VÉDELEM TUDOMÁNY
KATASZTRÓFAVÉDELMI ONLINE TUDOMÁNYOS FOLYÓIRAT

Lublóy Éva, Kaczur András, Huszár Zsolt, Csanaky Judit

APPLICATION OF COMBINED FIRE PROTECTION FOR STEEL STRUCTURES

Abstract

Nowadays, the fire protection of steel and reinforced concrete structures is very important. Steel is sensitive to high temperatures, so its protection needs to be solved. Fire protection of steel structures is a difficult task that can be solved with intumescent paint, mortar, fire protective coating and round concreting. However, fire protection and the construction industry pose an increasing challenge to professionals. The use of a combination of fire protection and thermal insulation materials for the fire protection of building structures can be an interesting and innovative solution. The problem with this solution is that we know very little about the fire protection of this kind of designs. Accordingly, we performed a laboratory experiment on the high temperature resistance of rock wool and fiberglass thermal insulation and plasterboard insulation.

Keywords: steel structures, fire protection, combined coatings

KOMBINÁLT TŰZVÉDELEM ALKALMAZÁSA ACÉL-SZERKEZETEKHEZ

Absztrakt

Napjainkban nagyon fontos az acél és vasbeton szerkezetek tűzvédelme. Az acél érzékeny a magas hőmérsékletre, ezért a védelmét meg kell oldani. Az acélszerkezetek tűzvédelme nehéz feladat, amely duzzadó festékkel, habarccsal, tűzvédő bevonattal vagy körbetonozással oldható meg. A tűzvédelem és az építőipar azonban egyre nagyobb kihívás elé állítja a szakembereket.

Érdekes és innovatív megoldás lehet a tűzvédelmi és hőszigetelő anyagok kombinációjának alkalmazása az épületszerkezetek tűzvédelmére. Ezzel a megoldással az a probléma, hogy nagyon keveset tudunk az ilyen típusú szerkezetek tűzvédelméről. Ennek megfelelően laboratóriumi kísérletet végeztünk a kőzetgyapot és üvegszálas hőszigetelés, valamint a gipszkarton magas hőmérsékleten viselkedésére vonatkozóan.

Kulcsszavak: acélszerkezetek, tűzvédelem, kombinált bevonatok

1. INTRODUCTION

In case of fire load, the physical properties of the steel change as the temperature rises. Steel undergoes a number of phase transitions in higher temperature ranges. The rate of change is different in case of hot-rolled and cold-formed steels. This can be explained by the different production technology of steels, since then the excess stress introduced during cold forming suddenly decreases because of the high temperatures. The variation of yield strength of steels for structural steels (A_c) is 400 °C, in case of cold formed steels (A_b) it starts to decrease at 300 °C and this change can be considered linear up to 700-800 °C (Figure 1). However, the decrease in modulus of elasticity begins at 100 °C, where the steel begins to soften. The critical temperature is 500 °C for hot-rolled steels and 400 °C in case of cold-formed steels. The critical temperature is the temperature where it passes from the linearly elastic range to the malleable plastic range. Then it suffers from large deformations under relatively small loads.

Nowadays, the fire protection of steel structures is getting more and more importance. Fire protection of steel structures can be solved with intumescent paint, mortar, fire protective coating and round concreting. In this paper, we examine the possibility of combined fire protection solutions such as the joint application of fire protection sheet and thermal insulation.

From the civil engineering point of view, the strength, stiffness and modulus of

elasticity of steel are the most important factors. However, in the field of thermal engineering, changes in thermal conductivity and specific heat are also very important. From a fire protection point of view, these two factors are the most important. They affect the rate of heating of the steel and the amount of energy required for heating, that is how the strength and stiffness characteristics change.

2. SIZING PRINCIPLES

According to the National Fire Regulation (Decree of Ministry of Interior 54/2014) [2], the fire resistance of building structures must be determined by laboratory tests or sizing technical calculation methods described in the standard MSZ EN 1992-1-2 [5].

Due to the two legislations, a structure must be designed and constructed in case of fire in the following way:

- the structure retains its load-bearing capacity for a certain period of time,
- the spread of fire and the generation of smoke must be limited in the building,
- the spread of fire to adjacent structures should be limited,
- people in the building should leave the building undamaged or be rescued according to other measures,
- the safe intervention of firefighters must be available.

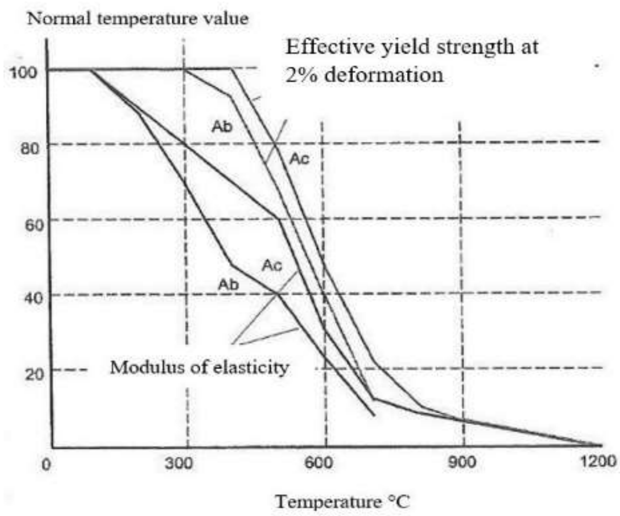

Figure 1- Variation of the yield strength of steel and the modulus of elasticity as a function of temperature [1].

The National Fire Regulation defines the fire resistance function (load-bearing, integrity, insulation) and the limit value (15, 30, 45, 60… minutes) of the various building structures, which must be taken into account during the design.

When planning for a fire load, the following tasks should be performed:

- the heat load must be specified,
- the spatial development of the temperature distribution in the structural elements must be determined,
- the mechanical behaviour of the support structure exposed to fire must also be determined.

EC1-1-2 [3] defines an important principle: if the requirements of fire resistance have been determined by a standard fire effect, the indirect effects transmitted from adjacent elements (inhibited deformations, effects due to the inhibition of thermal expansion, etc.) need not be taken into account. However, the effects of the temperature gradient within the element must already be taken into account. Based on it, simplified methods can be performed (for example tabular procedures and simplified calculation). In this case, the individual structural elements are checked separately [4].

However, if we want to control the whole structure, we need to consider the following effects and their consequences:

- inhibited thermal expansion in structural elements (e.g. frame columns);
- uneven temperature changes in statically indeterminate structures;
- non-uniform temperature distribution within the cross-section;
- thermal expansion of adjacent structural elements;
- the effect of thermal expansion of structural elements exposed to fire on the behaviour of structural parts outside the fire section [8].

If the support structure is examined in detail as a complete unit, the indirect effects of temperature cannot be ignored. Technical standards are the guidelines for the inclusion of values for indirect effects due to fire [8].

Fire design can be considered as an extraordinary design state, where the main effect is the temperature effect. As a representative value of the highlighted potential effect of $\psi_1 Q_1$, the common value of 1. Q_1 should be taken into account. The relevant load combination is the following [3]:

$$\sum_{j\geq 1} G_{k,j} "+" P "+" A_d "+" \psi_{1,1} Q_{k,1} "+" \sum_{i>1} \psi_{2,i} Q_{k,i}$$

where

G_k the characteristic value of the constant effect

P representative value of the tension effect (usually none)

A_d the design value of the extreme effect (temperature change)

$\psi_{1,1}$ the combination factor corresponding to the frequent value of the highlighted potential effect

$\psi_{2,j}$ combination factors belonging to the quasi-constant values of the additional possible effects.

Any reduction in permanent and payloads during combustion can be ignored. The values of the combination factors can be taken from EN 1991-1-2. The resistance of structure at the moment of the generation of fire (at time t = 0) $R_{fi,d,0}$ the resistance decreases as the spent time in the fire progresses. In state of emergency, the safety level required for the structure is lower than in state of permanent design. Therefore, after the generation of fire, the effect $E_{fi,d}$ decreases compared to the “normal temperature”. This reduction is at least 70%.

The strength tests must be implemented for the same period as the temperature tests, so the stability of the structure must be demonstrated for the duration of the fire resistance requirement.

There are three ways to prove fire resistance [4]:

1) expressed in terms of duration,
2) expressed in load capacity,
3) expressed in terms of temperature.

3. SIZING OF STEEL STRUCTURES

3.1. Calculation of unprotected steel structures

Critical temperature can be very important in case of calculating the load capacity of structures and clarifying the stability issues. During the static calculations, we checked the load capacity (utilization) of each structural element. In case of fire, a 30% reduction can be expected due to the reduction in load level. Therefore, based on *Table 2*, we give the decrease in strength of hot-rolled steel elements as a function of temperature. Based on the table, 500 °C is considered critical for strength, i.e. load capacity.

Table 1- Value of the reducing factors. [4]

Temperature	k_y° reducing factor (to the yield) $k_{y\theta} = f_{y\theta} / f_y$	k_p° reducing factor (to the proportionality) $k_{p\theta} = f_{p\theta} / f_y$	k_E° reducing factor (to the elastic modulus) $k_{E\theta} = E_{a\theta} / E_a$
20	1,000	1,000	1,000
100	1,000	1,000	1,000
200	1,000	0,807	0,900
300	1,000	0,613	0,800
400	1,000	0,420	0,700
500	0,780	0,360	0,600
600	0,470	0,180	0,310
700	0,230	0,075	0,130
800	0,110	0,050	0,090
900	0,060	0,0375	0,0675
1000	0,040	0,0250	0,0450
1100	0,020	0,0125	0,0225
1200	0,000	0,0000	0,0000

We can determine the temperature of steel in two steps. In the first step the outside air temperature should be determine. This can be defined by standard fire curves and heat and smoke modelling. In the second step, the temperature of the steel elements must be determined. In this case we distinguish uniform or uneven temperature rise within the profile. The calculation methods are included in MSZ EN 1993-1-2 standard [5]. After it has been determined, the amount of strength loss can be determined from *Table 1*. This value shall be compared with the utilization value resulting from the extraordinary load combination. If the decrease is below the occupancy level then the structure is appropriate, so no additional protection is required. However, if the utilization of the structure is lower, the critical temperature may be higher. If we know the utilization values, the critical temperature can be determined from *Table 1*.

3.2. Calculation of protected steel structures

Fire protection of steel structures is playing an increasingly important role nowadays. Fire protection of steel structures can be solved with intumescent paint, mortar, fire protective coating and round concreting. To calculate the critical temperature of steel it is important to determine the thickness of the paint, mortar and tile. These materials provide an extra insulation, but it does not matter to what extent the structure should be protected.

However, an interesting question is how effective the combined fire protection solutions (combined use of fire protection sheet and thermal insulation) are in terms of fire protection. We can find several data in the literatures on the mechanism of action of fire protection sheets and their effectiveness [6,7]. However, less data on the effectiveness of insulation materials and fire protection coatings have been found [8,9]. Within the framework of this research, we examined the thermal protection provided by a combined plasterboard with rock wool and fiberglass of different densities.

3.3. Experiments with combined fire protection

There is currently no calculation method for combined coating, therefore we examined the efficiency of combined systems in terms of fire protection of steel structures under laboratory conditions. Six types of fiberglass and six types of rock wool products were used during the test *(Table 2)*. As a result of the experiments, we compared the behaviour of rock wool products of different densities at high temperatures. During the test, the temperature of the steel I80 profile was measured at time T=0 and every 5 minutes thereafter, using the furnace and the thermocouple. This was measured until the **temperature** of the **steel profile** at the measurement site had **reached at least 650 °C**. At 650 °C, the yield strength of the steel material is only 35%

of its yield strength at normal temperature. At the end of the study this limit on was taken on the basis of an arbitrary decision.

Table 2- Summary of the planned tests.

Furnace (K) and mass - volume loss (T) tests				
Nr.	Material		Thermal conductivity [W/mK]	Density [kg/m³]
1.	Rock wool materials	Fixrock	0,039	32
2.		Airrock ND	0,035	50
3.		Airrock HD	0,035	70
4.		Steprock ND	0,038	140
5.		SMARTRoof Top	0,038	135
6.		Dachrock	0,040	152
7.	Fiberglass materials	Classic 039	0,039	12,5
8.		URSA DF 39	0,039	12,8-13
9.		Classic 037	0,037	15
10.		URSA SF32	0,032	30-32
11.		URSA FDP5	0,032	50,0
12.		URSA TSP	0,032	60-90

The temperature of the oven has been set so that its temperature should be maximum 1000 °C. This does not fully follow the indoor fire curve of the standard, but approximates it well in the final stage of the examination. At the end of the tests, the temperature of the steels was 658-841 °C, while the temperature of the furnace was between 951-1002 °C at the end of each experiment. The shortest test took 65 minutes; at this time the gas temperature was 651 °C in the heating chamber of the furnace. The gas temperature of the standard indoor fire curve was 657 °C at this time.

$$\theta_g = 20 + 345 \cdot log\, log\, (8 \cdot t + 1) \; = 20 + 345 \cdot log\, log\, (8 \cdot 65 + 1) \; = 657\, °C.$$

In the formula above, θg is the gas temperature in °C for the given fire section, while "t" is the time since the fire started in minutes. At the end of the 110 minute long test, the furnace temperature is 1002 °C due to the set temperature limit of 1000 °C (then 20 minutes continuously), the standard temperature of the standard indoor fire curve after 110 minutes

$$\theta_g = 20 + 345 \cdot log\, log\, (8 \cdot t + 1) = 20 + 345 \cdot log\, log\, (8 \cdot 110 + 1) = 1036\,°C,$$

so at the end of the test there was no significant difference between the gas temperature of the furnace and the fire curve according to ISO 834-1. The majority of the tests (75%) ended in 70-95 minutes. In this interval, the difference between the test and standard gas temperatures is even more favourable, only 1-13 °C. We ignore the furnace temperature differences during each test.

The furnace tests started with the closing of the furnace door at a time of T=0 min after the boxes were placed. The furnace should have been heated according to the standard fire curve according to ISO 834-1, but the temperature-time curve deviated from it. During the 12 tests (1-12), the heating of the furnace did not differ significantly. Although the temperature-time diagram of the furnace does not fit the standard (according to ISO 384-1) indoor fire curve, it behaves in a constant manner throughout the series of tests, so it subjects the specimens to almost the same heat load at the same times.

The design of the specimens is illustrated in **Figure 2**.

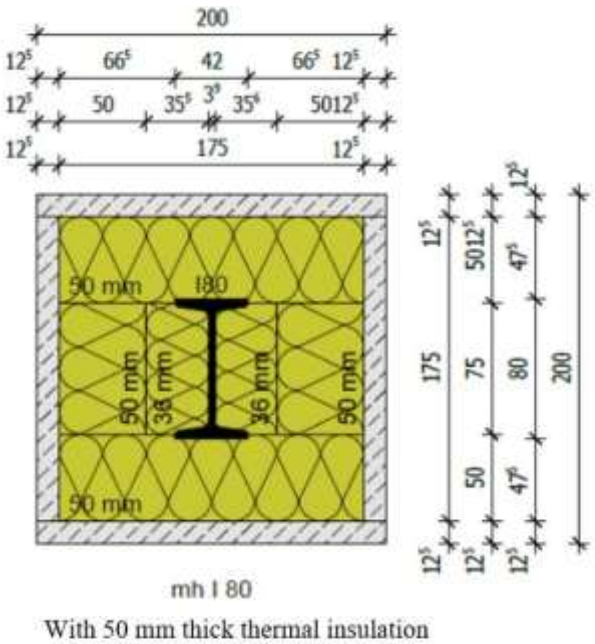

Figure 2 - Cross-sectional design of the specimen.

3.3.1. Test results for specimens with fiberglass insulation

General experience with specimens filled with fiberglass thermal insulation material and general results with regard to their behaviour under thermal stress:

Thermal insulation materials with a lower bulk density (12.5-15 kg/m^3) suffer from high compression at pressures perpendicular to their plane. In order to prevent the material from being compressed during the test (significantly changing the tested bulk density), the hot-rolled steel profiles were supported with 4 screws of appropriate length per specimen.

Due to its amorphous structure, glass does not have a definite melting point. In case of heating, it gradually softens depending on the ingredients. However, in case of the fiberglass materials, it can be said that the melting point of the glass is between 500 and 800 °C. As we will see from the weight loss tests, the specimen remained intact at 500 °C. All the specimens melted at 800 °C *(Figure 3).* During the test, first smoke and then condensation were observed near the oven at a temperature of 300 °C. It disappeared after a while, long before the test was completed. The temperature-time curve of the steel profile was similar in all cases: it started with a longer or shorter horizontal section depending on the bulk density (the thermal insulation material exerted the effect of thermal insulation). After the horizontal section, warming also started with a variable intensity depending on the bulk density of the material. After that depending on the material, the temperature of the steel profile hardly increased for 10-35 minutes (even in the context of bulk density, the temperature of the steel has mostly decreased). Then a nearly linear increase in temperature began until the end of the test. This ended at the end of the five minutes when the temperature of the steel profile had already reached 650 °C.

It can be stated that the higher is the bulk density of the thermal insulation material, the slower is the heating of the steel section *(Figure 4).*

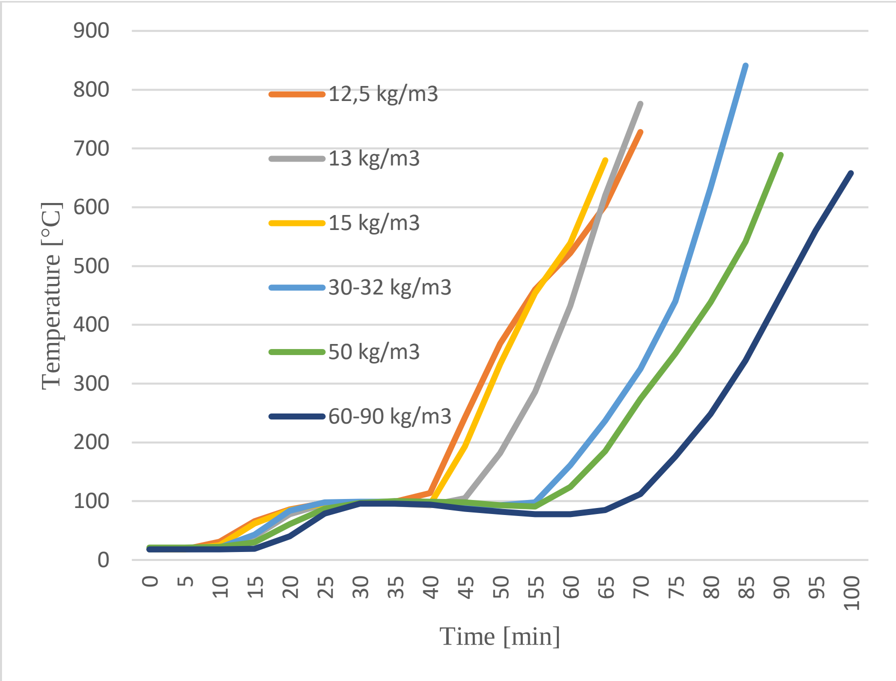

Figure 4- Temperature development of the steel profile in case of fiberglass insulation as a function of time

3.3.2. Test results in case of specimens with rock wool thermal insulation

Similar to the box-type specimens filled with fiberglass thermal insulation materials, the test results for boxes filled with rock wool thermal insulation materials are not presented in the test order, but in the order of the increasing bulk density of the tested materials. General experience with rock wool tests and general results on its behaviour under heat load:

- The lowest density (32 kg/m^3) rock wool insulation material also had sufficient stiffness against the pressure perpendicular to the quilt. Thus, the underlying I80 steel profile did not compress under its own weight to such an extent that the density under it changed significantly. As a result, it was not necessary to install a separate spacer in these specimens.
- The melting point of rock wool is above 1000 °C (in some types it even exceeds 1100 °C) therefore, due to the heat load limit of 1000 °C, we **were not observed any melting of rock wool material** on the specimens.

During the test, the structure of the thermal insulation material changed significantly in most cases. It became more compact, homogeneous, and its **volume** generally **decreased** unevenly along the material.

- The temperature-time curve of the steel profile was similar in all cases: it started with a shorter or longer horizontal section depending on the bulk density of the thermal insulation material (the thermal insulation material exerted the effect of thermal insulation). After this horizontal section, the heating of the steel profile also started with a variable intensity depending on the bulk density of the material. The heating continued to approximately the same temperature (95-97 °C) and then, depending on the material (density), the temperature of the steel decreased for about 15-25 minutes. After the temperature low, a slightly accelerating temperature increase started until the end of the study. This ended at the end of the five minutes where the temperature of the steel profile had already reached 650 °C.

Figure 3- Typical failure of fiberglass insulation.

- During these tests, smoke formation and condensation were also observed in these cases near the oven temperature (300 ° C). This disappeared near the furnace opening after a while, long before the test ended.
- Some rock wool materials typically compacted, while others lost their cohesion, becoming dusty or it fell apart.

- In case of rock wool, it can also be stated that the higher the bulk density of the thermal insulation material was, the slower the heating of the steel section was *(Figure 6)*.

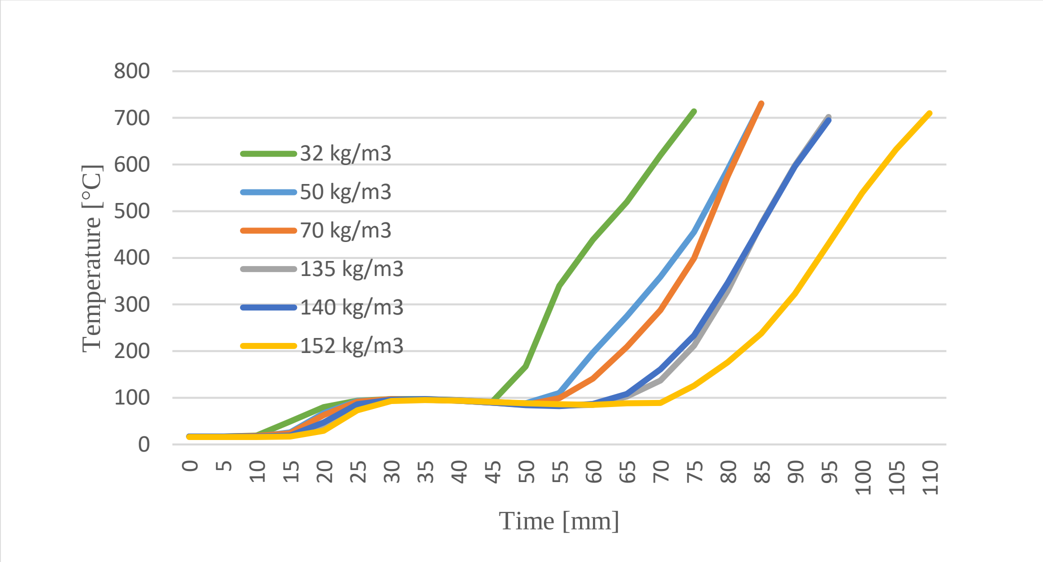

Figure 6 - Temperature development of the steel profile in case of rock wool insulation as a function of the time

4. SUMMARY

Fire protection of steel structures is becoming more and more importance today. Steel is sensitive to high temperatures, so its protection needs to be solved. Fire protection of steel structures is a more difficult task that can be solved with intumescent paint, mortar, fire protective coating and round concreting.

In this paper, we examined the possibility of combined fire protection solutions (combined use of fire protection sheet and thermal insulation). Based on the literatures in the topic, several data are available on the mechanism of action of fire protection sheets and their efficiency. [3,4]. However, we currently have little knowledge of combined fire protection solutions. Therefore, we examined the heat protection provided by a combined plasterboard with rock wool and fiberglass of different densities.

During our examination six fiberglass and six rock wool products were tested. As a result of the test, we compared the behaviour of fiberglass and rock wool products with different bulk densities at high temperatures according to type of material.

In case of fiberglass and rock wool insulation, it can be stated that the higher the bulk density was of the thermal insulation material, the slower the heating of the steel section was.

It can be stated that the effect of the additional insulating material can be taken into account in the fire protection of steel structures. However, it is advisable to calculate a value corresponding to the density of the insulating material.

5. ACKNOWLEDGMENT

The research was supported by the Higher Education Institutional Excellence Program announced by the Ministry of Human Resources, within the framework of the BME FIKP-VÍZ thematic program.

Figure 5- Typical failure of rock wool insulation.

REFERENCES

[1] Balázs L. Gy., Horváth L. et al. (2010) Szerkezetek tervezése tűzteherre az MSZ EN szerint (beton, vasbeton, acél, fa). Oktatási segédlet. MMK Tartószerkezeti Tagozat

[2] OTSZ 54/2014. (XII.5.) BM rendelet az Országos Tűzvédelmi Szabályzat kiadásáról III. fejezet Védelmi célok és tervezési alapelvek, V. fejezet Általános szerkezeti követelmények, 2. melléklet

[3] MSZ EN 1991-1-1: 2005 A tartószerkezetet érő hatások, Általános hatások, Tűznek kitett szerkezetet érő hatások, Magyar Szabványügyi Testület

[4] Balázs L. György, Horváth László, Kulcsár Béla, Lublóy Éva, Maros József, Mészöly Tamás, Sas Viktor, Takács Lajos Gábor, dr. Vígh László Gergely Szerkezetek tervezése tűzteherre az MSZ EN szerint (beton, vasbeton, acél, fa), ISBN: 978-615-5093-02-9 Kiadás éve: 2010. Kiadja: PI Innovációs Kft.

[5] MSZ EN 1993-1-2:2005 Eurocode 3: Acélszerkezetek tervezése 1-2. rész: Általános szabályok. Tervezés tűzterhelésre (NA készült; egyelőre angol nyelven szerezhető be az MSZT-nél)

[6] Szikra Cs., Takács L. (2010): „A Miskolc, Középszer u. 20 sz. alatti lakóépület tűzesetének sajátosságai", ÉPKO 2010, Nemzetközi Építéstudományi Konferencia, Csíksomlyó, Románia.

[7] Kopecskó Katalin: Fázisanalitikai módszerek alkalmazása a mérnöki gyakorlatban

[8] Wei Chen , Jihong Ye , Xianyong Li: Fire experiments of cold-formed steel non-load-bearingcomposite assemblies lined with different boards, Journal of Constructional Steel Research 158 (2019) 290–305

[9] Wei Chen , Jihong Ye , Xianyong Li: Thermal behavior of gypsum-sheathed cold-formed steel composite assemblies under fire conditions, Journal of Constructional Steel Research 149 (2018) 165–179

Lublóy Éva
Budapesti Műszaki és Gazdaságtudományi Egyetem
Budapest University of Technology and Economics
lubloy.eva@emk.bme.hu
Orcid: 0000-0001-9628-1318

Kaczur András
Schulek Frigyes Két Tanítási Nyelvű Építőipari Technikum
Frigyes Schulek Bilingual Technical Secondary School for Engineering and Architecture
kaczur.andras@t-online.hu
Orcid: 0000-0003-4975-9141

Huszár Zsolt
Budapesti Műszaki és Gazdaságtudományi Egyetem
Budapest University of Technology and Economics
huszarzs470@gmail.com
Orcid: 0009-0005-7970-5664

Csanaky Judit
Budapesti Műszaki és Gazdaságtudományi Egyetem
Budapest University of Technology and Economics
csanaky.judit@emk.bme.hu
Orcid: 0009-0001-4034-2596