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# An optimum selection of alloy for aluminium structures exposed to fire

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Subject review

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## An optimum selection of alloy for aluminium structures exposed to fire

Analytical methods for calculating fire resistance of aluminium structures, specified in (HRN) EN 1999-1-2, are presented in the paper. Since aluminium as a material loses its mechanical properties at lower temperatures compared to steel, the correct selection of aluminium alloy in terms of minimal reduction of mechanical properties is essential for satisfying fire-related requirements. For clarifying the influence of selecting aluminium alloy for obtaining an optimum fire resistance, a parametric analysis is presented to demonstrate the influence of aluminium alloy on the design fire resistance of a load-bearing aluminium column.

### Key words:

aluminium, tempering, fire, EN 1999-1-2, high-temperature capacity

Pregledni rad

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## Optimalni izbor legure za aluminijske konstrukcije izložene požaru

U radu su prikazane analitičke metode proračuna požarne otpornosti aluminijskih konstrukcija koje su usvojene u (HRN) EN 1999-1-2. Budući da aluminij kao materijal više gubi mehanička svojstva pri nižim temperaturama nego li čelik, ispravan odabir aluminijske legure u smislu minimalnog smanjenja mehaničkih svojstava je bitan za zadovoljavanje požarnih uvjeta. Radi objašnjenja utjecaja odabira aluminijske legure s obzirom na dobivanje optimalne požarne otpornosti, prikazana je parametarska analiza u kojoj je demonstriran utjecaj aluminijske legure na proračunsku požarnu otpornost nosivog aluminijskog stupa.

### Ključne riječi:

aluminij, temperiranje, požar, EN 1999-1-2, nosivost na visokim temperaturama

Übersichtsarbeit

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## Optimale Auswahl der Legierung für feuergefährdete Aluminiumkonstruktionen

In der Abhandlung werden analytische Methoden zur Berechnung der Feuerbeständigkeit von Aluminiumkonstruktionen dargestellt, die in (HRN) EN 1999-1-2 übernommen wurden. Da Aluminium als Material bei niedrigen Temperaturen mehr mechanische Eigenschaften verliert als Stahl, ist die richtige Auswahl der Aluminiumlegierung im Hinblick auf eine minimale Verringerung der mechanischen Eigenschaften wichtig, um die Brandbedingungen zu erfüllen. Um den Einfluss der Auswahl der Aluminiumlegierung auf die Erzielung eines optimalen Feuerwiderstandes zu erklären, wird eine parametrische Analyse dargestellt, in welcher der Einfluss der Aluminiumlegierung auf die berechnete Feuerbeständigkeit der tragenden Aluminiumsäule demonstriert wird.

### Schlüsselwörter:

Aluminium, Temperierung, Feuer, EN 1999-1-2, Tragfähigkeit bei hohen Temperaturen

## 1. Introduction

Aluminium is the second most important metal after steel when it comes to construction of load-bearing structures. Advantageous characteristics of aluminium for civil engineering applications, i.e. reduced material weight relative to steel (approximately 3 times less), high strength of base material (aluminium strength is comparable to traditional steel alloys S235 and S275), extrusion possibilities to achieve an optimum shape of cross section, and improved durability, make aluminium suitable for use in longer span structures and in practical situations when the weight of the structure needs to be minimised. It is only in the course of twentieth century that aluminium alloys gained wider acceptance as material suitable for use in load-bearing structures [1, 2]. One of the reasons that delayed the use of aluminium in civil engineering was the belated implementation of aluminium in modern European standards – Eurocodes, where guidelines for the design of aluminium structures were among the last ones to be adopted. When compared to steel, aluminium alloys exhibit a more complex behaviour when exposed to external conditions. They have therefore been the subject of intensive research, both on regional and global levels [3, 4]. A special problem in civil engineering practice is the behaviour of aluminium when subjected to elevated temperatures (fire). Considering the topicality of worldwide research focusing on the behaviour of aluminium in fire [5–7], the studies on behaviour of aluminium alloys and structural elements in fire conditions have also been a subject of research in the Republic of Croatia [8–10].

Aluminium structures are sensitive to the effects of high temperature due to the high value of the thermal conductivity coefficient ( $>100 \text{ W/m}^2\text{K}$ ) and the low melting point of the material (between  $560\text{--}660 \text{ }^\circ\text{C}$ ) [5–7]. For the case of aluminium alloys, the degradation of mechanical properties is significantly pronounced at temperatures higher than  $200 \text{ }^\circ\text{C}$ . Generally, the heat capacity of aluminium (expressed as the product of the mass and specific heat capacity) is lower than the one for steel, primarily because aluminium is three times lighter than steel, which is an additional reason that allows faster heating of aluminium than steel. High value of thermal conductivity causes faster heating of aluminium compared to steel, while low melting temperature increases creep sensitivity of aluminium, which was the initial motivation for the research started in the Republic of Croatia. Current research in the field of aluminium behaviour in the field of fire in the Republic of Croatia is related to the analysis of time-dependent deformation (creep) that occurs in the presence of certain thermo-mechanical boundary conditions, all of which have been presented in a series of scientific papers [8–10]. The aforementioned studies demonstrated the creep sensitivity of aluminium columns and quantified their creep resistance expressed as the total time during which aluminium columns retain their load-bearing capacity for a given temperature and load utilization factor. Apart from the high temperature in aluminium alloys caused

by fire, a problem also occurs when the high temperature by welding is introduced, which results in the mechanical properties decrease and the material weakening in the welding area, together with the heat affected area.

According to building regulations, determining the reliability of load-bearing structures in the event of fire is one of the essential requirements for a building. Any uncontrolled burning that can cause injury to people and destruction of material goods is called fire, which, according to new regulations for building structures in the Republic of Croatia (Technical Regulation for Building Structures NN 17/2017), is one of the extreme effects on the structure. The determination of the resistance of load-bearing aluminium structures in the event of high temperature (fire) is given by HRN EN 1999-1-2 [11]. A revision of the current Eurocode is currently undergoing at European level, namely the development of the 2<sup>nd</sup> generation of European standards for aluminium structures [7]. From the aspect of reliability, the issue of occurrence and effect of fire in a building can be defined on two levels:

- first level: measures and guidelines for the protection of people and property from fire (fire alarm, safety routes, fire compartments, fire suppression and smoke control - sprinkler and hydrant network) - architectural design parameters,
- second level: reliability analysis of load-bearing structures in case of fire - accidental design situation applied on the structure.

From all of the above mentioned it is evident that special attention should be given to the design of aluminium structures exposed to fire, which, together with the apparent lack of literature in this field, was the motivation to write this paper. Due to the large number of seemingly very similar aluminium alloys (i.e. there is a great diversity in mechanical properties for the alloys labelled as 'same' but with different temper), it is extremely important to make an optimal choice according to their performance at high temperature. Therefore, the aim of this paper is to analyse the influence of the alloy choice, i.e. their temper, on the structural resistance of the aluminium structure when subjected to fire.

## 2. Properties of aluminium alloys at elevated temperatures

### 2.1. Mechanical properties

In order to determine the aluminium alloys' resistance when subjected to fire, the design values of the mechanical properties of materials  $X_{fi,d}$  according to HRN EN 1999-1-2: 2015 are defined as follows:

$$X_{fi,d} = \frac{k_0 \cdot X_k}{\gamma_{M,fi}} \quad (1)$$

where:

$k_0$  – the reduction factor for a strength or deformation property ( $X_{k,0}/X_k$ ) dependent on the material temperature

$X_k$  – the characteristic value of a strength or deformation property ( $f_k$  or  $E_k$ ) for atmospheric temperature design according to HRN EN 1999-1-1:2015

$X_{k,\theta}$  – the value of a material property in fire design, generally dependent on the material temperature

$\gamma_{M,fi}$  – the partial safety factor for the fire situation for mechanical properties of aluminium.

The design values for the thermal properties of aluminium alloys  $X_{fi,d}$  are defined as follows:

- if an increase of the property is favourable for safety, than according Eq. (2):

$$X_{fi,d} = \frac{X_{k,\theta}}{\gamma_{M,fi}} \quad (2)$$

- if an increase of the property is unfavourable for safety, than according Eq. (3):

$$X_{fi,d} = \gamma_{M,fi} \cdot X_{k,\theta} \quad (3)$$

For thermal properties of aluminium, the partial safety factor for the fire situation according to [12] is  $\gamma_{M,fi} = 1,0$ . For thermal exposure up to 2 hours, 0,2 % proof strength at elevated temperature of the aluminum alloys is defined as following:

$$f_{o,\theta} = k_{o,\theta} \cdot f_o \quad (4)$$

where:

$f_{o,\theta}$  – 0,2 % proof strength at elevated temperature,

$f_o$  – 0,2 % proof strength at room temperature.

The Eq. (4) for determining  $f_{o,\theta}$  according to [11] uses the factor for reduction of 0.2 % proof strength. In order to determine the stiffness of an individual element in structural analysis it is also necessary to implement the reduced modulus of elasticity at elevated temperature, again by using the reduction factors. A graphical representation of the 0.2 % proof strength reduction and the reduction of the modulus of elasticity for aluminium alloys at high temperature according to [11] are shown in the following figures (Figure 1 and Figure 2).

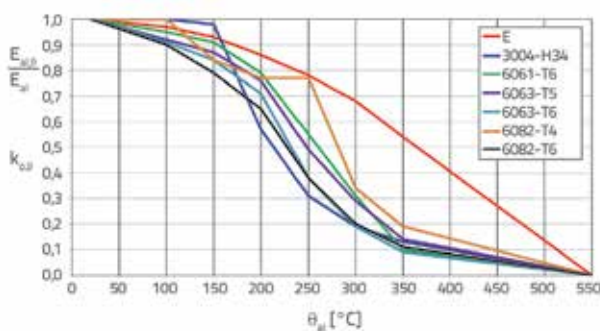


Figure 1. The 0.2% proof strength ratio  $k_{o,\theta}$  and ratio  $E = E_{al,\theta} / E_{al}$  for aluminium alloys EN-AW 3004 and alloys 6xxx at elevated temperature  $\theta_{al}$  [°C] for up to 2 hours of thermal exposure period [11]

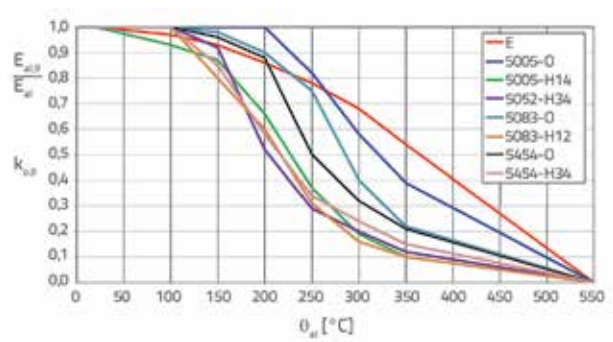


Figure 2. The 0.2 % proof strength ratio  $k_{o,\theta}$  and ratio  $E = E_{al,\theta} / E_{al}$  for aluminium alloys 5xxx at elevated temperature  $\theta_{al}$  [°C] for up to 2 hours of thermal exposure period [11]

The relative thermal elongation (strain) of aluminium alloys  $\Delta L/L$  for  $0^\circ\text{C} < \theta_{al} < 500^\circ\text{C}$  is determined as follows:

$$\frac{\Delta L}{L} = 0.1 \cdot 10^{-7} \cdot \theta_{al}^2 + 22.5 \cdot 10^{-6} \cdot \theta_{al} - 4.5 \cdot 10^{-4} \quad (5)$$

where:

$L$  – the initial length at 20 °C,

$\Delta L$  – the temperature induced elongation.

## 2.2. Thermal properties

The temperature increase in any material, including aluminium, depends on the material thermal properties: the specific heat capacity and the thermal conductivity coefficient. The specific heat capacity of aluminium alloys  $c_{al}$  for  $0^\circ\text{C} < \theta_{al} < 500^\circ\text{C}$  is calculated according to [11]:

$$c_{al} = 0,41 \cdot \theta_{al} + 903 \quad (6)$$

Graphical representation of specific heat capacity  $c_{al}$  depending on the temperature is shown in Figure 3.

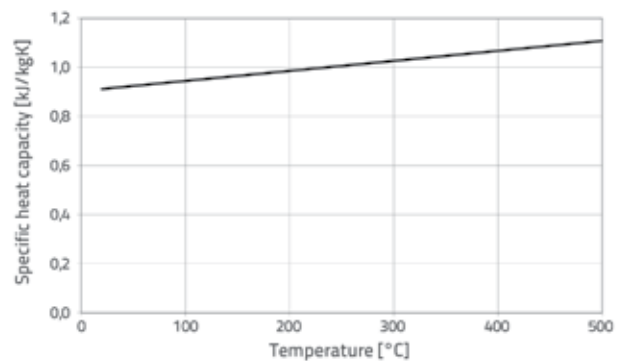


Figure 3. Specific heat capacity  $c_{al}$  as a function of temperature [11]

The thermal conductivity  $\lambda_{al}$  za  $0\text{ }^\circ\text{C} < \theta_{al} < 500\text{ }^\circ\text{C}$  for certain groups of aluminium alloys is determined by expressions (7) and (8) [11]:

- for alloys in 3xxx and 6xxx series:

$$\lambda_{al} = 0,07 \cdot \theta_{al} + 190 \text{ [W/mK]} \tag{7}$$

- for alloys in 5xxx and 7xxx series:

$$\lambda_{al} = 0,1 \cdot \theta_{al} + 140 \text{ [W/mK]} \tag{8}$$

Graphical representation of the thermal conductivity of aluminium alloys  $\lambda_{al}$  depending on the temperature is shown in Figure 4.

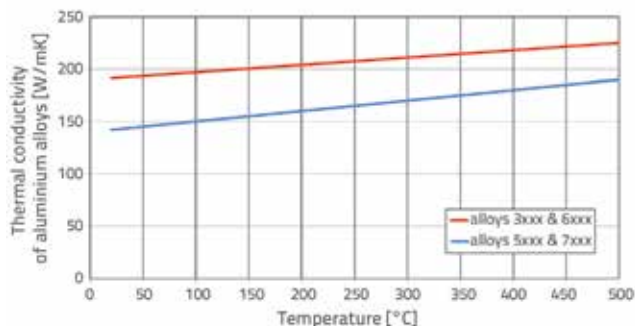


Figure 4 Temperature-dependent thermal conductivity [11]

### 3. Structural design of aluminium elements according to HRN EN 1999-1-2

Aluminium, like steel, is a non-combustible material. The fire effect on aluminium elements is manifested solely by the degradation of the mechanical properties of the material. The determination of the aluminium structural resistance in the event of fire is given by HRN EN 1999-1-2. Forced and restricted expansion and deformation caused by temperature changes in fire causes the change in internal forces and momentum, which must be taken into account when analysing structural behaviour. Exception can be made in cases where the change:

- may be recognized in advance as negligible or beneficial,
- are covered by conservatively selected reliance models and boundary conditions and / or are implicitly considered by conservatively determined fire safety requirements.

The following should be considered for determining indirect effects on load-bearing elements:

- thermal expansion of the elements is prevented, for example columns in multi-storey frame structures with rigid walls,
- different thermal expansion of elements of statically indeterminate structures, for example continuous elements,
- thermal gradients in cross section causing internal stresses,
- thermal expansion of adjacent elements, such as displacement at the top of a pillar due to the ceiling expansion or the expansion of suspended tendons (ropes),

- thermal expansion of elements affecting other elements outside the fire compartment.

The structural resistance of a load-bearing aluminium structure in case of fire event should be determined by using one or more of the following approaches:

- simple calculation model,
- advanced calculation model,
- experimentally.

Simple calculation models are simplified design methods for single element based on conservative assumptions, while advanced calculation models are the ones in which engineering principles are applied realistically for specific applications.

#### 3.1. Simple calculation methods

According to Eurocode 9 [11], the load-bearing function of an aluminium structure or structural element is maintained during time interval  $t$  if the condition is satisfied:

$$E_{fi,d} \leq R_{fi,d,t} \tag{9}$$

where:

- $E_{fi,d}$  – the design effect of actions for the fire design situation, determined in accordance with HRN EN 1991-1-2 as the internal forces and moments, combined or individual
- $R_{fi,d,t}$  – the design resistance of the aluminium structure or the separate structural element, for the fire design situation during time interval  $t$  expressed as the internal forces and moments, combined or individual.

Aluminium alloy cross-section classification can be graded similarly as for atmospheric temperature calculation design. This principle is based on the same relative decrease in the 0.2 % proof strength and the modulus of elasticity. Taking into account the actual decrease of the modulus of elasticity at a given temperature, where for the most aluminium alloys the decrease in the 0.2 % proof strength is larger than the modulus of elasticity decrease, the calculation can give a larger rotation capacity value and the lower (favorable) cross-section class. According to [11], the classification of cross sections in case of fire is the same as for the calculation at atmospheric temperature.

The design resistance  $N_{fi,t,Rd}$  of a tension element with unequal temperature distribution across the cross section for time interval  $t$  is determined from the following expression:

$$N_{fi,t,Rd} = \sum A_i k_{\theta,i} \frac{f_o}{\gamma_{M,fi}} \tag{10}$$

where:

- $A_i$  – an elemental area of the net cross-section exposed to temperature level  $\theta_i$  including a deduction if required to

allow for the effect of HAZ softening where the deduction is based on the reduced thickness of  $\rho_{o,haz} \cdot t$

$k_{o,\theta_i}$  – the reduction factor for the effective 0,2 % proof strength at temperature  $\theta_i$ . Value  $\theta_i$  is the elemental area  $A_i$  temperature value

$f_o$  – the 0,2 % proof strength,

$\gamma_{M,fi}$  – the partial safety factor for the relevant material property in case of fire.

The tension design resistance of the cross-section  $N_{fi,\theta,Rd}$  with a uniform temperature over the cross section  $\theta_{al}$ , is calculated according to the expression:

$$N_{fi,t,Rd} = k_{o,\theta} N_{Rd} \frac{\gamma_{Mx}}{\gamma_{M,fi}} \quad (11)$$

where:

$N_{Rd}$  – is the design tension resistance of a cross-section for the atmospheric temperature design

$\gamma_{Mx}$  – is the partial safety factor according to HRN EN 1999-1-1:2015.

For aluminium elements exposed to longitudinal tensile force with uniform or non-uniform temperature distribution across the cross section for time interval  $t$ , the following should be obtained:

$$\frac{N_{fi,Ed}}{N_{fi,t,Rd}} \leq 1.0 \quad (12)$$

where:

$N_{fi,Ed}$  – is the design value of the corresponding force for the fire design situation

$N_{fi,t,Rd}$  – the design cross-section resistance of a tension element for the fire design situation

Elements loaded with centric compressive force (compression elements) with uniform or non-uniform temperature distribution in the cross section for time interval  $t$  can be verified against buckling according to following expression:

$$\frac{N_{fi,Ed}}{N_{b,fi,t,Rd}} \leq 1.0 \quad (13)$$

where:

$N_{fi,Ed}$  – is the design value of the corresponding force for the fire design situation

$N_{b,fi,t,Rd}$  – is the design buckling resistance of a compression element for the fire design situation.

The design buckling resistance of a compression element  $N_{b,fi,t,Rd}$  for time interval  $t$  may be determined from:

$$N_{b,fi,t,Rd} = k_{o,\theta_{max}} N_{b,Rd} \frac{\gamma_{M1}}{1.2 \gamma_{M,fi}} \quad (14)$$

where:

$N_{b,Rd}$  – is the buckling resistance of the element for atmospheric temperature design,

1,2 – a reduction factor of the design resistance due to the temperature dependent creep.

The relative slenderness of the elements as well as the column buckling length  $L_{fi}$  are defined in the same way as for the atmospheric temperatures.

A column at the observed level (floor), fully connected (non-permeable joints) with the columns above and below, if any, is considered as effectively restrained if the structural fire resistance of the building elements separating the observed levels is at least equal to the structural resistance of the column (in case of fire). In the case of a braced frame in which each storey comprises a separate fire compartment with sufficient fire resistance, in an intermediate storey the buckling length  $L_{fi}$  of a column may be taken as  $L_{fi} = 0.5 L$ , and in the top storey the buckling length may be taken as  $L_{fi} = 0.7 L$ , where  $L$  is the height of the relevant storey, as shown in Figure 5 [11].

For the aluminium alloy elements subjected to bending with uniform or non-uniform temperature distribution across the cross section for time interval  $t$ , the following should be satisfied:

$$\frac{M_{fi,Ed}}{M_{fi,t,Rd}} \leq 1.0 \quad (15)$$

where:

$M_{fi,Ed}$  – is the design value of the corresponding moment for the fire design situation

$M_{fi,Rd}$  – is the design moment resistance of the cross-section for the fire design situation.

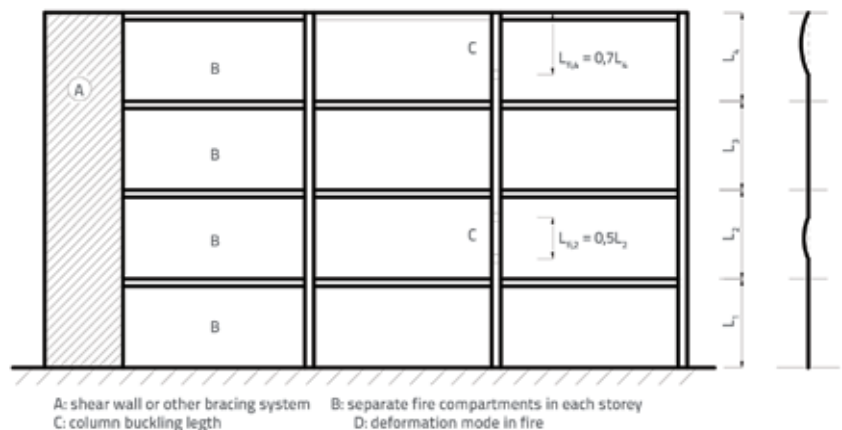


Figure 5. Examples of buckling lengths  $L_{fi}$  of columns in braced frames [11]

The design moment resistance  $M_{fi,t,Rd}$  of a cross-section with class 1 or 2 with a non-uniform temperature distribution for time interval  $t$  is determined from the following expression:

$$M_{fi,t,Rd} = \sum A_i z_i k_{o,\theta_i} \frac{f_o}{\gamma_{M,fi}} \quad (16)$$

where:

- $A_i$  – is an elemental area of the net cross-section exposed to temperature interval  $\theta_i$  including a deduction if required to allow for the effect of HAZ softening. The deduction is based on the reduced thickness of  $\rho_{o,haz} \cdot t$
- $z_i$  – is the distance from the plastic neutral axis to the centroid of the elemental area  $A_i$
- $k_{o,\theta_i}$  – is the 0,2 % proof strength ratio for the alloys strength at temperature  $\theta_i$ . Value  $\theta_i$  is the temperature of the cross section  $A_i$
- $\gamma_{M,fi}$  – the partial safety factor for the relevant material property for the fire situation.

The design moment resistance  $M_{fi,t,Rd}$  of a cross-section with class 3 or 4 with a non-uniform temperature distribution for time interval  $t$  is determined from the following expression:

$$M_{fi,t,Rd} = k_{o,\theta_{max}} M_{Rd} \frac{\gamma_{Mx}}{\gamma_{M,fi}} \quad (17)$$

where:

- $k_{o,\theta_{max}}$  – is the 0,2 % proof strength ratio for the alloys strength at temperature  $\theta_{al}$  equal to the maximum temperature  $\theta_{al,max}$  of the cross section reached at time  $t$ ,
- $M_{Rd}$  – is the moment resistance of the cross-section for atmospheric temperature design for class 3 and 4,
- $\gamma_{Mx}$  – is the material coefficient. The  $\gamma_{M1}$  is used in combination with  $M_{c,Rd}$  for atmospheric temperature and  $\gamma_{M2}$  used in combination with  $M_{u,Rd}$  for atmospheric temperature design.

The design moment resistance  $M_{fi,t,Rd}$  of a cross-section in class 1, 2, 3 or 4 with a uniform temperature distribution for time interval  $t$  is determined by the following expression:

$$M_{fi,t,Rd} = k_{o,\theta} M_{Rd} \frac{\gamma_{Mx}}{\gamma_{M,fi}} \quad (18)$$

where:

- $M_{Rd}$  – is the moment resistance of the cross-section for atmospheric temperature,
- $\gamma_{Mx}$  – is the material coefficient.  $\gamma_{M1}$  is used in combination with  $M_{c,Rd}$  for atmospheric temperature and  $\gamma_{M2}$  is used in combination with  $M_{u,Rd}$  for atmospheric temperature design.

For beams subjected to lateral-torsional buckling, the design buckling resistance moment  $M_{b,fi,t,Rd}$  of a laterally unrestrained beam for time interval  $t$  is determined by the following expression:

$$M_{b,fi,t,Rd} = k_{o,\theta_{max}} M_{b,Rd} \frac{\gamma_{M1}}{\gamma_{M,fi}} \quad (19)$$

where:

$M_{b,Rd}$  – is the design buckling-resistance moment for atmospheric temperature design.

For the aluminium elements subjected to shear force with uniform or non-uniform temperature distribution across the cross section for time interval  $t$ , the following expression is used:

$$\frac{V_{fi,Ed}}{V_{fi,t,Rd}} \leq 1.0 \quad (20)$$

where:

- $V_{fi,Ed}$  – is the design value of the corresponding shear force for the fire design situation,
- $V_{fi,t,Rd}$  – is the design shear resistance of the cross-section for the fire design situation.

The design shear resistance  $V_{fi,t,Rd}$  for time interval  $t$  is determined by the following expression:

$$V_{fi,t,Rd} = k_{o,\theta} V_{Rd} \frac{\gamma_{M1}}{\gamma_{M,fi}} \quad (21)$$

where:

- $k_{o,\theta}$  – is the 0,2 % proof stress ratio for the alloys strength at temperature  $\theta_{al}$ , where  $\theta_{al}$  is the maximum temperature of that part of the cross section which carries the shear force
- $V_{Rd}$  – is the shear resistance of the net cross-section for atmospheric temperature design.

When defining the design value of the net heat flux per unit area  $\dot{h}_{net}$  according to HRN EN 1991-1-2:2012/ 1:2014 it is necessary to use following values for emission coefficients:

- $\epsilon_m = 0.3$  za for clean uncovered surfaces of aluminium structures,
- $\epsilon_m = 0.7$  for painted and covered (e.g. sooted) surfaces of aluminium alloy structures.

The adopted model of calculation of a structural system according to the standard HRN EN 1999-1-2: 2015 has to reflect the expected behaviour of the structure (structural elements and joints) in a fire. To determine the appropriate internal forces  $E_{fi,d,t}$  during fire exposure, mechanical actions must be combined in accordance with the provisions of the standard HRN EN 1990: 2011 accidental design situation applied on the structure.

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature  $\Delta\theta_{al(t)}$  in an unprotected element during a time interval  $\Delta t$  is calculated with the following expression:



$$\Delta\theta_{al(t)} = k_{sh} \frac{1}{c_{al}\rho_{al}} \frac{A_m}{V} \dot{h}_{net} \Delta t \quad (22)$$

where:

- $k_{sh}$  – the correction factor taking into account the shadow effect,
- $A_m/V$  – the section factor for unprotected elements [ $m^{-1}$ ],
- $A_m$  – the exposed surface area of the element per meter length [ $m^2/m$ ],
- $V$  – the element volume per meter length [ $m^3/m$ ],
- $c_{al}$  – specific heat capacity of aluminium alloy [J/kgK],
- $\rho_{al}$  – the density of aluminium alloy [ $kg/m^3$ ],
- $\dot{h}_{net}$  – the design value of the net heat flux per unit area defined according to HRN EN 1991-1-2:2012/ 1:2014,
- $\Delta t$  – time interval [s].

For I-sections under nominal fire actions, the correction factor taking into account the shadow effect is determined by the following expression:

$$k_{sh} = 0,9 \frac{\left(\frac{A_m}{V}\right)_b}{\frac{A_m}{V}} \quad (23)$$

where:

$\left(\frac{A_m}{V}\right)_b$  – is the box value of the section factor.

For other cross-section shapes, the value of  $k_{sh}$  is determined as:

$$k_{sh} = \frac{\left(\frac{A_m}{V}\right)_b}{\frac{A_m}{V}} \leq 1,0 \quad (24)$$

For cross sections with a convex shape (e.g. rectangular or circular hollow sections) fully embedded in fire, the shadow effect has an insignificant influence and consequently the correction factor is  $k_{sh} = 1$ . Ignoring the shadow effect (i.e.  $k_{sh} = 1.0$ ) generally leads to conservative solutions. Figure 6. shows the analysis of temperature increase in an unprotected aluminium element using equation (22) for different values of the section factor. It can be seen that the temperature increase in the aluminium section, in case of exposure of the section to temperatures corresponding to the ISO fire curve, for the first 6 minutes is significant and that the section is heated to a temperature at which there is a significant effect on the reduction of the mechanical resistance. For this reason, the protection of aluminium structures with fire-resistant elements is recommended, especially if there is a possibility of a fire scenario relatively close to the elements of the aluminium structure.

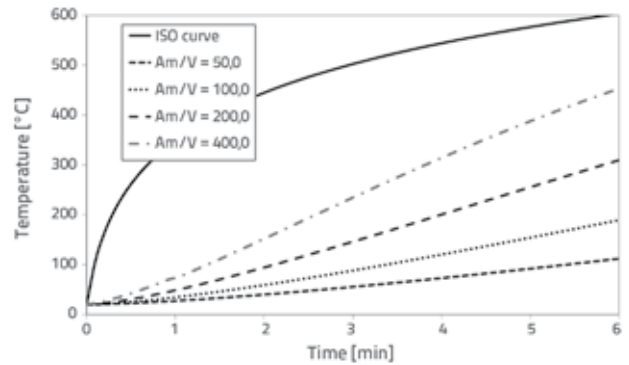


Figure 6. Analysis of temperature increase in an unprotected aluminium element for different section factor values

The temperature increase in an insulated aluminium element is determined by the following expression:

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p / V (\theta_{g,t} - \theta_{a,t})}{d_p c_a \rho_a (1 + \varphi / 3)} \Delta t - (e^{\varphi/10} - 1) \Delta\theta_{g,t} \quad (25)$$

$$\varphi = \frac{c_p \rho_p}{c_a \rho_a} d_p A_p / V$$

where:

- $c_p, \rho_p$  – are the specific heat capacity [J/kgK] and the density of the fire protection material [ $kg/m^3$ ]
- $\lambda_p, d_p$  – is the thermal conductivity of the fire protection material [W/mK] and the thickness of fire protection material [m]
- $A_p/V$  – is the section factor for aluminium elements insulated by fire protection material [ $m^{-1}$ ]
- $\theta_{g,t}$  – is the temperature at the surface of insulation material [ $^{\circ}C$ ]
- $\theta_{a,t}$  – is the aluminium temperature from previous time interval t [ $^{\circ}C$ ].

### 3.2. Advanced calculation models

Advanced calculation models are based on the basic physical behaviour and thus provide a reliable approximation of the expected behaviour of the relevant structural component in fire conditions. In addition, they should include additional calculation models for determining:

- development and temperature distribution in structural elements (thermal response model),
- mechanical behaviour of the structure or any part of it (mechanical response model).

Advanced calculation models may be used for any heating curve (fire curve) if the material properties for the appropriate temperature range are known. In addition, these models can be used for all types of cross sections (unprotected and protected). Advanced thermal response calculation models should be based on recognized principles and assumptions of heat transfer theory.

By using the thermal response model, following should be considered:

- appropriate thermal actions specified in the standard HRN EN 1991-1-2,
- changes in the thermal properties of the material as a function of temperature.

The influence of moisture content and moisture movement in the fire protection material can be neglected, which gives a conservative solution. Advanced mechanical response calculation models should be based on the recognized principles and assumptions of structural mechanics theory taking into account changes in the mechanical properties of materials with temperature. Mechanical analysis should also take into account the effects of heat-induced deformation and stress due to temperature rise and temperature differences, as well as:

- the combined effects of mechanical and thermal effects together with geometrical imperfections,
- temperature-dependent mechanical properties of the material,
- non-linear geometrical effects,
- effects of nonlinear material properties including favourable effects of loading and unloading on structural stiffness.

For temperatures above 170° C and for duration longer than 30 minutes, the effects of transient thermal creep must be taken into account in case of aluminium. Deformations in the ultimate limit state specified by the calculation method should be limited to ensure that all parts of the structure are compatible. The design shall take into account the ultimate limit state beyond which the calculated deformation of the structure could cause a failure due to the loss of a suitable support of one of the elements. The calculation of the elements exposed to buckling can be carried out using a sinusoidal initial imperfection with a maximum value at mid-height according to the maximum allowable deviations specified in HRN EN 1090-3.

#### 4. The influence of alloy selection on the fire resistance of an aluminium compression element (column)

##### 4.1. Scope of parametric analysis and calculation method

The calculation for three compression elements with different length: 2.5, 3.0 and 3.5 m is carried out simultaneously. For each element, an extruded square hollow profile with the same external dimensions (SHS 100x100) and the varied thickness (4,

5 and 6 mm) is adopted. In addition to the geometric parameters listed, two alloys that are commonly used in practice EN AW 6061-T4 and EN AW 6061-T6 are considered within the parametric analysis. The alloys considered are basically the same except that their temper obtained during production is significantly different, i.e. by changing the processing (state) and thus the behaviour at high temperature. A variation of these parameters resulted in total of 18 combinations, Table 1, which are analysed in Table 1.

Table 1. Parameters of the compression elements (columns) analysed SHS 100x100xt

Label	Wall thickness, t [mm]	Alloy EN AW 6061-	Length, L [m]
01_4-T4-2.5	4	T4	2.5
02_4-T4-3.0			3.0
03_4-T4-3.5			3.5
04_4-T6-2.5		T6	2.5
05_4-T6-3.0			3.0
06_4-T6-3.5			3.5
07_5-T4-2.5	5	T4	2.5
08_5-T4-3.0			3.0
09_5-T4-3.5			3.5
10_5-T6-2.5		T6	2.5
11_5-T6-3.0			3.0
12_5-T6-3.5			3.5
13_6-T4-2.5	6	T4	2.5
14_6-T4-3.0			3.0
15_6-T4-3.5			3.5
16_6-T6-2.5		T6	2.5
17_6-T6-3.0			3.0
18_6-T6-3.5			3.5

The cross-section classification was performed in accordance with [11, 13]. Due to the generally low buckling resistance of aluminium elements in the event of fire, [5-7], the analysis was performed for a presumed resistance over a period of 5 minutes. The analysis was performed for the fire scenario with the ISO fire curve applied [14]. The numerical calculation below is in accordance with European standards [11, 14], and the aim is to show a decrease in the resistance with a temperature rise for the different quality of the aluminium element (same alloy, different temper). For each increase in  $\Delta\theta_{a(t)}$  from the initial temperature  $\theta_{air}$ , the value of the reduction coefficient  $k_{0,\theta}$  (Table

Table 2. Reduction factor  $k_{0,q}$  dependence on temper and temperature [11]

T [°C]	20	100	150	200	250	300	350	550
$k_{0,\theta,T4}$	1.00	0.90	0.75	0.50	0.23	0.11	0.06	0
$k_{0,\theta,T6}$	1.00	0.95	0.91	0.79	0.55	0.31	0.10	0



2) is interpolated and the resistance obtained for the column at room temperature  $N_{b,Rd}$  ([15] with reduced buckling length) is reduced, which gives the new resistance of the column  $N_{b,fi,Rd}$ . The initial temperature  $\theta_{al} = 20$  °C for  $t = 0$  min increases incrementally for the calculated value  $\Delta\theta_{al(t)}$ . This development, the temperature increase with assumed uniform temperature distribution over the cross section in an unprotected aluminium element at some time interval  $\Delta\theta_{al(t)}$ , can be calculated according to expression (11).

For each new temperature value obtained in the aluminium element  $\theta_{al}$ , the initial resistance of the element according to expression (12) decreases depending on  $k_{\theta}$ , which represents the ratio of the 0,2 % proof strength reduction. The buckling length  $L_{cr}$  of the considered compressive element, which is a column between two floor structures, is 50 % lower in a fire situation [11]. In the event of a fire, a change in the modulus of elasticity due to a change in temperature may be considered. The change in the modulus of elasticity [5] determines the coefficient  $\alpha_{\theta}$  which, in addition to the slenderness, also affects the coefficient  $e$  which defines the cross-sectional classification. Since the value  $\bar{\lambda}$  is actually a quotient of  $\bar{\lambda}$  and  $\alpha_{\theta}$ , it means that the lower slenderness and higher resistance of the element to buckling would be obtained. However, the mentioned modification of the modulus of elasticity will not be used here because in the buckling calculation according to [11] and the Croatian National Appendix [12], the buckling design resistance of the column under fire condition is determined without taking

the more favourable cross-sectional class obtained by applying the reduced modulus of elasticity. This means that for this design,  $\bar{\lambda}_{\theta} = \bar{\lambda}$  applies but with reduced  $L_{cr}$  buckling length. An additional reduction factor (1,2) is introduced to calculate the buckling resistance of the element, which takes into account the creep of aluminium alloys at high temperature.

#### 4.2. Parametric analysis results and discussion

A summary of the parametric analysis is shown in Table 3. where the buckling resistance of the element is given depending on the fire exposure time ( $t = 0, 2.5$ , and  $5.0$  min). In addition to this, the ratios of resistance at prescribed time interval and the initial resistance for  $t = 0$  min are given, which are the clear indicator of the decrease in the resistance of the element in fire. It is noted that  $N_{b,fi,t=0,Rd}$  is the buckling resistance of the element for the accidental fire situation at time  $t = 0$  min and that it is calculated with the two times lower buckling length compared to the element calculated for the permanent load situation ( $N_{b,Rd}$ ). For the group of elements that are 3 meters long, Figure 7 shows the temperature-time curves of the elements and the buckling resistance depending on the fire exposure time. The solid line shows the resistance for the elements made of EN AW 6061-T6 alloy, while the dashed line shows the resistance for the elements made of EN AW 6061-T4. The dotted line shows the temperature change of the SHS cross section depending on the wall thickness ( $DT, t$ ). The curves for the other element

Table 3. The axial compression capacity of an element depending on the time of fire exposure

Time	$t = 0.0$ min		$t = 2.5$ min		$t = 5.0$ min	
Sample / Buckling resistance	$N_{b,fi,t=0,Rd}$ [kN]	$N_{b,fi,t=2.5,Rd}$ [kN]	$N_{b,fi,t=2.5,Rd} / N_{b,fi,t=0,Rd}$ [%]		$N_{b,fi,t=5.0,Rd}$ [kN]	$N_{b,fi,t=5.0,Rd} / N_{b,fi,t=0,Rd}$ [%]
01_4-T4-2.5	123	87.3	71		9	7
02_4-T4-3.0	118	84.3			8.7	
03_4-T4-3.5	112	80.3			8.3	
04_4-T6-2.5	241	215	89		37.5	16
05_4-T6-3.0	230	205			35.8	
06_4-T6-3.5	214	190			33.3	
07_5-T4-2.5	152	121	80		19.4	13
08_5-T4-3.0	146	117			18.7	
09_5-T4-3.5	139	111			17.8	
10_5-T6-2.5	331	305	92		114	35
11_5-T6-3.0	312	288			108	
12_5-T6-3.5	289	267			99.8	
13_6-T4-2.5	180	153	85		37.6	21
14_6-T4-3.0	172	146			35.9	
15_6-T4-3.5	165	140			34.6	
16_6-T6-2.5	393	368	94		200	51
17_6-T6-3.0	370	346			188	
18_6-T6-3.5	338	317			172	

lengths considered are analogous to the curves shown in Figure 7.

The results shown in Table 3 show the analogue behaviour of elements with different lengths. For the same cross section, alloy and the temper, the relative decrease of resistance is the same regardless of the element slenderness. In the groups with different temper, T4 and T6, for which the basic difference is in the nature of maturation after the heat treatment, the alloy EN AW 6061-T6 already at time  $t = 0$  min, has almost the double buckling resistance compared to the alloy EN AW 6061-T4. However, for the EN AW 6061-T6 alloy there is also a greater effect on the resistance at time  $t = 0$  min for the change of thickness. For the cross section with a wall thickness of 4 mm which is class 4, the increase of wall thickness to 5 mm results in 36 % higher resistance ( $N_{b,fi,t=0,Rd}(11\_5-T6-3,0)/N_{b,fi,t=0,Rd}(05\_4-T6-3,0) = 312/230$ ). As a comparison, for EN AW 6061-T4 alloys the same change in thickness results in 24 % higher resistance (146/118). For a fire action of 5 minutes long, any increase in wall thickness for both alloys results in at least doubled resistance value.

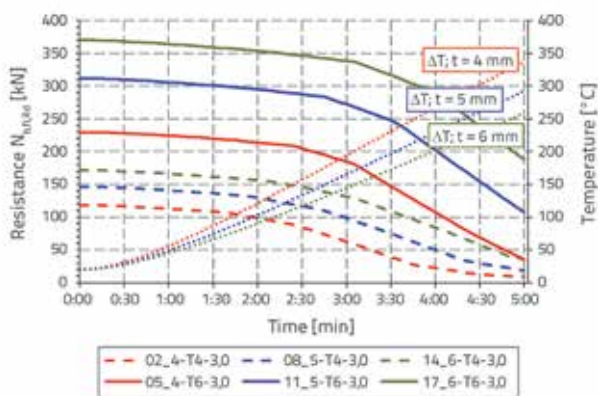


Figure 7. Resistance and temperature of the element with length of  $L = 3,0$  m as a function of fire exposure time

The decrease in resistance during fire depends on the reduction coefficients, Table 2, which differs for the alloys considered, due to different temper. Thus, for the EN AW 6061-T4 alloy, the decrease is much larger than for the EN AW 6061-T6 alloy, and deviations in the residual resistance of the element between these two alloys are particularly noticeable when the wall thickness is increased. For example, for a fire duration of 2.5 minutes, the resistance of the element with the lowest wall thickness (4 mm), for alloy EN AW 6061-T4 decreases to 71 % of the initial resistance (at time  $t = 0$  min) while the residual resistance of the alloy EN AW 6061-T6 is 89 % of the initial resistance. For the 5 minute duration and the same wall thickness, a large decrease in resistance is observed, so for EN AW 6061-T4 alloys it is 7 %, and for EN AW 6061-T6 alloys 16 % of the corresponding initial resistance value (at time  $t = 0$ ). For the maximum wall thickness observed, after 5 minutes, 21 % of the initial resistance remains for EN AW 6061-T4, while EN AW 6061-T6 alloy retains 51 % of the initial resistance value.

The relative change in the buckling resistance of the elements in fire action shows significant differences for the two alloys considered. Thus, it can be seen from Table 3, and the graphical representation in Figure 7, for elements of 3 meters in length, which the total reduction of resistance for 2.5 or 5 minutes of fire duration, compared to the initial resistance, is significantly different for two elements which share the same cross section but different alloys. It can be concluded that the choice of alloy and the temper determines the initial resistance of the element for both, the atmospheric temperature and for the case of fire. Thus, at the time  $t = 0$  min, the resistance of EN AW 6061-T6 alloys is twice higher than for the EN AW 6061-T4 alloy, while in the event of fire, due to twice higher bending length, the resistance of EN AW 6061-T6 results in 4- 6 times the resistance of the EN AW 6061-T4 alloy. If one alloy is considered separately, a large difference in resistance is made by changing the wall thickness for each alloy sample group.

### 4.3. Parametric analysis conclusion

This parametric analysis showed the difference in behaviour between two nominally identical alloys EN AW 6061 obtained from the same admixtures, silicon and magnesium elements, but tempered differently at the end of production. Both alloys, due to their different maturation methods, natural (T4) and artificial (T6), have a different reduction in proof strength, i.e. buckling resistance in case of fire. The naturally matured alloy exhibits half of the resistance value at the same temperature compared to the artificially matured alloy for all the observed lengths of the compressed element.

The decrease in resistance during fire is conditioned by the reduction coefficients, given in Table 3, which differ for both temper of the same alloy. Thus, for the EN AW 6061-T4 alloy, and the same cross-section, the decrease is much larger than for the EN AW 6061-T6 alloy. These differences in the residual resistance of the element between these two alloys are particularly noticeable for thicker cross-sections. For the same profile of an aluminium element and the increased length (slenderness), it can be seen that the EN AW 6061-T6 alloy exhibits greater decrease in the reduction resistance than the EN AW 6061-T4 alloy, despite the higher initial resistance.

The choice of alloy and temper essentially defines the resistance of the compressive element in a fire. In general, the 6xxx series alloys have mediocre mechanical properties, but they are very lightly shaped, well welded and have good anti-corrosion properties. However, the considered alloys with different tempers, EN AW 6061-T4 and -T6, very quickly lose their buckling resistance and they have a high reduction in strength for fire duration of just 5 minutes. It is noted that this parametric analysis was performed only for unprotected aluminium elements in order to provide an insight into the influence of alloy selection, i.e. temper, on the calculation of the buckling resistance at elevated temperature. In practice, exposed aluminium profiles must be protected against fire

by coatings or insulating materials for which an adequate resistance calculation is required.

## 5. Conclusion

Aluminium structures are extremely sensitive to the effects of elevated - fire temperatures solely due to the very rapid degradation of mechanical properties of structural elements under the influence of high temperature. Therefore, understanding the behaviour of materials and the choice of cross-section dimensions of aluminium structures is crucial for purposeful design in fire conditions. As shown in the example with determining the load bearing capacity of an aluminium element (column), it is of the highest importance in this work

to make an optimal choice of alloy and the temper, which will maximally delay the loss of load-bearing capacity of aluminium elements in fire. Naturally, for longer fire duration, it is necessary to realistically evaluate the fire development to be able to design the cost-effective and safe protection of aluminium structures against fire.

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