Research Article

Design analysis of a steel industrial building with wide openings exposed to fire

Burak Kaan Cirpici [a,*]

[a] *Department of Civil Engineering, Erzurum Technical University, 25050 Erzurum, Turkey*

ABSTRACT

In order to design a fire-resistant steel structure, the change in the physical and mechanical properties of the steel at high temperatures must be known. As the temperature of steel structural elements increases during fire, their strength decreases considerably. After a certain temperature, these strength drops reach critical levels. Therefore, collapses and various deformations (buckling, arching, etc.) occur. To prevent these collapses during the fire, various fire protection materials must be applied to the structural members such as column and beam. Columns are the most critical structural elements in a steel bearing system. While the possible collapse of the columns may cause the collapse of the whole structure, the beams alone may not cause the collapse of the structure, and the column-beam junctions directly affect the spread of fire. Since there will be many openings and gaps in industrial buildings, the spread and growth of a possible fire becomes very serious. Special fire protection measures are therefore required. In this study, the behavior of a steel industrial structure designed and designed under the influence of Standard Fire (ISO 834) was investigated, the distribution of the temperatures in the structural elements was determined, the required fire protection material was selected, and both protected and unprotected steel temperatures were determined. This design against fire is designed to provide fire resistance for 1 hour (60 min) for this structure. During this period, the type and optimum thickness of the protection material to be applied before reaching the critical temperature values for which the strength of the steel material would lose and would be damaged and compared with the temperatures that would occur in the structural elements without applying fire protection. According to the findings of the study, it was concluded that 25 mm drywall box protection material should be applied on the inner columns and 20 mm on the edge columns and 15 mm on the corner columns. In addition to this, it was concluded that spray beams (intumescent coating) of different thicknesses between 15-20 mm were applied to the beams depending on the location and the load to be affected and the type of joint. After these applied passive fire protection materials, the temperatures obtained in the structural elements reached to 500-550 as a result of 1-hour fire design. These temperatures are acceptable temperature values given the strength drop in critical temperature ranges for steel under the 1-hour fire condition.

ARTICLE INFO

Article history:
Received 7 January 2020
Revised 3 February 2020
Accepted 24 February 2020

Keywords:
Unprotected steel
Protected steel
Passive fire protection system
Fire design
Industrial steel structure

1. Introduction

As is well known, buildings might have a damage from foreseen extreme events such as earthquakes, natural hazards as well as fires and explosions. An experimental study to examine the fire damage of unprotected structural steel members in an industrial fabric building has been performed by Piroglu et al. (2017). In that work, tensile tests were performed on various columns and a tubular space truss member so as to determine the post-

* *Corresponding author*. Tel.: 444-5-388 ; Fax: +90-442-230-0036 ; E-mail address: burak.cirpici@erzurum.edu.tr (B. K. Cirpici)
ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2020.03.001

fire mechanical properties in order to help for final decision whether removal, reusage or strengthening of the industrial steel building. The verification of the minimum fire resistance of existing industrial building has been done by Bilotta et al. (2017) with the help of some regulations to ensure occupant safety as well as a very limited structural damage with particular reference to intumescent coatings protected steel structural members. A 2D thermo-plastic model has been set up by Molkens and Hanus (2017) by considering thermal contribution of non-structural concrete walls to limit the steel temperature rise of the bearing elements in a steel frame system. Kmet et al. (2016) presented an analysis of an industrial hall located on a thermal power plant damaged by fire dramatically using non-destructive and destructive tests of steel and concrete materials, geodetic surveying of selected structural members, numerical modelling and static analysis.

This study developed herein this paper includes the design, manufacturing drawings and calculations of the steel industry structure in Erzurum (39.886448°, 41.269547°) according to AISC360-10, TBDY-2018 and TÇY-2016-7 standards. At the same time, the September 11, 2001 attack on the twin towers in the United States has shown that steel structures are at least as important as the other strength principles in fire protection. In this study, the fire protection of the planned steel structure is also predicted and the ability to resist fire is mentioned (Wang et al., 2015; Wang et al., 2013; Zhang et al., 2012b; Zhang et al., 2012a).

The model is a 60×32 meter industrial building with 11-roof truss and 10 openings. The ridge span is 20 meters and in the case of side protrusions it is 6 meters.

S235 and 490 MPa electrodes were used as steel class. Soil class ZB, Earthquake Ground Motion DD-2 is assumed when constructing the spectrum curve.

Crane design was not made in the structure. The 3D view and front view of the structure taken from the SAP2000 program is shown in Figs. 1 and 2, respectively. A wide variety of joint types and images are shown in Fig. 3.

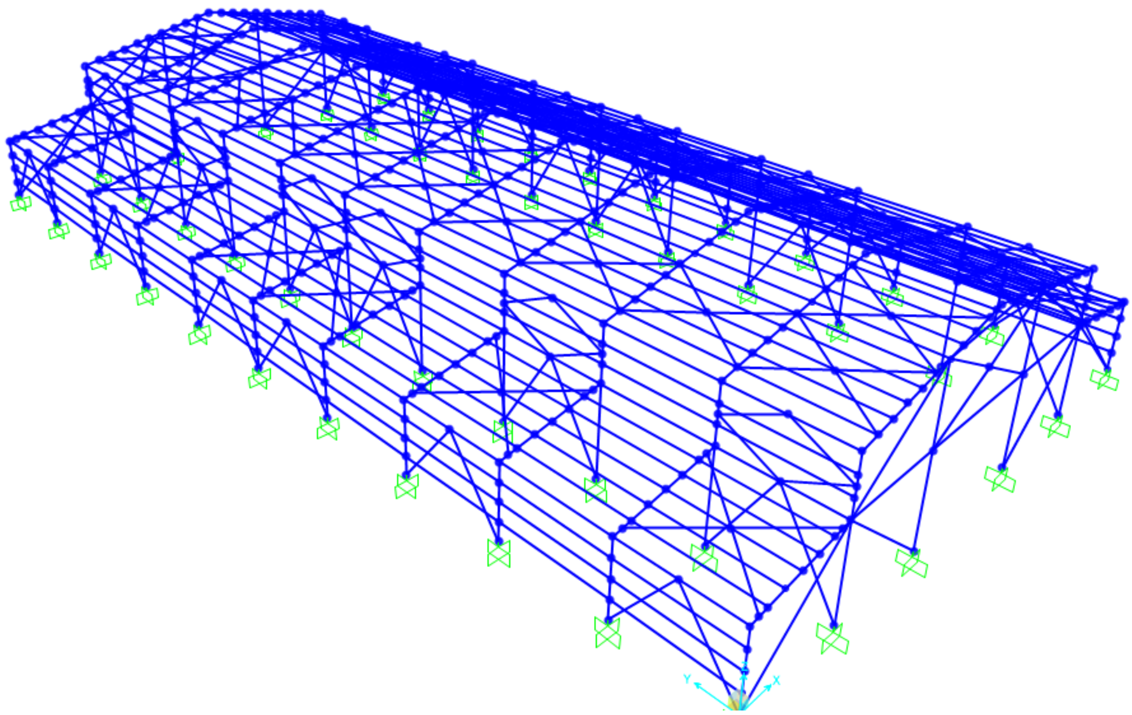


Fig. 1. 3D view of the industrial building.

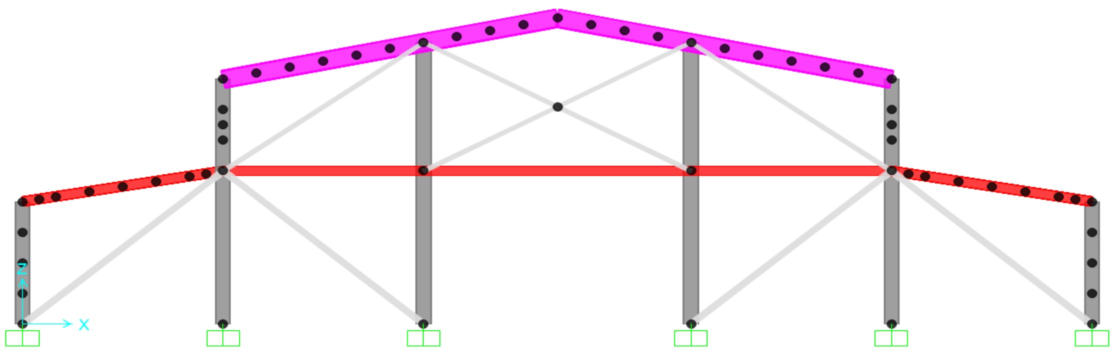
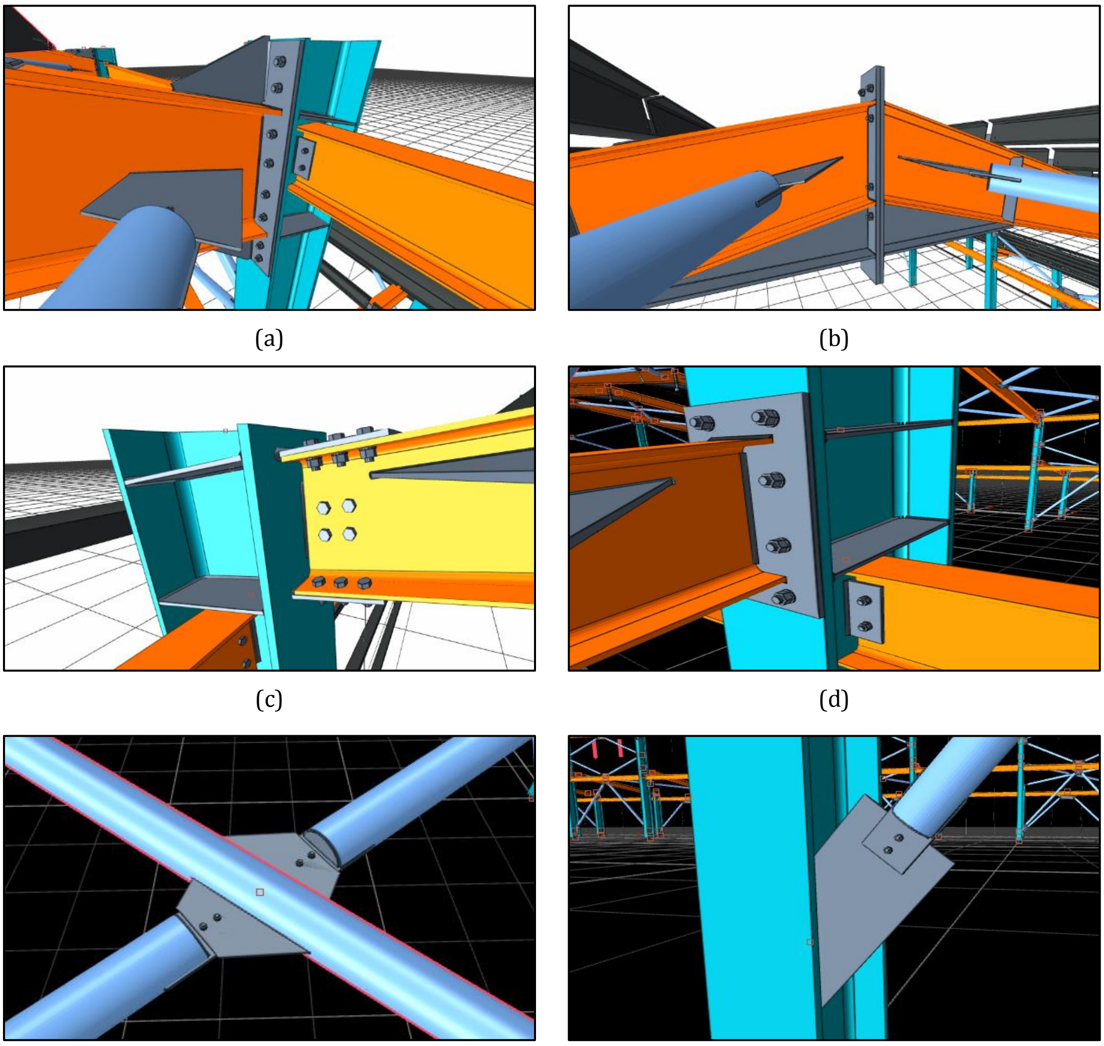


Fig. 2. Front view of the structure.



(a) (b) (c) (d) (e) (f)

Fig. 3. (a) Column-beam (ridge) joint with rigid face plate; (b) Beam-beam connection with face plate; (c) Bolt joint with head plate (side ridge 1); (d) Cross-beam junction (side ridge 2); (e) Cross-body combination; (f) Cross-end combination.

2. Determination of Loads

The load calculations required for the model are classified as dead loads (fixed and roofing loads) and moving loads (snow, wind, fire and earthquake loads) and required calculations for the design have been performed with the help of relevant regulations TSE 498, TBDY-2018, ÇYTHY-2016. In this study, fire loads are taken into account in the load combinations by taking 50% of the total of all moving loads that will affect the structure (CEN, 2005). The general load table for the loads calculated and considered for the structure is shown in Table 1.

Table 1. Main loads for the design.

Roofing load (kN/m^2)	0.150	
Snow load (kN/m^2)	1.950	
Fire load (kN/m^2)	1.325	
Wind load in Y-direction (kN/m^2)	Input = 0.64	Output = 0.32
Wind load in X-direction (kN/m^2)	Input (0-4 m) = 0.40	Output (0-4 m) = 0.20
	Input (4-5 m) = 0.10	Output (4-5 m) = 0.20
	Input (5-8 m) = 0.40	Output (5-8 m) = 0.20
	Input (8-10 m) = 0.13	Output (8-10 m) = 0.32

3. Dimensioning the Structural System

The analysis and design of the system was done in SAP2000. After the necessary material definitions, loads and freedoms were adjusted in the program, changes were made in the design part in accordance with the project design criteria and the sections were dimensioned according to AISC 360/10-LRFD. In addition, framing type, simple moment frame type (OMF), which is suitable for the ductility level of the model, was made in SAP2000 program. Since the earthquake load that will affect the structure is calculated by mode coupling method, the effect of seismic behavior to be created and effected by the selected regulation is limited. The sections obtained as a result of SAP2000 design are presented in Table 2.

Table 2. Dimensioned sections.

Columns	HEB450
Front (facade) purlins	UPN140
Roof purlins	UPN180-200
Diagonals	TUBOD168.3*4-177.8*4
Brace members	S420 Ø0.012 m
Beams between trusses	IPE330
Ridge	IPE600

4. Fire Design

4.1. Thermal properties of steel material

4.1.1. Specific heat (C_{st})

The specific heat-temperature relation is:

If $20°\mathrm{C} \leq T_{st} < 600°\mathrm{C}$;

$$C_{st} = 425 + 7.73 \times 10^{-1} T_{st} - 1.69 \times 10^{-3} {T_{st}}^2 + 2.22 \times 10^{-6} {T_{st}}^3 \quad (1)$$

If $600°\mathrm{C} \leq T_{st} < 735°\mathrm{C}$;

$$C_{st} = 666 + \frac{13002}{738 - T_{st}} \quad (2)$$

If $735°\mathrm{C} \leq T_{st} < 900°\mathrm{C}$;

$$C_{st} = 545 + \frac{17820}{T_{st} - 731} \quad (3)$$

If $900°\mathrm{C} \leq T_{st} < 1200°\mathrm{C}$;

$$C_{st} = 650 \quad (4)$$

where C_{st} is the specific heat $\left(\frac{\mathrm{J}}{\mathrm{kg}} \cdot \mathrm{K}\right)$.

4.1.2. Thermal conductivity (λ_{st})

The thermal conductivity, specific heat and density of steel structural steel has been obtained from Eurocode 3 Part 1.2 (CEN, 2005).

The thermal conductivity of steel is:

If steel temperature T_{st} (K) is lower than 800°C ;

$$\lambda_{st} = 54 - 3.33 \times 10^{-2}\, T_{st} \quad (5)$$

If steel temperature is higher than 800°C;

$$\lambda_{st} = 27.3 \quad (6)$$

where λ_{st} is the steel thermal conductivity (W/mK). Fig. 4 presents the thermal conductivity of steel-temperature relationship based on EN 1993-1-2.

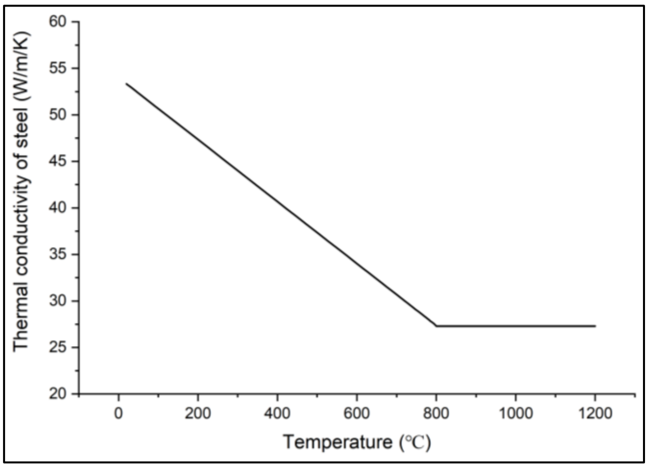


Fig. 4. Variation of thermal conductivity of steel with temperature (CEN, 2005).

4.2. Fire design of unprotected steel

Calculation method for unprotected steel structural element; the heat entering the surface area exposed to heat over a short period of time (Δ_t) is equal to the heat required to raise the temperature of the steel.

$$\varepsilon = \varepsilon_f \times \varepsilon_m \quad (7)$$

Emissivity coefficient (ε) is calculated by multiplying emissivity coefficient under fire condition (ε_f) with emissivity of the material (ε_m).

$$\varepsilon_f = 1.0 \quad \varepsilon_m = 0.5 \quad (8)$$

$$h_{con} = 25 \times (T_{g,t} - T_{st}) \quad (9)$$

$$h_{rad} = \varepsilon_f \times \varepsilon_m \times \sigma \times \left[(T_{g,t} + 273.15)^4 - (T_{st,unprotected} + 273.15)^4\right] \quad (10)$$

$$h_{net} = h_{rad} + h_{con} \quad (11)$$

h_{con} – Amount of heat passing through the unit area by convection
h_{rad} – Amount of heat passing through the unit area by radiation
h_{net} – Net (total) heat quantity per unit area
$T_{g,t}$ – Time-dependent fire (gas) temperature
$\mathrm{T}_{st,unprotected}$ – Unprotected steel temperature

$$k_{sh} = \frac{0.9\times\left(\frac{A_m}{V}\right)_b}{\left(\frac{A_m}{V}\right)} \tag{12}$$

$$\Delta\theta_{st,t} = k_{sh} \times \frac{\frac{A_m}{V}}{C_{st}\times\rho_{st}} \times h_{net} \times \Delta_t \tag{13}$$

k_{sh} – Temperature correction factor
ρ_{st} – Unit mass of steel material (kg/m^3)
Δ_t – Time interval (sn)
$\Delta\theta_{st,t}$ – Steel temperature rise per unit time

For the time interval, the maximum time specified in Eurocode 3 is 30 s. However, in this study, the temperature calculations were made in 5 second time steps for both protected and unprotected cases to obtain more accurate results.

4.3. Fire design of protected steel

The calculation method is similar to unprotected steel, but the equation is slightly different. Because the heat transfer coefficients are not included in the equation due to the assumption that the outer surface temperature of the fire protection material is the same as the fire gas temperature (Wang, 2002).

$$\emptyset = \frac{C_p\times\rho_p}{C_{st}\times\rho_{st}} \times d_p \times \frac{A_m}{V} \tag{14}$$

$$\Delta\theta_{st,t} = \frac{\lambda_p \times\frac{A_m}{V}}{d_p\times p_{st}\times C_{st}} \times \frac{(T_{g,t}-T_{st,protected})}{\left(1+\frac{\emptyset}{3}\right)} \times \Delta t - \left(e^{\frac{\emptyset}{10}} - 1\right) \times \Delta\theta_{g,t} \tag{15}$$

$\emptyset$ - Shape factor of steel with protection material
λ_p - Thermal conductivity coefficient of fire protection material (W/mK)
C_p – Specific heat of fire protection material (J/kgK)
ρ_p – Unit mass of fire protection material (kg/m^3)
d_p – Thickness of fire protection material (mm)
$\Delta\theta_{g,t}$ – Fire (gas) temperature rise per unit time

4.3.1. Fire protection systems

Many fire protection coatings are produced from calcium silicates or gypsum plasters with low thermal conductivity. Coatings made of calcium silicate are in layers and the inner layer is the least damaging layer in fire. Gypsum plaster coatings have good fire insulation property. Coating systems are very easy to apply, they are applied dry and finished with decorative materials (Fig. 5). However, they are slow and expensive compared to spray applied systems.

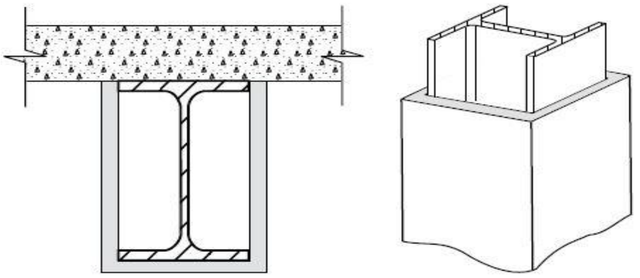


Fig. 5. Panel protection representation.

5. Structural Fire Design

5.1. Column design

In order to facilitate the calculations before moving to the fire design section, the mapping of the columns was performed and then, according to this mapping, both symmetrical columns and the load they would carry could easily be determined by the areas to be exposed to fire.

Box coating was chosen as the fire protection material in the columns.

Since the fire design calculations in steel structures are very long and complicated by hand procedure, fire design program was created by using Microsoft Excel program. Macros section was used in Microsoft Excel. Loads to columns are classified for easier analysis, including inner, edge and corner columns, as the columns will vary according to their position Fig. 6.

SC001	SC002	SC045	SC046	SC003	SC004
SC005	SC006			SC007	SC008
SC009	SC010			SC011	SC012
SC013	SC014			SC015	SC016
SC017	SC018			SC019	SC020
SC021	SC022			SC023	SC024
SC025	SC026			SC027	SC028
SC029	SC030			SC031	SC032
SC033	SC034			SC035	SC036
SC037	SC038			SC039	SC040
SC041	SC042	SC047	SC048	SC043	SC044

Fig. 6. Settlement map of columns in considered industrial structure.

Internal Columns (6-7-10-11-14-15-18-19-22-23-26-27-30-31-34-35-38-39):

Numbered inner columns shown in Fig. 6, span openings, column heights, material properties and most importantly the areas to be exposed to fire were calculated and entered into the developed FIRE_EXCEL spreadsheet as shown in Figs. 7 and 8.

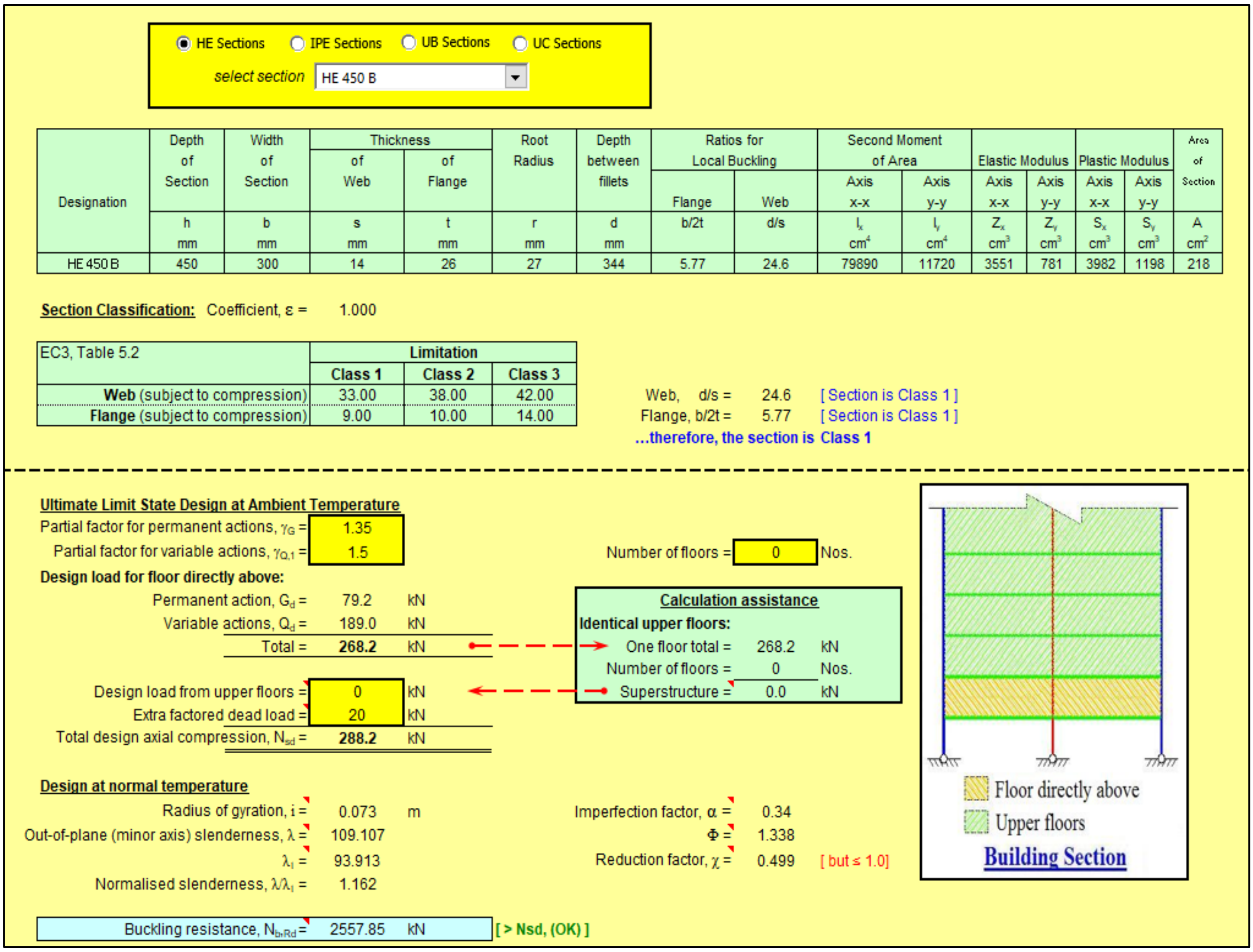
As a result of the analyses, the temperature distributions that will occur in the inner columns under the effect of Standard fire (ISO 834) are shown in Fig. 9 as unprotected and protected against fire. Non-uniform temperature distribution has been obtained for the unprotected members since the specific heat (C_{st}) changes dramatically after around 650°C whereas this behavior has not seemed for the protected members due to the low temperature values. Hence, non-uniform temperature values have been obtained for all unprotected steel members including columns and beams. The application of a 25 mm plasterboard box coating resulted in temperatures less than 550-600°C which were critical temperatures for steel at the end of 1 hour in the inner columns. When we look at the unprotected steel column, it has reached 900°C, which is a critical temperature for the steel to deform and lose its load-bearing capacity.

Edge Columns (2-3-5-8-9-12-13-16-17-20-21-24-25-28-29-32-33-36-37-40-42-43):

20 mm plasterboard fire-protected and unprotected steel temperatures of edge columns are shown in Fig. 10. Since the fire is exposed from the 3 surfaces on the side columns, slightly lower temperatures (temperature difference of 60°C at the end of 60 minute) were obtained than the corner columns. It can be concluded that a slightly thinner fire-retardant material can be used for the side columns.

Corner Columns (1-4-41-44):

For the corner columns, 15 mm plasterboard has been used as the fire protection material to decrease the steel temperatures at the end of fire design time (60 min). As the fire exposure side of these columns is less than the other column types, low insulation thickness might be preferred. The obtained protected steel temperature results are around 500°C which was the aimed design temperature for the steel (Fig. 11).



HE Sections | IPE Sections | UB Sections | UC Sections

select section: HE 450 B

Designation	Depth of Section h (mm)	Width of Section b (mm)	Thickness of Web s (mm)	Thickness of Flange t (mm)	Root Radius r (mm)	Depth between fillets d (mm)	Ratios for Local Buckling Flange b/2t	Ratios for Local Buckling Web d/s	Second Moment of Area Axis x-x I_x (cm⁴)	Second Moment of Area Axis y-y I_y (cm⁴)	Elastic Modulus Axis x-x Z_x (cm³)	Elastic Modulus Axis y-y Z_y (cm³)	Plastic Modulus Axis x-x S_x (cm³)	Plastic Modulus Axis y-y S_y (cm³)	Area of Section A (cm²)
HE 450 B	450	300	14	26	27	344	5.77	24.6	79890	11720	3551	781	3982	1198	218

Section Classification: Coefficient, ε = 1.000

EC3, Table 5.2	Limitation Class 1	Class 2	Class 3
Web (subject to compression)	33.00	38.00	42.00
Flange (subject to compression)	9.00	10.00	14.00

Web, d/s = 24.6 [Section is Class 1]
Flange, b/2t = 5.77 [Section is Class 1]
...therefore, the section is Class 1

Ultimate Limit State Design at Ambient Temperature
Partial factor for permanent actions, γ_G = 1.35
Partial factor for variable actions, $\gamma_{Q,1}$ = 1.5
Number of floors = 0 Nos.
Design load for floor directly above:
Permanent action, G_d = 79.2 kN
Variable actions, Q_d = 189.0 kN
Total = 268.2 kN
Calculation assistance
Identical upper floors:
One floor total = 268.2 kN
Number of floors = 0 Nos.
Superstructure = 0.0 kN
Design load from upper floors = 0 kN
Extra factored dead load = 20 kN
Total design axial compression, N_{sd} = 288.2 kN

Design at normal temperature
Radius of gyration, i = 0.073 m
Out-of-plane (minor axis) slenderness, λ = 109.107
λ_1 = 93.913
Normalised slenderness, λ/λ_1 = 1.162
Imperfection factor, α = 0.34
Φ = 1.338
Reduction factor, χ = 0.499 [but ≤ 1.0]

Buckling resistance, $N_{b,Rd}$ = 2557.85 kN [> Nsd, (OK)]

Fig. 7. Entering the necessary properties for fire design of inner columns in FIRE_EXCEL.

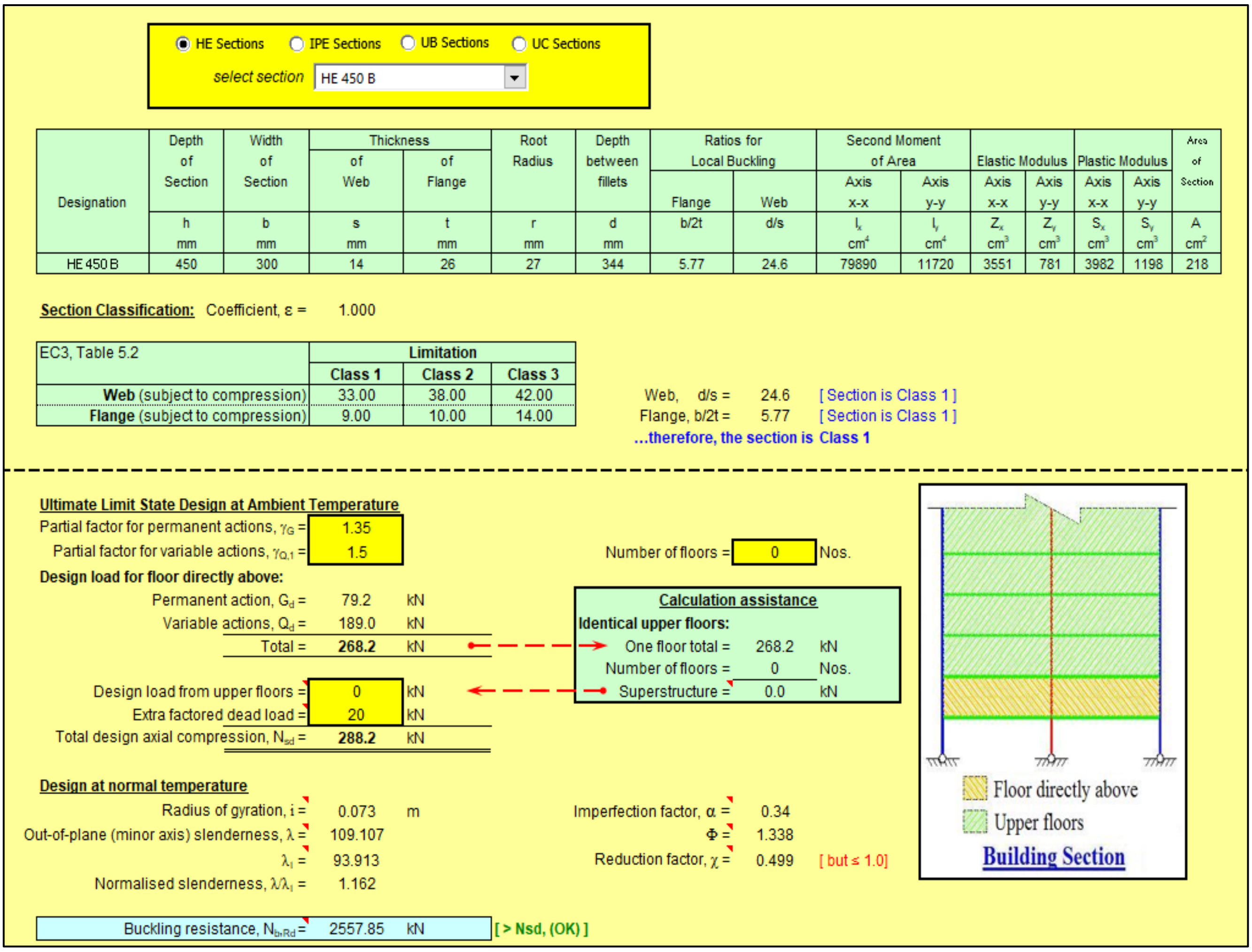


Fig. 8. Performing the necessary controls for the column (buckling, etc.).

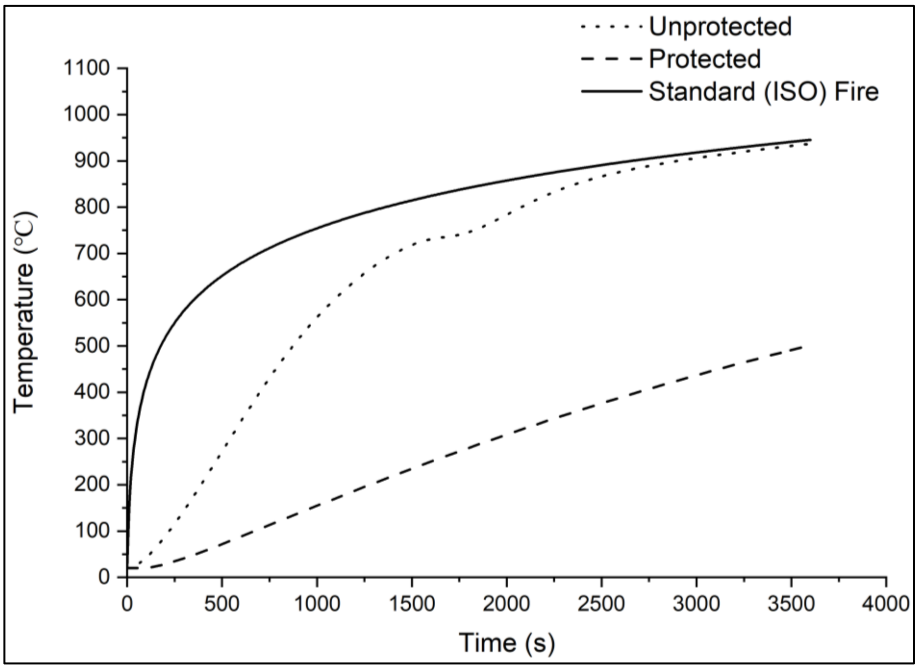


Fig. 9. Temperature distributions for inner columns.

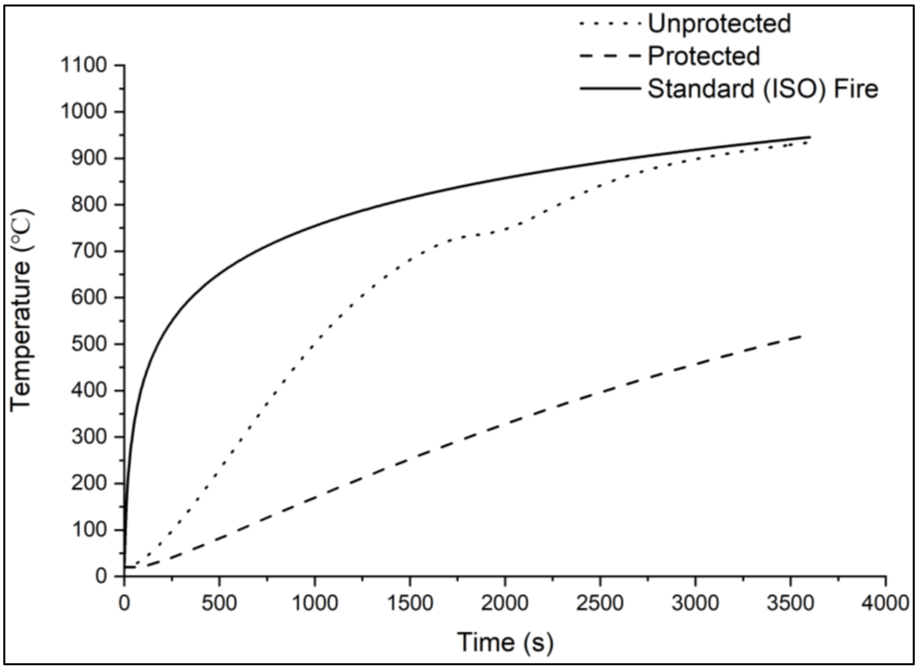


Fig. 10. Temperature distributions for edge columns.

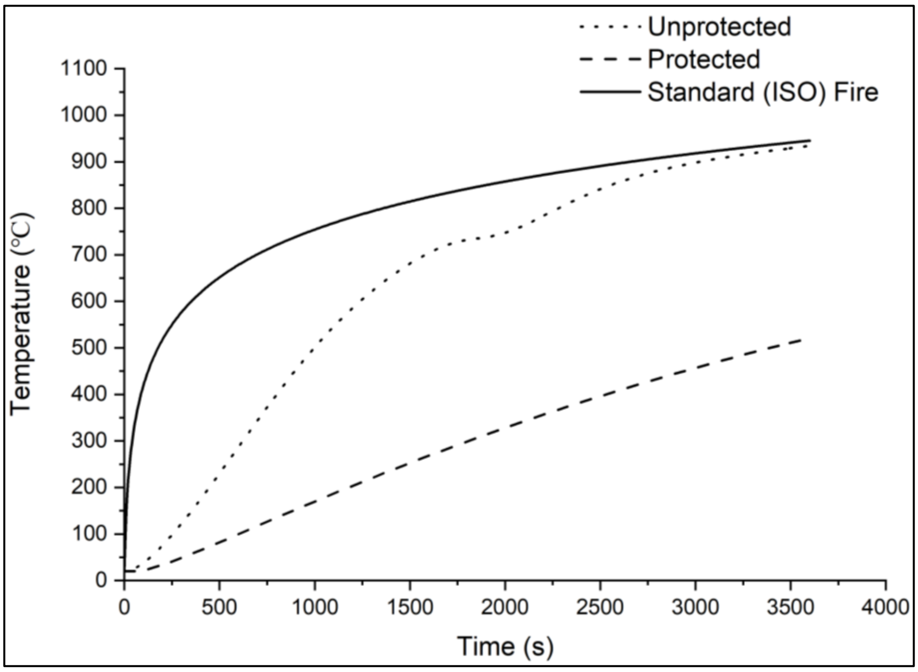


Fig. 11. Temperature distributions for corner columns.

5.2. Beam design

Beam placement map, shown in Fig. 12, is created to provide ease of operation and to make calculations faster and more accurately, just as columns and areas to be used in the fire, loads, and symmetrical beams were determined from this map and colored with the same color. Selected and fire-designed beams are different beams (loading, span openings, etc.) in the system. Different fire performance and temperature distributions were obtained due to differences in physical properties. The remaining beams are symmetrical and identical to the selected beams. Intumescent coating was applied to the beams, as it would be more suitable to manufacture and apply (Cirpici et al., 2016a; Cirpici et al., 2016b), (Cirpici et al., 2019a; Cirpici et al., 2019c; Cirpici et al., 2019d; Cirpici et al., 2019b).

Figs. 14-18 present the temperature distribution on protected and unprotected steel beams designed in the industrial building. Unprotected beam temperatures reach to the fire temperature (ISO-834) within 25 minutes while the protected steel temperatures are kept at around proposed temperature (500°C) by applying 15-20 mm intumescent paint.

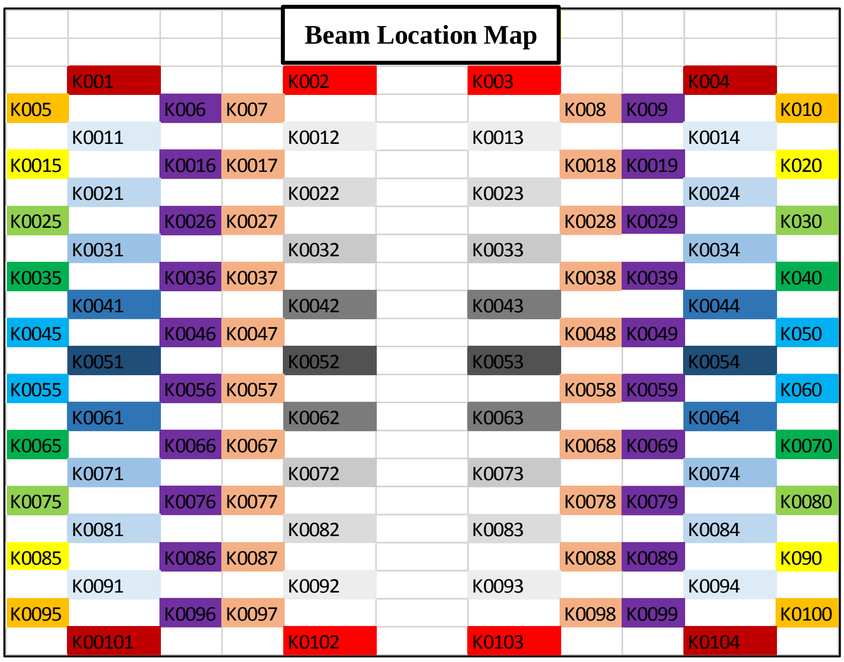


Fig. 14. Settlement map of beams in considered industrial structure.

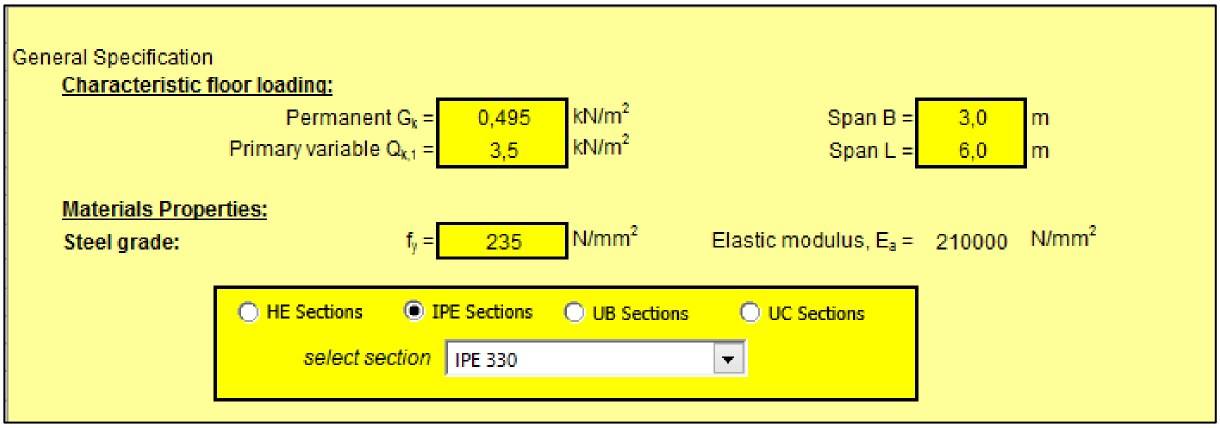


Fig. 13. Entering the necessary properties for fire design of inner columns in FIRE_EXCEL.

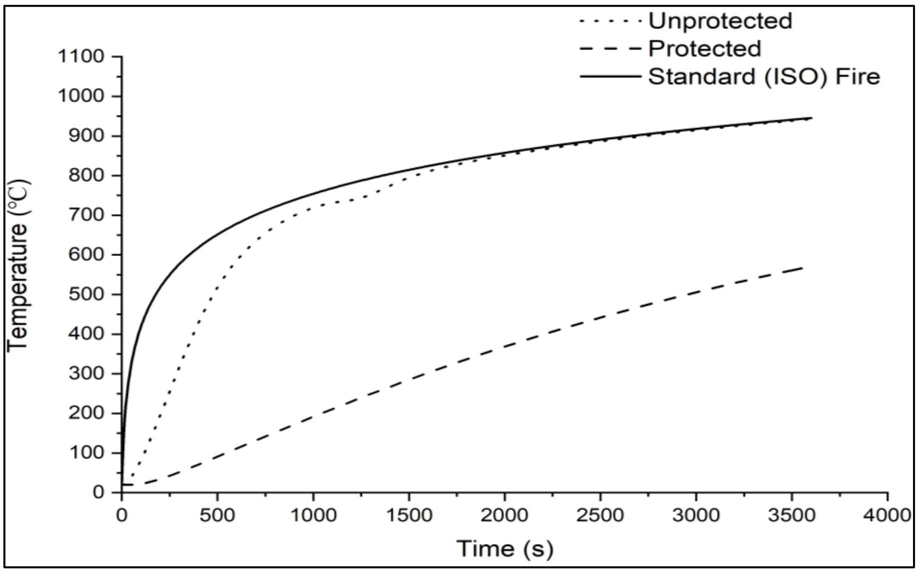


Fig. 14. Temperature distributions on beam numbered as (01).

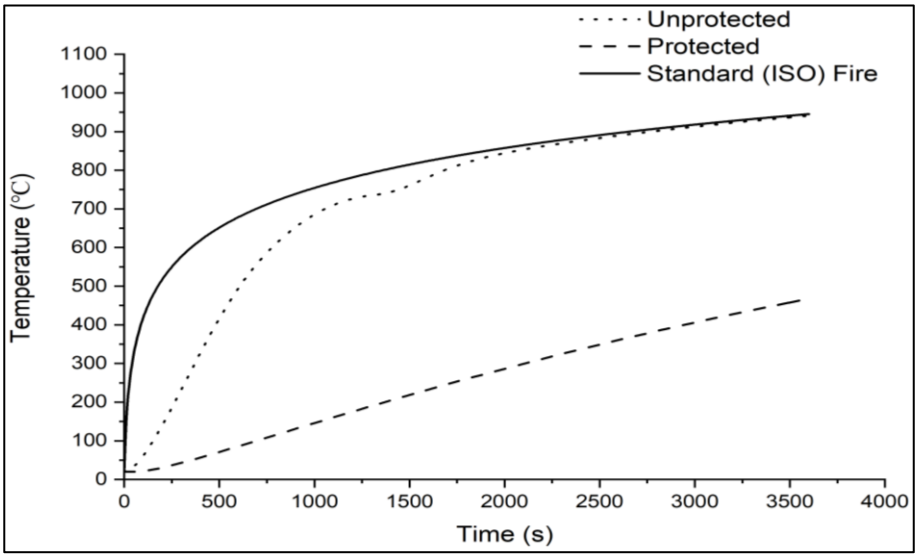


Fig. 15. Temperature distributions on beam numbered as (02).

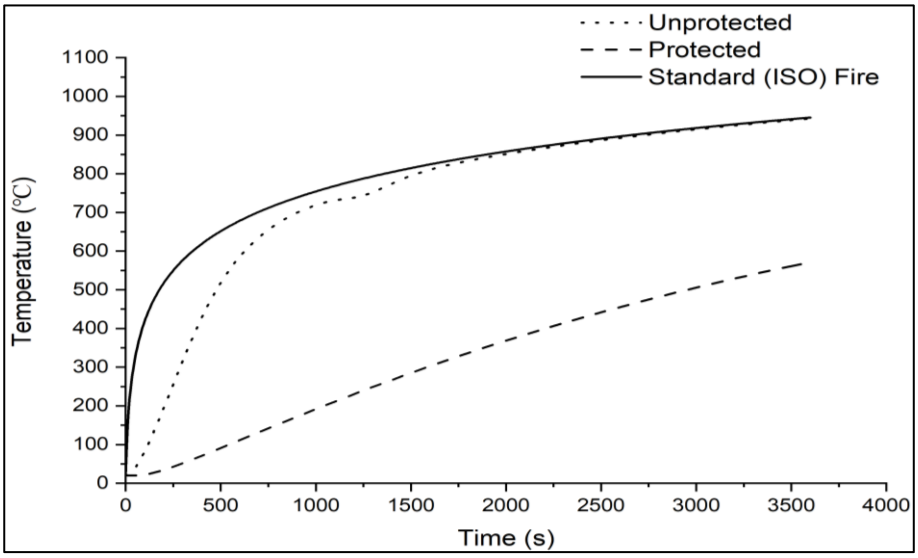


Fig. 16. Temperature distributions on beam numbered as (45-46-47).

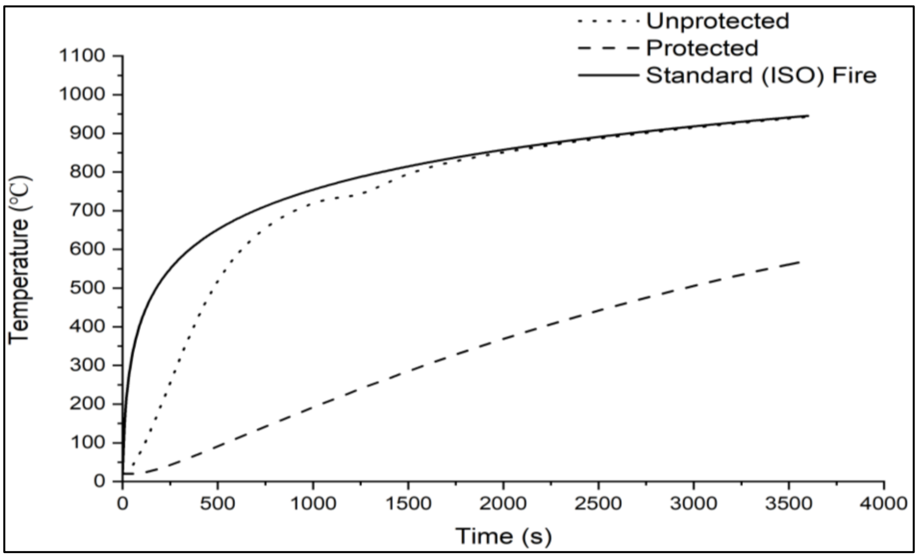


Fig. 17. Temperature distributions on beam numbered as (51).

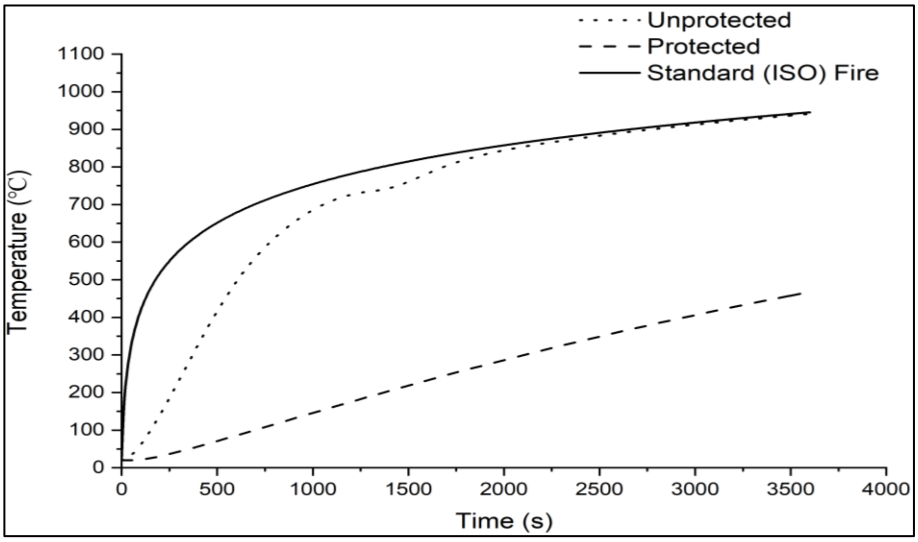


Fig. 18. Temperature distributions on beam numbered as (52).

6. Conclusions

In this study, the behavior of a large steel industrial structure with wide openings under fire effect (Standard Fire - ISO 834) and temperature distributions in the structural elements were determined as fire protected and unprotected. Model analysis, downloads and dimensions, joint calculations and verifications were performed with the help of SAP2000 v18, Tekla Structures 2016i, Idecad 8.62 and IdeaStatica 9 programs. Fire design of columns and beams, which are critical in the fire, among the types of structural elements dimensioned, were made. The thickness of the protection material (plasterboard box protection) in the inner columns was determined as 25 mm, 20 mm in edge columns and 15 mm in corner columns. For the beams, the same intumescent paint protection thickness as 20 mm has been considered for all beams. The load that the columns and beams reach to temperatures of approximately 950°C without protection after 1 hour in a standard fire and is between approximately 450-550°C for the protected steel depending on the load, span openings and fire exposure surfaces. This is the temperature at which the steel begins to lose its strength considerably. When steel rises above these temperatures, more than fifty percent of its strength will be lost, so collapse might be expected. However, the 60-minute design is sufficient for the necessary evacuation.

References

Bilotta A, De Silva D, Nigro E (2017). Structural fire safety of existing steel buildings: Possible general approach and application to the case of the intumescent coatings. *Applications of Structural Fire Engineering*, 80-85.

CEN (2005). EN 1993-1-2: Eurocode 3. Design of Steel Structures. Part 1.2: General Rules - Structural Fire Design. BSI: London.

Cirpici BK, Orhan SN, Kotan T (2019a). Numerical modelling of heat transfer through protected composite structural members. I*nternational Civil Engineering and Architecture Conference 2019 (ICEARC 2019)*, Trabzon, Turkey.

Cirpici BK, Orhan SN, Kotan T (2019b). Numerical modelling of heat transfer through protected composite structural members. *Challenge Journal of Structural Mechanics*, 5(3), 96-107.

Cirpici BK, Orhan SN, Kotan T (2019c). Thermal performance and response of composite slabs profiled with protected steel decking under various fire scenarios. *4th International Conference on Advances in Natural & Applied Sciences (ICANAS 2019)*, Ağrı, Turkey.

Cirpici BK, Orhan SN, Kotan T (2019d). Thermal performance of protected composite slab-beam systems exposed to fire. *3rd International Conference on Advanced Engineering Technologies*, Bayburt, Turkey.

Cirpici BK, Wang YC, Rogers B (2016a). Assessment of the thermal conductivity of intumescent coatings in fire. *Fire Safety Journal*, 81, 74-84.

Cirpici BK, Wang YC, Rogers BD, Bourbigot S (2016b). A theoretical model for quantifying expansion of intumescent coating under different heating conditions. *Polymer Engineering & Science*, 56(7), 798-809.

ÇYTHY-2016 (2016). Çelik Yapıların Tasarım, Hesap ve Yapım Esasları Yönetmeliği. Çevre ve Sehircilik Bakanlığı, Ankara, Turkey.

Kmet S, Tomko M, Demjan I, Pesek L, Priganc S (2016). Analysis of a damaged industrial hall subjected to the effects of fire. *Structural Engineering and Mechanics*, 58(5), 757-781.

Molkens T, Hanus F (2017). Contribution of non-structural concrete walls to the fire resistance of unprotected steel frames. *Applications of Structural Fire Engineering*, 86-91

Piroglu F, Baydogan M, Ozakgul K (2017). An experimental study on fire damage of structural steel members in an industrial building. *Engineering Failure Analysis*, 80, 341-351.

TBDY-2018 (2018). Türkiye Bina Deprem Yönetmeliği. Deprem Etkisi Altında Binaların Tasarımı için Esaslar. Afet ve Acil Durum Yönetimi Başkanlığı, Ankara, Turkey.

TS-498 (1997). Yapı Elemanlarının Boyutlandırılmasında Alınacak Yüklerin Hesap Değerleri. Turkish Standard Institute, Ankara, Turkey.

Wang L, Dong Y, Zhang C, Zhang D (2015). Experimental Study of Heat Transfer in Intumescent Coatings Exposed to Non-Standard Furnace Curves. *Fire Technology*, 51(3), 627-643.

Wang LL, Wang YC, Yuan JF, Li GQ (2013). Thermal conductivity of intumescent coating char after accelerated aging. *Fire and Materials*, 37(6), 440-456.

Wang YC (2002). Steel and Composite Structures - Behaviour and Design for Fire Safety. Spon Press, London, UK.

Zhang Y, Wang YC, Bailey CG, Taylor AP (2012a). Global modelling of fire protection performance of an intumescent coating under different furnace fire conditions. *Journal of Fire Sciences*, 31(1), 51-72.

Zhang Y, Wang YC, Bailey CG, Taylor AP (2012b). Global modelling of fire protection performance of intumescent coating under different cone calorimeter heating conditions. *Fire Safety Journal*, 50, 51-62.