Fire exposed aluminium structures

Johan Maljaars
NIMR, Delft, the Netherlands
TNO Building Structures and Systems, Delft, the Netherlands
Eindhoven University of Technology, Eindhoven, the Netherlands
Joris Fellinger
TNO Centre for Fire Research, Delft, the Netherlands
Frans Soetens
Eindhoven University of Technology, Eindhoven, the Netherlands
TNO Building Structures and Systems, Delft, the Netherlands

Material properties and mechanical response models for fire design of steel structures are based on extensive research and experience. Contrarily, the behaviour of aluminium load bearing structures exposed to fire is relatively unexplored. This article gives an overview of physical and mechanical properties at elevated temperature of frequently applied aluminium alloys, found in relevant literature and discusses mechanical response models currently applied for fire exposed aluminium structures. A comparison is made with steel structures exposed to fire.

Key words: Physical and mechanical properties of aluminium, fire design of aluminium

1 Introduction

The last decades, more and more load-bearing structures are built in aluminium alloys. The success of aluminium can be attributed to specific properties, such as the low density, good corrosion resistance and the freedom in design thanks to the extrusion process. These and other properties are beneficial in case of structures such as fast ferries, helicopter decks and living quarters on oil platforms.
A wide variety in aluminium alloys and tempers (the temper depends on the treatment) exists. Material properties differ between these alloys and tempers. In general however, aluminium alloys have a high thermal conductivity and low melting temperature, between 580 °C and 650 °C. This combination makes aluminium relatively sensitive to fire exposure.
Although material properties and response of structural elements are well known at room temperature (see e.g. Talat [5], Kammer [18] and Mazzolani [28]), this is not the case under fire conditions. Lack of knowledge on the behaviour of fire exposed aluminium structures has resulted on the one hand in conservative mechanical response models in standards, such as the European code on fire exposed aluminium structures EN 1999-1-2 [3] and on the other hand in difficulties with getting aluminium structures accepted by approving bodies.
The second section of this article concerns the heating of aluminium sections. Mechanical

properties of heated aluminium alloys are discussed in the third section. The fourth section gives an overview of existing mechanical response models for aluminium structures exposed to fire.

2 Thermal response and physical properties

The temperature development in the cross-section of a non-combustible member is given by the well-known Fourier equation:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial\theta}{\partial z}\right)=\rho\cdot c\frac{\partial\theta}{\partial t} \qquad (1)$$

Equation (1) shows that the temperature inside the member depends on the conductivity (λ) and the product of density and specific heat ($\rho{\cdot}c$), which is called thermal capacitance.
The boundary conditions of equation 1 are determined by the heat flux to the member surface. This heat flux is the summation of heat flux by convection and heat flux by radiation. The latter is directly related to the emissivity of the surface of the heated member.
Thus, besides the thermal properties of the fire itself, heating of an aluminium member depends on the thermal conductivity, thermal capacitance and emissivity of the member. These properties depend on the chemical composition of the material, and may therefore vary per alloy. As the treatment does not change the chemical composition, it is not expected that physical properties depend on the temper, although no tests were found to evaluate this assumption. The relevant physical properties are outlined in the following sections.

*2.1 **Thermal conductivity***

Especially at elevated temperature, the amount of test results on the thermal conductivity found in literature is limited. Tests are reported by Kammer [18], Brandes [10], Holman [17] and in the SFPE Handbook of Fire Protection Engineering [6]. The results are shown in figure 1, together with the thermal conductivity of aluminium alloys according to EN 1999-1-2 [3] and the thermal conductivity of steel according to the European code on fire exposed steel structures, EN 1993-1-2 [2]. From tests carried out it is concluded that the thermal conductivity is different for different alloys.

Figure 1 shows that thermal conductivity of aluminium is high compared to steel. Unless a structural element is exposed to fire on some sides and protected at other sides, e.g. by gypsum board, the member temperature can be regarded as uniform. The exact value for the thermal conductivity is then not very relevant.
The high thermal conductivity also leads to elevated temperatures in parts of the structure not directly exposed to fire.

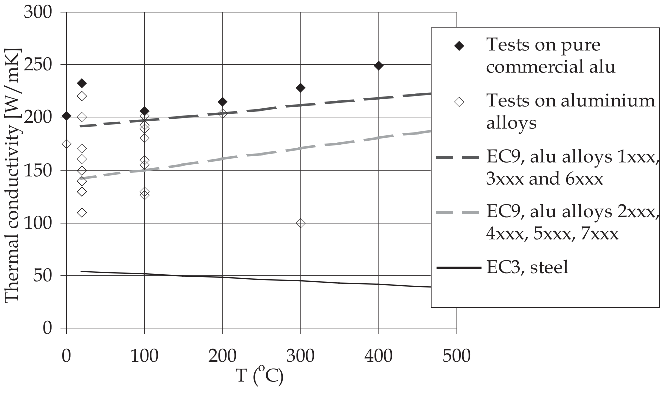

Figure 1. Thermal conductivity of aluminium alloys and of steel

2.2 *Specific heat and thermal capacitance*

Specific heat is the amount of heat needed to raise the temperature of a unit mass of a substance by one degree. Kammer [18] summarises test results on the specific heat.
The specific heat resulting from these tests varies little with the type of alloy, but it depends on the temperature. According to data in EN 1999-1-2 [3], the specific heat of aluminium varies from 913 J/kg °C at room temperature to 1108 J/kg °C at elevated temperature, which is 2,1 and 1,7 times higher than that of steel, respectively.
Equation (1) shows that the temperature of an aluminium member is related to the product of specific heat and density. The density of aluminium is 2700 kg/m3, which is 2,9 times lower than the density of steel. Consequently, the thermal capacitance is lower than in case of steel.

2.3 *Emissivity*

Emissivity of the member can be described as the ease with which a substance radiates its own thermal energy. For ideal grey opaque media, the absorption of radiation equals the emissivity, the rest of the incident radiation is reflected. The emissivity depends on the condition of the surface. The temperature of the aluminium surface is of minor importance for the emissivity (Talat [5]).
In real fires surfaces are almost always (partially) covered with soot. EN 1999-1-2 [3] specifies a coefficient of emissivity of 0.7 for covered (e.g. sooted, but also painted) aluminium surfaces. This coefficient is equal to the value given for covered steel surfaces.
In case of external exposed aluminium members, i.e. members not engulfed in flame, or in case of a ‘clean’ fire such as in a standard fire test in a gas oven, the member surface is not sooted and the emissivity is related to plain aluminium. The emissivity resulting from tests varies from 0,03 to 0,11 for new, plain aluminium and 0,05 to 0,31 for heavily oxidised aluminium (Kammer [18], Holman [17] and Twilt [31]). The influence of alloying elements on the emissivity coefficient is small (Kammer [18]). Plain aluminium members thus reflect most

of the radiative heat emitted by the fire. The coefficient of emissivity of plain aluminium specified by EN 1999-1-2 [3] is 0,3. This value is low when compared to steel: EN 1993-1-2 [2] specifies a coefficient of emissivity of 0.7 for steel.

2.4 *Evaluation of thermal response*

Aluminium heats faster than steel because of the high conductivity and low thermal capacitance. Only in case of plain aluminium, low emissivity prevents very fast heating. As an example, figure 2 gives the member temperature of unprotected steel and aluminium sections exposed to a standard fire. The dark grey lines indicate square hollow sections 50x50x2 mm, light grey indicates the same sections, but with a wall thickness of 0,8 mm. The temperature is determined with the equations in EN 1993-1-2 [2]and EN 1999-1-2 [3], which are based on equation (1):

$$\Delta\theta_t = k_{sh}\frac{1}{c\cdot\rho}\frac{A_m}{V}h_{net,d}\cdot\Delta t \qquad 2)$$

In which:

$\Delta\theta_t$	=	Increase in temperature of the member;
k_{sh}	=	Correction factor for the so-called shadow effect;
A_m/V	=	Section factor for unprotected aluminium members;
$h_{net,d}$	=	Design value of the net heat flux per unit area (determined with EN 1991-1-2);
Δ_t	=	time interval, which should not be taken as more than 5 seconds.

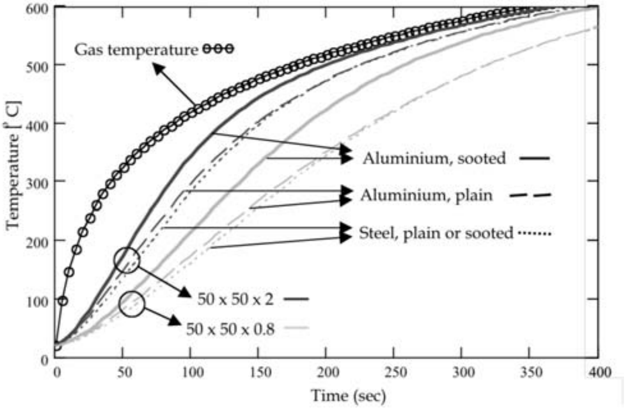

Figure 2. Heating of aluminium and steel square hollow sections

As expected, aluminium sections covered with soot heat faster than steel sections. Apparently, the temperature development in plain aluminium sections is approximately equal to the temperature development in steel sections with the same dimensions (or section factor). Because of specific properties of aluminium, such as extrusion possibility, thin wall thicknesses are applied in many aluminium structures, so that such structures heat fast compared with conventional steel structures.

3 Mechanical properties

A temperature rise in metal structures results in thermal expansion and reduced mechanical properties, which are discussed in this chapter. As the mechanical properties differ per alloy and temper, the chapter starts with a short overview of alloys and tempers.

3.1 ***Alloys and tempers***

Wrought alloys are indicated with a four-digit number according to the international Registration Record administrated by the Aluminum Association. The first digit indicates the dominant alloying element and the other digits indicate a specific alloy. For structural engineering, particularly alloys in series 5xxx (aluminium magnesium alloys) and 6xxx (aluminium magnesium silicon alloys) are of importance because of a combination of moderately high strength, good corrosion resistance and good weldability.

The temper depends on the treatment. Some alloys, such as those in the 6xxx series, are heat treatable. Heat treatment makes use of the property that at higher temperature, more alloying elements can be dissolved in the aluminium matrix than at low temperatures. During production, a large amount of the alloying element(s) is dissolved in aluminium at a temperature just below the melting temperature. Following, rapid quenching leaves the matrix in a supersaturated, unstable condition. The unstable condition gradually changes in a stable condition by formation of precipitate particles, through which extra strength is obtained (called ageing). For example, tempers starting with T4 indicate that aging takes place at room temperature (naturally ageing). For most alloys, this process takes years. To speed up ageing, it is possible to heat the supersaturated alloy to a moderately elevated temperature (120 to 180 ˚C) for a specific period of time (mostly several hours). Tempers starting with T5 and higher indicate alloys with this treatment (artificial ageing).

For non-heat treatable alloys, extra strength can be obtained through work hardening. Work is done during rolling, extruding, drawing or bending below the recrystallisation temperature. Tempers starting with H indicate work-hardened non-heat treatable alloys.

Alloys that are only annealed and which have not undergone additional treatment are indicated with temper O. An overview of treatment possibilities for various alloy series is given in figure 3. For more information on treatments, see Altenpohl [7] or Kammer [18].

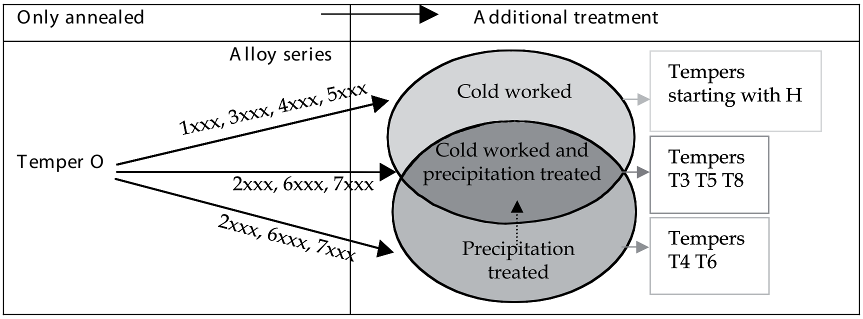

Figure 3. Overview of treatment possibilities

3.2 ***Thermal expansion***

Aluminium expands when subjected to an increasing temperature. Thermal expansion of aluminium may lead to significant changes in structural behaviour:

- In cases where expansion of a heated element is restrained (e.g. in case of elements with a temperature gradient) high internal stresses may result;
- In statically undetermined structures, expansion of aluminium may lead to significant changes in the load distribution (Eberwien [14]);

Kammer [18] and Brandes [10] give test results on thermal expansion. The resulting coefficient of linear thermal expansion of pure aluminium varies linearly from $22{,}8 \cdot 10^{-6}$ at ambient temperature to $27{,}4 \cdot 10^{-6}$ at 500 °C. The coefficient varies little with the alloy.
The thermal expansion of aluminium is approximately 1,9 times higher than that of steel.
As the modulus of elasticity of aluminium is only one third of the modulus of elasticity of steel (see section 3.3), thermal stresses in the elastic range in aluminium are lower than in case of steel with equal temperature increments (approximately 2/3 of steel).

3.3 ***Strength, stiffness and ductility at elevated temperature***

Mild steel has a clearly defined yield point at room temperature, but shows inelastic mechanical behaviour at elevated temperature. Aluminium alloys have inelastic mechanical properties both at room and elevated temperature. At room temperature, the Ramberg-Osgood relation is mostly used to describe the stress-strain relation, see e.g. Mazzolani [28]. The stress at an irreversible plastic strain of 0,2% (f_o) is usually applied as the yield strength. This section gives an overview of the development of the mechanical properties at elevated temperature.

3.3.1 0,2 % proof stress and tensile strength

With increasing temperature, the strength of metals generally decreases (Koser [22]).
Voorhees and Freeman [32] and Kaufman [20] reported tensile tests on various aluminium alloys after various exposure times. The alloys incorporated in these reports are limited to those frequently applied in the USA. Tensile tests on alloy 6082, which is applied in many

structures in Europe, are reported in Hepples and Wale [16], Broli and Mollersen [11], Amdahl, Eberg and Langhelle [8], Kleive and Gustavsen [21], Langhelle [25] and Bergli and Moe [9]. The strength at room temperature and at elevated temperature depends on the alloy and the temper. For most alloys and tempers, the 0,2% proof stress already decreases significantly at a temperature of 150 °C. The 0,2% proof stress at a temperature of 350 °C is on average reduced to 20 % of the strength at room temperature after an exposure period of 30 minutes. As a comparison, the yield stress of steel is not yet reduced at this temperature according to the data in EN 1993-1-2 [2].

Figure 4 shows the 0,2% proof stress of heat treatable alloy 6063 in tempers T42 and T6 after an exposure period of 0,5 hours. The strength of temper T42 increases at moderately elevated temperature, as this temperature speeds up the ageing process (see paragraph 3.1).

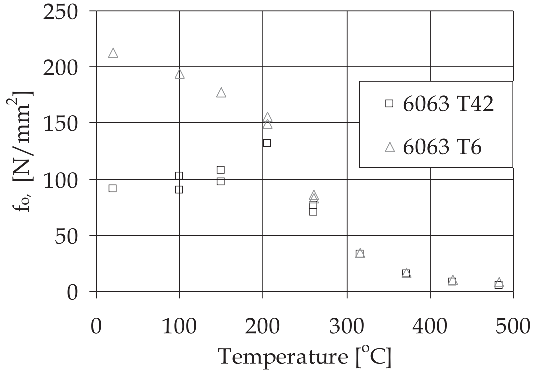

Figure 4. Tensile test results - 0,2% proof stress of alloy 6063 with various tempers

Figure 5 shows the 0,2% proof stress of the non-heat treatable alloy 5083 with tempers O and H113. The significant difference in strength at room temperature between these tempers vanishes at elevated temperature. The strengthening effect of the work hardening is rapidly lost and the same strength remains as for the untreated material. This was also found for other alloys and tempers.

The tests data show that the difference between 0,2% proof stress and tensile strength decreases at increasing temperature, for all alloys and tempers. In case of non-heat treatable alloys, the strength does not vary for different thermal exposure periods. The strength of heat treatable alloys however depends on the thermal exposure period. According to data in Kaufman [20], the strength of 6xxx alloys at temperatures up to 425 °C after an exposure period of 0,5 hours reduces up to 80% of the strength at the same temperature after 0,1 hours.

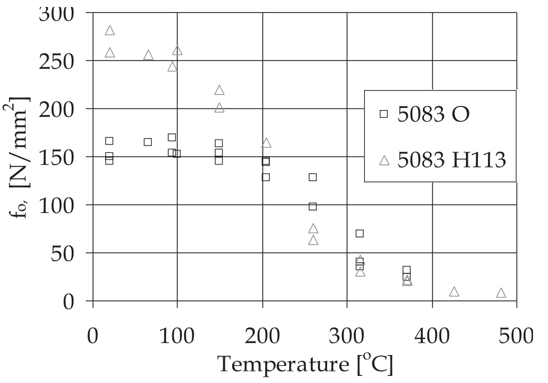

Figure 5. Tensile test results - 0,2% proof stress of alloy 5083 with various tempers

Tensile tests at elevated temperature were only carried out on a limited number of alloys. When analysing the data however, the strength of different alloys in the same series and with the same temper shows an approximately equal decrease. As an example, figure 6 shows the 0,2% proof stress (left-hand picture) and the relative 0,2% proof stress (proof stress relative to that at room temperature, right-hand picture) of alloys in series 6xxx and temper T6, according to data by Kaufman [20]. The relative 0,2% proof stress corresponds reasonable for different alloys in this series, with this temper. When analysing data on other combinations of alloys and tempers, this seems to be the case for most combinations of alloy series and tempers.

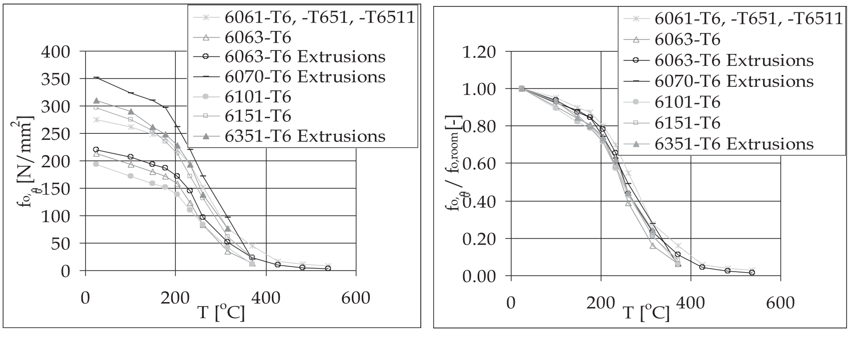

Figure 6. 0,2 % proof stress (left-hand) and relative 0,2% proof stress for alloy series 6xxx temper T6

3.3.2 Modulus of elasticity

The modulus of elasticity (E) can either be determined with an unloading-reloading cycle (adiabatic modulus of elasticity) or with the reflection of (sound) waves sent through the material (isothermal or dynamic modulus of elasticity). The first method was e.g. applied on alloys in series 5xxx and 6xxx in Kaufman [20], the second method was applied by

Richter and Hanitzsch [29]. Results are shown in figure 7, together with the modulus of elasticity given in EN 1999-1-2 [3].

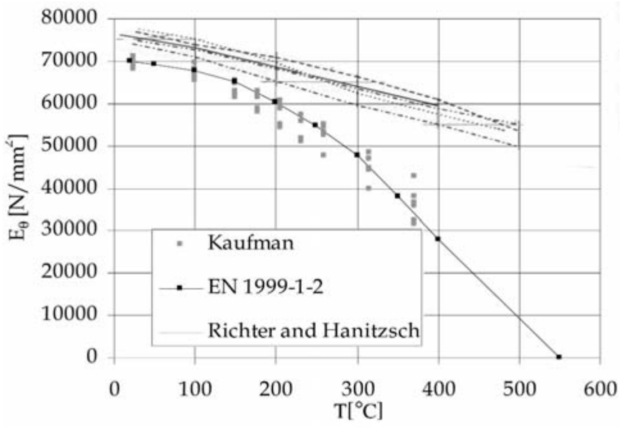

Figure 7. Adiabatic (Kaufman, 5xxx and 6xxx) and isothermal (Richter and Hanitzsch) modulus of elasticity

Figure 6 shows that the isothermal modulus of elasticity does not correspond with the adiabatic modulus of elasticity at elevated temperature. This is possibly due to viscoplastic behaviour, see section 3.4. Only a few data on the modulus of elasticity were found for temperatures exceeding 370 °C. For fire design, the adiabatic modulus of elasticity is of interest.
Except for naturally aged heat-treatable alloys (temper T4 and lower), the reduction in 0,2% proof stress at elevated temperature is larger than the reduction in modulus of elasticity.
On the contrary, in case of steel, the stiffness reduces faster than the strength for temperatures up to 900 °C, according to data in EN 1993-1-2 [2].

3.3.3 Rupture strain

For increasing temperatures, the rupture strain increases for most tempers until a temperature of approximately 400 °C. Exceptions are naturally aged heat-treatable alloys, for which ageing at moderately elevated temperature increases the strength, but reduces the rupture strain as they approach the artificially aged condition.
In case of temperatures exceeding 400 °C, data tabulated by Kaufman [20] show a decrease in rupture strain while Voorhees and Freeman [32] report an increase. The difference is attributed to the measurement technique not being straightforward. No extensive data was found in literature on the strain at the ultimate tensile strength.

3.4 ***Viscoplastic behaviour (creep)***

Creep is time dependent distortion of material due to loading. Creep results in elongation of material and decrease in strength and stiffness. While creep of aluminium is neglected at ambient temperature in design standards, it may become significant at elevated temperature. Creep deformations are divided in primary creep with decreasing creep rate, in secondary creep with constant creep rate and in tertiary creep with increasing creep rate (Kraus [23]). Creep rupture takes place at the end of the tertiary stage.

Voorhees and Freeman [32] and Kaufman [20] give elongation percentages after various exposure periods at constant elevated temperature and the time to rupture of various alloys and tempers at various stress levels. Kaspersen and Soras [19], Krokeide [24] and Broli and Mollersen [11] carried out creep tensile tests on alloy 6082 T6 at various temperatures with various stress levels. Their results are discussed in Eberg et al. [12] and in Langhelle [25]. Also Hepples and Wale [16] carried out creep tensile tests on alloy 6082 T6. Only Voorhees and Freeman [32] gave a limited amount of creep test results for temperatures exceeding 320 °C. The tests showed a strong increase of creep deformations and a decrease in the time to rupture for increasing stress level and temperature.
According to data in Kaufman [20], the average creep rupture stress of various alloys for rupture after one hour is 79% and 66% of the tensile strength at temperatures of 204 and 316 °C, respectively.

Hepples and Wale [16] carried out creep tests to determine whether creep in the secondary stage influences the strength. The specimens of alloy 6082 were loaded with 30 % of the proof stress at ambient temperature. The thermal exposure period was 30 minutes up to two hours. They found no influence of this creep period on the strength. However, the strain after rupture was significantly reduced. More tests with various stress levels should be carried out to determine whether this conclusion holds in general.

3.5 ***Evaluation of structural material response***

The decrease in strength and stiffness at elevated temperature for most aluminium alloys and tempers is much larger than in case of steel. Creep cannot be neglected at elevated temperature. As an example, the material characteristics according to EN 1993-1-2 [2] and EN 1999-1-2 [3] of a square hollow section 50x50x2 are given in figure 8. The left-hand picture shows the yield strength and the right-hand picture the modulus of elasticity, relative to the properties at room temperature, of sections of steel and aluminium alloy 6063 T6 that are covered with soot. Note that the influence of creep periods is not taken into account in the material properties of EN 1999-1-2 [3], as it is assumed that the 0,2% proof stress is sufficiently conservative (Lundberg [27]).

As expected, both strength and stiffness of the aluminium sections reduce faster than that of steel sections with equal dimensions. It should be noted that both the aluminium and steel sections require protection in order to obtain the required fire-resistant period.

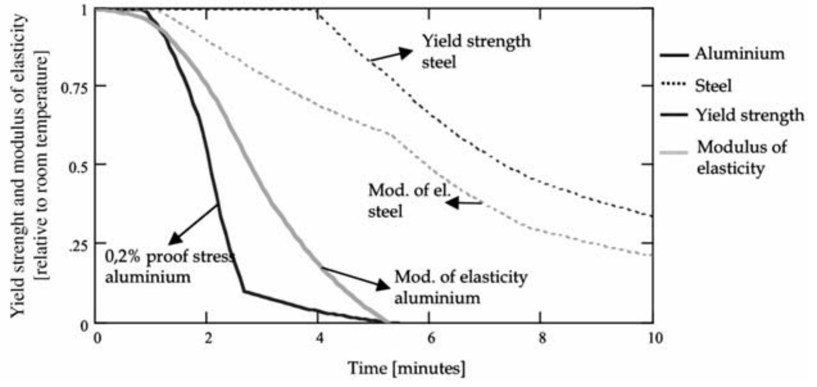

Figure 8. Mechanical properties of steel and aluminium square hollow section 50 x 50 x 2 exposed to a standard fire

The tensile and creep tests described in this chapter were carried out after an exposure period at a constant elevated temperature. In real fire exposed structures however, the temperature increases from room temperature to maximum temperature, while the load is in many cases assumed to remain constant. Tensile tests after a period with increasing temperature with constant load were not found in literature. It is recommended to obtain such data in future tests. With these tests, it should be determined whether creep is significant in real fire situations. Tests with the same heating rate but not loaded during heating can be carried out in order to determine the reference strength; i.e. the strength without creep influence.

4 Mechanical response models for structures in EN 1999-1-2

Calculation methods for fire design of aluminium structures exposed to fire are the Norwegian standard NS 3478 [4] and the European standard EN 1999-1-2 [3]. The latter is the most recent standard and is discussed in this chapter. When available, the models are compared to test results on components.

4.1 ***Response models for entire structures***

Where a global structural analysis is carried out, EN 1999-1-2 [3] prescribes that the relevant failure mode in fire exposure, the temperature-dependent material properties and member stiffness and effects of thermal expansions and deformations shall be taken into account.
As EN 1999-1-2 [3] provides no simple calculation models for entire structures or parts of entire structures, advanced calculation models should be used. Advanced calculation models

may be used in association with any heating curve, provided that the material properties are known for the relevant temperature range.
As the development and validation of advanced mechanical response models is complicated and time consuming for most structures, advanced models are usually not applied. On the other hand, these models may give the best approximation of the real structural behaviour during a fire. Besides, redistribution of forces can only be taken into account when the entire structure is evaluated. Advanced response models may therefore result in more economical structures.

*4.2 **Response models for individual members***

When advanced models are not applied, EN 1999-1-2 [3] provides simple calculation models for the evaluation of structures exposed to fire. Simple calculation models can be applied when the structure is divided in separated members and each member is analysed individually. Some simplifications of the real mechanical response may be applied:

- The reactions at supports and internal forces and moments at boundaries of the considered part of the structure may be assumed to remain unchanged throughout the fire exposure.
- Only the effects of thermal deformations resulting from thermal gradients across the cross-section need to be considered. The effects of axial or in-plain expansion may be neglected.

These simplifications mean that load redistributions due to changes in stress-strain relations during fire and due to thermal deformations are being neglected. Also stresses resulting from restrained thermal expansion are not considered. In reality, these thermal stresses may influence the load bearing capacity significantly.
Notably, the thermal gradient in aluminium structures is generally negligible due to the high thermal conductivity, excluded sections that are exposed to some sides and protected at other sides.

4.2.1 Strength of the cross-section

In case of members in tension, it should be verified whether the design resistance of the gross cross-section, taking into account the material properties at elevated temperature, is larger than the normal force. EN 1999-1-2 [3] gives rules both for a uniformly distributed temperature and a non-uniformly distributed temperature. In case of non-uniform temperature distribution, the contribution of each part of the cross-section with a specific temperature is taken into account by using the 0,2% proof stress at that temperature. In case of welding, the strength of the heat affected zone should be determined multiplying the 0,2% proof stress of the parent material at elevated temperature with the reduction coefficient for the weld at room temperature.

4.2.2 Stability

The ratio between the 0,2% proof stress and the modulus of elasticity for aluminium alloys is high compared to steel. This makes aluminium sections (partly) in compression relatively sensitive to buckling. The following types of buckling are distinguished:

1. Global buckling of a member in compression (flexural, torsional or flexural-torsional);
2. Global buckling of a member in bending (lateral-torsional);
3. Local buckling.

Ad 1. In the Eurocodes for steel and aluminium structures, the buckling resistance is related to the relative slenderness (λ_{rel}), which depends on the square root between strength and stiffness, see equation (4). A relatively high value for the relative slenderness means that the section is relatively sensitive to buckling. The mathematical relation between the ultimate buckling resistance and the relative slenderness is called a buckling curve and takes into account influence of geometrical imperfections, residual stresses and inelastic material characteristics.

$$\lambda_{rel} = \sqrt{\frac{N_{pl}}{F_{cr}}} \sim \sqrt{\frac{f_o}{E}} \qquad 3)$$

In fire design, the relative slenderness according to EN 1999-1-2 [3] should be determined with material properties at room temperature. As the ratio between strength and stiffness decreases at increasing temperature, the relative slenderness and thus the sensitivity to buckling may be overestimated at elevated temperature.
In addition, the buckling curve at room temperature should be applied to determine the buckling resistance with this relative slenderness. A study to whether this buckling curve is also appropriate at elevated temperature was not found.

In an experimental research on steel members in compression (Franssen et al. [15] and Talamona et al. [30]) it was concluded that a relative slenderness determined with material properties at elevated temperature gives a better correlation with the buckling resistance than using material properties at ambient temperature. A buckling curve for steel columns at elevated temperature was proposed. This buckling curve is less favourable than the buckling curves at room temperature, possibly caused by the fact that steel has a yield limit at room temperature, but inelastic material characteristics at elevated temperature. The method is applied in EN 1993-1-2 [2].

It is possible that the lateral deflection increases during buckling because of creep. EN 1999-1-2 [3] takes this into account by dividing the buckling resistance with a creep factor. This creep factor is given as 1,2, independent of the temperature and the time at elevated temperature. Thus:

$$N_{b,fi,t} = \frac{f_{o,\theta}}{f_{o,room}} \frac{N_b}{1{,}2} \qquad (4)$$

With

$N_{b,fi,t}$ = Buckling resistance at fire conditions

N_b = Buckling resistance at room temperature

Tests have been carried out on columns in compression of alloy 6082 with an additional bending moment (Langhelle [25], Langhelle et al. [26] and Eberg et al. [13]). 14 tests were carried out with constant load and a temperature linearly increasing in time. The critical temperature of tests with a relatively slow heating rate (so that the resistance was reached after approximately one hour) was approximately equal to the critical temperature of tests with a fast heating rate (resistance reached after 20-25 minutes). This may indicate that creep has no influence on the buckling resistance for the parameter field researched. Research is necessary to determine whether this conclusion holds for other alloys, load levels and a fire exposure period up to two hours.

Ad 2. The calculation model for buckling resistance of members subjected to lateral-torsional buckling in EN 1999-1-2 [3] is basically equal to that of members in compression, i.e. the slenderness should be determined with material properties at room temperature and the buckling curves for room temperature should be applied. However, no creep factor is taken into account in the calculation model for the buckling resistance for members in bending.

Ad 3. Research on local buckling at elevated temperature (see figure 9) has not yet been carried out. Therefore, no calculation model is implemented in EN 1999-1-2 [3] for local buckling. Calculation models for local buckling of steel structures are also not available in EN 1993-1-2 [2]. Local buckling is however specifically important for aluminium structures, because of the high ratio between strength and stiffness and because the extrusion process opens the possibility to design members of arbitrary shapes with thin wall thickness. However, due to the decreasing ratio between the 0,2% proof stress and the modulus of elasticity at elevated temperatures, it is expected that the sensitivity for local buckling decreases. This assumption was checked with some preliminary finite element models (figure 9).

Local buckling may 1. dominate the overall strength in case of compression or bending, may 2. interact with global buckling, and may 3. influence the rotational capacity (and thus influences the possibility for redistribution of forces). Therefore, the development of a model for local buckling is a first and essential step for design models for fire exposed aluminium structures.

4.2.3 Connections

Connections in aluminium structures are welded, bolted or adhesive bonded. Fundamental research on the behaviour of aluminium connections exposed to fire was not found in literature. Simple calculation models for strength and stiffness of connections are not given in EN 1999-1-2. Instead, it is stated that the resistance of connections between members does

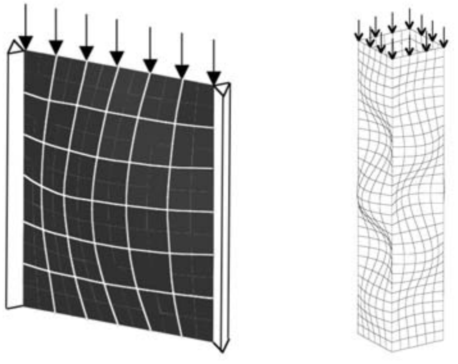

Figure 9: Examples of FEM models of local buckling of a plate (left hand) and of a section (right hand)

not have to be checked provided that the thermal resistance of the fire protection of the connection is not less than the minimum value of the thermal resistance of the fire protection of any of the aluminium members joined by that connection.
No information is available on the stiffness of connections and the development of forces in the connections during fire.

4.3 ***Evaluation of mechanical response models***
Only a limited number of fundamental studies was found on structural behaviour of fire exposed aluminium components. Most mechanical response models in EN 1999-1-2 are therefore either based on research on steel structures, or the same response models are applied as for room temperature. A mechanical response model for local buckling is not available and research on local buckling has neither been carried out on aluminium nor on steel structures. No information was found regarding the influence of unequal thermal expansion of a partially insulated member on (local or global) buckling.

5 Conclusions and further work

The literature survey has led to the following conclusions:
- Physical properties are relatively independent of the alloy;
- Especially the high conductivity (2 to 4 times the conductivity of steel) and low density (one third of that of steel) cause aluminium alloys to heat quickly. Therefore, most aluminium structures need passive fire protection to meet standard fire resistance requirements.
- Thermal expansion of aluminium is approximately two times that of steel. However, the modulus of elasticity is only one third of that of steel. This means that thermal stresses when expansion is restrained are lower than in case of steel structures.
- Mechanical material properties at elevated temperature depend on the alloy and temper.

In general, strength and stiffness of aluminium alloys are reduced significantly at moderately elevated temperatures. At a temperature of 350 °C, the strength is already reduced to 30%;

- The strengthening effects of tempering and work hardening is rapidly lost at moderate elevated temperatures of 150-250 °C. Beyond this temperature, there is hardly any difference between the strength of tempered and non-tempered aluminium of the same alloy;
- Except for naturally aged alloys, the modulus of elasticity reduces less fast than the strength at increasing temperature;
- It is not yet clear whether creep should be accounted for in mechanical response models;
- Mechanical response models of aluminium structures exposed to fire, applied in the recently developed standard EN 1999-1-2 [3], are not yet fully validated with tests or numerical research. Mechanical response models for local buckling do not exist.

Future research will concentrate on local buckling of sections exposed to fire. The influence of changes in material characteristics and creep influence on critical buckling load and ultimate resistance will be determined. Additional, it is aimed at determining the influence of unequal expansion on the buckling resistance in case of a partially insulated member.

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