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Performance analysis of a simple aluminium structure in fire conditions

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Abstract:
In this study, a performance analysis of a simple aluminum (EN AW-6061 T6) structure is presented under fire conditions. A simple structure was also analyzed in a steel (S235) building variant for comparison purposes. All loads were determined in accordance with Eurocode rules. Internal forces were calculated using the SCIA Engineer 19.1. Cross-section resistances and element stability checks were performed using EN1993-1-1 and EN1993-1-2 for steel and EN1999-1-1 and EN1999-1-2 for aluminum. The main conclusion of this study is that aluminum, although initially more expensive than steel, can offer rational solutions for structures in which the difference in structural performance in fire conditions between aluminum and steel is not sufficiently drastic to yield significantly higher costs for fire protection in aluminum. Furthermore, aluminum building variants offer less mass, easier transport, and resistance to corrosion. Hence, for structures with the aforementioned factors as the main demands, aluminum can be a better option than steel.

Keywords:
Aluminum; steel; fire; EN AW-6061 T6; S235; fire resistance

1 Introduction

Aluminum is the most common metal on Earth, accounting for approximately 8 % of the Earth's crust. It is widely used in construction in external facades, roofs and walls, windows and doors, and staircases. However, it is also used as a structural material owing to its lightness, high strength, and durability.
Aluminum is currently considered as a building material in future because of its favorable mechanical properties when compared to standard construction steel. Furthermore, notable worldwide quantities also favor the more frequent use of aluminum alloys in everyday construction [1]. A significant number of structures worldwide are made of aluminum. Some examples include the road bridge Arvida over the river Saguenay in Quebec, Canada, and the pedestrian bridge Hem-Lenglet in Hauts-de-France. The former structure is entirely made of aluminum, weighs around 200 t with a total span of 153.62 m, and an arch span of 91.5 m. The latter structure has a total length of 83 m and a main-span length of 63 m [2].
Currently, aluminum has attracted significant research attention, especially under fire conditions. Hence, the behavior of aluminum members exposed to constant temperature and a new model for creep under fire conditions has been examined [1].

1.1 Mechanical properties of aluminum

Aluminum has many advantages as a structural material. The mechanical properties of aluminum and a comparison with carbon steel properties are listed in Table 1.

Table 1. Mechanical properties of aluminum and carbon steel [3]

Property	Aluminum	Carbon Steel
Density at 20 °C (g/cm^3)	2.70	7.85
Melting point (°C)	660	1400
Young's modulus of elasticity (GPa)	70	210
Mean specific heat (0-100 °C) (J/(kg °C))	920	470
Thermal Conductivity (0-100°C) (J/(sm))	240	54
Coefficient of Linear Expansion (0-100 °C) (1/°C)	23.5×10^{-6}	12×10^{-6}
Poisson's ratio	0.34	0.30

Aluminum has low density, which is approximately 2.9 times lighter than carbon steel. However, it also has high strength, and some aluminum alloys are comparable to S235 and S275 steels. Furthermore, its modulus of elasticity is three times lower than that of steel. Hence, its deformation is higher than that of steel.
It is highly resistant to corrosion because of the properties of aluminum oxide (Al_2O_3), which forms a thin (0.01 mm) layer on the element surface and protects the element from further corrosion. However, this leads to problems with welding.
Given that the melting point of aluminum oxide is approximately 2030 °C, it is extremely difficult to weld aluminum. Specifically, the density of aluminum oxide is higher (3.95 g cm^{-3}) than that of aluminum, which creates another welding problem: it sinks into aluminum when melted. Therefore, the oxide must be removed from the metal before welding. Given that aluminum exhibits high thermal conductivity and a low melting point, it has a smaller window of workability than other metals and can easily lead to burn through.
Apart from its high strength, low density, and corrosion resistance, aluminum is also an aesthetically pleasing material. Hence, it can lead to architecturally attractive buildings.
In addition to welding, aluminum has a low structural capacity at high temperatures. It has a very low melting point of 660 °C, which is more than two times lower than that of carbon steel, and thereby, it is more susceptible to the development of creep strain. The reduction in the modulus of elasticity of aluminum, according to EN 1991-1-2 [4], is shown in Figure 1.

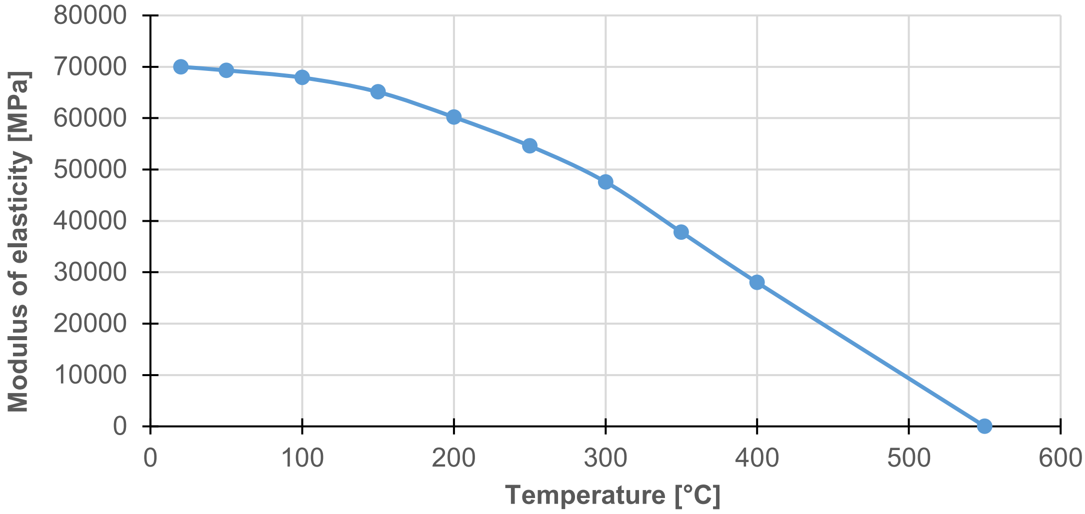


Figure 1. Modulus of elasticity with respect to temperature for aluminum [4]

2 Performance objective

The objective of this study is to analyze the performance of aluminum members under fire conditions when compared to that of steel counterparts. For comparison purposes, the same structure was modeled with aluminum and steel variants. The structural members were protected from fire with gypsum board encasement. The differences in the performances of aluminum and steel were observed using different necessary thicknesses of gypsum boards to retain load-bearing functionality after 30 min of standard fire exposure.

The structure shown in Figure 2 was subjected to a compartment fire. Its structural system consisted of columns (C), beams (A1, A2, B1, B2), and concrete slabs. In the middle, a non-bearing fire-separation wall separated the object into fire compartments. The dimensions of the building are shown in the picture in Figure 2.

The location of the building is Split, Croatia, and the elevation is 100 m above sea level.

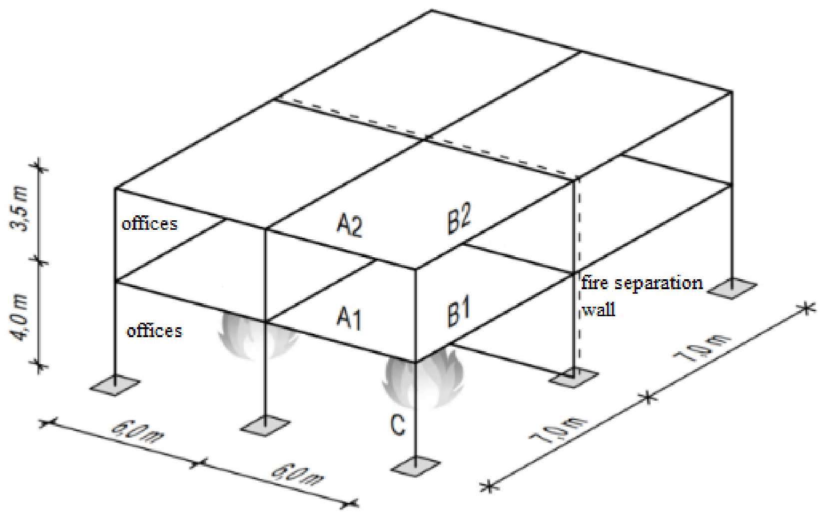


Figure 2. Dimensions of the observed structure

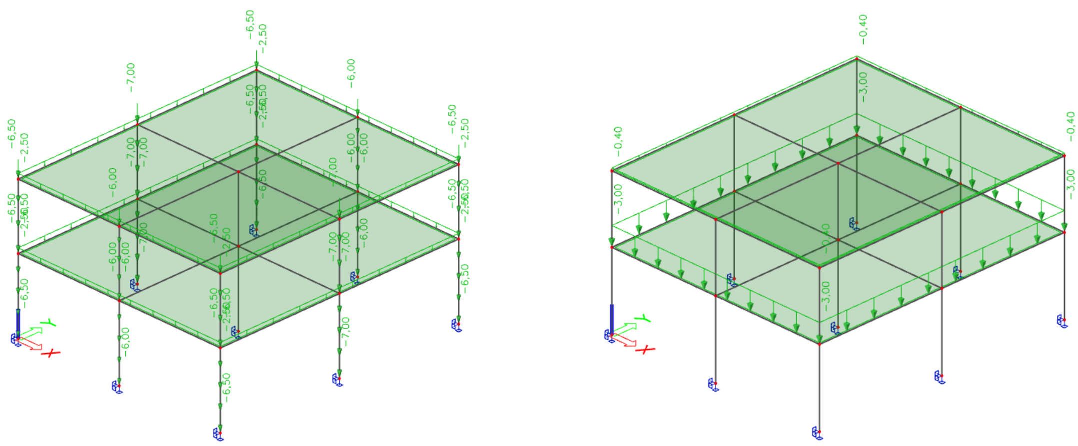
3 Model and loads

Two structural models were developed. One model in the aluminum variant using EN AW-6061 (T6) alloy and other in steel variant using grade S235. The columns were modeled using a fixed joint in the footing. The beams were modeled as plate ribs and continuously connected to a plate along the entire length of the beam. Furthermore, they were placed eccentrically below the plate. For analysis, the beam was considered as a distinct entity that fully collaborates with the plate. Beams were rigidly connected with columns with the exception of A1 beams, which had hinges on both ends. The fire separation wall was considered as a non-load bearing member and was added as a load.

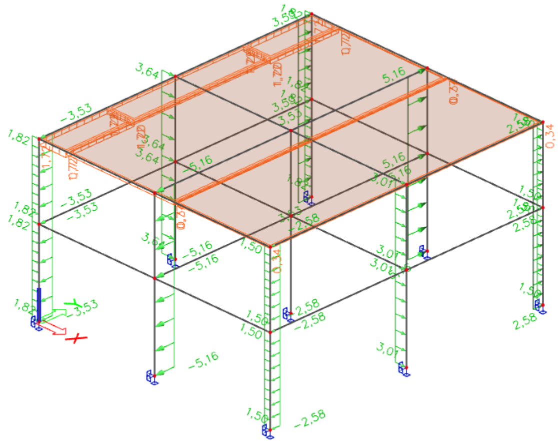
Table 2. Basic loads and assumptions

Load	Basic assumption
Additional permanent load	Weight of facade g=1 kN/m^2, flooring and installations g=2.5 kN/m^2
Imposed live load	Office area q=3 kN/m^2, roof area q=0.4 kN/m^2
Wind	Base wind speed v_0=25 m/s
Snow	Characteristic value s_k=0.5 kN/m^2
Temperature change - summer	T_{in}= 20 C° T_{out}= 49 C°
Temperature change - winter	T_{in}= 25 C° T_{out}= -5 C°

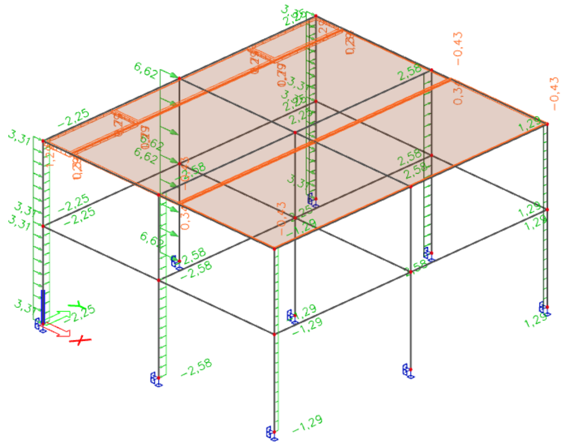
The applied loads included self-weight (automatically calculated by software), additional permanent load (weight of installations, floor layers, facade, fire separation wall, etc.), imposed live load, loads due to wind, snow, and temperature change, and fire load. All the loads were determined using Eurocode 1991 [4-8]. Basic loads and assumptions are listed in Table 2, and they are applied to the structural model in Figure 3.



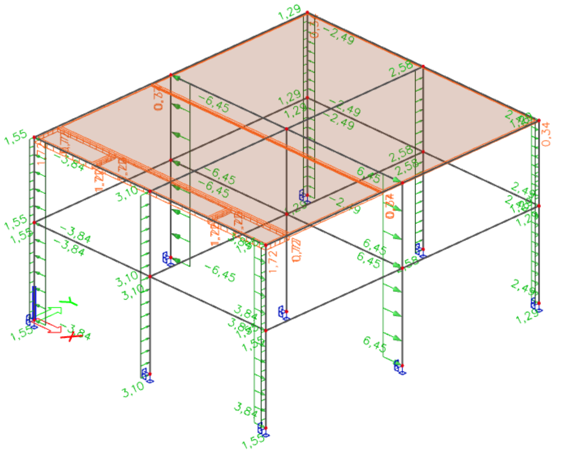
Additional permanent load Imposed live load



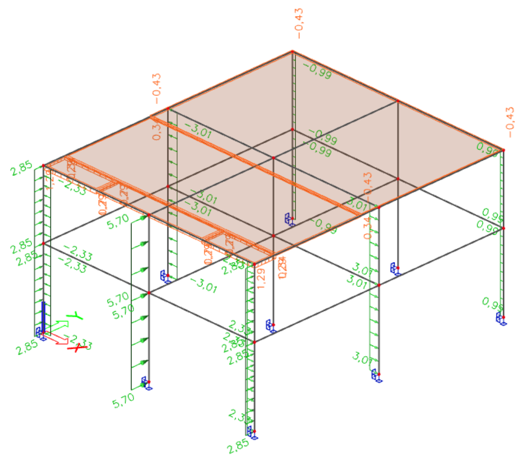
Wind 1 in x direction



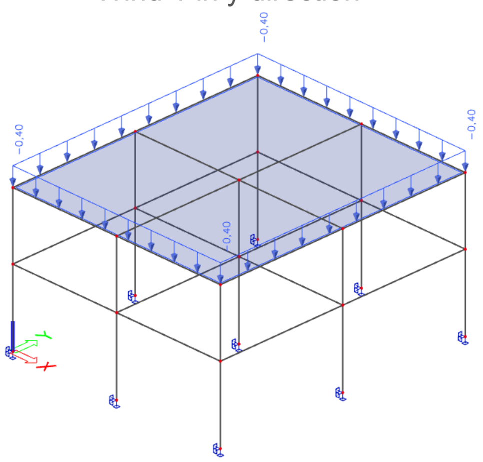
Wind 2 in x direction



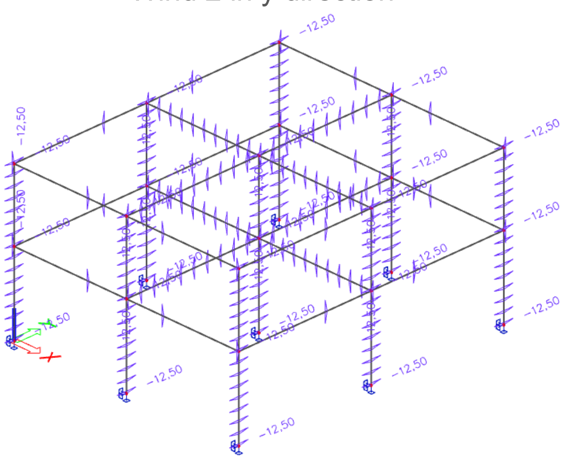
Wind 1 in y direction



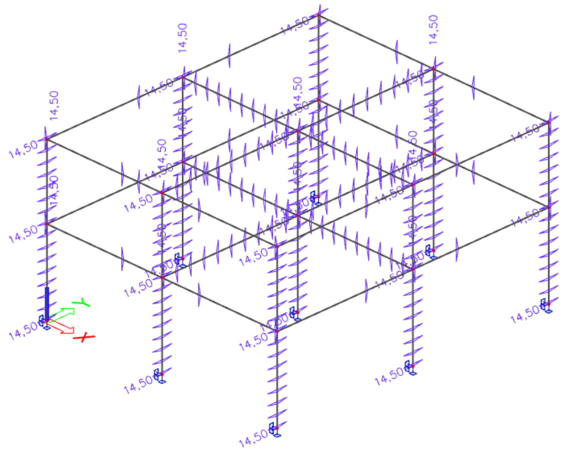
Wind 2 in y direction



Snow



Temperature change (winter)



Temperature change (summer)

Figure 3. Fundamental loads used to design the load-bearing members

The height of the ground floor was 4 m and that of the first floor was 3.5 m. The spans of the beams were 7 m (B beams) and 6 m (A beams). The slabs were 150 mm thick and were made of class C 25/30 concrete reinforced with B500B rebars, which were not designed in this study.

4 Structural analysis

The beams and columns fabricated from aluminum and steel were designed in accordance with their respective Eurocodes (EN 1999 for aluminum and EN 1993 for steel) [9,10]. The ultimate limit state should be satisfied for two combination classes:

i. fundamental combinations:

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_{Q,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i}\leq\frac{R_{ki}}{\gamma_R} \quad (1)$$

ii. accidental combinations:

$$\sum_{j\geq 1}G_{k,j}+A_d+(\psi_{1,1}\ or\ \psi_{2,1})Q_{k,1}+\sum_{i>1}\psi_{2,i}Q_{k,i}\leq\frac{R_{k,\theta}}{\gamma_{R,fi}} \quad (2)$$

The elements were first designed to satisfy the fundamental combinations. Subsequently, fire protection was designed in the form of gypsum boards to satisfy accidental combinations. The cross sections used are shown in the table below with their respective utilization factors. In the steel variant, all cross sections used were from the HEA family, and in aluminum variant a geometrically parameterized "I" section was used with labels "I gh (H; B; ta; s; ts; th)". The labels are explained in Figure 4.

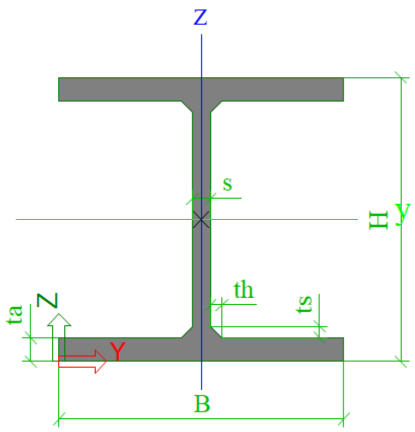


Figure 4. Labeling of aluminum cross sections

Table 3. Designed cross sections and their utilization factors

S235				EN AW-6061 T6			
Element	Cross section	Area (cm^3)	Utilization factor	Element	Cross section	Area (cm^3)	Utilization factor
Column	HEA260	86.82	0.90	Column	I gh (350; 300; 18; 10; 27; 27)	153.98	0.95
Beam A	HEA240	76.84	0.87	Beam A	I gh (250; 260; 13; 8; 24; 24)	97.04	0.91
Beam B	HEA240	76.84	0.93	Beam B	I gh (290; 280; 13; 8; 24; 24)	105.44	0.98

The total weight of steel was approximately twice the weight of aluminum. Specifically, the weight of steel was 83.36 kg/m^2, while that of aluminum was 42.17 kg/m^2.
For fire protection, a hollow encasement of gypsum boards of uniform thickness was designed. There are two different types of box encasements used: gypsum on all sides of the member and gypsum on three sides with a concrete slab on the fourth as shown in Figure 5. The boards that were used exhibited the following properties:
ρ_p= 800 kg/m^3
c_p= 1700 J/(kg°C)

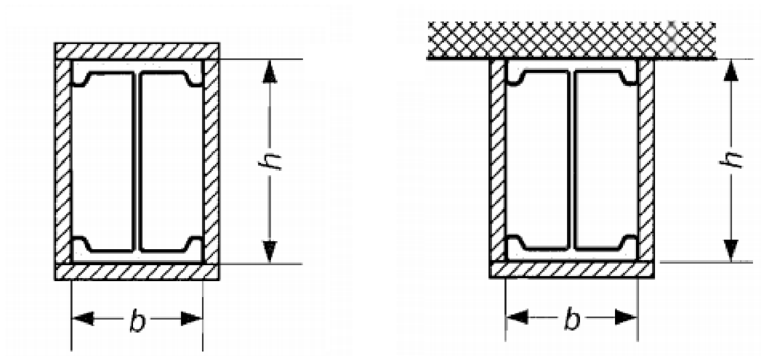


Figure 5. Hollow encasement of uniform thickness exposed to fire from 4 (left) and 3 sides (right) [9]

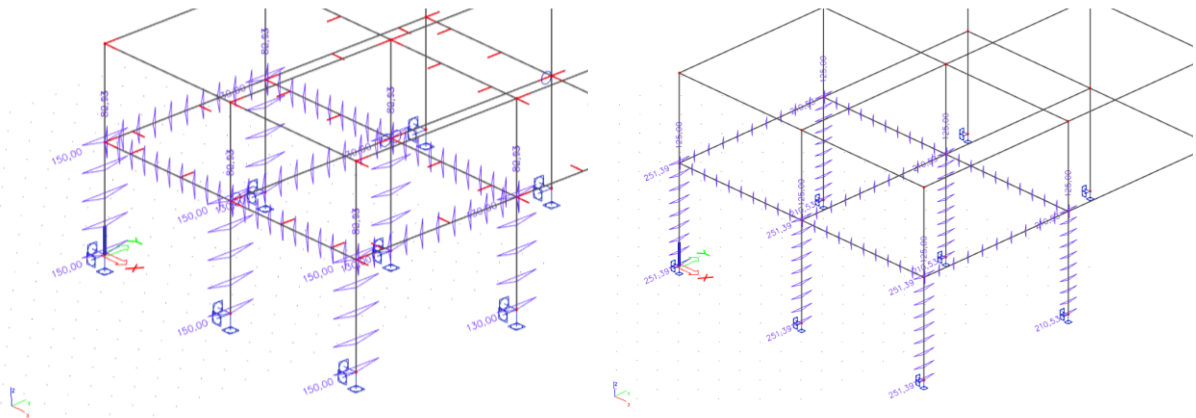
The temperatures were determined using Eurocodes EN 1993-1-2 [10] and EN 1999-1-2 [9]. For a uniform temperature distribution in a cross section, the temperature increase $\Delta\Theta al(t)$ in an insulated member during a time interval Δt should be obtained from:

$$\Delta\theta_{al(t)} = \frac{\lambda_p/d_p}{c_{al}\rho_{al}}\frac{A_p}{V}\left[\frac{1}{1+\phi/3}\right](\theta_{(t)} - \theta_{al(t)})\Delta_t - (e^{\phi/10} - 1)\Delta\theta_{(t)} \quad (3)$$

but $\Delta\theta_{al(t)} \geq 0$;

$$\phi = \frac{c_p\rho_p}{c_{al}\rho_{al}} d_p \frac{A_p}{V} \quad (4)$$

where:
A_p/V denotes the section factor for aluminum members insulated by fire protection material (1/m).
$\theta_{(t)}$ denotes the ambient gas temperature at time *t* (°C).
$\theta_{al(t)}$ denotes the aluminum temperature at time *t.*
$\Delta\theta_{(t)}$ denotes the increase in ambient temperature during the time interval *Δt* (°C).
d_p denotes protection thickness [9].
The selected time–temperature curve corresponded to the standard ISO-834 curve and time step Δt was selected as 0.1 min or 6 s, which is less than Δtmax= 30 s. [9]
The temperature rise after 30 min of standard fire was calculated for the assumed thickness of the gypsum boards. Then, it is applied as a thermal load in the software as shown in Figure 6. All beams were exposed to fire from three sides because the plate was above the upper flange. The outer columns were treated as exposed from all sides and columns by the fire separation wall from three sides.
In the steel variant, the assumed necessary thickness of the gypsum board protection was 2 cm for the columns and 3 cm for the beams. In the aluminum variant, 1-cm thicker protection was used when compared to that in the steel variant.



Temperatures in the aluminum variant   Temperatures in the steel variant

Figure 6. Temperatures of structural members during fire

Given that the calculated temperatures were not very high, a decrease in the modulus of elasticity was not considered for stress distribution. However, it was considered for the member resistance calculation. The critical elements are shown in Figure 7, and they are subjected to the following fire combination:

$$1.0\times(G+\Delta G) + 0.3\times(q+w) + 1.0\times f, \quad (5)$$

where:
G - self weight.
ΔG - additional permanent load.
q - imposed live load.
w - wind load.
f - fire load.

Table 4. Temperatures and utilization factors of elements after 30 min of fire exposure

S235				EN AW-6061 T6			
Element	Protection thickness d_p (cm)	Temperature θ_{30} (°C)	Utilization factor	Element	Protection thickness d_p (cm)	Temperature θ_{30} (°C)	Utilization factor
Column	2	231	0.77	Column	3	150	0.70
Beam	3	146	0.95	Beam A	4	101	0.92
				Beam B	4	102	0.79

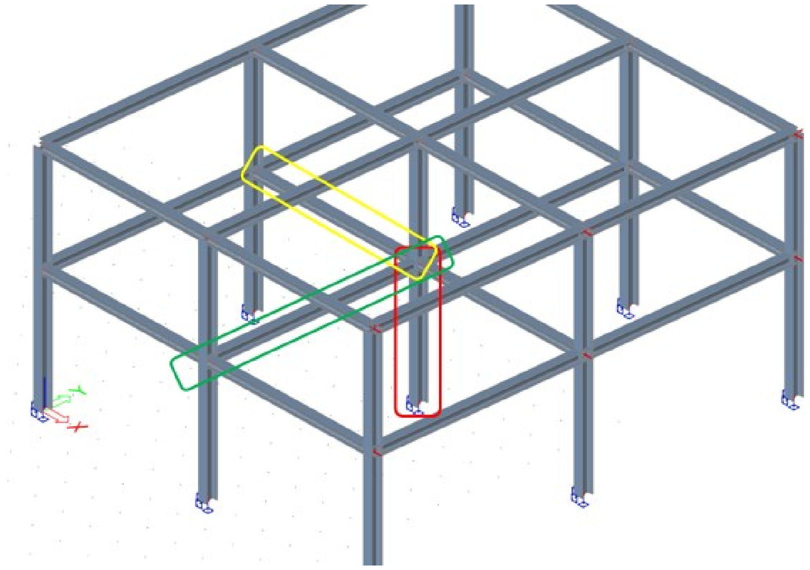


Figure 7. Critical members (red - column, yellow - beam A, green - beam B)

5 Discussion

In this example, the required thickness of fire protection for satisfying fire resistance of class R30 in all the steel members was 1 cm lower than that in aluminum counterparts. Furthermore, the rise in temperature over time is shown in Figure 8. Specifically, steel members reached approximately 50% higher temperatures than aluminum members with two thirds the thickness of gypsum for columns and three-quarters for beams. This difference is not significant because the strength of steel and aluminum does not decrease significantly at these temperatures. However, some other factors should be considered. The elements were initially designed for fundamental combinations, and thus, they had a low reserve for load capacity. Additionally, the structure as a whole was very rigid. This implies that thermal expansion leads to significant axial compression due to the inability of the members to expand. Hence, higher temperatures could not be reached, and consequently, the expected significant difference in the decrease in strengths of steel and aluminum was not observed.

With respect to material consumption, the aluminum variant required half the mass (42.17 kg/m^2) of the steel variant (83.36 kg/m^2).

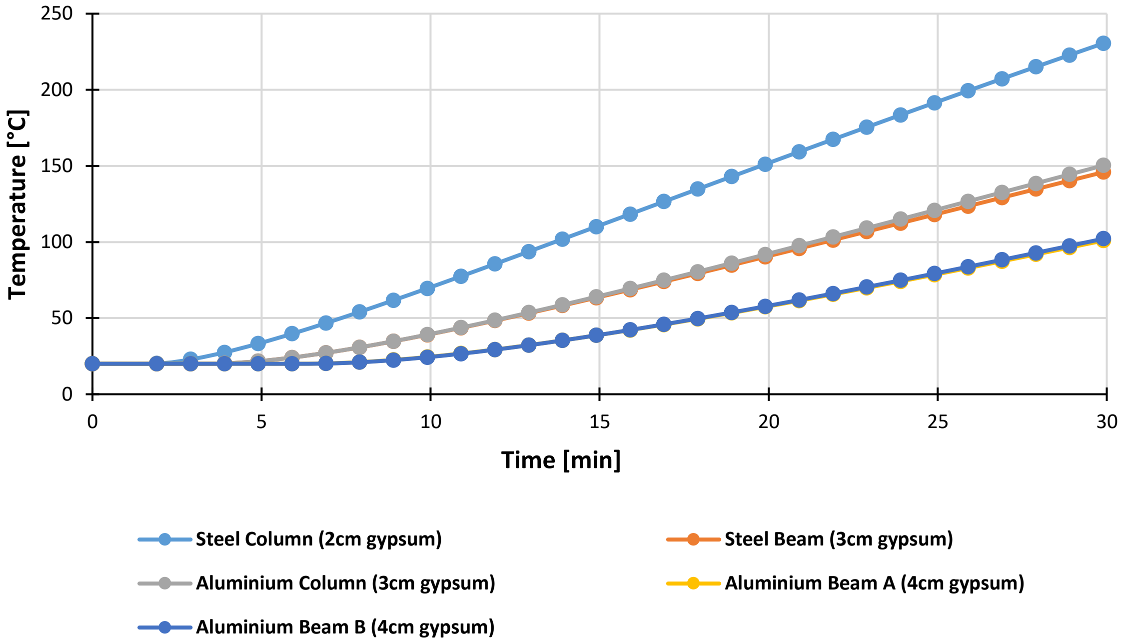


Figure 8. Temperature increase in members during fire exposure

6 Conclusion

As a construction material, aluminum exhibits certain advantages over steel, namely corrosion resistance, lower specific weight, aesthetic characteristics, and high strength. It can be compared to lower strength steel such as S235. However, it has low resistance to heat. The results of this study indicated that aluminum building variant leads to a lower mass solution. Aluminum is expensive and requires higher level of fire protection than steel. However, it does not require corrosion protection, and given its lower mass, it has lower transportation costs. Furthermore, it can be handled by machines (e.g., cranes) with a lower load bearing capacity, which can further reduce costs.

In this study, a rigid, statically indeterminate structure was observed. This structure design leads to high compressive strains in members for even relatively small temperature changes. This is due to the nature of materials to expand when they are heated. The results indicated that there is only a small difference in the required fire protection between steel S235 and aluminum alloy EN AW-6061 T6. In this case, aluminum offers a viable solution with a lower mass and better corrosion resistance at the cost of thicker fire protection.

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