comes in many different forms: ceramic fiber bulk, ceramic fiber blanket, ceramic fiber board, ceramic fiber module, ceramic fiber paper, ceramic fiber rope, ceramic fiber cloth, etc.

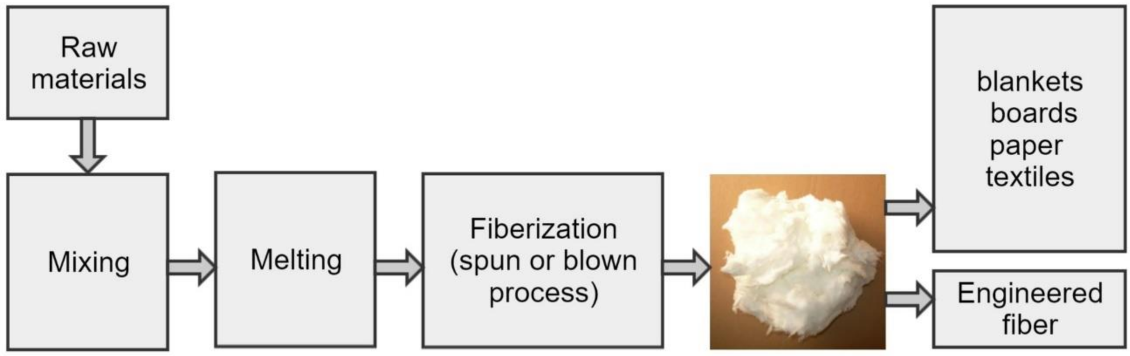

Figure 15. Manufacturing process of ceramic fiber products

Ceramic fiber blankets (Figure 16) provide fire protection by wrapping a non-combustible layer of insulating material around the steelwork and thus slowing the heating rate of the structure. The blanket's flexibility enables it to be easily controlled and fit into tight spaces.

Figure 16. High-temperature blankets (37, 26)

In many instances, the mineral wool has a foil facing (see Figure 16 – on the right). The foil provides the protection against the mechanical action and the weather protection of ceramic fiber. It also contributes to fire-protective properties of blankets. The article (42) describes the insulation mechanism of ceramic fiber aluminum foil blankets. Their good insulation properties are achieved by three ways – weakening of heat conductivity, heat convection, and heat radiation. Due to the structure of fibre, the heat has to conduct along the fiber which is not vertical to the protected surface. This virtually makes the conductive way longer and weakens the heat conductivity. The high porosity of fiber in combination with the compactness of the foil restrains air's convection. Heat radiation is weakened due to reflective properties of the aluminum foil.

Special attention should be given to the implementation of joints (seams) between pieces of blankets. They have to be carried out with the use of special tapes by qualified personnel according to relevant certificates.

3.5 Intumescent coatings vs. flexible blanket systems

Table 2. Comparison between intumescent coatings and flexible blanket systems

	Intumescent coatings	*Flexible blanket systems*
Protection thickness range, mm	5 – 22	10 – 50
Usage time at ambient temperature	longer	shorter
Possibility of off-site application	yes	no
Application process	wet	dry
Weight of fire protection	low	low
Resistance to vibration	yes	yes
Curing time	yes	no
Necessity in additional elements, fasteners	yes (mesh-containing) no (mesh-free)	yes (metal “clip-bands”)
Ease of maintenance and repair	yes	yes
Weatherproof	yes	yes

Finish appearance	smooth or “orange peel” surface	uneven (“blanketed” surface)
Required coating thickness	controlled by operating personnel;	controlled by manufacturer;
Ability to cover complex shapes	yes	yes

The comparison above (Table 2) illustrates how important it is to fully understand the requirements for a fire protection coating. The main point is the fact that the use of the chosen method has to be appropriate for the specific case (specific structure and specific external environment). It is also necessary to make a cost estimation in order to assess the efficiency of every method.

4 Fire protection of reinforced concrete structures

Generally reinforced concrete structures exhibit good performance under the fire conditions. Concrete has a low thermal conductivity (50 times lower than steel) and therefore heats up very slowly in a fire. Until concrete is not damaged as a result of cracking or spalling, it provides protection for reinforcing steel against high temperature occurring during a fire.

Nevertheless, concrete is gradually fracturing under the action of fire.

4.1 High-temperature effect on reinforced concrete structures

The section describes the behavior of concrete at high temperatures. Under the influence of temperature different unfavourable processes (reactions) occurs within concrete (see Table 3).

Table 3. High-temperature action on concrete (7)

250 – 300°C	Concrete strength reduces. It comes with a failure of hardened cement paste (due to decompounding of calcium hydroxide).
550°C	Quartz grains contained in concrete aggregates (sand and gravel) start to crack and quartz transforms into a new form –

	tridymite. The cracking occurs because quartz grains increase in volume. It leads to microcracking.
Over 550°C	Destruction of other concrete constituents.

The above table concerns standard concrete. However, as a result of researches, refractory concrete was developed. It is Portland cement-based concrete which is able to resist 1100°C and even higher temperatures. Therefore, one of the ways to increase the fire resistance of a structure is to use refractory concrete.

As concrete is a composite material its behavior at high temperatures depends on the behavior of hardened cement paste, aggregates and on their interreacting.

One of the consequences of a high-temperature impact on concrete is spalling. Spalling of concrete is the splitting and breaking of the concrete element's surface layers during thermal exposure. There are three types of concrete spalling – aggregate spalling, corner spalling and explosive spalling. The most dangerous type of concrete spalling is the explosive spalling. It is the ejection of pieces of concrete from the heated surface at high velocities (9). The reasons for this phenomenon are pore pressure and thermal stresses (9, 17). The mechanism of concrete spalling due to pore pressure formation within a heated concrete element is shown in Figure 17. When free water temperature in concrete reaches a value of 100°C it starts to vapour. Some of this vapour moves toward the interior of a reinforced concrete member where it gets cold and condenses. That creates a wet zone (water clog). The pore pressure rises. If the maximum pore pressure is greater than the local strength of the concrete the spalling occurs. (9)

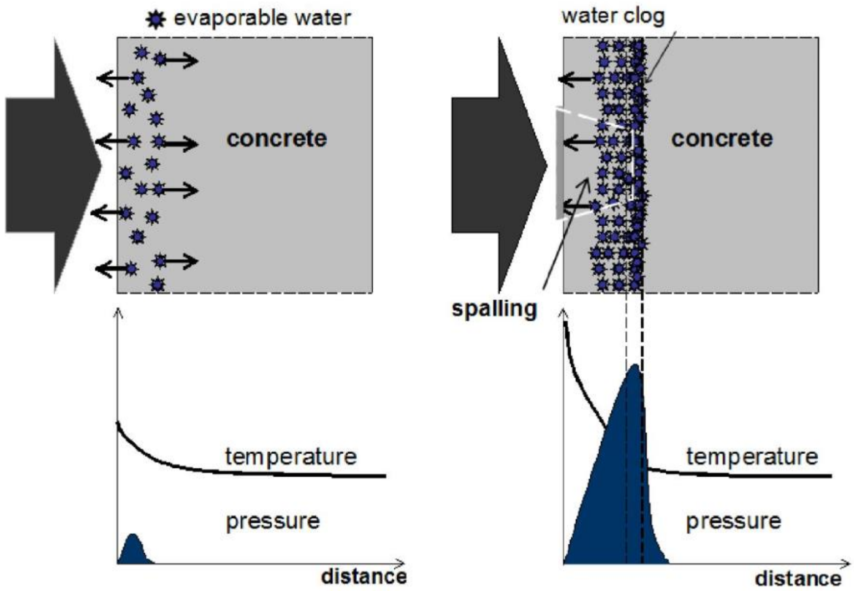

Figure 17. Mechanism of concrete spalling due to pore pressure formation within a heated concrete element (17)

The second probable reason of explosive spalling is the development of thermal gradients in concrete with the temperature rise. They cause high compressive stresses close to the heated surface and tensile stresses in the cooler interior regions. (9, 16) Many studies (17, 9, 16) assume that concrete spalling is a complex phenomenon caused by various factors.

Removal of concrete cover pieces bares reinforcement and exposes it to fire. The steel reinforcement is more sensitive than concrete at high temperatures. As noted above steel strength reduces significantly with temperature. The temperature of the reinforcement steel depends on the duration of the fire, the cross-section shape and the thickness of the concrete cover. Concrete having lower thermal conductivity protects steel from rapid heating. Regulations prescribe a minimum thickness of concrete cover of the reinforcement for a specific fire resistance period in order to delay the increase in temperature of the steel. The "goal" of concrete is to limit the reinforcement temperature during the exposure time to a level below 500 – 550°C. (18)

The failure mechanism of a reinforced concrete member depends largely on the type of the element (beam, column, wall, slab) and on the support conditions. For example, simply-supported single span beams lose their loadbearing capacity due to the excessive heating of the tensile reinforcement. The failure of statically indeterminate beams may occur not only at midspan but also close to the supports.

Results of different researches show that one of the reasons of structural failure under the fire conditions is the loss of bond stress between concrete and reinforcement. Bond stress is the force of adhesion per unit area of contact between two bonded surfaces. In this view ribbed bars are more preferable than plain bars. Figure 18 shows how the adhesion between concrete and reinforcement (Y-axis) changes with a rise in temperature (X-axis). Plot line 1 relates to the plain bars and line 2 relates to the ribbed bars. At the temperature 350°C, the adhesion between the plain bars and concrete is almost lost whilst the adhesion between ribbed bars and concrete still retains the initial value. The diagram is based on the results of the researches conducted by Concrete and Reinforced Concrete Research Institute. (24)

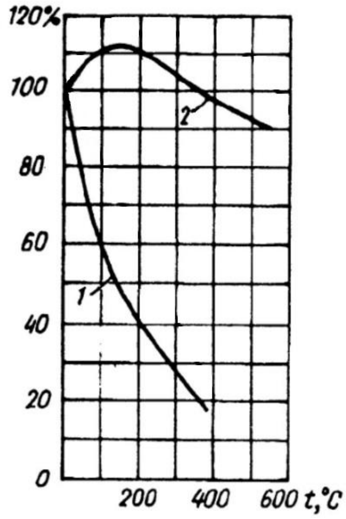

Figure 18. The action of temperature on the adhesion between concrete and reinforcement (24)

4.2 Fire protection methods

As it has been noted above, concrete itself plays a major role in the fire protection of reinforcement. Consequently, some concrete structures are able to resist fire during the required period of time without any fire protection. But often the required fire resistance is more than the one which a structure element has. In that case, additional fire-protection measures have to be taken. In addition, the occurrence of explosive spalling should be eliminated.

Passive fire protection of concrete structures is essentially oriented to the preventing of explosive spalling. Fire protection is provided by creating some thermal insulating barrier which slows down the heating of concrete and increases the time when the concrete surface temperature value is lower than the critical one. The following fire protection methods are used for concrete and reinforced concrete structures:

- to use fire protection materials:
  - thin intumescent coatings/paints;
  - cementitious coatings;
  - boards or sheets made of fire protection materials;
- to increase the thickness of concrete cover (to apply an additional concrete layer). (20)

Cementitious and intumescent coatings are the most common methods of passive fire protection used for concrete structures. Spray application of these methods allows covering round-shaped elements. The disadvantage of concrete covering is its weight; cementitious coatings applied to a minimum practical thickness of 30 mm to 60 mm have lower thicknesses than concrete coating and do not require molding for installation. Board and sheet materials predominantly are less durable and less scratch-resistant than cementitious or intumescent coatings. The protection mechanism of intumescent coatings was explained above. The cementitious coatings are described below.

4.3 Cementitious coatings

Cementitious fireproofing coatings are usually based on Portland cement and lightweight aggregates (1). Vermiculite is a material used as such an aggregate for cementitious fireproofing mixtures.

Vermiculite is a hydrous phyllosilicate mineral. It undergoes significant expansion when heated. The exfoliated vermiculite consists of harmonica-shaped grains that contain millions of air bubbles, which are responsible for vermiculite's insulation property and low weight (see Figure 19).

Figure 19. Exfoliated vermiculite

The vermiculite grain that is mixed with the cement has grade 0-3 mm. Vermiculite mortar is a lightweight cement mortar with fire-resistant and insulating effect. Exfoliated vermiculite is very efficient at retaining moisture, and in case of fire, this turns to steam which has a cooling effect on a substrate and thus delays its temperature rise. In addition, vermiculite mortar is a durable shrink-free and crack-free mortar. During high-pressure action (e.g. in case of a jet fire) the coating does not crush and crack.

Combustion gases and toxic gases evolved during a fire may seriously affect a human's health. In case of fire pungent smoke can slow evacuation of people. One of the advantages of vermiculite is the fact that it is an eco-friendly material, because it does not evolve toxic agents during combustion.

The benefit of the use of cementitious coatings is the lower cost compared with the intumescent option.

5 Composite structures

The term “composite structures” here means structures made of two materials: steel and concrete. In fact, a composite section is a steel hollow section filled with concrete and reinforcement (see Figure 20). Reinforcing of a concrete core allows to reduce the section sizes of a steel shell and hence the cross-section of a structural member.

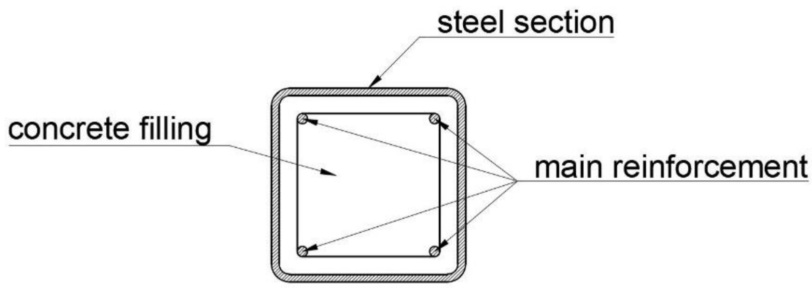

Figure 20. Cross-section of a concrete-filled hollow column

Concrete filled steel tubular elements have lots of advantages (38):

- aesthetic appearance (smooth surface);
- corrosion resistance (closed shape does not have sharp corners);
- steel enclosure protects concrete filling from environmental and mechanical impacts during operation;
- all benefits of steelwork in terms of installation (e.g. ability of welding);
- higher load bearing capacity without increasing the outer dimensions of a structural element;
- increase of concrete strength (due to the restrained effect of a steel tube);
- local buckling resistance of hollow steel section is higher because of concrete filling.

One of the advantages of composite structures is their fire-resistance properties. Concrete improves fire resistance so that the fireproofing material can be reduced or even omitted.

5.1 Structural behavior under the fire conditions

At ambient temperature the load is carried by both – steel and concrete. When a structure is exposed to fire, steel is able to carry loads only during the early stages. The temperature in the unprotected outer steel shell increases rapidly. As the steel shell gradually loses strength and stiffness, the load is transferred to the concrete core. Concrete filling starts carrying more and more of the load. (39) In case of a jet fire, the steel tube provides good protection for concrete against the mechanical impacts. In addition, the steel tube prohibits excessive spalling of concrete happening at high temperatures.

5.2 External protection of steel shell

Additional measures should be taken to make the structures corrosion resistant. Concrete filling protects the internal surface of the steel hollow section increasing its corrosion resistance compared with an unfilled hollow section. But protection coating should be applied to protect the external surface.

In some cases when extended fire resistance is required the application of additional fire protection might be necessary. In this regard any fire protection methods used for steel protection are applicable.

5.3 Construction of composite structures

Concrete filled steel tubes are widely used as columns. Figure 21 illustrates the erection of the composite column. It is preferable to insert reinforcement into the steel tube at the manufacturing phase. When reinforcement is installed the steel tube column is erected in a vertical position. After the joints are complete, the tube is filled with concrete. Generally, filling of composite structures with concrete is done on-site. The construction advantage of composite structures is that the need for formwork is eliminated. The hollow section steel member acts as a formwork for concrete filling. Two typical methods of concrete filling operation are shown in Figure 22. The pump filling is shown on the left and gravity filling is shown on the right. (14) But small length tubes can be filled off-site. Off-site filling reduces the number of site operations and speeds up the building process.

Figure 21. The erection of steel tube column (8)

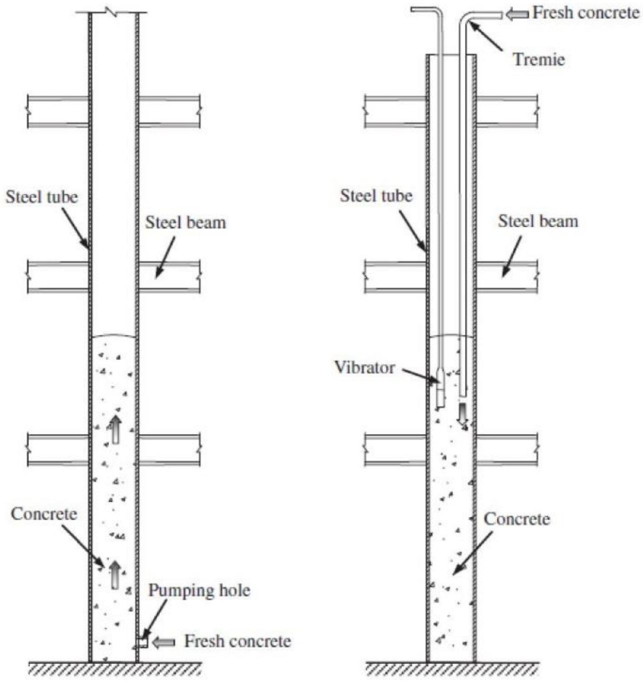

Figure 22. Methods of concrete filling (14)

Literature (22, 34) provides many variants of beam-to-column connections. Some examples:

- fin plate connection;
  The connection consists of a plate welded to the column, to which the beam web is bolted on a site.
- through fin plate connection;

The fin plate is inserted through the steel hollow section tube and then welded to it. The beam web is bolted to the fin plate on the site.

- connections with external and internal diaphragms;
- continuation of beam cross-section through the tube column.

6 Summary

Civil engineers working in oil and gas industry, petroleum refining industry and in linked industries have to consider sector-specific issues of the field. One of them is the fire risk. Fire effects largely depend on the fire resistance of load-bearing structures. Therefore, it is crucial to provide them with adequate passive fire protection.

It may be reasonable to conclude that concrete filled hollow section structures are preferred from the viewpoint of fire resistance. The combined action of steel and concrete in such structures makes them durable and able to resist the fire even without additional fire protection coatings.

In order to make steel structures and concrete structures fire resistant, a fire protection barrier has to be created on the surface of a structural member. Today, the market offers fire protection materials of all types. Materials have different shapes, properties, application methods and protection mechanisms. An engineer has to fully understand the requirements for a particular fire protection coating. Without the knowledge of them, it is impossible to highlight the best fire protection method and assure that some method is more preferable than the other ones. The choice of a method of fire protection always should be made on the basis of the following criteria:

- type of fire;
- value of required fire resistance;
- the complexity of a structure shape;
- type of a structural member to be protected (column, beam, bracing system);
- weight restrictions for fire-protection coatings;
- acting load (static or dynamic);

- temperature and humidity conditions of the environment not only during operational cycle but also during construction;
- the aggressiveness of the environment;
- required work completion time (required ease and quickness of installation);
- aesthetic requirements to structure.

In case of hydrocarbon fire, the most relevant passive fire protection methods are ceramic fiber blankets and intumescent coatings – for steel structures, and cementitious and intumescent coatings – for concrete structures.

One of the results of this thesis is the work instruction created for civil engineers of Neste Jacobs. The instruction describes the passive fire protection design process in brief and the civil department responsibilities in more detail, including the scheme-guide, the example of critical temperature determination of steel beam and the example of using tabulated data (Method B) for the reinforced concrete column in accordance with (12).

7 Figures

8 Tables

9 List of references

1. Aaronite Group. Cementitious coatings are generally based on Portland cement plus lightweight aggregates.
http://www.aaronite.it/en/fireproofing/sprayed-light-cement/
(Accessed on 16.04.18)

2. Aaronite Group. Fires. A Hydrocarbon Fire.
http://www.aaronite.it/en/fireproofing/fires/
(Accessed on 28.04.18)

3. Abramov, A. 2014. Fireproofing of building metal structures.
http://security-info.com.ua/articles/?ELEMENT_ID=2326
(Accessed on 24.03.18)

4. Advance Matrix Contracting. Structural Steel Protection Systems.
http://www.advancematrix.com/service/structural-steel-protection-systems/#prettyPhoto
(Accessed on 30.04.18)

5. Boake, T.M., Boulanger, S. 2012. Architecturally exposed structural steel.
http://architecturenow.co.nz/articles/architecturally-exposed-structural-steel/#img=10
(Accessed on 30.04.18)

6. Bourbigot, S., Duquesne, S. 2010. Investigation of Intumescent Coatings for Fire Protection – Application to Jet-Fire.
https://ori-nuxeo.univ-lille1.fr/nuxeo/site/esupversions/de49df5a-0eb0-45a7-8084-828c6c08cd95
(Accessed on 6.05.18)

7. Bragin, V. 2015. Fire-resistance of concrete: impacts of high temperatures on horizontal concrete structures. Refractory concrete.
https://masterabetona.ru/betonirovaniye/321-ognestojkost-betona
(Accessed on 08.04.2018)

8. CompositeSolutions. Concrete-filled tubes.
https://composolutions.wordpress.com/research/lines-of-research/concrete-filled-tubes/
(Accessed on 30.04.18)

9. Deeny, S., Stratford, T., Dhakal, R.P, Moss, P.J., Buchanan, A.H. 2013. Spalling of Concrete: Implications for Structural Performance in Fire.
https://www.researchgate.net/publication/46047666_Spalling_of_concrete_Implications_for_structural_performance_in_fire
(Accessed on 24.04.18)

10. EN 1990. Eurocode: Basis of structural design.

11. EN 1991-1-2. Eurocode 1: General actions. Actions on structures exposed to fire.

12. EN 1992-1-2. Eurocode 2: Design of concrete structures. Part 1-2: General rules. Structural fire design.

13. EN 1993-1-2. Eurocode 3: Design of steel structures. Part 1-2: General rules. Structural fire design.

14. Fathalizadeh A. 2017. Introducing Concrete Filled Tube structural technology. Journal of Civil Engineering Researches, pp, 25 – 27.

15. Fire safety. Fireproofing of metal.
http://pb-russia.ru/doc/pb_info/Fire_of_Shield/
(Accessed on 28.04.18)

16. Fu, Y., Li, L. 2010. Study on mechanism of thermal spalling in concrete exposed to elevated temperatures.
https://www.politesi.polimi.it/bitstream/10589/123762/3/Concrete%20Modeling%20in%20Hot%20Conditions-Cracking%20Behavior%20and%20Material%20Stiffness%20Decay.pdf
(Accessed on 25.04.18)

17. Hager, I. 2013. Behaviour of cement concrete at high tempareture. Bulletin of the Polish Academy of Sciences, Technical Sciences.
https://www.researchgate.net/publication/237857451_Behaviour_of_cement_concrete_at_high_temperature
(Accessed on 25.04.18)

18. Hellenic Cement Industry Association. Concrete in fire conditions.
http://www.hcia.gr/en/cement-concrete/uses-concrete/mellon_skuro-dema_purkagia/
(Accessed on 01.05.18)

19. Helsel, J. 2016. Intumescent Coatings: A Review of Current and New Technologies.
https://ktauniversity.com/intumescent-coatings-technologies-review/
(Accessed on 24.03.18)

20. Himpark NORD. Fireproofing of concrete.
http://www.himpark.ru/s_ognezashhita_betona.html
(Accessed on 08.04.18)

21. Jotun. 2013. Jotachar JF750 brochure.
https://jotunimages.azureedge.net/images/images/Jotachar%20JF750_tcm48-48365.pdf
(Accessed on 05.04.18)

22. Liew, J.Y.R., Xiong, M. 2015. Design Guide for Concrete Filled Tubular Members with High Strength Materials

23. LPCD news. Epoxy Intumescent Coating Systems for Fire Protection. http://www.redbooklive.com/filelibrary/Articles/EPOXY_INTUMESCENT_COATING_SYSTEMS_FOR_THE_CORROSION_PROTECTION_AND_FIRE_PROTECTION_OF_STRUCTURAL_STEEL_~_IFJ.pdf (Accessed on 23.03.18)

24. Milovanov, A.F. 1998. Fire resistance of reinforced concrete structures. Moscow: Stroyisdat.

25. Morgan Advanced Materials. Morgan Advanced Materilas Gains EU Certification for Structural Steel Fire Protection System. 2017. http://www.morganadvancedmaterials.com/en-gb/media-centre/press-releases-morgan-issued/morgan-advanced-materials-gains-eu-certification-for-structural-steel-fire-protection-system/ (Accessed on 30.04.18)

26. Morgan. FireMaster Blankets. http://www.morganfireprotection.com/en-gb/products/firemaster-blankets/ (Accessed on 05.05.18)

27. Nedviga, E.S., Solovyova, K.I., Kiselev, S.S. 2015. Fire protection methods of building structures. Young Scientist (№ 24), pp. 160 – 163. https://moluch.ru/archive/104/24562/ (Accessed on 04.04.2018)

28. NEFTOK. Reasons of oil combustion and fire-fighting methods. https://neftok.ru/raznoe/gorenie-nefti.html (Accessed on 28.04.18)

29. Nikitin, V.A. Fireproofing of metal structures. http://www.ograx.ru/articles/publication/97/ (Accessed on 24.03.18)

30. Phan, L.T., McAllister, T.P., Gross, J.L., Hurley, M.J. 2010. Best Practice Guidlines for Structural Fire Resistance Design of Concrete and Steel Buildings. https://nvlpubs.nist.gov/nistpubs/technicalnotes/nist.tn.1681.pdf (Accessed on 30.04.18)

31. Rawlins. What Is An Intumescent and How Does Intumescent Paint Work. https://www.rawlinspaints.com/steel-intumescent-paint (Accessed on 24.03.18)

32. Research Institutes of Sweden. Fire resistance classes. https://www.sp.se/en/index/services/fire_classes/Sidor/default.aspx (Accessed on 04.05.18)

33. Scarborough, W.R. Fire-resistive Coatings. http://www.paintsquare.com/store/assets/201508_FireResistive.pdf (Accessed on 14.04.18)

34. Schneider, S.P., Alostaz Y.M. 1996. Connections to concrete-filled steel tubes. pp. 62 – 88.

35. SteelConstruction.info. Fire protecting structural steelwork. https://www.steelconstruction.info/Fire_protecting_structural_steelwork (Accessed on 31.03.18)

36. Ukranian steel conctruction center. Basics of the metalwork fire protection. https://www.uscc.ua/ru/tekhnicheskaya-podderzhka/konsalting-po-ognezashhite/deyatelnost (Accessed on 30.04.18)

37. Unifrax. http://www.unifrax.eu.com/web/goldminev2.nsf/ByUNID/AA2D17D0F8CA701A80257BB2005055AD?OpenDocument&msg= (Accessed on 05.05.18)

38. Wang, Y.C. 2014. Design Guide for Concrete Filled Hot Finished Structural Hollow Section (SHS) Columns. https://www.steelconstruction.info/images/8/85/CFT_Design_Guide_March_2014.pdf (Accessed on 30.04.18)

39. Wardenier, J., Packer, J.A., Zhao, X.-L., van der Vegte G.J. 2010. Hollow Sections in Structural Applications. http://212.150.245.105/shared/eBooks/Hollow_Sections_2nd_Edt.pdf (Accessed on 29.04.18)

40. Vassart, O., Zhao, B., Cajot, L.G., Robert, F., Meyer, U., Frangi, A. 2014. Eurocodes: Background & Applications Structural Fire Design. http://eurocodes.jrc.ec.europa.eu/doc/2012_11_WS_fire/report/2012_11_WS_fire.pdf (Accessed on 30.04.18)

41. Wikipedia. High-temperature insulation wool. https://en.wikipedia.org/wiki/High-temperature_insulation_wool (Accessed on 25.03.18)

42. Zibo Double Egret Thermal Insulation Co., Ltd. 2015. Insulation mechanism od insulation 50 mm foil ceramic blanket. http://www.ceceramicfiber.com/Article/Insulationmechanismo_1.html (Accessed on 05.05.18)

43. NSC. 2006. Intumescent fire protection of tall buildings. http://www.newsteelconstruction.com/wp/intumescent-fire-protection-of-tall-buildings/ (Accessed on 12.05.18)

Appendix 1. The overall overview of protection methods used for steel structures (27, 29, 30)

	Advantages	*Disadvantages*	*Application features (recommendations)*	*Applicability (hydrocarbon fire)*
Concrete encasement, *brick facings*	durability; good weather resistance (especially moisture resistance); protection against corrosion;	heavy weight; need for reinforcement; high labour intensity; repair and renewal complexity; cannot be used for fire protection of floor structures (trusses, beams) and bracing systems; space utilization (due to large protection thickness);	The method is virtually not used in structures built presently. It is applied in renovation and restoration works in order to strengthen structures.	No
Board facings, *sheet materials*	high vibration resistance achieved by means of mechanical fasteners; maintainability; good decorative, environmental and operational characteristics; no preparation of steel is necessary prior to applying the protection; dry application; thickness is guaranteed (boards/sheets are factory manufactured);	need for mounting fasteners by welding; not applicable for structures with a complex shape (trusses, bracing systems);	Generally used for structures with simple configuration (e.g. columns or beams).	No
Spray protection *(e.g. plasters)*	relatively low material cost; can be applied rapidly; can be used to cover complex shapes; highly resistant to impact and wear and tear;	undulating finish; decreased resistance to vibration; wet on-site application (depends on other site operations);	Delivered as dry mixtures and applied on surfaces after mixing with water. Application is carried out mechanically. Due to undulating finish, it is usually preferred in surfaces, which are hidden from view.	No

Flexible blanket systems	easy to install and remove; no mixing, dry application; can be used to cover complex shapes; no worries about applying proper thickness; low weight; good resistance against wear and tear;	poor appearance; relatively large thickness;	Blankets are wrapped around the structure. The blanket's flexibility enables it to be easily controlled around beams and fit into tight spaces.	Yes
Intumescent coatings/paints	can be applied off-site as well as on-site; good finish appearance; durability in severe jet-fire tests; resistant against wear and tear at practically all temperatures (especially epoxy based intumescents);	vulnerability to environmental exposure at the time of application; relatively high cost; labour-consuming application;	Can be applied for structures with any configuration.	Yes