DESIGN OF ALUMINIUM STRUCTURES FOR THE ENTERTAINMENT INDUSTRY AND ANALYSIS OF THEIR BEHAVIOR IN FIRE CONDITIONS

Stefania Arangio, Chiara Crosti, Marco Zampetti
Sapienza University of Rome, School of Engineering
Rome, Italy
E-mail: stefania.arangio@uniroma1.it, chiara.crosti@uniroma1.it, marcozampetti@gmail.com

1. ABSTRACT

Aluminium alloys are often used for temporary structures in the entertainment industry, such as temporary staging, towers or trusses for roof structures. For this kind of applications the structural elements are designed taking into account various aspects related to both the material properties and the temporary use, which are discussed in the first part of this paper. In the second part, the behavior of such structures exposed to fire is considered. A truss beam is analyzed considering the following scenario: during the construction phase, the truss elements are lifted using appropriate rigging equipments (chains, hooks, slings, etc.); usually the slings are made of polyester and, after lifting, are left on the truss. This material is very inflammable, so the possibility that the slings goes up in flames is considered; the behavior of the structure exposed to elevated temperature is analyzed and the structural safety is assessed.

2. INTRODUCTION

In recent years, the use of aluminium as a construction material has been increasing. Aluminium structures are widely used for trusses and towers of temporary structures in the entertainment industry. The early trusses, in the 1970s, were manufactured from steel and aluminium; however steel was not favored because of its weight and its tendency to corrode. Aluminium trusses were preferred as each truss could be easily lifted by one or two people and was not prone to rust [1]. Moreover, the possibility to extrude sections provided the possibility to design easily various types of sections.
In the past, these kind of structures tended to be erected without proper consultation with the statutory authorities or professional structural engineers, but various projects, even if of temporary nature, showed that the design of this kind of structures includes a variety of factors, involving experts from several disciplines.
Nowadays various regulations have been issued which consider several technical aspects as structural design, lifting, and use (see for example Eurocode 9 [2], the Standards issued by the British Standards Association [3,4,5], the US Standards [6,7]).

As already said, the main advantageous properties of aluminium structures are the lightness and the corrosion resistance. One of the main drawbacks of this material is the relatively fast reduction of constitutive properties at elevated temperatures: as shown in detail in section 3, the strength and the Young modulus present a 50% reduction at less than 300 °C, while the steel shows the same decay around 600 °C.
For this reason, in the design phase, scenarios that can lead to an unexpected fires should be taken into account. In this work the following scenario is analyzed: a beam which carries lighting for the stage has been lifted by using a rigging equipment with polyester slings (Figure 1). After lifting, during the show, the slings are left on the truss. The polyester is very inflammable, so the possibility that the slings goes up in flames is considered and the behavior of the structure is assessed.

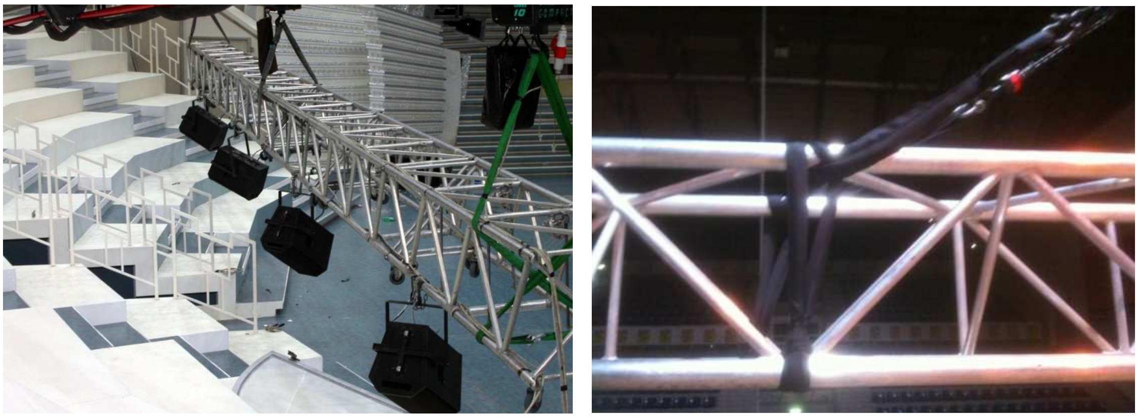

Fig. 1: The beams are often lifted by using polyester slings

3. ASPECTS OF THE DESIGN OF ALUMINIUM STRUCTURES FOR THE ENTERTAINMENT INDUSTRY

The use of aluminium temporary structures in the entertainment industry has been increasing over recent years. Concerts or other events that use temporary structures need to install these structures in a number of venues and would essentially be the same in each occasion. Clearly it would be inappropriate and very expensive to fabricate these structures specifically for each venue. So what was required were structures which could be erected quickly, readily demountable and which could be moved easily from one venue to another. Truck packing was also a consideration in the design of trusses because it allows saving on transportation. A typical truss element with fast connections is shown in Figure 2.
The early trusses, in the 1970s, were manufactured from steel and aluminium; however steel was not favored because of its weight and its tendency to corrode. Aluminium, or better aluminium alloys, was preferred for its mechanical properties.

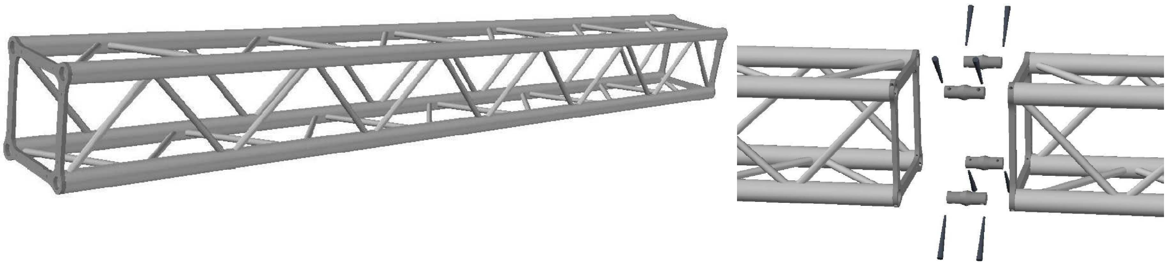

Fig. 2: Typical truss element and an example of connection

At the beginning, these structures tended to be erected without a specific design carried out by structural engineers, but past experiences showed that this kind of projects, even if of temporary nature, include tasks involving people from a variety of disciplines and need a specific and accurate design. Nowadays several standards and regulation exist [2,3,4,5,6,7], which are described more in detail in section 2.2. Also the academic research showed interest on various aspects: for example, various aspects related to the design are dealt with in [8], and experimental research on pinned girder section connections, which allow for an easy assembly and disassembly of the truss girders, is described in [9].

3.1 Mechanical properties of the aluminium alloys

Aluminium is often alloyed with other elements to improve properties such as its strength.
In fact, the strength of the pure material is low, about 60 o 140 N/mm^2. By alloying with other elements and by cold working or heat treatment, tensile strengths as high as 600 N/mm^2 can be achieved. The principal alloying elements are copper, magnesium, manganese, silicon and zinc.
A four digit number issued by the Aluminium Association is used to designate the different alloys, where the first number indicates the mayor alloying element. A letter after the number indicates the treatments. In the entertainment industry one of the most popular alloy is the EN AW 6082 T6 considered in this study, where 6xxx indicates an alloy made mainly by magnesium and silicon, and the code T6 is the temper condition, which means that the alloy is solution treated and artificially aged to improve the strength of the material. The mechanical properties of EN AW 6082 T6 are schematized in Table 1, compared with those of steel with similar strength.
Note that for aluminium alloys it is not considered the yield stress as reference value for design as it happens for steel, because the material does not present a defined yielding point with hardening behavior as the steel: as reference value for the calculation, the stress at a strain of 0.2%, $f_{0.2}$ is considered.

Mechanical properties					
AW 6082	$f_{0.2}$ = 260 MPa	f_u = 310 MPa	E = 70000 N/mm^2	ρ = 2700 kg/m^3	α = 23,4 x 10^6/°C
S 235	f_y = 235 MPa	f_u = 360 MPa	E = 210000 N/mm^2	ρ = 7850 kg/m^3	α = 12 x 10^6/°C

There are also some downsides to the use of aluminium alloys. The effect of welding at the connections between tubes and braces needs to be carefully considered during the design process. As said, alloys in series 6xxx applied in structural applications are hardened by a heat treatment. When structures of hardened alloys are welded, the material close to the weld is exposed to severe heath input that reduces the strength of this zone compared to the hardened parent metal. The zone with reduced strength is called the heath affected zone (HAZ). The width of the heat affected zone is governed by the amount of heat required to produce the weld and how easily the heat is dissipated. Some indication for the evaluation of its extension are given in EN 1999, where the reduction of the strength is denotes as $\rho_{haz} = f_{haz}/ f_{parent}$. An example is shown in Figure 3.

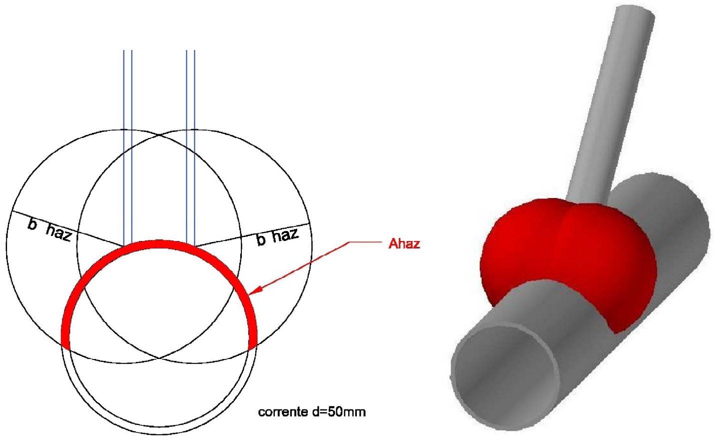

Fig. 3: Extension of the heath affected zone

3.2 Standards and codes for aluminium structures for the entertainment industry

In the early days trusses for the entertainment industry were often fabricated and used without allowable load tables or certification. During the years the authorities became aware of the dangers involved and demanded that the user substantiate the use of trusses by calculation or testing. Major manufacturers provided simple structural calculation and allowable load tables for the standard products.
But these kinds of structures are used repetitively and in different configurations, so the simple applications of these existing standards might not be adequate. The design, manufacture, and use of aluminium trusses and towers in the entertainment industry were thus deemed to be very important issues. The writing of a suitable standard was one of the first projects undertaken in the United States by the Entertainment Service and Technology Association (ESTA). The standard has now become a full American Standard issued by the American National Standards Institute, the ANSI E1.2 “Design, manufacture and use of aluminium trusses and towers” [7].
However, a number of major manufacturers have fabrication facilities both in the United States and in Europe, and many shows starts in Europe and then tour the US and vice versa. Thus the need for a parallel document was obvious. In Europe, at the moment the aluminium structures are dealt with in various standards and codes. The structural design can be addressed with the Eurocodes and other EN standards; for example EN1999-1-1 (Design of aluminium structures – General rules) [2], EN 754 (Cold drawn rod/bar and tube), EN 755 (Extruded rod/bar, tube and profiles). In the UK a reference standard for the design of aluminium structures is the BS 8118 “The Structural use of Aluminium” [3]. The mentioned documents deals with aluminium structures but are not referred specifically to temporary structures for the entertainment industry. A European common regulation is missing. Useful documents in this sense have been published by the British Standard Institute: for example BS 7905 “Specification for design and manufacture of aluminium and steel trusses and towers”[4], and BS 7906 – Part 2 “Code of practice for the use of aluminium and steel trusses and towers”[5]. They are the first standards issued written specifically on the subject in Europe and can be considered the parallel document of the US ANSI E1.2.

4. BEHAVIOR OF ALUMINIUM STRUCTURES UNDER FIRE CONDITIONS

Traditionally, aluminium alloy structures do not rate highly with regards to fire resistance. This is because aluminium alloys are generally less resistant to high temperatures than

other structural materials as steel and reinforced concrete. The temperature required to melt aluminium is 570 to 660 °C, about half that of steel. The coefficient of thermal expansion of aluminium is about twice that of steel and the thermal conductivity is about four times greater than steel (Table 1). These are important properties when considering how the material behaves in the event of a fire [10,11,12]. When an aluminium structure is subjected to the heat of a fire, the relatively high thermal conductivity enables the heat to be rapidly conducted away from the exposed area. It will, however, cause the temperature to rise elsewhere in the structure.
The mechanical properties of aluminium decreases at elevated temperature very rapidly compared to those of steel. In Figure 4 (left hand) the continuous curve represents the temperature dependent strength (0.2 values) of aluminium, expressed on percent of the normal strength, $k_{o,\theta}$, according to EN1999 [13]:

$$f_{0,\theta} = k_{0,\theta} \cdot f_0$$

where $f_{o,\theta}$ is 0,2% strength at elevated temperature, and $f_{o,\theta}$ is 0,2% strength at room temperature. The dotted curve shows the temperature dependent yield stress of steel. This diagram shows that the strength of aluminium would be severely compromised in the event of a fire. Figure 4 (right hand) shows the temperature dependent elasticity modulus of aluminium and steel. The values are normalized with the room temperature value. From the diagrams it is possible to note that the strength and the Young modulus present a 50% reduction at less than 300 °C, while the steel shows the same decay around 600 °C.

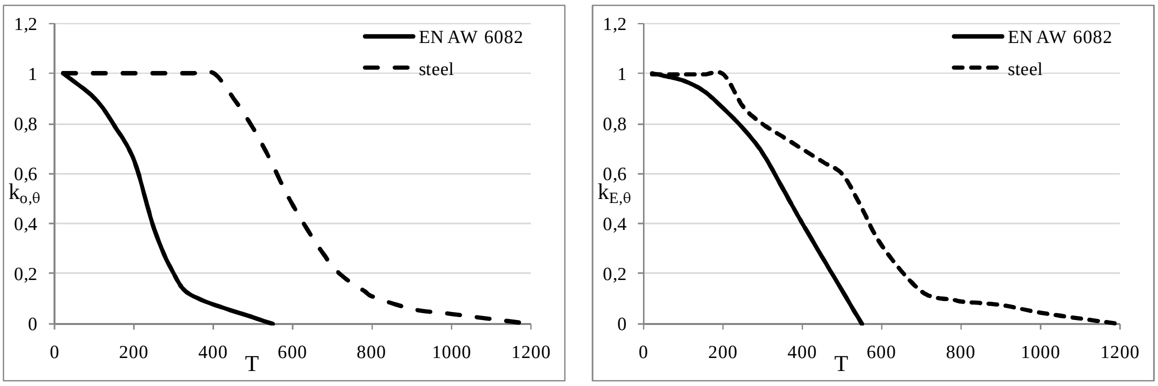

Fig. 4: Left hand: Relative value of the 0,2% strength of aluminium and yield strength of steel versus temperature – Right hand: Relative value of the Young's modulus of aluminium and steel. The values are normalized with the respective room temperature values.

The thermal properties of the aluminium (thermal expansion α_θ , specific heath c_{al}, and thermal conductivity λ_θ) vary with temperature, θ_{al}, according to the following equations, proposed In EN1999-2 [13]:

$$\alpha_\theta = 22.5 \cdot 10^{-6} + 0.01 \cdot 10^{-6} \cdot \theta_{al}$$

$$c_{al} = 0.41 \cdot \theta_{al} + 903 \qquad \text{(J/kg°C)}$$

$$\lambda_\theta = 0.07 \cdot \theta_{al} + 190 \qquad \text{(W/m°C)}$$

Regarding the heath affected zone, EN 1999-2 does not specify a strength reduction at elevated temperature. The standard assumes that the coefficient ρ_{haz} at elevated temperature is equal to the value at room temperature. This is accepted because it has been proven that ρ_{haz} tends to unity at increasing temperature, so there is no longer difference in the strength of material with initial different tempers [11].

Summarizing, the most typical features of aluminium alloys at high temperature are the following:

- high conductivity, higher than that of steel, at all temperatures;
- owing to low weight, a relatively low volumetric heat capacity compared with steel;
- a relatively rapid decrease in mechanical strength with increasing temperature, compared with other structural material.

In the following a case study is presented in order to evaluate how this features influence the structural behavior.

5. CASE STUDY: ASSESSMENT OF A STRUCTURE FOR THE ENTERTAINMENT INDUSTRY UNDER FIRE

The behavior of aluminium structures under fire is assessed by considering a case study. The suspended beam shown in Figure 5 is studied. In particular, a scenario that considers the possibility of a fire of the polyester sling used for lifting and suspending the beam is analyzed.

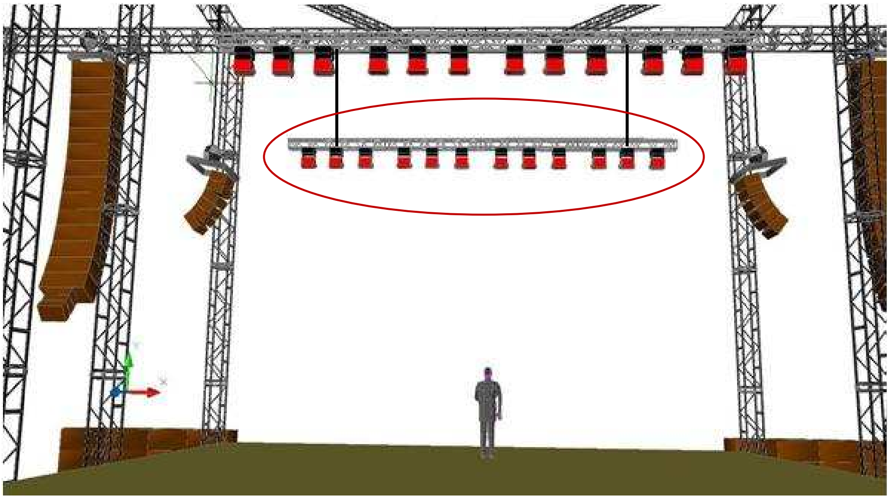

Fig. 5: Suspended beam considered in the case study

The beam is 12 m long. The tubes are 50x4 mm and the braces 30x3 mm. The considered aluminium alloy is the EN AW 6082, whose mechanical properties are in Table 1. The beam is loaded with a uniformly distributed load of 1 kN/m which represents the system of sound and lighting. The finite element model of the structure is shown in Figure 6. The small red squares show the position of the slings where the fire is considered to start. The fires of the slings have been modeled using the standards fire curve defined in ISO 834.

In the structural analysis geometrical and material non linearity are taken into account.

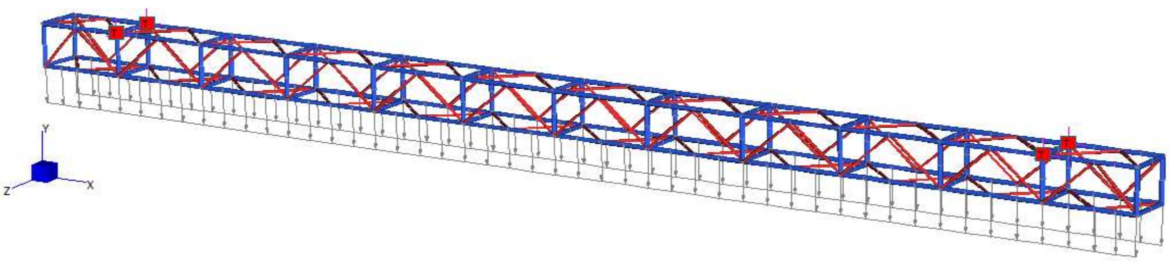

Fig. 6: Finite element model of the considered beam

In Figure 7 the vertical displacement of the middle span point of the beam versus time during the fire is shown. It is possible to note that the displacements are in substantial accord with the shape of the ISO curve. The deformed shape of the entire structure is shown in Figure 8. Due to the fast decreasing of the mechanical properties the beam has significant displacements after only few seconds.

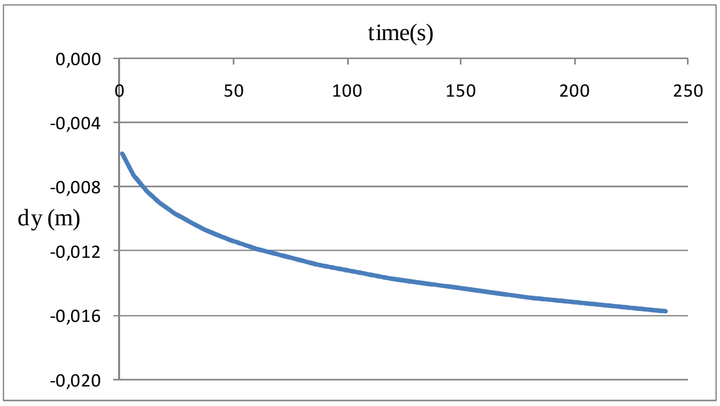

Fig. 7: Vertical displacements in the middle span point

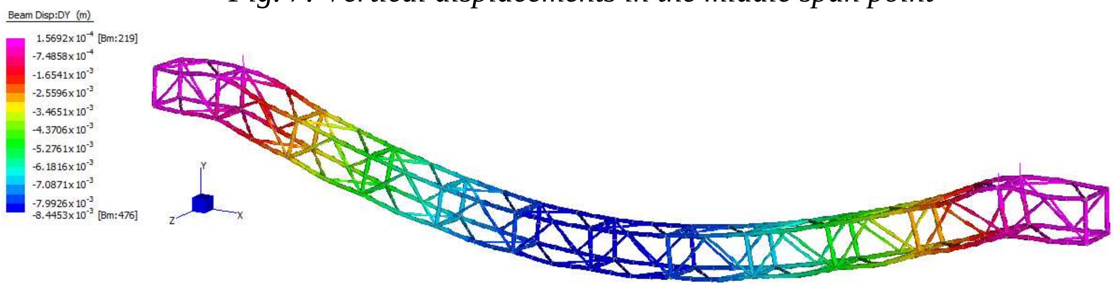

Fig. 8: Finite element model subjected to fire: vertical displacements at t=14 s

It is interesting to observe the behavior of the rod located between the restraints at both the ends of the beam, close to the points where the fire starts. In Figure 9 the axial stress in this element is shown. For the first few seconds it increases rapidly, then it starts decreasing. This happens mainly for two reasons: the first one is that the high thermal conductivity of the material enables the heat to be rapidly conducted away from the exposed area; the second one regards the thermal expansion of the elements that allows a decreasing of the stress. The stress in all the elements and the distribution of the temperature are shown in Figures 10 and 11. Even if the heath is transmitted rapidly, the mechanical properties of the material decrease very fast and the elements close to the fire reach the 0.2% strength in only 15 seconds.

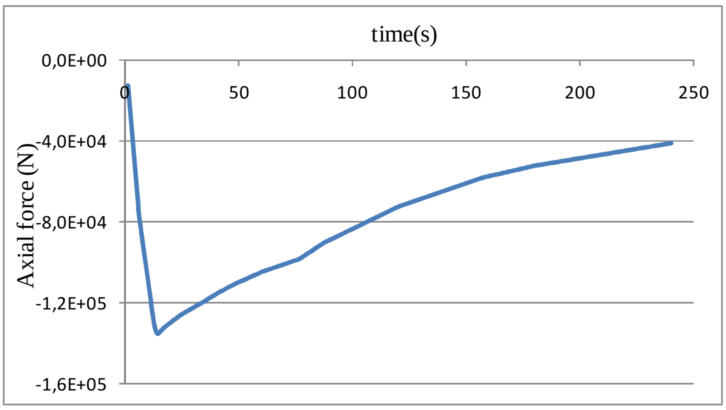

Fig. 9: Normal stress in the element between the restraints

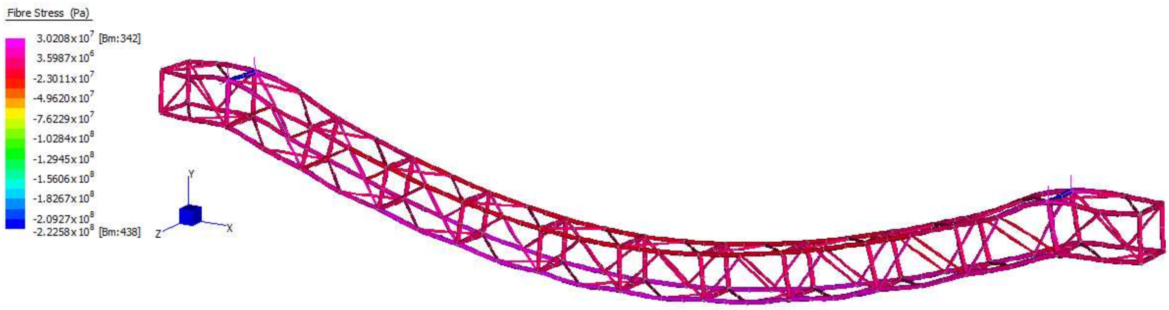

Fig. 10: Stress in the elements and deformed shape at t=14 s

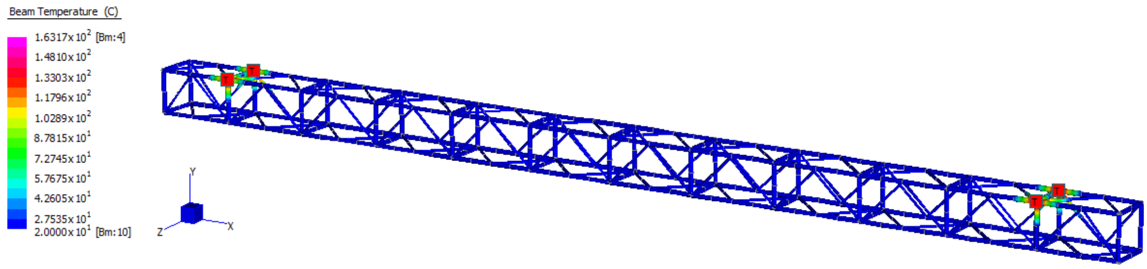

Fig. 11: Distribution of the temperature at t=14 s

The issue of possible fire is often not considered in the design of structures for the entertainment industry but this simple case study has shown that a fire during a performance could lead easily to the collapse of the structure in a very short time. Recently, various countries are moving a first step towards safety by replacing the commonly used polyester slings with slings made of less inflammable materials.

6. CONCLUSION

In this paper some specific aspects related to the design of aluminium structures for the entertainment industry have been presented. The structural features of aluminium elements depend on both the mechanical properties of the material and the temporary use of the structures. In the early days trusses for the entertainment industry were often fabricated and used without allowable load tables or certification but during time the authorities became aware of the dangers involved and the fist standards were issued. Some of the existing standards, like the Eurocode 9, regard the design of aluminium structures but do not treat specifically the topic of the structures for the entertainment industry. In the United States a full standard that deals with design and use of trusses and towers is the ANSI E1.2 that is widely used. In Europe a similar document has been issued by the British Standards Association but a specific document used in the entire Europe still does not exist.
One aspect that is often not considered in the design of aluminium structures for the entertainment industry is the possibility of fire. Aluminium alloys are generally less resistant to high temperatures than other structural materials as steel and reinforced concrete. The material melts at about 600 °C and the mechanical properties decrease at elevated temperature very rapidly. In order to assess the structural safety of aluminium structures exposed to fire, a case study has been considered. The analyzed scenario considers the possibility of a fire of the polyester sling used for lifting and suspending a beam that supports lighting. This simple case study has shown that a fire during a performance could lead easily to the collapse of the structure in a very short time, so the issue of fire safety should be properly taken into account. Recently, various countries are

moving a first step towards safety by replacing the commonly used polyester slings with slings made of less inflammable materials.
The results obtained in this case study are strongly related to the boundaries condition (loads, restrains) of the analyzed elements. In order to assess the structural safety of this kind of structures, different arrangements of the trusses should be analyzed and compared, including plane frames and 3-dimensional constructions.

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