ANALYSIS AND ECONOMIC COMPARISON OF STEEL COLUMNS DESIGN IN FIRE CONDITIONS

Roman Červenka*,1

* roman.cervenka@stuba.sk
1 Slovak University of Technology in Bratislava, Vazovova 5, 512 43 Bratislava

Abstract

Load-bearing structures must provide both safety and economic efficiency. Steel columns are being optimized for fire-resistance due to rising material costs. STN EN 1993-1-2 standard provides guidelines for designing fire resistant structures and determining the appropriate protection measures. Fire protection methods include sprays, coatings, and claddings. This study analyses and compares various design approaches for steel columns in fire conditions, emphasizing economic efficiency.

Keywords

Steel, columns, buckling, fire, efficiency

1 INTRODUCTION

The protection of a steel load-bearing structure must be designed to provide both structural safety and economic efficiency. In the event of a fire, the structure must withstand fire exposure for a sufficient duration to facilitate the protection of human lives. An unprotected steel load-bearing structure cannot maintain its load-bearing capacity for an extended period under fire conditions due to its material properties. Therefore, fire protection measures such as intumescent coatings, fireproof sprays, or cladding must be applied. Steel structures designed in accordance with STN EN 1993-1-2 standard [1] must meet the load-bearing capacity criterion, i.e. must retain their structural integrity for the required fire resistance period. The computational model must accurately reflect the expected structural behaviour under fire conditions. Simplified calculation models and conventional design solutions generally provide conservative results. If these methods are not applicable, design approaches based on advanced numerical models or fire testing must be employed [2]. This paper focuses on the economic comparison of steel column designs based on an advanced computational model using the OZone software [3].

Behaviour of columns in frame structures exposed to fire

Selecting the appropriate buckling length is essential to determine the buckling resistance of a column under both normal temperature conditions and fire exposure. The procedure for determining the buckling length of a steel column subjected to fire, as outlined in Article 4.2.3.2 of STN EN 1993-1-2 standard [1], is similar to the method used for normal temperature conditions described in Article 6.3.1.1 of STN EN 1993-1-1 standard [4].
According to STN EN 1993-1-2 standard [1], it can be assumed that fire affects only one floor (fire compartment), while the unheated structural elements in the floors above and below maintain significantly higher stiffness compared to the heated elements. As a result, the buckling lengths of fire-exposed columns are shorter than those of columns at normal temperatures.
In braced frames, each floor is treated as a separate fire compartment, and the heated column is considered "fixed" to the colder columns in the floors above and below [1]. Additionally, beam connections in braced frames are either pinned or semi-rigid, which has little impact on rotational stiffness. This allows for the consideration of a buckling length of $0.5 \times L$ for intermediate floors and $0.7 \times L$ for the first and last floors [1]. However, in reality, buckling lengths differ from those specified in the European standard, tending to exceed the prescribed values, which presents a more critical scenario. Several researchers have studied this issue [5]. Buckling lengths in this study were considered as $1 \times L$, because the assumption that the buckling length in a fire is truly halved remains uncertain.
The Eurocodes do not provide specific guidelines for determining the buckling lengths of fire-exposed columns for unbraced frames.

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2 METHODOLOGY

Fire loads

In fire conditions, loading is categorized into mechanical loading, which is necessary for structural analysis, and thermal loading, which is required for heat transfer analysis. The primary effect of fire is thermal loading, which raises the temperature of structural elements, leading to changes in their physical and mechanical properties. Thermal loading is represented by temperature-time curves or fire models [6].

The ISO 834 standard fire curve is used in the testing of structural elements in furnaces for fire resistance. Although it only indirectly expresses fire temperatures, its implementation has enabled the improvement of structural fire reliability through analytical calculations. Advanced fire models account for gas properties, mass transfer, and energy exchange. One approach is the single-zone model, which assumes a uniform, time-dependent temperature distribution within the fire compartment. Two-zone models consider a variable upper hot gas layer with a uniform temperature and a lower cooler layer with a time-dependent temperature gradient. These models can be developed using computational software such as OZone [3].

The primary risk to a structure during a fire is the degradation of the mechanical properties of construction materials. As temperature increases, these properties deteriorate. Reduced values of obtained strength, compressive strength, proportional limit, and modulus of elasticity at elevated temperatures are obtained by multiplying the corresponding ambient temperature values by a reduction factor specified in STN EN 1993-1-2 standard [1]. The design mechanical load in fire conditions *Ed* (kN, kN/m^{-1}, kN/m^{-2}, etc.) is determined according to the rule for accidental design situations, as specified in Clause 6.4.3.3 (1) of STN EN 1990 [7].

$$E_d = E\{G_{k,j}; P; A_d; (\Psi_{1,1} \text{ or } \Psi_{2,1})Q_{k,1}; \Psi_{2,\mathrm{i}}Q_{k,i}\} \qquad j \geq 1; i > 1 \tag{1}$$

where the symbol $G_{k,j}$ (kN, kN/m^{-1}, kN/m^{-2}, etc.) represents permanent loads, P (kN, kN/m^{-1}, kN/m^{-2}, etc.) represents pre-stressing, A_d (kN, kN/m^{-1}, kN/m^{-2}, etc.) refers to accidental actions, $Q_{k,1}$ (kN, kN/m^{-1}, kN/m^{-2}, etc.) is the leading variable loads, and $Q_{k,i}$ (kN, kN/m^{-1}, kN/m^{-2}, etc.) represents secondary variable loads. The factors $\Psi_{1,i}$ (dimensionless unit) and $\Psi_{2,i}$ (dimensionless unit) for the frequent and quasi-permanent values of variable loads are provided in Table 3.2.1, which is derived from STN EN 1990 standard [7].

According to STN EN 1990 standard [7], only the loads that can realistically occur during fire are considered in load combination calculations. The values of variable loads are determined following the rules specified in STN EN 1990 standard [7]. Cases where snow loads can be disregarded due to melting are assessed individually.

A key parameter dependent on loading is the critical temperature of the structural member. This is the temperature at which failure of the steel element is expected to occur for a given load level, assuming uniform temperature distribution (Fig. 1).

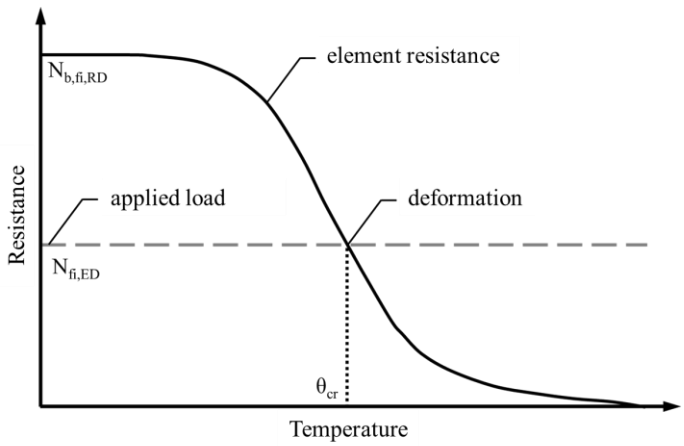

Fig. 1 Critical temperature of the element [8].

Analysis

A braced frame structure, consisting of two spans and four stories, was created to represent an office building for the comparison of steel column designs. The span lengths was 7 m, and the story heights were 3 m. The distance between transverse frames was 9 m. Column No. 4, located on the top floor beneath a flat roof, was selected for assessment. The permanent load on the column consists of the self-weight of Kingspan KS1000 RW120 roof panels and the roof load-bearing structure, composed of purlins with an HEA140 cross-section and trusses with an IPE220 cross-section. The variable load is due to snow, with the hypothetical building situated in snow load zone 2 at an altitude of 226.4 m above sea level. The scheme of the building structure is shown in Fig. 2.

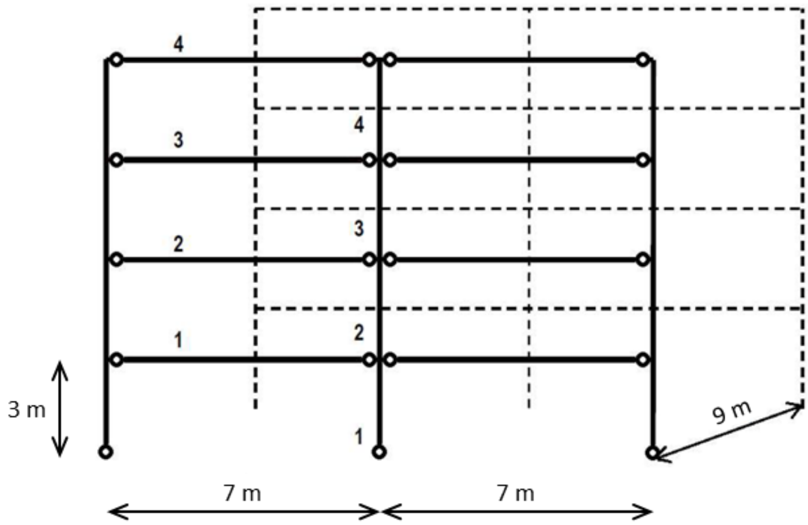

Fig. 2 The scheme of the researched building structure.

An advanced fire model analysis was conducted using OZone software [3] to determine the temperature development over time and the critical temperature at which the element fails. The fire compartment was defined with dimensions of 18 × 7 × 3 m. A 17 m section of the wall consists of windows with a height of 1.2 m, and the windowsill height is 0.9 m is along the longer side. The fire-exposed room area was 126 m², and the fire load density for this office space was determined by OZone [3] to be 568.2 MJ/m². The design fire resistance for the assessed column was specified as R30.

The column was analysed for buckling resistance. The design was assessed according to Article 6.3.1.1 (1) of STN EN 1993-1-1 standard [4] under normal temperature conditions. In fire conditions, based on the temperature of the column obtained from OZone, the reduction factors for the modulus of elasticity and yield strength of steel were determined in accordance with Table 3.1 from STN EN 1993-1-2 standard [1]. The bBuckling resistance of the column under fire conditions was assessed according to Article 4.2.3.2 (1)(2)(3) of STN EN 1993-1-2 standard [1].

Cross-section without fire protection optimally designed for normal temperature

The column designed for ambient temperature conditions is subjected to a design axial force of 216.2 kN, which results from the combination of the specified loads. In the case of a braced frame, the buckling lengths were equal to the system height of the column, i.e., 3 m. An HEB 100 cross-section was selected, with a buckling resistance of 276.1 kN under the given boundary conditions, corresponding to a 78.3% utilization of the cross-section.

The applied load was determined based on the accidental load combination, resulting in a design axial force of 120.1 kN in the fire situation. The buckling lengths of the column were not reduced. Since the design fire resistance of the column was specified as R30, the observed column temperatures were evaluated at 30 minutes of fire exposure.

A temperature-time curve was generated for a real fire scenario based on the input parameters, along with a temperature curve derived from the ISO 834 standard fire curve using the OZone software. The temperature-time curves for the simulated fire compartment are shown in Fig. 3.

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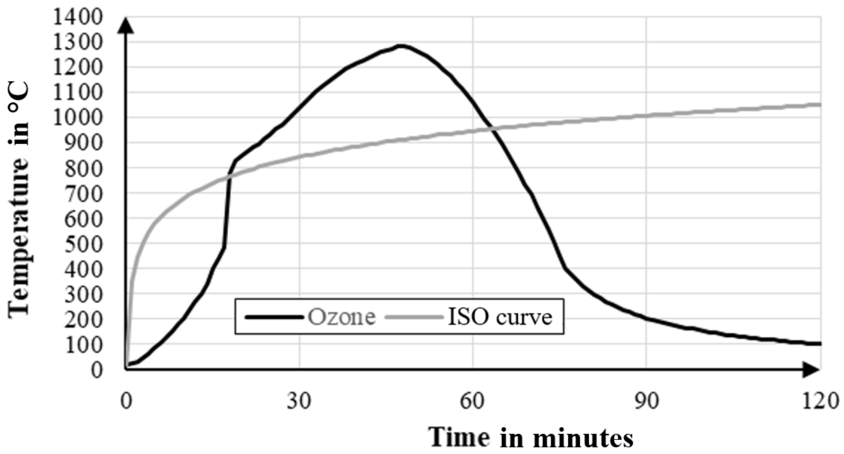

Fig. 3 Temperature curves for real fire and ISO 834.

The column temperature-time curves were determined using the OZone software based on the room temperature-time curves. The critical temperature of the column, at which structural failure occurs, was 559.01 °C. The column reached this critical temperature approximately 11 minutes in the fire.

The column temperature at 30 minutes for an HEB 100 cross-section without fire protection, according to the real fire temperature-time curve, was 993.72 °C. At such a high temperature, the mechanical properties of steel are significantly reduced. Consequently, the yield strength and modulus of elasticity were reduced in accordance with STN EN 1993-1-2 standard [1]. The load-bearing capacity of the cross-section at this temperature was only 11.7 kN, resulting in a cross-section utilization of 1,026%.

The column temperature at 30 minutes, according to the ISO 834 standard fire curve, reached 814.2 °C for an HEB 100 cross-section without fire protection. Due to this high temperature, the yield strength and modulus of elasticity were also reduced according to the standard. The load-bearing capacity of the cross-section at this temperature was only 23.5 kN, leading to a cross-section utilization of 511%.

Spray-protected cross-section

Promapaint-SC3: Promapaint-SC3 is a water-based intumescent coating [9]. The thickness of the coating is determined according to the manufacturer's catalogue. The cross-section is designed based on the design temperature, which should be lower than the critical temperature of the structural element. For an HEB 100 cross-section, the design temperature was set at 550 °C, which corresponds to 97% utilization, given the critical temperature of 559.01 °C. The coating thickness was determined based on the section factor (A_p/V), where "A_p" represents the surface area per unit length, and "V" represents the volume per unit length of the element. The section factor is expressed in m^{-1}. For a fire-resistance rating of R30, the selected coating thickness was 1.951 mm.

Promapaint-SC4: Promapaint-SC4 is also a water-based intumescent coating [9]. The thickness of the coating for Promapaint-SC4 was determined in a similar manner to Promapaint-SC3, with 97% utilization as well. The only difference is in the coating thickness, which in this case is only 0.229 mm. The layer sequence for the application of the fire protection coating for Promapaint-SC3/SC4 is shown in Fig. 4.

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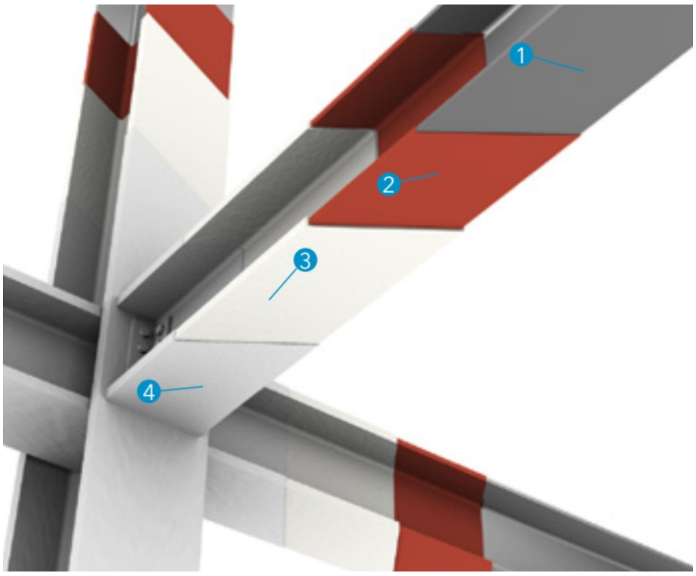

Fig. 4 Promapaint-SC3/SC4 layer sequence:
1 – Cleaned steel, 2 – Primer layer, 3 – Promapaint-SC3/SC4, 4 – Final topcoat.

Cross-section protected by coatings

Promaspray-P300: The material composition of this coating is based on vermiculite and gypsum mixed with water [9]. The spray thickness was selected according to the manufacturer's catalogue. The utilization was also 97%. The change lies in the thickness of the coating, which in this case was 10 mm. The layer sequence for the application of the fire protection coating for Promaspray-P300 is shown in Fig. 5.

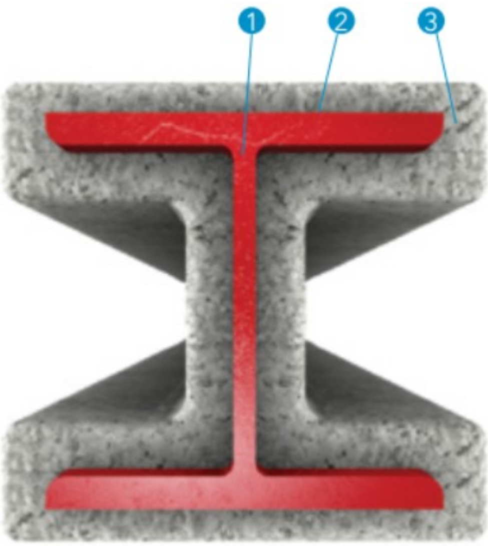

Fig. 5 Promaspray-P300:
1 – Cleaned steel, 2 – Primer layer, 3 – Promaspray-P300.

OZone: In the OZone computational software, the selected fire protection method was a fire-resistant coating, specifically "Spray Mineral Fiber", with predefined material properties. For an HEB 100 cross-section protected by a 6 mm layer of "Spray Mineral Fiber", the column temperature at 30 minutes, according to the real fire temperature-time curve, was 540 °C. In the structural analysis, the yield strength and modulus of elasticity were reduced in accordance with STN EN 1993-1-2 standard. The load-bearing capacity of the cross-section at this temperature was 135.1 kN, resulting in a cross-section utilization of 89%. For the ISO 834 standard fire curve, the column temperature reached 559.4 °C with a 7 mm thick sprayed coating. The load-bearing capacity of the cross-section at this temperature was 120.1 kN, leading to a cross-section utilization of 99.99%.

Cross-section of protected fireproof cladding

Knauf Fireboard: Knauf FIREBOARD is a gypsum fibreboard, where the core of modified gypsum is reinforced with glass fibres and wrapped in a special fleece fabric [10]. The minimum thickness of the cladding is 12.5 mm. The possibility of using the gypsum fibreboard is also available in the OZone programme. The temperature of the column with an HEB 100 section protected by a 12.5 mm Knauf Fireboard cladding was 316°C in the 30th minute according to the real fire temperature curve. The section resistance at this temperature was 216.3 kN. The utilization of the section was only 56%.

The column temperature in the 30th minute was 404°C with the same thickness of the protective material in the case of the ISO 834 temperature curve. The section resistance at this temperature was 196.3 kN. The utilization of the section was only 61%. The cladding of the section with Knauf Fireboard fire protection is shown in Fig. 6.

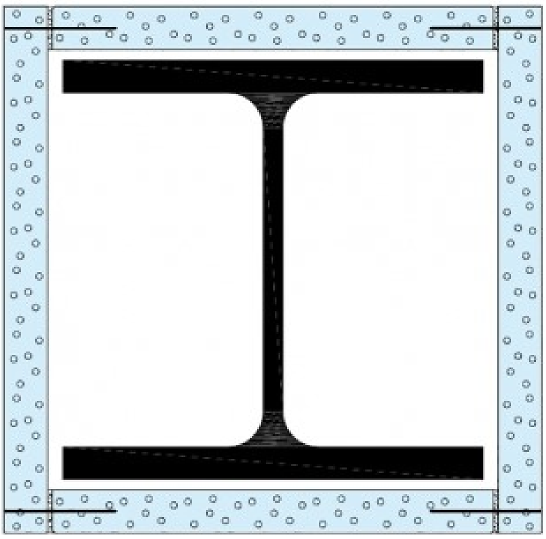

Fig. 6 Steel cross-section covered with a layer of Knauf Fireboard fire-resistant cladding.

Promatect-H: Promatect-H is a self-supporting fire-resistant board with moisture resistance, based on a cement composition [9]. A material with similar properties to Promatect-H is available in the OZone programme. The temperature of the column with an HEB 100 section protected by an 8 mm Promatect-H cladding was 468.4°C in the 30th minute according to the real fire temperature curve. The section resistance at this temperature was 176 kN. The utilization of the section is only 68%.

In the case of the ISO 834 temperature curve, the column temperature in the 30th minute was 542.8°C with an 8 mm cladding thickness. The section resistance at this temperature was 133 kN. The utilization of the section was 90%. The cladding of the section with Promatect-H fire protection is shown in Fig. 7.

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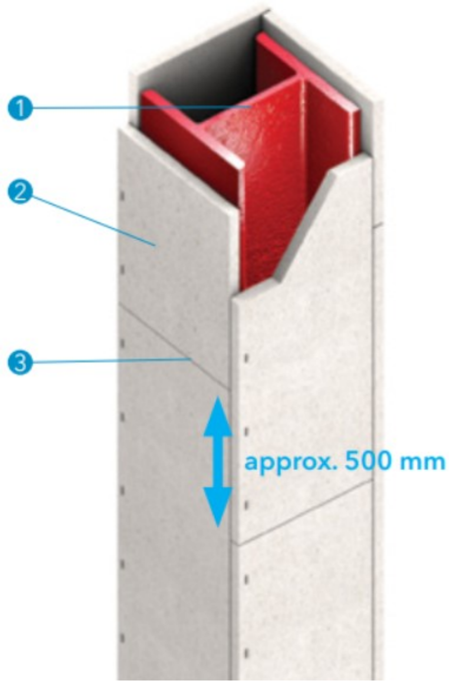

Fig. 7 Promatect-H:
1 – cleaned steel, 2 – fireproof cladding, 3 – board joints.

Cross-section without fire protection designed for fire resistance R30

It is possible to design a structural element for fire resistance by increasing its cross-sectional area without any fire protection in certain specific cases with shorter fire resistance requirements (e.g., R30),. The case of the analysed column, located on the top floor and with its highest load due to snow, can be considered a situation where increasing the cross-sectional area might be a suitable solution. A column with an HEB 220 section, primarily designed for fire resistance R30, was chosen as an alternative to fire protection measures.

The critical temperature at which the column would fail was 922.02 °C. The critical temperature was reached by the column after approximately 31 minutes of fire exposure. The temperature of the column with the HEB 220 section, without fire protection, was 878.9 °C at the 30th minute according to the temperature curve from a real fire. The cross-sectional resistance at this temperature is 148.4 kN, with the utilization of the section being 82%.

At the 30th minute, the temperature of the column with the HEB 220 section, without fire protection, was 758.5 °C according to the ISO 834 temperature curve. The cross-sectional resistance at this temperature was 289.9 kN, with the utilization of the section being 42%.

Since the column's cross-section was primarily designed for a fire-resistance rating of R30, its utilization at normal temperature under a design load of 216 kN was only 9.3%. The design buckling resistance was 2,335 kN.

3 RESULTS

The summarized results from the design analysis are presented in the following Tab. 1 and Tab. 2, comparing the material properties of the fire protection materials used and their respective prices.

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Tab. 1 Comparison of steel column designs in a fire situation.

Cross-section	Fire protection type	Product	Fire load	Temperature at R30 (°C)	Fire mat. thickness (mm)	Utilization (%)
HEB100	Non-protected	–	20°	20	–	78
			Hot Zone	994		1,026
			ISO 834	815		510
	Spray	Promapaint-SC3	–	550	1.951	97
		Promapaint-SC4		550	0.229	97
	Coating	Promaspray-P300	–	550	10	97
		Ozone coating	Hot Zone	540	6	89
			ISO 834	559	7	99
	Cladding	Knauf Fireboard	Hot Zone	316	12,5	56
			ISO 834	404		61
		Promatect-H	Hot Zone	468	8	68
			ISO 834	543		90
HEB220	Non-protected	–	20°	20	–	10
			Hot Zone	879		82
			ISO 834	759		42

Tab. 1 compares the utilization of the cross-section at the given thickness of the applied fire protection. Based on the applied fire temperature curve, the fire protection thickness for the steel column cross-section was designed to ensure that the temperature of the column at the observed time (30 minutes) remains lower than the critical temperature at which the column would fail. The utilization of the cross-section represents the utilization of the buckling resistance at the given temperature. The design temperature of 550 °C was selected for the HEB 100 section at R30, according to the manufacturer's catalogue [8] for the Promapaint spray and Promaspray coatings. The cross-section utilization in this case represented the comparison of the design temperature and the critical temperature. The range in cross-section utilization results was quite large; however, all protections were designed to meet the R30 fire resistance requirement. The least utilized cross-section occurs when using Knauf Fireboard, which was due to its minimum allowable thickness of 12.5 mm.

Tab. 2 compares the designs from an economic perspective. The table also lists the weights of the materials for the required material thicknesses. The material weights and costs were calculated based on the amount needed to protect a single HEB 100-column section. Fire protection coatings and sprays also require application, which represents additional costs. For fire sprays, the estimated working time was approximately 5 hours at an hourly rate of 40 €/hour, including consumables. For fireproof coatings, the estimated working time was approximately 4.5 hours at an hourly rate of 30 €/hour, including consumables. The cheapest alternative, based on the comparison, was fire protection with Knauf Fireboard cladding, with a total cost of 234.2 €. The most expensive alternative for fire protection in this case was the Promapaint-SC3 fire spray, with a total cost of 416.1 €. The difference between the cheapest and the most expensive fire protection solution was up to 78%.

Tab. 2 Economic comparison of steel column designs in fire situations.

Comparison of designs					Price while maintaining R30 resistance				
Cross-section	**Fire protection type**	**Fire mat. thickness (mm)**	**Fire mat. weight (kg)**	**Utilization (%)**	**Steel[1] (€)**	**Fire mat.[1] (€)**	**Work[1,2] (€)**	**Total price (€)**	**Price deviation (%)**
HEB100	–	–	–	78 1026 510		–	–	–	–
	Promapaint-SC3	1.951	6.5	97		130.9	200	**416.1**	***78***
	Promapaint-SC4	0,229	0,78	97		16.4		**301.6**	***29***
	Promaspray-P300	10	6.09	97	85.2	19.3	200	**304.5**	***30***
	Ozone coating	6 7	not known	89 99		–	not known	–	–
	Knauf Fireboard	12.5	13.48	56 61		14	135	**234.2**	***0***
	Promatect-H	8	8.77	68 90		52,3	135	**272.5**	***16***
HEB220	–	–	–	10 82 42	303.7	–	–	**303.7**	***30***

Notes:

1) Price for material for 1 column with 3 m height.

2) The estimated working time is 4-5 hours at an hourly rate of 30-40€/hour (including consumables).

4 DISCUSSION

The protection of a steel load-bearing structure must be designed to provide both safety and economic efficiency. Fire protection design for steel structures is always specific to the given structure and cannot be universally determined as the best or most cost-effective solution due to the variability of materials, their properties and costs. Each material has distinct characteristics – some are suitable only for indoor use, while others can be used outdoors. Additionally, each material has specific requirements regarding humidity and environmental conditions.

A specific case, such as designing a column on the upper floor subjected only to roof structure loads and snow, combined with a fire resistance requirement of R30, allows for the use of an unprotected cross-section. Economically, this solution is 30% more expensive than the cheapest protected alternative. However, it eliminates the need for additional fire protection work after the column is installed. It should be noted that application costs in this study were only estimated, and actual values may vary. The percentage deviation or final price difference can also significantly change depending on labour costs in different cities, regions, or countries.

A cost-saving option in fire design is the reduction of buckling length according to STN EN 1993-1-2 standard [1]. In fire conditions, for braced frames, the buckling length can be reduced to half the system height due to the fixed heated column to the cooler columns above and below it. However, this option was not considered in the calculations to allow for better comparison of results and because the assumption that the buckling length in a fire is truly halved remains uncertain.

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5 CONCLUSION

Ranking of fire protection materials based on table results for the given structure from the cheapest to most expensive:

- Knauf Fireboard Cladding: €234.2, is the cheapest solution, which also provides a sufficient safety margin, as its utilization at 30 minutes of fire exposure is only 61%,
- Promatect-H Cladding: €272.5, with utilization of 90%,
- Promapaint-SC4 Spray: €301.6, with utilization of 97%,
- Unprotected HEB220 Section: €303.7, with utilization of 82%,
- Promaspray-P300 Coating: €304.5, with utilization of 97%,
- Promapaint-SC3 Spray: €416.1, with utilization of 97%.

The results of the analysis and economic comparison of steel column designs indicate that fire protection design cannot be generalized. Designers must consider all specific aspects of the given structure, material costs, and labour costs to select a solution that is not only safe but also economically efficient.

The research was focused on 2D braced frame structures, with plans to continue the study on 3D frame structures. In the next phase, a column will be designed along the entire height of the frame under fire conditions. The column will be divided into smaller segments, with their properties changing depending on temperature variations. Similarly, the beam will be segmented, and the effect of its stiffness changes on the buckling lengths of the column will be examined. A similar approach will also be applied to other boundary conditions in an un-braced frame.

References

[1] European Committee for Standardization (CEN). EN 1993-1-2 – Design of Steel Structures, Part 1.2: General Rules – Structural Fire. Brussels, Belgium: s.n., 2004.
[2] Bellová, Mária et al. Navrhovanie konštrukcií na požiarnu odolnosť podľa eurokódov. Bratislava: MABAG spol. s.r.o., 2010. pp. 1–216. ISBN 978-80-89113-69-9.
[3] ArcelorMittal. OZone 3.0.2. Liege: University of Liege, 2017.
[4] European Committee for Standardization (CEN). EN 1993-1-1 – Design of Steel Structures, Part 1.1: General Rules – General rules for buildings. Brussels, Belgium: s.n., 2006.
[5] Červenka, Roman. Buckling length of steel columns in frame structures stressed by fire. In: Juniorstav 2024: proceedings of the 26th International Scientific Conference on Civil Engineering. Brno: ECON publishing, 2024, pp. 1–7 [online]. ISBN 978-80-86433-83-7. ISSN 3029-5904. Available at: https://doi.org/10.13164/juniorstav.2024.24050
[6] Wald, F. et al. Structural Steel Design according to Eurocodes. Praha: Czech Technical University Publishing House, 2012. pp. 1–193. ISBN 978-80-01-05046-0.
[7] European Committee for Standardization (CEN). EN 1990 – Basis of structural design. rue de Sassart 36, B-1050 Brusel: s.n., 2009.
[8] Štujberová, Magdaléna. Vybrané problémy navrhovania konštrukcií na účinky požiaru. Bratislava: Slovenská technická univerzita v Bratislave, Publishing STU, 2009.
[9] Promat Handbook. Fire Protection of Load-bearing Steel Structures [Online]. Promat, d.o.o. Promat. 01/2024. [Accessed 18/10/2024.] Available at: https://etex.azureedge.net/pi704519/original/240910135/structural-steel-protection-handbook-promat-see-en-2024-01
[10] Systémy pre suchú výstavbu, podlahy, omietky a fasády [Online]. KNAUF, s.r.o. [Accessed 18/10/2024.] Available at: https://knauf.com/en-GB/search?query=fireboard