Available online at www.ijournalse.org

**Emerging Science Journal**

(ISSN: 2610-9182)

Vol. 8, No. 1, February, 2024


# Analysis of the Heating of Steel Structures During Fire Load

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**Abstract**

During the preparation of our article, we present in detail the changes in the thermotechnical parameters of carbon steel and corrosion resistance during fire. After that, we present in detail the calculation of the heating of steel structures without fire protection. We feel this is important because it is not possible to provide stainless steel with fire protection for aesthetic reasons, and it is also not typical for thin-walled galvanized structures. We also present the calculation of structures with fire protection in detail and present the background for editing commonly used nomograms. Such a nomogram is also available in the literature, but it can be considered true with significant simplifications. During the practical planning, the applied fire protection regulations were highly standardized. Realizing that there is no design nomogram for these types of solutions, we created and published them in our article. The advantage of these is that the applicable design can also be found as the optimum of the designs considered to be potentially good. With this solution, we can save time during planning, and we can also get a more cost-effective solution for the fire protection cover. The advantage of the presented method is that, if required, the editing of the nomograms can be extended to other designs by knowing the material characteristics and the layer thickness. Another option of the presented method is that the solution can also be applied to special fire loads, and nomograms can be produced for them as well (e.g., hydrocarbon fires).

**Keywords:**

Steel Structures;
Carbon Seel;
Corrosion Resistant;
Fire Load;
Design Nomograms.

**Article History:**

| | | | |
|---|---|---|---|
| **Received:** | 12 | October | 2023 |
| **Revised:** | 24 | December | 2023 |
| **Accepted:** | 08 | January | 2024 |
| **Published:** | 01 | February | 2024 |

## 1- Introduction

According to the data of the Hungarian Central Statistical Office (KSH) [1], 45,602 fires occurred in Hungary in 2022. During these accidents, 112 people died and 923 were injured. We can complete these data with the statistics of MABISZ (Association of Hungarian Insurance Companies) [2]. In 2022, insurance companies paid out 6,503 million HUF to their retail customers (16.67 million € at an exchange rate of 390 HUF/€). This amount is an underestimate of the actual damage, as only 72–73% of residential properties are insured, resulting in lower claims. In addition, industrial damages are not included in this amount. Even a simple and inexpensive solution such as smoke alarms can effectively reduce injuries and fatalities. A significant proportion of injuries and deaths occur due to smoke inhalation and asphyxiation rather than direct fire exposure. Protecting our structures is a more complex task. The primary concern is to ensure that the health and lives of the occupants and the intervening firefighters are not put in danger. The issue of the reuse of structures after a fire is rarely addressed during our daily work. So, many of the damaged buildings have been demolished and are unsuitable for renovation. This approach is neither optimal from an economic point of view nor from

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**DOI:** http://dx.doi.org/10.28991/ESJ-2024-08-01-01

a primary raw material usage point of view. This approach is also not appropriate for priority installations, such as critical infrastructure networks. In this paper, we reflect on the fire protection of expensive steel structures, presenting a design method based on standard methods but meeting the requirements of practical praxis. It can use simple nomograms to shorten the design time, select the section with the optimum profile factor or the right fire protection coating, and adjust its thickness to provide extra resistance beyond the minimum resistance specified in the regulations. Based on scientific findings, this innovative approach is also having an impact on social and economic life [3].

The MSZ EN 1993-1-2:2013 standard presents the design of steel structures in cases of fire resistance (apart from the design of steel-concrete mule structures) [4]. As the knowledge on corrosion-resistant steels contained in this standard is incomplete, we supplemented this information with the guidelines of the Design Manual for Structural Stainless Steel, 4th edition [5]. In this paper, we have not examined martensitic corrosion-resistant steels, as their use is not generally associated with civil engineering. There are two options for a designer to quantify the fire load. The simplest option is the prescriptive method, which allows the average gas temperature to be determined without knowing the characteristics of the fire section. It is valid for all points in the fire section. The MSZ EN 1991-1-2:2005 standard [6] gives a nominal fire curve in the form of a closed formula for three cases. These are the standard, the external, and the hydrocarbon fire curves. In addition to these, practical life also requires the use of other special fire curves, which are not specified in the standard. In the case of the performance-based method, knowledge of the parameters specific to the fire stage is already required. The resulting gas temperature is a function of it. The standard [6] presents a simple parametric temperature-time curve and also describes the local fire load. It also mentions the use of complete fire models. In this paper, we do not deal in detail with the quantification of the fire load.

Fire protection planning is typically approached from the direction of structural design, and more and more complex models are used during planning [7–10]. This idea requires the designer to use special software. On the other hand, it is also possible to carry out the planning in a simpler way or even to take the fire effect into account during a preliminary design. The simplest way to do this is to use design nomograms, which are limited in the literature. Recognizing this deficiency, we also dealt in detail in our previous articles with the creation of nomograms applicable to the investigation of railway tunnel fires [11–13]. Whichever method the designer uses, knowledge of the necessary theoretical background is required. This knowledge is included in the fact that the book is limited only to the design of steel structures [14], while other authors provide information on several materials in their books [15]. It is advisable to supplement this knowledge with knowledge that is based on real laboratory measurements so that, for example, the operation of the combined fire protection cover can be better understood [16]. In this article, going beyond the editing of the general nomograms, we specifically provide them for the solutions used in practice in order to facilitate the selection of the applied fire protection solution. The flowchart of the design is illustrated in Figure 1.

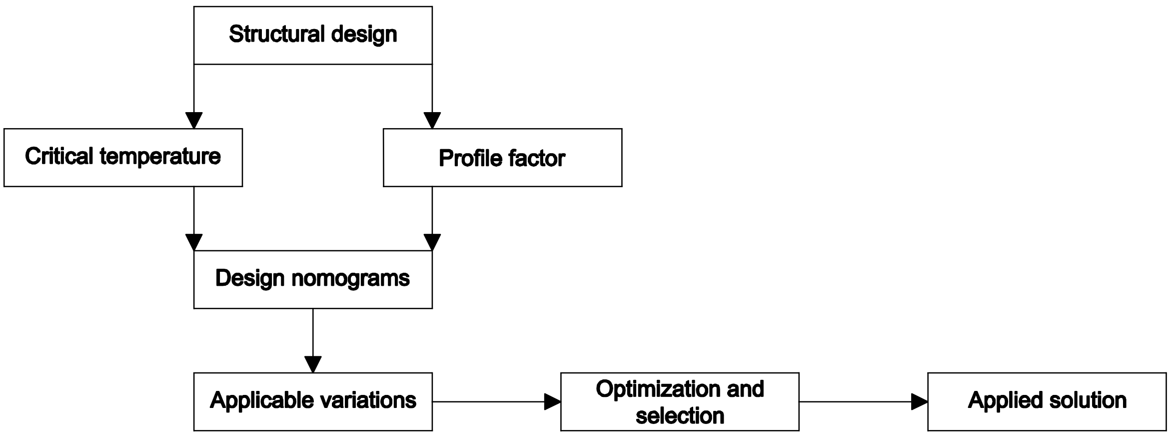


**Figure 1.** **Flowchart of the design procedure**

During the preparation of our article, we proceeded as recommended by the standards [4, 6]. Where we deviated from this, we indicated it in the text. In all cases, the deviations represented an approximation in favour of safety.

## 2- Changes in Thermal Parameters of Metals under Fire Effect

Fire changes not only the strength parameters but also the thermal properties of structural materials.

### *2-1- Thermal Conductivity Factor*

The coefficient of thermal conductivity is a general property of a material. This shows the rate at which heat entering the surface of the material can pass through the material. In case of carbon steel structures, the value of the thermal conductivity coefficient can be determined as a function of temperature, according to Equation 1 [4]:

If 20 °C ≤ $\theta_a$ < 800 °C:

$$\lambda_a = 54 - 3.33 \times 10^{-2} \times \theta_a \tag{1-a}$$

If 800 °C ≤ $\theta_a$ ≤ 1200 °C:

$$\lambda_a = 27.3 \tag{1-b}$$

where $\lambda_a$ is thermal conductivity of the steel [W/mK], $\theta_a$ is temperature of the steel [°C].

Equation 2 gives the evolution of the coefficient of thermal conductivity of corrosion-resistant steels as a function of temperature [4]. However, some research distinguishes between the types of corrosion-resistant steels [5]. Some literatures, recommended Equation 2 for austenitic and duplex steels, while others recommended Equation 3 for ferritic steels. The presented relationships are valid for $\theta_a$ ≤ 1200 °C.

$$\lambda_a = 14.6 + 1.27 \times 10^{-2} \times \theta_a \tag{2}$$

$$\lambda_a = 20.4 + 2.28 \times 10^{-2} \times \theta_a - 1.54 \times \ 10^{-2} \times \theta_a^2 \tag{3}$$

where $\lambda_a$ is thermal conductivity of steel [W/mK], and $\theta_a$ is temperature of the steel [°C].

Figure 2 illustrates the thermal conductivity of different types of steel as a function of the temperature.

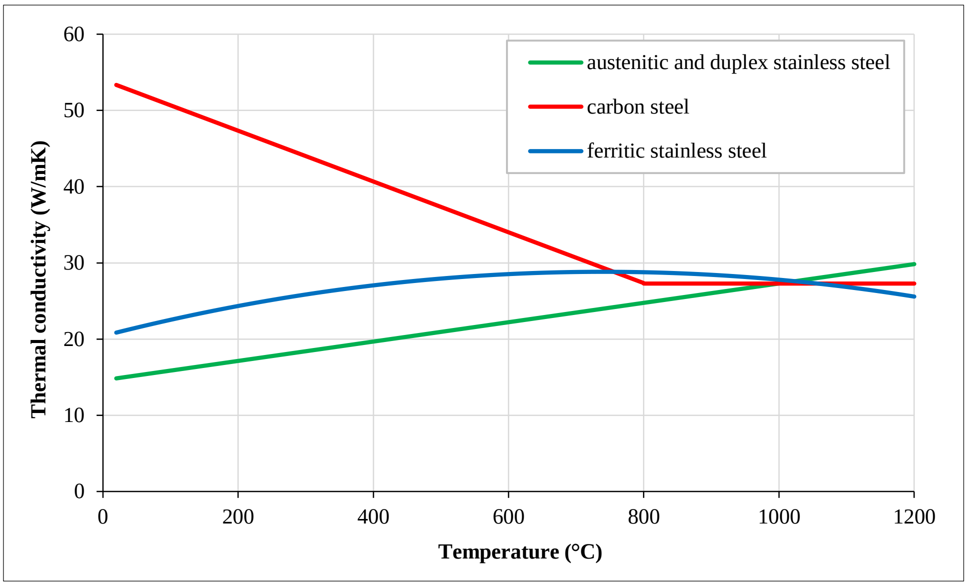


**Figure 2. Thermal conductivity of different types of steels as a function of material temperature**

### *2-2- Specific Heat*

The specific heat of a substance is the number of calories needed to raise the temperature of one gram by 1°C. In case of carbon steel structures, its value can be determined according to Equation 4 [4]:

If 20 °C ≤ $\theta_a$ < 600 °C:

$$c_a = 425 + 7.73 \times 10^{-1} \times \theta_a - 1.69 \times 10^{-3} \times \theta_a^2 + 2.22 \times 10^{-6} \times \theta_a^3 \tag{4-a}$$

If 600 °C ≤ $\theta_a$ < 735 °C:

$$c_a = 666 + \frac{13002}{738 - \theta_a} \tag{4-b}$$

If 735 °C ≤ $\theta_a$ < 900 °C:

$$c_a = 545 + \frac{17820}{\theta_a - 731} \tag{4-c}$$

If 900 °C ≤ $\theta_a$ ≤ 1200 °C:

$$c_a = 650 \tag{4-d}$$

where $c_a$ is specific heat of the steel (J/kgK), $\theta_a$ is temperature of the steel (°C).

Equation 5 gives the evolution of the specific heat as a function of temperature for corrosion resistant steels [4]. However, some literature distinguishes between the types of corrosion resistant steels [5]. Some literatures recommended Equation 5 for austenitic and duplex stainless steels, while other recommended Equation 6 for ferritic stainless steels. The presented relationships are valid for $\theta_a \leq 1200$ °C.

$$c_a = 450 + 0.28 \times \theta_a - 2.91 \times 10^{-4} \times \theta_a^2 + 1.34 \times 10^{-7} \times \theta_a^3 \quad (5)$$

$$c_a = 430 + 0.26 \times \theta_a \quad (6)$$

Figure 3 illustrates the relationship between specific heat and temperature for different types of steels.

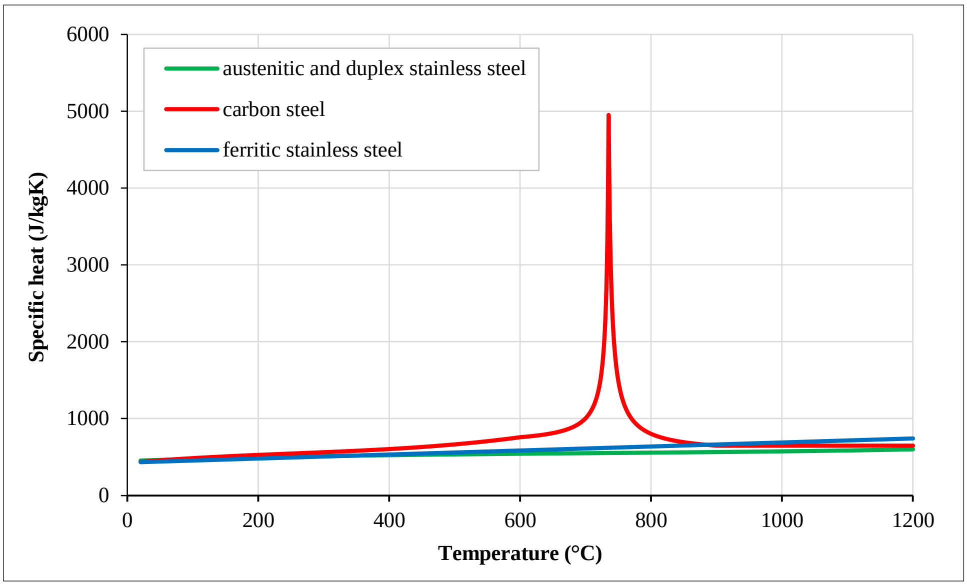


**Figure 3. Specific heat of different types of steel as a function of material temperature**

### *2-3- Density*

According to the standards the density of structural materials is independent from the temperature of the material. In case of steels, the standard is 7850 (kg/m$^3$) [4], which can be used for carbon steels. For corrosion resistant steels, the value for carbon steels should be used [4]. Other literature gives more precise values. We summarised them in Table 1 [5].

**Table 1. Density of corrosion resistant steels**

| Quality of material | Type | Density (kg/m$^3$) |
|---|---|---|
| 1.4301 | Austenitic | 7900 |
| 1.4307 | | 7900 |
| 1.4401 | | 8000 |
| 1.4318 | | 7900 |
| 1.4404 | | 8000 |
| 1.4541 | | 7900 |
| 1.4571 | | 8000 |
| 1.4062 | Duplex | 7800 |
| 1.4162 | | 7700 |
| 1.4362 | | 7800 |
| 1.4482 | | 7800 |
| 1.4462 | | 7800 |
| 1.4662 | | 7700 |
| 1.4003 | Ferritic | 7700 |
| 1.4016 | | 7700 |
| 1.4509 | | 7700 |
| 1.4521 | | 7700 |
| 1.4621 | | 7700 |

## 3- Steel Structures without Protection

Practical designs have shown that unprotected steel structures can provide about 15 minutes fire resistance. This statement is true. This is also acceptable in case of structures, such as the increasingly common cold-formed Z and C elements of cross-section class 4. They are suitable on a cell-by-cell basis, especially as their load-bearing capacity does not cause a progressive failure process, so they do not break down. By changing their static frame, they can continue to function as rope curves, with ever-increasing deformations. However, designers often do not take into account that these elements are also integrated into the bracing system of the structure. However, in this case, they must already meet increased fire resistance requirements and cannot be allowed to behave in a rope curve. So, it may be necessary to abandon their use and revert to the use of traditional rolled sections. This is also justified by the fact that these elements are manufactured in a galvanised finish for weight reduction and "maintenance-free" corrosion protection. For this reason, we can only apply reactive fire protection to them if their calculated critical temperature is below the melting point of zinc. The critical temperature in case of elements of Class 4 cross-section is 350 °C, without static testing. A more precise calculation is also possible, but in this case, the designer has to pay attention to every detail. If the design is not precise, it is also possible that the reactive fire protection that foams on the molten anchor layer will drop off the structural element and not prevent it from heating up.

The other practical use of unprotected structural elements comes from the architectural concept. In this case the designer tries to show the structure with its "pure metal" appearance. In this case, they often prefer to use corrosion-resistant steels, but fire protection is not possible in this form. As shown in the examples, the study of the heating of unprotected metal structures cannot be neglected. So, we discuss the issue in the paper with similar thoroughness as the examination of structures with protection. In case of practical calculation, we present a method to determine the temperature change of a structural element in small time steps [4]. It is recommended to perform the calculation in a spreadsheet program, as it is necessary to handle a huge amount of data to the calculation. The change in temperature can be calculated with Equation 7. According to the Standard [4], the magnitude of the time step for testing an unprotected structural element is Δt = 5 [s].

$$\Delta\Theta_{a,t} = \mathrm{k}_{sh} \times \frac{1}{c_a \times \rho_a} \times \frac{A_m}{V} \times \dot{h}_{net,d} \times \Delta\mathrm{t} \quad (7)$$

where $\Delta\theta_{a,t}$ is temperature change of the steel (°C), $k_{sh}$ is factor for the shadow effect (-), $c_a$ is specific heat of steel (J/kgK), $\rho_a$ is density of the steel (kg/m$^3$), $A_m/V$ is profile factor (1/m), $h_{net,d}$ is design value of heat flux per unit area (W/m$^2$), and Δt is time step (s).

The shadow effect can be calculated in case of I-sections, according to Equation 8. For other sections, Equation 9 is recommended to use.

$$\mathrm{k}_{sh} = 0.9 \times \frac{(A_m/V)_{box}}{A_m/V} \quad (8)$$

$$\mathrm{k}_{sh} = \frac{(A_m/V)_{box}}{A_m/V} \quad (9)$$

where $k_{sh}$ is factor to take into account the shadow effect (-), $A_m/V$ is profile factor (1/m), $(A_m/V)_{box}$ is the coupon factor of the inclusion node (1/m).

The standard [4] allows the shadow effect to be ignored in order to increase the safety. In this case, the relation in Equation 7 is simplified to the relation in Equation 10.

$$\Delta\Theta_{a,t} = \frac{1}{c_a \times \rho_a} \times \frac{A_m}{V} \times \dot{h}_{net,d} \times \Delta\mathrm{t} \quad (10)$$

where the legend is the same as in Equation 7.

In practice, we can calculate the profile factor of an unprotected section as the ratio of the perimeter exposed to fire to the cross-sectional area of the section. When the section is connected to a slab, or to a wall, the fire perimeter is reduced accordingly. The calculation principle of the profile factor is illustrated in Figure 4. The $A_m/V$ value should not be less than 10 (1/m).

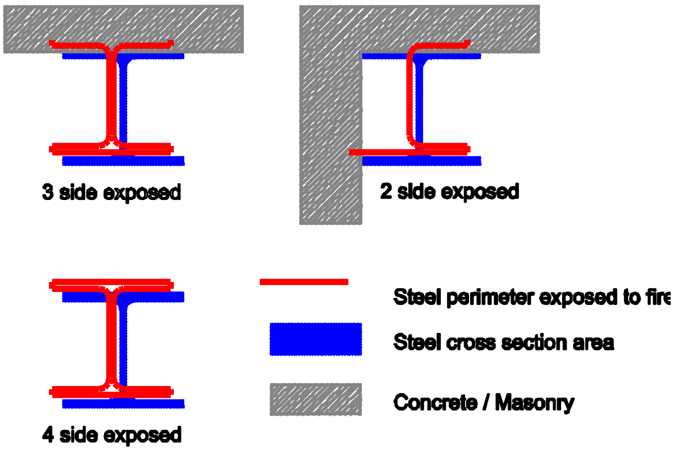


**Figure 4. Calculation principle of the profile factor in case of unprotected structural elements**

The design value of the heat flux per unit area can be determined from [6] using Equation 11. The design value is calculated as the sum of the radiative and convective components of the heat flux. We determined the radiative component according to Equation 12 and the convective component according to Equation 13:

$$\dot{h}_{net,d} = \dot{h}_{net,r} + \dot{h}_{net,c} \tag{11}$$

$$\dot{h}_{net,r} = \sigma \times \Phi \times \varepsilon_f \times \varepsilon_m \times [(\Theta_r + 273)^4 - (\Theta_m + 273)^4] \tag{12}$$

$$\dot{h}_{net,c} = \alpha_c \times \left(\Theta_g - \Theta_m\right) \tag{13}$$

where $h_{net,d}$ is the design value of heat flux per unit area (W/m$^2$), $h_{net,r}$ is the radiative component of the heat flux (W/m$^2$), $h_{net,c}$ is convection component of the heat flux (W/m$^2$), $\alpha_c$ is the convective heat transfer coefficient (W/m$^2$K), $\Theta_m$ is the surface temperature of the structural element (°C), σ is the Boltzmann constant (W/m$^2$K$^4$), Φ is the layout factor (-), $\varepsilon_m$ is the surface emissivity of the structural element (-), $\varepsilon_f$ is emission factor of the fire (-).

The values of each parameter are as follows:

- as conservative approximations with Φ=1.0 and $\varepsilon_f$=1.0 value,
- the Boltzmann constant is 5,67×10$^{-8}$ W/m$^2$K$^4$.

We summarized the values of the convective heat transfer coefficient in Table 2. We presented the values for the surface emissivity of the structural element in Table 3.

**Table 2. Convective heat transfer coefficient values**

| Fire curve | $\alpha_c$ (W/m$^2$K) | Source |
|---|---|---|
| Standard | 25 | [6] |
| ASTM E119 | 25 | * |
| External | 25 | [6] |
| Smoulder | 25 | ** |
| Hydrocarbon | 50 | [6] |
| Modified hydrocarbon | 50 | *** |
| RABT-ZTV road | 50 | |
| RABT-ZTV rail | 50 | |
| Eureka 90 | 50 | |
| Eureka 120 | 50 | |
| RWS | 50 | |
| Parametric | 35 | [6]**** |
| Local fire | 35 | |

* The curve is actually the same as the standard fire curve;
** The curve shows similar properties to the standard fire curve;
*** Technically hydrocarbon fire curves;
**** Can be considered as a simple fire model.

**Table 3. Surface emission factors of structural elements**

| Structural material | $\varepsilon_m$ (-) | Source |
|---|---|---|
| Carbon steel | 0.7 | [2] |
| Galvanised carbon steel | vary according to temperature | [5] |
| Corrosion-resistant steel | 0.4 | [2] |

Jirku & Wald [17] examined the change in the surface emissivity of galvanized structures during a fire test. Their analysis showed that the emission factors up to 450 °C can be taken into account with a value of 0.32. Then, as the molten zinc flows down, the original surface will be revealed, with an emissivity of 0.70. It should be noted that galvanizing is not a fireproof coating, but it can delay the heating of structural steel. For this reason, it is useful to include the effect of galvanizing in the calculation of the thin-walled, hot-dip galvanized structures. It should be noted that the EC standard [4] does not mention this.

During the research, we implemented a calculation procedure in MS Excel. It allows the automated generation of nomograms for the design of fire curves for the structural materials and prescriptive methods under consideration. In the case of performance-based firing processes, the large number of parameters makes the creation of nomograms pointless.

Due to space limitations, we present only three typical nomograms in this paper:

- Unprotected carbon steel structures with an ISO 834 fire curve,
- Unprotected galvanized carbon steel structures for the ISO 834 fire curve,
- Unprotected 1.4301-grade austenitic corrosion-resistant steel structures with an ISO 834 fire curve.

In the nomograms, the individual curves are generated based on the $A_m/V$ parameter. The parameter takes a value between 10 and 400 [1/m] in all cases.

The nomogram in Figure 5 illustrates the sizing curves in the case of unprotected carbon steel structures. It can be seen that in all cases, the graphs have a plateau at temperatures around 735 °C. This is due to the fact that, as illustrated in Figure 5, the specific heat of carbon steel is singular as a function of temperature. The heat input here is not used to raise the temperature of the steel but to transform the crystal structure.

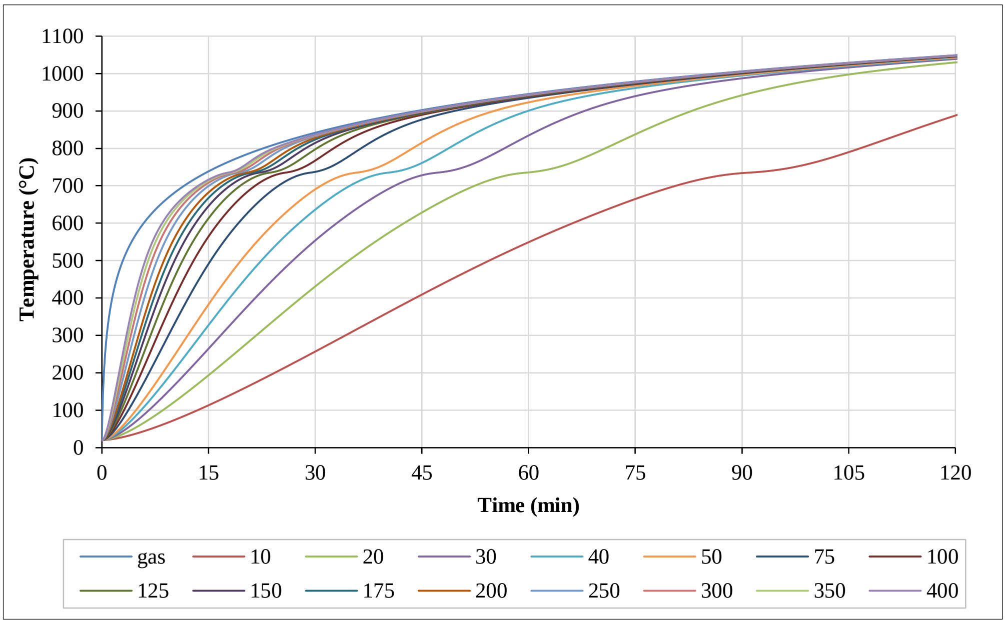


**Figure 5. Design nomogram for standard fire load in case of carbon steel structures - unprotected structural elements**

The nomogram in Figure 6 illustrates the sizing curves in case of unprotected galvanized carbon steel structures. It can be seen that in all cases, at temperatures around 735 °C, the graphs have a platea, as we can see it in Figure 10. Here we also observe a new break in the curves at 400 °C. The reason for this is that the destruction of the anchor layer is taken into account here. The surface emissivity changes from 0.32 to 0.70. It causes faster heating in the temperature zone above 400 °C.

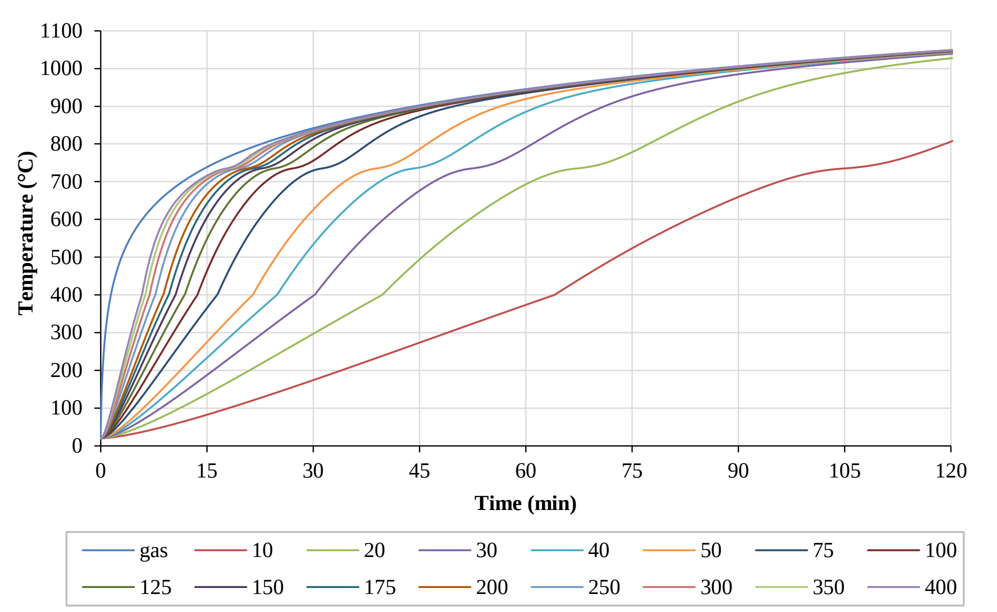


**Figure 6. Design nomogram for standard fire load in case of galvanized carbon steel structures - unprotected structural elements**

The nomogram shown in Figure 7 illustrates the sizing curves in the case of unprotected 1.4301-grade austenitic corrosion-resistant structures. It can be seen that these curves are continuous. This is because we can describe the temperature variation of the material properties with a continuous function. The surface emissivity is also constant during the firing process.

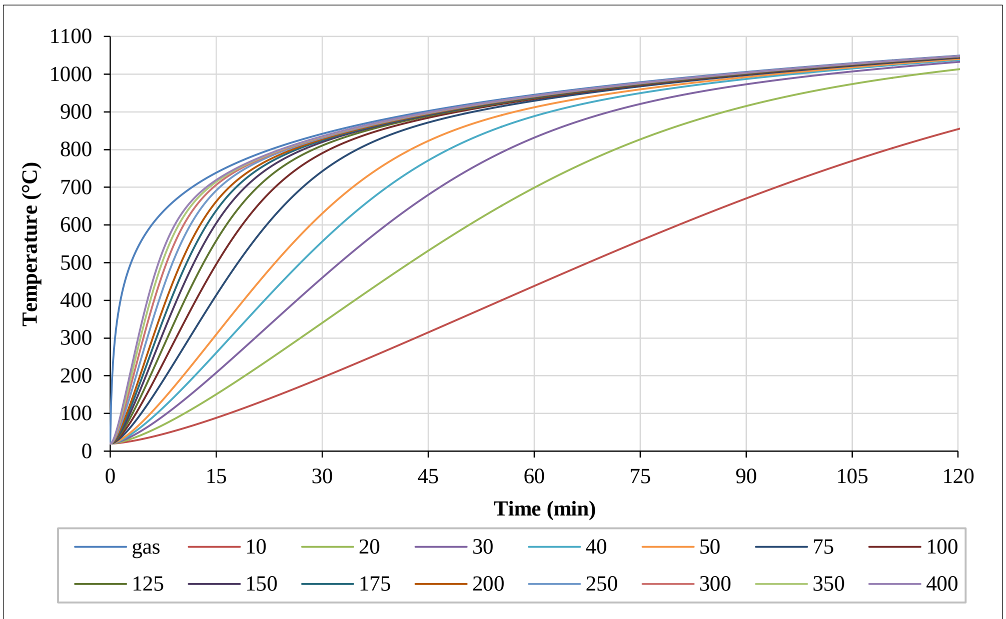


**Figure 7. Design nomogram for standard fire load for 1.4301 grade austenitic corrosion resistant steel structures - unprotected structural elements**

## 4- Protected Metal Structures

As we mentioned above, steel structures without the application of a fire protection coating or encasement can be proven to withstand a fire for approximately 15 minutes. As our supporting structures must be able to withstand longer periods in case of fire load, it is essential to provide appropriate fire protection. In addition to economic and technical aspects, aesthetic considerations are also important in the case of design. Eurocode also includes the calculation of the heating of protected structural elements [4]. For practical calculation, the standard presents a similar method as for unprotected structures. Accordingly, we determined the change in temperature of a structural element in minor steps. The calculations should be performed in a spreadsheet program, as large amounts of data need to be handled for the calculations.

We can calculate the temperature variation according to equation 14, taking into account the condition in Equation 15. According to the standard, the magnitude of the time step for testing a protected structural element is Δt = 30 (s).

$$\Delta\Theta_{a,t} = \frac{\lambda_p/d_p}{c_a \times \rho_a} \times \frac{A_p}{V} \times \left(\frac{1}{1+\phi/3}\right) \times \left(\Theta_{g,t} - \Theta_{a,t}\right) \times \Delta t - \left(e^{\phi/10} - 1\right) \times \Delta\Theta_{g,t} \tag{14}$$

$$\text{but} \quad \Delta\Theta_{a,t} \geq 0 \quad \text{in case of, when} \quad \Delta\Theta_{g,t} > 0 \tag{15}$$

where $\Delta\theta_{a,t}$ is changes in steel temperature (°C), $c_a$ is specific heat of steel (J/kgK), $\rho_a$ is density of the steel (kg/m$^3$), $\lambda_p$ is thermal conductivity of the fire retardant (W/mK), $d_p$ is thickness of the fire protection material (m), $A_p/V$ is profile factor (1/m), Φ is relative thermal performance of the fire protection material (-), $\Theta_{g,t}$ is gas temperature at time instant "t" (°C), $\Theta_{a,t}$ is temperature of the steel at time "t" (°C), $\Delta\theta_{g,t}$ is change in gas temperature (°C), Δt is magnitude of the time step [s].

The relative thermal storage of the fire retardant can be determined from Equation 16.

$$\phi = \frac{c_p \times \rho_p}{c_a \times \rho_a} \times d_p \times \frac{A_p}{V} \tag{16}$$

where Φ is relative thermal storage of the fire retardant (-), $c_p$ is temperature-independent specific heat of the fire retardant (J/kgK), $\rho_p$ is density of the fire retardant (kg/m$^3$), $c_a$ is specific heat of steel (J/kgK), $\rho_a$ is density of the steel (kg/m$^3$), $d_p$ is thickness of the fire protection material (m), $A_p/V$ is a profile factor (1/m).

When the relative thermal storage of the fire retardant is neglected, the heating of the structural element can be determined by Equation 17, considering safety and the caveat in Equation 15. This equation only includes the thermal conductivity of the fire retardant in the thermal parameters of the material. This is fortunate because often all the parameters are not available for the design. It also simplifies the creation of design nomograms, as we will show later. However, this conservative approach can lead to significant over-planning.

$$\Delta\Theta_{a,t} = \frac{\lambda_p/d_p}{c_a \times \rho_a} \times \frac{A_p}{V} \times \left(\Theta_{g,t} - \Theta_{a,t}\right) \times \Delta t \tag{17}$$

$$\text{but} \quad \Delta\Theta_{a,t} \geq 0 \quad \text{in case of, when} \quad \Delta\Theta_{g,t} > 0 \tag{15}$$

where $\Delta\theta_{a,t}$ is temperature change of the steel (°C), $c_a$ is specific heat of steel (J/kgK), $\rho_a$ is density of the steel (kg/m$^3$), $\lambda_p$ is thermal conductivity of the refractory material (W/mK), $d_p$ is thickness of the fire protection material (m), $A_p/V$ is profile factor (1/m), $\Theta_{g,t}$ is gas temperature at time instant "t" (°C), $\Theta_{a,t}$ is temperature of the steel at time "t" (°C), Δt is size of the time step [s].

After rearranging Equation 17, we obtain the Equation 18. After examining it, it is visible that the quantities specific to fire protection can be combined as shown in Equation 19. Using this auxiliary quantity, we arrive at Equation 20.

$$\Delta\Theta_{a,t} = \frac{\lambda_p}{d_p} \times \frac{A_p}{V} \times \frac{1}{c_a \times \rho_a} \times \left(\Theta_{g,t} - \Theta_{a,t}\right) \times \Delta t \tag{18}$$

$$\xi = \frac{\lambda_p}{d_p} \times \frac{A_p}{V} \tag{19}$$

$$\Delta\Theta_{a,t} = \xi \times \frac{1}{c_a \times \rho_a} \times \left(\Theta_{g,t} - \Theta_{a,t}\right) \times \Delta t \tag{20}$$

where $\Delta\theta_{a,t}$ is changes in steel/aluminium temperature (°C), ξ is auxiliary quantity (W/m$^3$K), the other parameters are the same as in Equation 17.

The great advantage of Equation 20 is that, in this form, it allows the generation of design nomograms. During the research, we developed a computational procedure implemented in MS Excel in order to automate the generation of design nomograms for the structural materials and prescriptive method fire curves under consideration. In the case of performance-based firing processes, the large number of parameters makes the creation of nomograms pointless. Due to space limitations, we present only one typical nomogram in this paper. This illustrates the heating of a carbon steel structural element under standard fire conditions.

In the nomogram, the individual curves are generated based on the parameter ξ. The parameter takes a value between 100 and 5000 (W/m$^3$K). We illustrated the resulting nomogram in Figure 8.

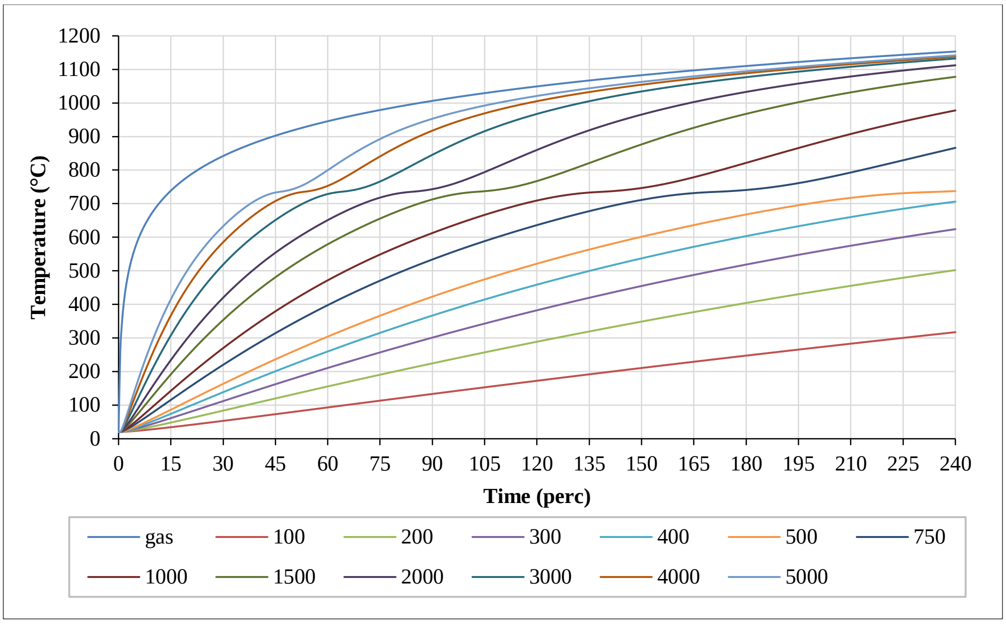


**Figure 8.** **Design nomogram for standard fire load for carbon steel structures - structural elements with protection**

In practice, we can calculate the profile factor of a protected section as the ratio of the inner perimeter of the fire protection envelope to the cross-sectional area of the section. In the case of profile-tracking fire protection, we can determine the profile factor according to the principles shown in Figure 4. The calculation principle of the profile factor for a box design is illustrated in Figure 9. The gap dimensions $c_1$ and $c_2$ in the figure must not exceed h/4.

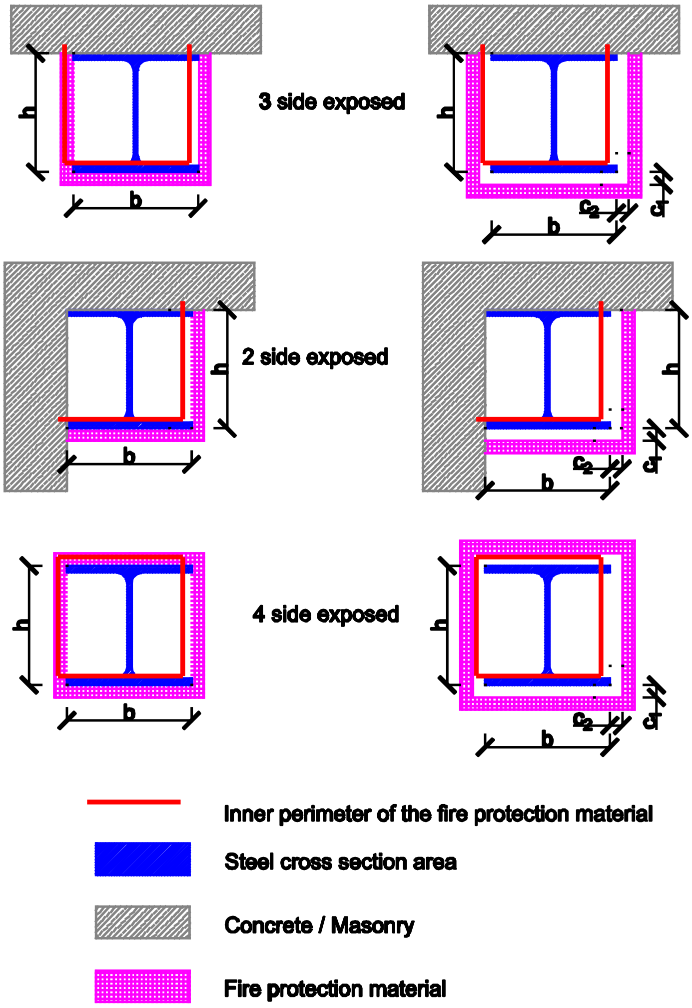


**Figure 9.** **Calculation principle of the profile factor in case of structural elements with protection**

In practice, there are two typical ways to design the protection. If we use encasement, it is possible to dispose of the structure. This can be seen on the left side of Figure 10. It is also possible to use fire protection mortar to provide box protection (not possible with filled-out encasement), as shown on the right side of Figure 10.

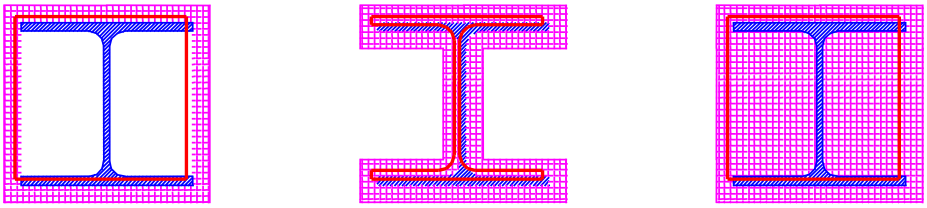


**Figure 10. Design options for fire protection**

With regard to fire retardants, manufacturers' products can be divided into two main categories. There are reactive and passive fire retardants. The reactive (swelling) materials foam at 220-250 °C to form a carbon-based foam. This protects the structure from heating up. The thickness of the dry layer applied to the structure varies from a few tenths of a millimeter to a few millimeters. The thickness of the insulating layer formed by foaming during the fire can be 40–60 times the original dry layer thickness.

We have to take care during the design, as foaming has a space requirement that must be provided; otherwise, we cannot achieve the intended layer thickness and fire protection [18]. Another important design issue is hot dip galvanizing. If the critical temperature of the structure exceeds the melting point of zinc, then the foaming material slips through the anchor layer and flows off the protected structure [19]. The low weight and aesthetic appearance of the protection system are advantages of using reactive materials. These are often not negligible considerations in the case of visible structural elements. They typically provide a fire resistance limit of R15–R120 [18]. Passive fire protection materials are installed with a constant layer thickness. This includes various fire protection mortars and coatings [18]. These also include the protection of steel structures by encasing them in concrete or sheeting.

These techniques were already in conscious use before the advent of modern dimensioning methods. The used layer thicknesses are typically in the range of 8–60 mm and typically provide a fire resistance limit of R15–R240. We can design the slabs with a higher self-weight than mortar protection with a lower body density. In the case of mortar, the surface is usually rustic and less aesthetically demanding, but with the right technology, we can achieve a smooth surface. The use of tiles gives a more aesthetic surface [18]. The thermal parameters of the fire retardants are also required for the application of Equations 14 and 17 of the presented calculation method. These are often limited for designers, so we have tried to provide information on the materials. Table 4 summarizes the material properties [14].

**Table 4. Thermal parameters of fire retardants (1)**

| Material | Specific heat (J/kgK) | Thermal conductivity (W/mK) | Density (kg/m$^3$) |
|---|---|---|---|
| Intumescent coatings | 1200 | 0.10 | 100 |
| Sprayed mineral fiber coating | 1200 | 0.12 | 300 |
| Sprayed vermiculite coating | 1200 | 0.12 | 350 |
| Sprayed perlite coating | 1200 | 0.12 | 350 |
| Sprayed vermiculite (perlite) and cement thick coating | 1100 | 0.12 | 550 |
| Sprayed vermiculite (perlite) and gypsum thick coating | 1100 | 0.12 | 650 |
| Vermiculite (perlite) and cement board | 1200 | 0.20 | 800 |
| Calcium silicate fiber board | 1200 | 0.15 | 600 |
| Calcium silicate fiber and cement board | 1200 | 0.15 | 800 |
| Plasterboard | 1700 | 0.20 | 800 |
| Compressed fiber boards (mineral wool, basalt wool) | 1200 | 0.20 | 150 |
| Normal concrete | 1000 | 1.60 | 2300 |
| Lightweight concrete | 840 | 0.80 | 1600 |
| Hollow brick masonry | 1200 | 0.40 | 1000 |
| Solid brick masonry | 1200 | 1.20 | 2000 |
| Concrete block masonry | 1200 | 1.00 | 2200 |

While collecting data, we came across a paper written by Król [20], where it details the characteristics of fireproofing materials for historic steel-beam slab structures. We summarized the materials in this paper and their thermal parameters in Table 5.

**Table 5. Thermal parameters of fire retardants (2)**

| Material | Specific heat (J/kgK) | Thermal conductivity (W/mK) | Density (kg/m³) |
|---|---|---|---|
| normal concrete | 840 | 1.70 | 2400 |
| cement mortars | 840 | 1.00 | 2000 |
| lime - cement mortar | 840 | 0.82 | 1850 |
| lime mortar | 840 | 0.70 | 1700 |
| gypsum mortar | 840 | 0.52 | 1300 |

As we pointed out earlier, nomograms constructed under the used approximations tend to be safe. However, the extent of this approximation may become excessive and result in uneconomically oversized fire protection. The relative thermal conductivity (Φ) of the fireproofing material (such as concrete) can be significant in the case of materials with high density and high layer thicknesses. Designed with a single layer of mesh reinforcement, it can be used in thicknesses of up to 80 mm. To draw attention to the magnitude of the difference, we have created an illustrative pair of nomograms. We made the diagrams taking into account the material properties according to Table 4 for the inspection of concrete pavements with a layer thickness of 80 mm. Figure 11 illustrates the case where relative heat storage is not considered, while Figure 12 illustrates the case where it is considered. In the nomograms, the individual curves are generated based on the $A_p/V$ parameter. The parameter takes a value between 10 and 500 (1/m) in all cases.

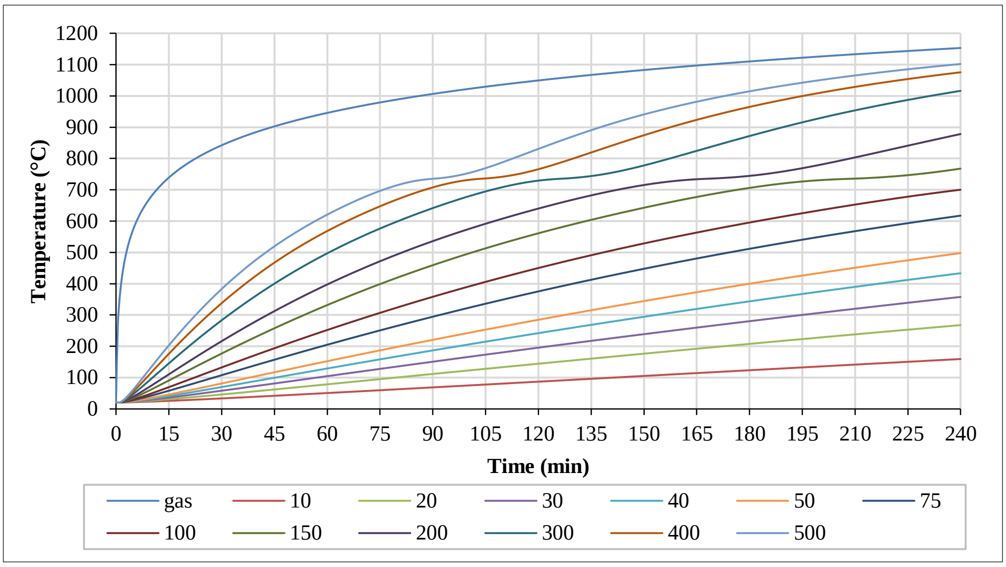


**Figure 11. Design nomogram for standard fire load in case of carbon steel structures - 80 mm concrete protection - without consideration of relative thermal storage**

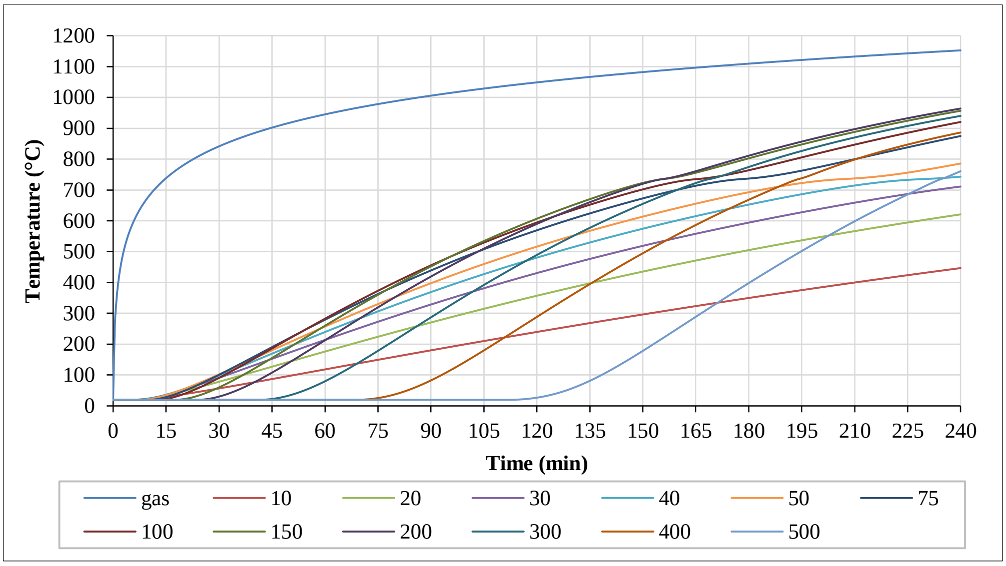


**Figure 12. Design nomogram for standard fire load in case of carbon steel structures - 80 mm concrete protection - taking into account relative thermal storage**

As we can see in Figure 12, the temperatures of the structural elements are significantly lower than the determined elements in Figure 11. Another striking difference is that in Figure 12, a plateau appears for a significant period of time at 20 °C in terms of the developed temperatures. This is due to the application of the clause in Equation 15.

It is easy to see how much more accurate nomograms can be constructed by taking into account real material properties and relative heat storage than those available in the literature. However, the implication of it is that there must be more nomograms than in the case of the uniform solution. In order to facilitate the everyday work of designers, we have developed sizing nomograms for the types of solutions commonly used in practice. We have taken into account here the material characteristics and the relative thermal storage according to Table 4.

The tested designs are:

- 80 mm concrete cover (see Figure 12),
- 120 mm solid brick masonry (see Figure 13),
- 12.5 mm (layer 1) plasterboard sheet (see Figure 14),
- 25.0 mm (layer 2) plasterboard sheet (see Figure 15),
- 30.0 mm (layer 1) calcium silicate fiber board (see Figure 16),
- 25.0 mm (1 mm dry film thickness) intumescent coating (see Figure 17)

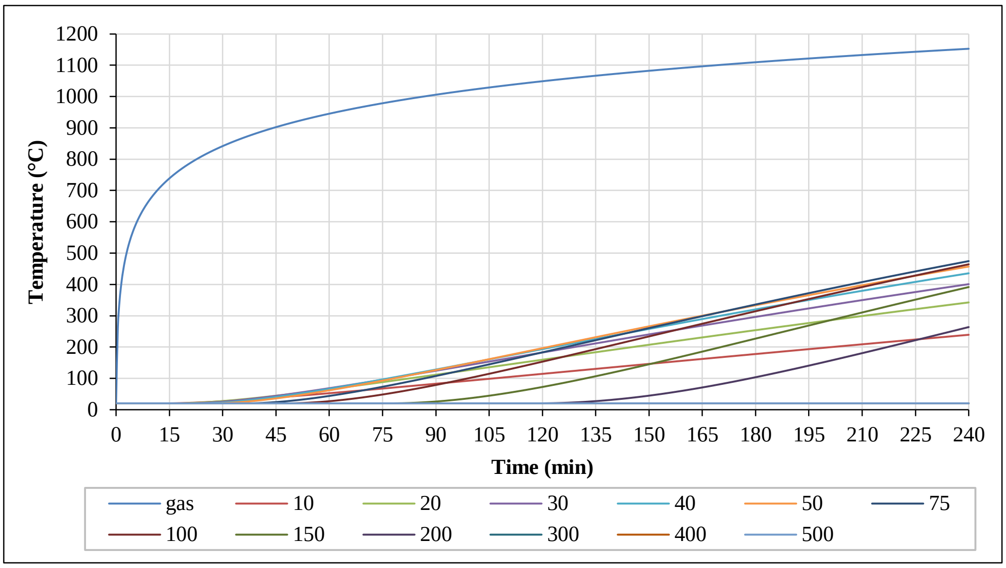


**Figure 13.** Design nomogram for standard fire load in case of carbon steel structures - 120 mm solid brick masonry - with relative heat storage

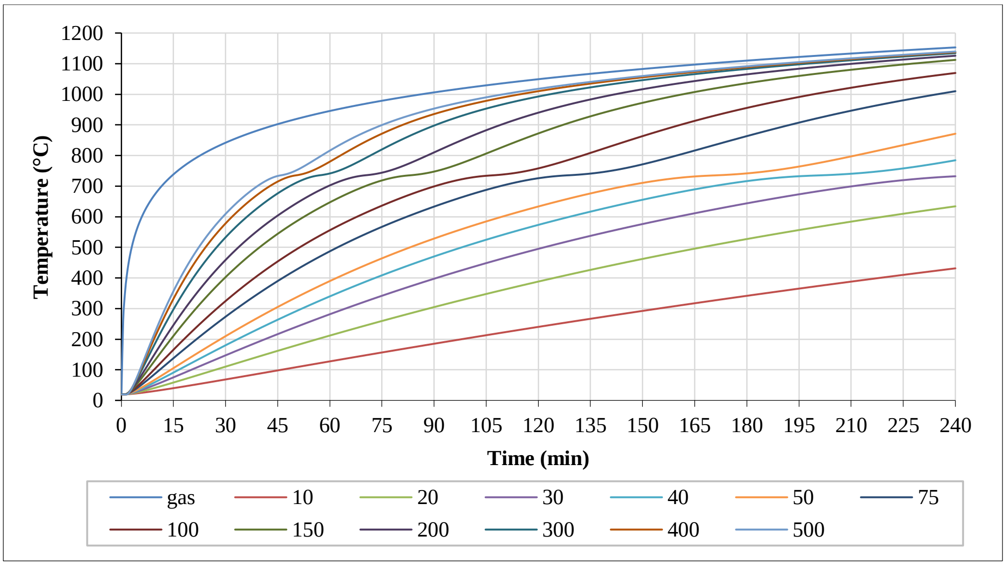


**Figure 14.** Design nomogram for standard fire load in case of carbon steel structures - 12.5 mm gypsum plasterboard - taking into account relative thermal storage

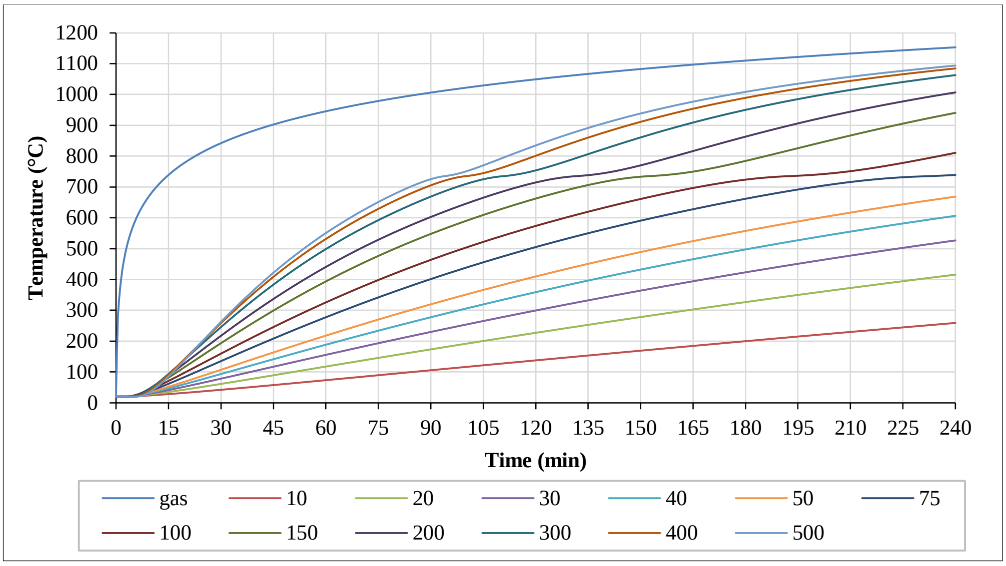


**Figure 15.** Design nomogram for standard fire load for carbon steel structures - 25.0 mm gypsum plasterboard - taking into account relative thermal storage

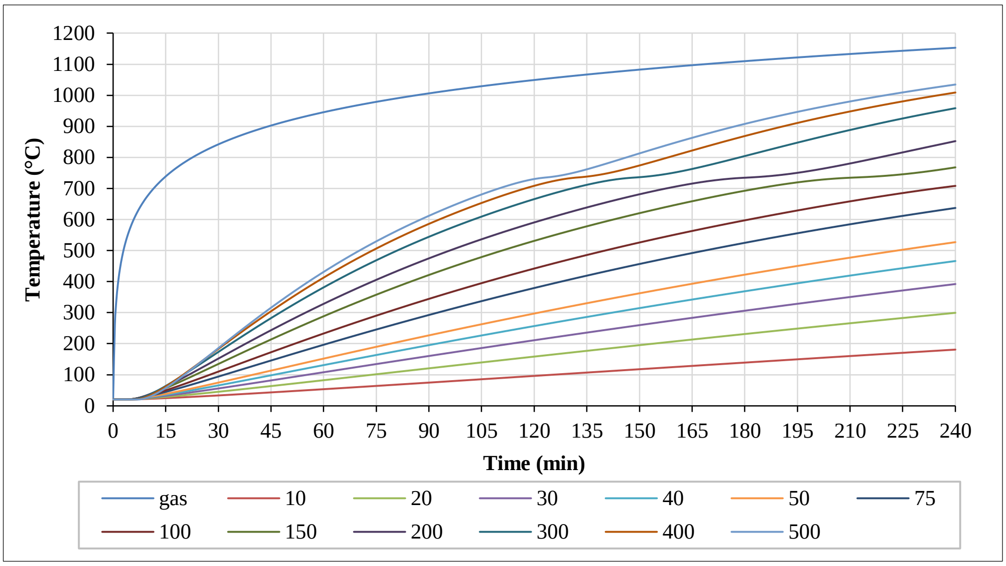


**Figure 16.** Design nomogram for standard fire load in case of carbon steel structures - 30.0 mm calcium silicate fiber board - taking into account relative thermal storage

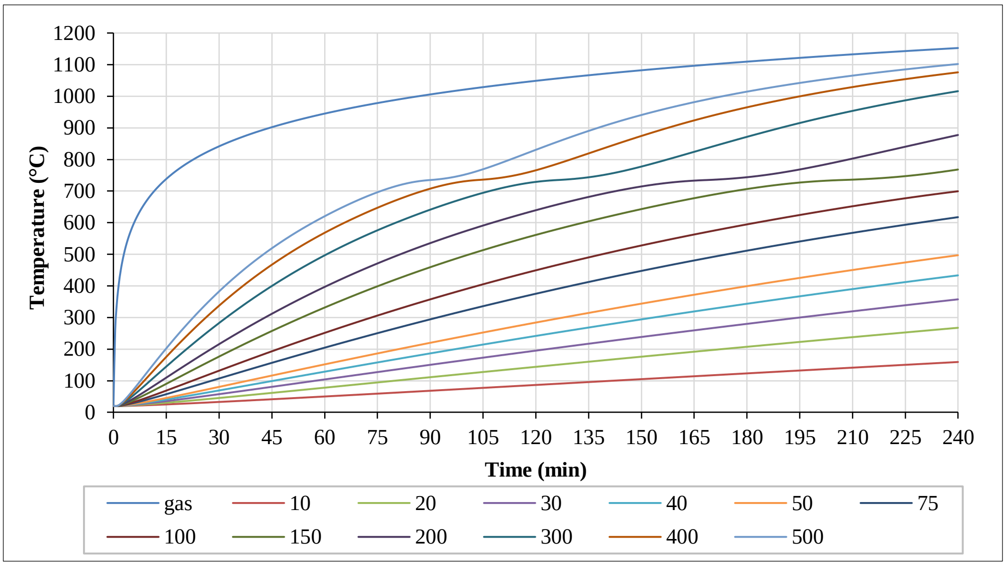


**Figure 17.** Design nomogram for standard fire load in case of carbon steel structures - 25.0 mm intumescent coating - taking into account relative thermal storage

Limitations of the presented method and nomograms:

- When editing each nomogram, we took into account the material characteristics listed in Table 4, which are also recommended by the ECCS.
- It is also possible to edit the nomograms with values other than these. These can be validated based on laboratory tests [16].
- The effect of the water content on fire protection was not investigated. This is also a possibility, which is presented in detail in several studies [13, 14].

In the case of swellable paint, we have used an approximation of 25 times the original dry film thickness for the firing.

As can be seen in the presented design nomograms, the neglect of relative heat storage in all cases indicates an approximation in favor of safety. If the fire protection performance of the structure can be verified in this way, no further examination is necessary. On the other hand, in cases where compliance cannot be demonstrated to a small extent, it is worthwhile to use the new nomograms presented in our article during planning and use them to verify the compliance of the structure. In the case of low relative heat storage, these graphs hardly differ from the one edited without consideration, but in cases where this value is high, a significant difference can be observed. In order to verify the adequacy of the graphs, we used the Heat Transfer freeware program [21], which provided similar results. In order to further develop the method, we also want to take into account the effect of the water content in the fire protection materials, the possible effect of which has already been presented in the case of tunnel fires [13].

## 5- Conclusion

During the research, after a short introduction, we have analyzed the thermal parameters of different steels (carbon and corrosion-resistant) and their changes at high temperatures due to fire load. After that, we discussed the calculation possibilities and difficulties of heating unprotected and protected steel structures according to standards. The knowledge provided by the standard has been supplemented with knowledge relevant to everyday engineering. These include the testing options for hot-dip galvanized structures and a summary of the thermal parameters applicable to fire protection. By combining these insights, we have shown that the use of uniform design nomograms based on previous logic can lead to the uneconomical design of fireproofing. To overcome this, we have produced designing nomograms for the cases considered relevant for everyday professional practice, taking into account the thermal properties of fire retardants, thus allowing for more accurate design requirements. The approach we use is important not only because it makes planning easier through precise nomograms but also because it paves the way for other factors to be taken into account. Manufacturers of fire protection materials will be given the opportunity to provide more precise correlations with their exact knowledge of the thermal parameters during the compilation of their aids. From now on, it is also possible to test structures not only for the generally applied standard fire effect but also to extend the applicability of nomograms in fire protection planning to the case of any fire curve. We consider it our goal to edit such nomograms for external and hydrocarbon fires, as they may be relevant for the profession.

## 6- Declarations

### *6-1- Author Contributions*

Conceptualization, Z.M.; methodology, J.S.; investigation, D.B.M.; writing—original draft preparation, Z.M.; writing—review and editing, L.B.; supervision, É.L.; funding acquisition, Z.M. All authors have read and agreed to the published version of the manuscript.

### *6-2- Data Availability Statement*

Data sharing is not applicable to this article.

### *6-3- Funding*

This article was supported by István Széchenyi University (Győr).

### *6-4- Institutional Review Board Statement*

Not applicable.

### *6-5- Informed Consent Statement*

Not applicable.

### *6-6- Conflicts of Interest*

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

## 7- References


[1] KSH. (2024). Accidents at work, accidents at home and fires, Hungarian Central Statistical Office, Budapest, Hungary. Available online: https://www.ksh.hu/stadat_files/ege/hu/ege0042.html (accessed on January 2024). (In Hungarian).

[2] MABISZ. (2022). Last year, insurance companies paid HUF 6.5 billion for fire damage. Association of Hungarian Insurance Companies (MABISZ), Budapest, Hungary. Available online: https://mabisz.hu/tuzkarokra-65-milliard-forintot-fizettek-ki-tavaly-a-biztositok/ (accessed on January 2024). (In Hungarian)

[3] Didenko, I., Valaskova, K., Artyukhov, A., Lyeonov, S., & Vasa, L. (2022). Quality of Scientific Activity as a Determinant of Socio-Economic Development. Economics and Sociology, 15(3), 301–318. doi:10.14254/2071-789X.2022/15-3/17.

[4] MSZ EN 1993-1-2:2013. (2013). Eurocode 3: Design of steel structures, part 1-2: General rules. Design of structures to fire, Magyar Szabványügyi Testület (MSZT), Budapest, Hungary.

[5] The Steel Construction Institute (SCI). (2021). Design manual for structural stainless steel ($4^{th}$ Ed.). The Steel Construction Institute (SCI), Berkshire, United Kingdom.

[6] MSZ EN 1991-1-2:2005. (2005). Eurocode 1: Effects on structures, Part 1-2: General effects. Effects on structures exposed to fire. Magyar Szabványügyi Testület (MSZT), Budapest, Hungary.

[7] Nemer, S., Szalai, J. A., & Papp, F. (2023). The overall imperfection method for fire design situation. Engineering Structures, 283. doi:10.1016/j.engstruct.2023.115884.

[8] Szalai, J., Nemer, S., & Papp, F. (2021). The use of the Overall Imperfection Method for fire design situation. SSRN Electronic Journal: Proceedings of the 8th International Conference on Coupled Instabilities in Metal Structures (CIMS 2021), Lodz University of Technology, Poland. doi:10.2139/ssrn.3866475.

[9] Nemer, S., & Papp, F. (2021). Numerical investigation on flexural buckling behavior of hot-rolled steel columns at elevated temperatures. Periodica Polytechnica Civil Engineering, 65(3), 918–927. doi:10.3311/PPci.17799.

[10] Nemer, S., & Papp, F. (2021). Influence of imperfections in the buckling resistance of steel beam-columns under fire. Pollack Periodica, 16(2), 1–6. doi:10.1556/606.2021.00303.

[11] Majorosné, L. É. E., & Major, Z. (2023). Thermal testing of tunnel masonry (Part 1) Theoretical foundations. Sínek Világa, 3, 14–23. (In Hungarian).

[12] Lublóy, É., & Major, Z. (2023). Thermal testing of tunnel masonry (Part 2) Practical knowledge. Sínek Világa, LXV(5), 2–8. (In Hungarian).

[13] Lublóy, É., & Major, Z. (2023). Thermal testing of tunnel masonry (Part 3) Passive fire protection. Sínek Világa, LXV(6), 2–8. (In Hungarian).

[14] Franssen, J. M., & Real, P. V. (2016). Fire Design of Steel Structures: EC1: Actions on structures; Part 1-2: Actions on structure exposed to fire; EC3: Design of steel structures; Part 1-2: Structural fire design. John Wiley & Sons, Hoboken, United States. doi:10.1002/9783433601570.

[15] Lublóy, É., Major, Z., Szép, J., Hlavicka, V., & Biró, A. (2023). Dimensioning for fire load according to Eurocode Design of reinforced concrete, steel, wood, masonry and mule structures. TERC Kereskedelmi és Szolgáltató Kft, Budapest, Hungary.

[16] Lublóy, É., Kaczur, A., Huszár, Z., & Csanaky, J. (2023). Application of combined fire protection for steel structures. Védelem Tudomány: Katasztrófavédelmi Online Tudományos Folyóirat, 7(2), 1–18. (In Hungarian).

[17] Jirku, J., & Wald, F. (2015). Influence of Zinc coating to a temperature of steel members in fire. Journal of Structural Fire Engineering, 6(2), 141–146. doi:10.1260/2040-2317.6.2.141.

[18] Regina, S. (2021). Application and design of fire protection systems. Lecture of the Chamber of Engineering Training, Budapest, Hungary.

[19] Györgyi, B. (2021). Fire protection of steel structures with fire retardant paints - failure after failure? Available online: http://www.vedelem.hu/letoltes/anyagok/872-acelszerkezetek-tuzvedelme-tuzvedo-festekekkel-%E2%80%93-hibat-hibara.pdf (accessed on January 2024). (In Hungarian).

[20] Król, P. A. (2017). Practical fire safety assessment of steel-beam floors made according to the old technologies – An exemplary case study. Influence of the initial assumptions on the final results of analyses. Periodica Polytechnica Civil Engineering, 61(4), 857–872. doi:10.3311/PPci.9662.

[21] FIN Software (2024). Structural Software FIN EC, Heat Transfer, Prague, Czech Republic. Available online: https://www.finesoftware.eu/structural-analyses/heat-transfer/ (accessed on January 2024).