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The constitutive behaviour of aluminium alloys at high temperatures

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Subject review

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The constitutive behaviour of aluminium alloys at high temperatures

The paper presents a review of research on aluminium alloys as structural elements, highlighiting their positive characteristics and potentital applications, as well as certain weaknesses – especially during fire. Papers examining the mechanical properties and time-dependent deformations under different temperature testing conditions are particularly discussed. This paper also provides an overview of potential rheological models that could be suitable for advanced research on the behaviour of aluminium at elevated temperatures.

Key words:
aluminium, aluminium alloys, fire, mechanical properties, creep

Pregledni rad

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Konstitutivno ponašanje aluminijskih legura pri visokim temperaturama

U radu dan je pregled istraživanja aluminijskih legura kao konstruktivnih elemenata s težištem na pozitivnim svojstvima i potencijalnim primjenama, ali i na određenim slabostima, osobito tijekom požara. Posebno su obrađeni radovi, pod cijelim spektrom uvjeta ispitivanja aluminijskih legura, o mehaničkim svojstvima i vremenski ovisnim deformacijama. Naposljetku je dan osvrt na potencijalne reološke modele koji bi bili prikladni za naprednija istraživanja ponašanja aluminija pri visokim temperaturama.

Ključne riječi:
aluminij, aluminijske legure, požar, mehanička svojstva, puzanje

1. Introduction

1.1. Aluminium as a naterial

Despite being the third most abundant element in the Earth's crust, aluminium was not discovered as an element until the early 19th century, making it a relatively new material. When first introduced in its pure form, it was considered a noble metal, more valuable than platinum. However, due to its inadequate mechanical properties in the pure form, the development of appropriate aluminium alloys became essential for its application in load-bearing structures. Depending on the alloying elements used, different aluminium alloys, or alloy series, with characteristic mechanical properties can be achieved. For structural applications, only suitable and proven alloys that exhibit sufficient strength, corrosion resistance, weldability, and compatibility with specific project requirements may be used.
The structural use of aluminium alloys began in the 20th century, and today, alongside steel, aluminium represents the most significant metal employed in load-bearing construction elements. Due to its unique properties, the use of aluminium alloys in the construction industry has increased substantially over the past few decades. Unlike steel, aluminium is non-ferromagnetic, does not rust, and can be used without paints or protective coatings. One of its key advantages is its density, which is approximately one-third that of steel, resulting in significantly lighter structures (Table 1). The mechanical properties of aluminium improve at lower temperatures, and unlike steel, it is not prone to brittle fracture in cold conditions. Its aesthetically pleasing appearance, combined with the fact that it requires no additional surface protection, also makes it a popular material in non-load-bearing facade systems. Another advantage lies in advances in manufacturing processes and the full recyclability of aluminium alloys suitable for structural use, making aluminium an exceptionally sustainable material [1].

Figure 1. The Crystal, London – a roof made entirely of 100 % recycled aluminium [4]

According to the Council for Aluminium in Building, 75 % of all aluminium produced since the late 19th century was still in use in 2008, and it is estimated that between 70 % and 98 % of the aluminium currently used in construction will be recycled [2]. It is important to note that the properties of aluminium remain unchanged during the recycling process. Compared to the late 20th century, the aluminium production process has seen significant improvements, resulting in a more than 75 % reduction in energy consumption required for alloy production, this, in turn, has led to a nearly 40 % reduction in greenhouse gas emissions (carbon footprint) [3]. Furthermore, suitable alloys can be easily extruded into complex cross-sectional shapes, which is not the case with conventional materials such as steel or concrete.
One of the earliest applications of aluminium was in the construction of the Washington Monument in 1884, located in Washington, D.C., United States. At the time, aluminium was an extremely rare and expensive material, and the total quantity used (just under 3 kilograms) was employed to fabricate the tip of the obelisk [5]. In the 1920s, the introduction of electrolysis significantly reduced the cost of aluminium production by approximately 80 %, which led to more widespread and practical applications. Both the structural framework and interior of the Empire State Building (completed in 1931) were made using aluminium [6]. The oldest known use of aluminium in construction is considered to be the cladding of the dome of the Church of San Gioacchino in Rome, Italy, with aluminium sheets in 1898 (Figure 2. a) [7]. A modern-day example is the striking aluminium roof of the Ferrari World amusement park in Abu Dhabi, United Arab Emirates, covering an area of 200,000 m² (Figure 2. b) [8].

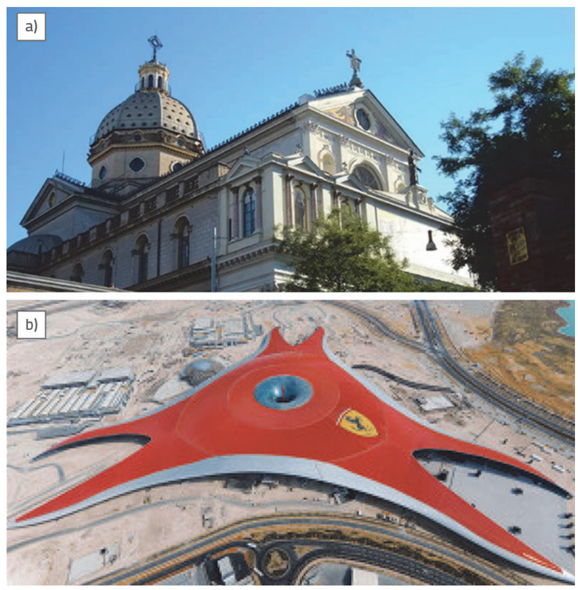

Figure 2. a) the Church of San Gioacchino in Rome [7]; b) Ferrari World in Abu Dhabi [8]

Figure 3. The Wave residential building, Almere, the Netherlands [9]

Figure 4. Arvida Bridge, Quebec, Canada [10]

Figure 5. Aluminium pedestrian bridge, Brossard, Canada [12]

Due to its low weight and corrosion resistance, the most common applications of aluminium alloys in construction involve structures located in humid or corrosive environments, structures in inaccessible locations or those requiring specialised transport, as well as long-span roofing systems where variable loads are relatively small compared to permanent loads. The residential building The Wave in Almere, the Netherlands, features an attractive wavy facade for which aluminium was the ideal material choice, owing to the complex required shapes and the high levels of salt and moisture in the environment. The structural elements of the building are made of concrete [9].

The Arvida Bridge (Figure 4), built in Canada in 1950, was the first bridge in the world constructed entirely from aluminium. The total mass of the bridge is 163 tonnes, which is less than half the weight of an identical structure made of steel [10]. It still holds the record for the aluminium bridge with the longest main span, measuring 91.5 metres, followed by pedestrian bridges with main spans ranging from 50 to 65 metres [11].

Figure 5 shows an aluminium pedestrian bridge in Canada, with a span of 44 metres, assembled from three segments in just one day.

According to current data, the construction industry accounts for 25 % of global aluminium production [13]. Aluminium alloys are classified into two categories: wrought alloys, which are melted in a furnace and subsequently shaped by casting into moulds, and cast alloys, which are primarily processed in the solid state. The final form of wrought alloys is achieved through various processes such as rolling, forging, extrusion, and similar techniques. Classification depends on the alloy's heat treatment capability, particularly for series that are heat-treatable, such as the 6xxx series. Wrought alloys are divided into nine series based on the combination of alloying elements. In the designation of each series, the first digit indicates the primary alloy group, while the second digit refers to modifications derived from the original alloy. The last two digits are for identification purposes. Formisano et al. [14] have addressed the advantages of using aluminium alloys in construction, emphasising their high potential for application in the extrusion of complex profiles, the behaviour of joints, and devices for seismic protection in steel frame structures. This paper will primarily focus on wrought aluminium alloys with magnesium and silicon as the principal alloying elements, designated numerically as EN AW 6xxx or chemically as AlMgSi. The role of magnesium is to improve corrosion resistance, particularly in alkaline environments. These alloys are among the most widely used due to their good weldability, formability, and corrosion resistance. For structural applications within the 6xxx series, the following alloys are deemed suitable: EN AW-6082, EN AW-6061, EN AW-6005A, EN AW-6106, EN AW-6063, and EN AW-6060, all of which have durability rating B [15]. The properties and behaviour of the 6082-T6 alloy have been extensively investigated at the Faculty of Civil Engineering, Architecture and Geodesy in Split – Torić et al. [16]. Their research identified the comparative characteristics of aluminium and steel, thereby paving the way for more frequent use of aluminium in construction. Given the need for further research, special attention

Table 1. Comparison of the mechanical properties of steel and aluminium at room temperature

Mechanical properties at room temperature	Steel (EN 1993-1-1)			Aluminium (EN 1999-1-1)	
	S235	S275	S355	6060 T66	6082 T6
Density [kg/m³]	≈ 7850			≈ 2700	
Unit weight [kN/m³]	≈ 78.5			≈ 27	
Modulus of elasticity [MPa]	210 000			70 000	
Poisson´s ratio	0.3			0.3	
Shear modulus [MPa]	≈ 81 000			≈ 27 000	
Ultimate strength [N/mm²]	360	430	490	215 (110)	300 (185)
Coefficient of linear thermal expansion [K⁻¹]	$12 \cdot 10^{-6}$			$23 \cdot 10^{-6}$	
Thermal conductivity [W/m°C]	~ 54			~ 240	
Specific heat [J/kg°C]	~ 440			~ 920	
Melting point [°C]	1425-1540			660	

will be given to the 6060-T66 alloy. This is a base alloy from the 6xxx series that has been solution heat-treated and artificially aged. When subjected to controlled processing procedures, it achieves superior mechanical properties compared to the same alloy in the T6 temper.

1.2 Aluminium structures in fire conditions

Increasing attention is being paid to the effects of extreme actions on structures, and fire is unquestionably classified as one of the them, due to its unpredictability and intensity. Fire is defined as any combustion process that spreads uncontrollably and may cause injury to people or property damage. Unfortunately, major incidents often serve as catalysts for recognising exceptional load cases. One such example is the 1974 high-rise fire in São Paulo, Brazil, in which 179 people died, prompting significant changes in fire protection regulations.

For a structure designed with fire resistance in mind, mechanical performance must be ensured for a specified period of fire exposure, during which the load-bearing system must retain its function up to a defined critical temperature or time. Evacuation must be possible before structural collapse occurs. Standard regulations specify typical fire resistance durations of 30, 60, 90, and 120 minutes. Investigative reports into the World Trade Center attacks concluded that, despite the design accounting for aircraft impact, the prolonged exposure of structural elements to high temperatures was the principal cause of the collapse. Upon impact, the fire protection on the steel elements was damaged, leading to the structural failure approximately after 60 minutes. Since fire cannot be precisely defined in terms of its development and effects, it is essential to consider a broader context of investigation, beginning with the materials used, the type of structure, and the nature of the fire load itself. The impact on a structure during a fire, during extinguishing, and the subsequent reduction in material properties must be evaluated at the material level. Although structural metals such as steel and aluminium are non-combustible and do not degrade through burning, fire exposure results in the degradation of their mechanical properties. As the occurrence of fire cannot be predicted, preventive measures are essential to ensure sufficient safety and to delay structural failure long enough to allow for the safe evacuation of occupants. Aluminium alloys have a lower melting temperature and thus aluminium structures reduced fire resistance. The mechanical properties of aluminium degrade more rapidly under high temperatures than those of steel. For certain alloys, this degradation begins at temperatures above 100 °C, with significant reductions observed above 200 °C. As the rate of temperature rise in a material depends on its thermal properties, it is important to study both the specific heat capacity (Figure 6.) and the thermal conductivity coefficient (Figure 7.) of aluminium in relation to temperature. The challenge of fire resistance in aluminium structures is further intensified by the high thermal conductivity of aluminium alloys, which causes heat to spread rapidly through structural elements and leads to a relatively quick reduction in load-bearing capacity. However, aluminium, being a highly reflective metal, exhibits a surface emissivity value that is approximately half that of carbon steel [17].

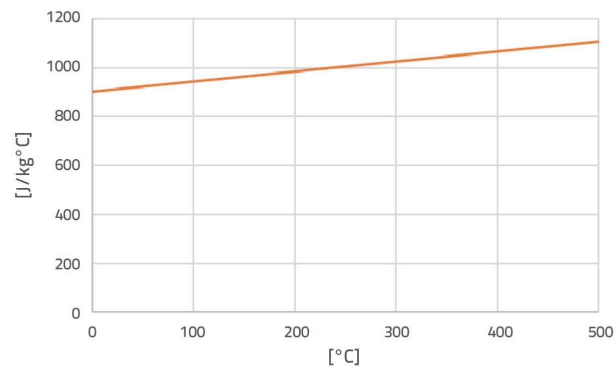

Figure 6. Specific heat capacity of aluminium alloys as a function of temperature

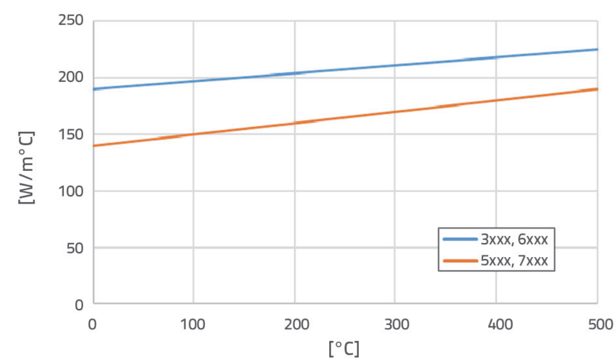

Figure 7. Thermal conductivity coefficient of aluminium alloys as a function of temperature

The constitutive behaviour of aluminium alloys at elevated temperatures is significantly influenced by time-dependent deformations - creep. When metallic elements are exposed to temperatures exceeding 170 °C for periods longer than 30 minutes, the effects of transient thermal creep must be taken into account. In aluminium alloys at high temperatures, particularly when assessing the buckling resistance of structural elements under fire conditions, an additional reduction factor of 1.2 is introduced into the calculation to account for this phenomenon [18].

1.3. Regulations - standards – European requirements

Four international standards governing the use of structural aluminium alloys and the design of aluminium structures are currently in use worldwide. These are listed in Table 2.

In Europe, the design of load-bearing aluminium elements is carried out by the models provided in Eurocode 9, supplemented by national annexes. Part 1-1 [15] provides general rules for structural design, while Part 1-2 [22] sets out guidelines for designing structures with fire resistance. Parts 1-3 to 1-5 address specific form of aluminium structures. Fire, as an

Table 2. International standards for the design of aluminium structures

International standards for the design of aluminium structures	
Standard ID	**Standard Title (description)**
AA ADM-2020 [19]	Aluminum design manual
Australian/New Zealand standard: AS/NZS 1664:1997 [20]	Aluminium structures
European standard: EN 1999:2007 [15]	Design of aluminium structures
Chinese standard: GB 50429-2007 [21]	Code for design of aluminium structures

exceptional action on load-bearing structures, is addressed in seven out of ten Eurocodes. For fire-exposed surfaces, thermal action is expressed in terms of net heat flux, accounting for both convective and radiative heat transfer. Gas temperature is calculated using either a standard temperature-time curve or by a fire model. Experimental studies on the reduction of mechanical properties have determined the ratios of 0.2 % proof strength at elevated temperatures to that at room temperature, which are provided in the Eurocode. These values are defined up to a temperature of 550 °C for exposure durations of up to two hours. The same issue has also been investigated for the modulus of elasticity in most alloys, although values for some still need to be established through future testing. Manufacturing is subject to control procedures, whereby each combination of alloy and temper, designed for a specific market and in accordance with the relevant standard, defines an individual alloy under strict specification requirements. Given the growing popularity of aluminium, Dokšanović et al. [23] analysed values specified by the standard in comparison with those obtained experimentally, in order to improve the accuracy of mechanical property estimations. In tests on the bending resistance of various 6xxx-series aluminium alloys, Montuori et al. [24] showed that the values defined by regulations can often be very conservative compared to experimental results. Sometimes, design codes fail to account for the specific differences between aluminium and steel, applying similar methodologies to both. Through further testing and evaluation, these codes can be refined to reflect better the unique characteristics of each material and structural system [25]. Eurocode 3, Part 1-2 [26], proposes a general stress–strain model for steel in fire conditions, composed of a linear portion, an elliptical transition, and a yield plateau. This model includes an implicit creep component, the influence of which was studied by Torić et al. [27] through an analysis that excluded time-dependent deformation (creep) in steel elements. They concluded that the creep implicitly included in Eurocode is not sufficiently conservative to account for all potential heating rates that may occur during fire exposure of structural elements. Given that the typical stress–strain curve for aluminium differs from that of steel, Eurocode 9, Part 1-2 [22], bases its general fire model for aluminium on a curve proposed by Ramberg and Osgood [28]. The values of the 0.2 % proof strength defined in Eurocode 9 Part 1-2 are based on steady-state tests. According to Maljaars and Katgerman, strength data should instead be based on transient state tests, as current values may, depending on the alloy, be unreliable or overly conservative for fire-resistance design [29]. This hypothesis should certainly be further examined through comparisons of different testing methodologies.

2. Research overview

2.1. Experimental investigations on aluminium specimens

Numerous research teams are working towards a more comprehensive understanding of the properties of aluminium alloys and the behaviour of structures made out of them. Georgantzia et al. [30] conducted an extensive review of existing experimental, numerical, and analytical studies under the different conditions and applications relevant to aluminium alloys. Many existing studies have focused on investigating the material characteristics of aluminium alloys and the behaviour of aluminium structures at ambient temperatures, whereas their response and residual load-bearing capacity after exposure to elevated temperatures remain under-researched. Only a limited number of studies have been published on the topic of fire stability, with a comprehensive summary presented in Table 3.

One of the pioneers of both theoretical and experimental research into the effect of creep on the buckling of aluminium columns was Chapman [63], who attempted to predict stability loss under constant load. The buckling behaviour of aluminium alloys has been investigated in numerous experiments conducted at room temperature [38, 40, 41, 45, 47, 49, 51, 52]. Kaufman compared tensile test results for more than 150 aluminium alloys and their respective tempers at various elevated temperatures. He pointed out that, for most aluminium alloys, the ratio of elastic modulus at elevated temperatures to that at room temperature does not decrease at the same rate as the ratio of 0.2 % proof strength under the same conditions [64]. To investigate time-dependent deformations or stresses, particularly when a material is subjected to elevated temperatures, Shivakumar et al. [65] conducted creep tests on the aluminium alloy 6061-T6 across a temperature range from 300 °C to 400 °C and under various stress levels. Related work has been carried out by Zhao et al. [66] on steel and Kumar et al. [67] on aluminium at 150 °C. It has been observed that the shape of the stress–strain curve varies depending on the type of aluminium alloy. Moreover, even for the same alloy, the stress–strain curve differs in form when the alloy is at room temperature compared to when it is exposed to fire [29, 62].

Table 3. Experimental investigations on aluminium

ROOM TEMPERATURE INVESTIGATIONS		
Test type	**Material**	**Reference**
Tensile	Al – 6xxx, 7xxx – T6	[31] (2009)
Tensile (and cyclic)	Al – 6082, 7020 – T6	[32] (2018)
Tensile	Al – 7075 – T6	[33] (2021)
Bending*	Al – 6061 – T6	[34] (2015)
Bending	Al – 6061 – T6, 6063 – T5	[35] (2017)
Compression	Al	[36] (1997)
Compression	Al – 6082 – T4, 6082 – T6	[37] (1997)
Compression	Al – 6060 – T4, 6060 – T6	[38] (1997)
Compression	Al – 6082 – T4, 6082 – T6	[39] (1999)
Compression	Al – 6xxx	[40] (2000)
Compression	Al – 6063 – T5, 6061 – T6	[41] (2006)
Compression (and/or bending)*	Al – 6061 – T6	[42] (2006)
Compression (and/or bending)	Al – 6061 – T6	[43] (2006)
Compression*	Al – 6082 – T6	[44] (2010)
Compression	Al – 6xxx	[45] (2011)
Compression*	Al – 6061 – T6, 6063 – T5	[46] (2014)
Compression*	Al – 6061 – T6, 6063 – T5	[47] (2015)
Compression (eccentric)	Al – 6082 – T6	[48] (2016)
Compression*	Al – 6061 – T6, 6063 – T5	[49] (2017)
pCompression (eccentric)*	Al – 6082 – T6	[50] (2019)
Compression*	Al – 6061 – T6	[51] (2020)
Compression*	Al – 7A04 – T6	[52] (2020)
Shear*	Al	[53] (2020)
Shear	Al – 6061 – T6	[54] (2021)
ELEVATED TEMPERATURE INVESTIGATIONS		
Test type	**Material**	**Reference**
Tensile	Al – 6082 – T6	[16] (2017)
Tensile	Al – 6063 – T5, 6061 – T6	[55] (2019)
Tensile	Al – 6082 – T6	[56] (2019)
Tensile	Al – 6xxx, 7020 – T6	[57] (2020)
Tensile	Al – 6063 – T5	[58] (2023)
Compression*	Al – 6082 – T6, 7108 – T79	[59] (2000)
Compression	Al – 5083 – H111, 6060 – T6	[60] (2009)
Compression*	Al – 6061 – T6	[61] (2018)
Compression*	Al – 6063 – T5	[62] (2023)

*the tests were preceded by a tensile testing of the material sample to determine its mechanical properties

Maljaars et al. [60] conducted numerous experimental investigations to define the stress–strain relationships of aluminium alloys at elevated temperatures and to examine the overall behaviour of alloys under such conditions, placing particular emphasis on the influence of material creep. In their tests on alloy 6060-T66, necessary for determining mechanical properties, they varied the strain range and strain rate depending on whether the test aimed to reach the 0.2 % proof strength or failure, while also accounting for temperature. They demonstrated that aluminium loses the majority of its load-bearing capacity within the temperature range of 175–350 °C. Therefore, chosen passive fire protection should be efficient for at least that temperature interval. Moreover, such protection must be sufficiently flexible to accommodate deformations induced by thermal loading [68]. Jiang et al. [61] investigated the behaviour of aluminium alloy 6061-T6 columns under compressive loading, including defects resulting from fire exposure. Six temperature levels were adopted, up to 400 °C, including room temperature (20 °C). After reaching the target temperature and a soak period at that temperature, compression tests were carried out to failure.

Torić et al. [16] conducted two types of experimental tests to determine deformation due to mechanical loading and creep deformation, using steady-state creep tests. The first test type involved a constant stress rate of 10 MPa/s applied to specimens preheated to achieve a nearly uniform temperature across the sample - the heating process was followed by a 30-minute soak period at a constant furnace temperature. The second test type focused on determining creep deformation. Specimens were uniformly heated and held at the target temperature for 60 minutes, after which they were subjected to a constant stress level at that temperature for up to 20 hours. Based on this experimental investigation of the 6082-T6 alloy, the critical temperature range for creep deformation was determined to be between 200 °C and 300 °C. Furthermore, an analytical model for creep deformation was proposed, which proved adequate for representing the experimental results, taking into account all three stages of the creep process.

Liu et al. [56] based their study on the aluminium alloy 6082-T6, where specimens were heated to eight different temperatures ranging from 100 °C to 550 °C and then either air-cooled or sprinkled with water to simulate fire suppression by water. Subsequent steady-state tensile tests were carried out at room temperature to evaluate the residual mechanical properties. Su et al. [55] conducted tensile tests on alloys 6063-T5 and 6061-T6 at temperatures up to 600 °C. Initial testing was performed at 24 °C. Both steady-state and transient tests were carried out, and the resulting values were compared with American and European standards.

Sun et al. [58] investigated the behaviour of alloy 6063-T5 by applying a heating rate of 15 °C/min from 20 °C (representing ambient temperature and initial mechanical properties) up to 550 °C, followed by post-fire material testing. After reaching the target temperature, specimens were exposed to it for 30 minutes and then allowed to cool naturally. Specimen geometry and strain rates conformed to those specified in EN ISO 6892-1 [69]. Once again, the significant effect of thermal exposure on the properties of structural aluminium alloy, particularly above 200 °C, was confirmed, and a series of models was proposed for estimating residual properties. In addition, they conducted compressive tests [62] on columns made from the same alloy and subjected to identical conditions, highlighting the often-overlooked influence of strain hardening.

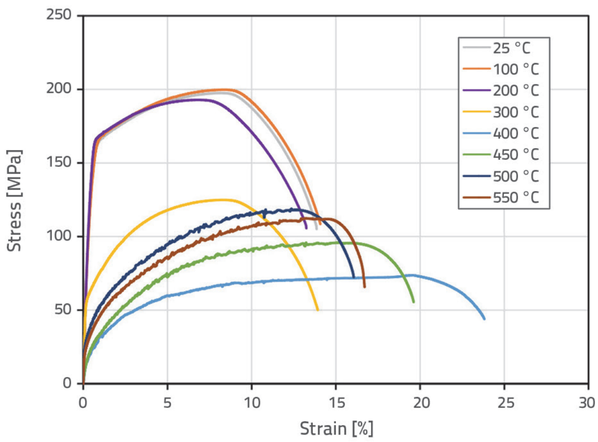

Figure 8. Stress-strain curves for a 4 mm thick specimen [58]

Due to its favourable characteristics, aluminium is increasingly being investigated in the form of composite beams made of aluminium alloys and concrete. In contrast to conventional steel–concrete composites, these systems offer reduced weight along with improvements in corrosion resistance and maintenance, while still meeting structural load-bearing requirements. Such composites may prove particularly suitable for long-span bridges and industrial structures. In addition, research is being conducted on fibre-reinforced polymer (FRP) aluminium composites to mitigate the risk of surface pitting corrosion, to which some aluminium alloys are prone [70].

Given the variety of applications, aluminium alloys are being studied at all levels and across related engineering disciplines [71–73], potentially contributing to a broader perspective and more widespread implementation in construction.

Chybiński et al. [74] examined 6060-T6 alloy specimens under both static and dynamic loading regimes, comparing changes in microstructure. Most of the tests were carried out at room temperature and at elevated temperatures to observe the material's behavioural changes. Alloy 6060 is susceptible to pitting corrosion due to its specific microstructure; however, this corrosion resistance can be improved through heat treatment, especially artificial ageing [75, 76].

In addition to frequent simulations conducted alongside experimental tests to validate the results, simulation methods using software such as ABAQUS are becoming increasingly popular. These involve the development of finite element (FE) models or numerical analyses, which are validated against data available in the literature [77–80]. Numerical simulations present certain challenges, but they complement the limited dataset obtained from experimental investigations, upon which the models are calibrated. Stress–strain curves obtained through material testing are adapted and applied within the corresponding models. To simulate mechanical properties is commonly employed the Ramberg–Osgood model which is used per Eurocode to define the stress–strain relationship. However, due to convergence issues, some authors prefer the exponential model proposed by Hopperstad, whose parameters are fitted to match the Ramberg–Osgood curve [77, 78].

Aluminium alloys exhibit significant variability at the constitutive level, which is reflected in differing values of the Ramberg–Osgood exponent. Once the constant material properties are defined, this allows for numerous analyses involving variations of non-dimensional parameters of cross-sectional geometry and span lengths. Creep is described using the Dorn–Harmathy model, which accounts for both primary and secondary creep phases. To calibrate this model, specific material properties must be identified. The influence of stress is incorporated through the Zener–Holloman parameter, while the temperature dependency is described by the Arrhenius equation. Mesh density in the simulation depends on the system and is not constant; it generally increases near cross-sections where maximum moments are expected to occur.

2.2. Assessment of properties and behaviour of auminium alloys

The microstructure of aluminium is formed in the shape of crystalline lattices and is, as such, susceptible to defects that influence its material properties. A particular type of defect is the presence of voids, typically formed during thermal treatment of the metal, which facilitate the diffusion-based movement of atoms within the solid metal. When metallic materials are subjected to sustained loading over time, the phenomenon of creep occurs, which becomes especially pronounced at elevated temperatures. In general, creep deformation as a function of time is divided into three phases: the primary phase, characterised by a decreasing strain rate; the secondary phase, during which the strain rate is constant and minimal; and the tertiary phase, marked by an accelerating strain rate leading to failure. Creep deformation significantly reduces material strength. Therefore, the topic of creep, particularly under fire conditions, has been of interest since the early use of aluminium in structural applications.

The earliest investigations into creep deformation of metal beams under non-stationary fire heating conditions began with the work of Harmathy [81, 82]. He recognised the importance of creep in fire-like processes and developed an "extended" model based on the originally proposed Dorn creep model [83], who as early as the 1950s advocated for experimental verification of creep phenomena and understood creep as a consequence of microstructural changes induced by high temperatures. According to Harmathy, analytical and numerical methods at the time were not sufficiently suited to the practical demands of beam calculations under thermal loading. As a result, he proposed his own model, although limitations still exist - particularly regarding the distribution of applied loads.

At the beginning of the 21st century, Suzuki et al. [84] conducted a series of tests on aluminium alloy columns and beams under fire loading conditions in order to determine the relationship between stress and critical temperature. They developed numerical equations for predicting the temperature increase of structural elements, as well as an equation for estimating the critical temperature of elements exposed to heating. Their model was validated using experimental data obtained from fire resistance tests on aluminium columns and beams.

Maljaars et al. [85] pointed out limitations in the constitutive model proposed by Harmathy [81], particularly cases in which it could not be applied. They developed a finite element model as a tool for verifying constitutive behaviour of aluminium alloys under fire exposure. They also noted that the existing model is not representative for the 6xxx series alloys, which are characterised by an early development of the tertiary creep phase. Specifically, Maljaars et al. [29] selected two commonly used structural alloys, 5083-O/H111 and 6060-T66, with differing high-temperature responses, in order to develop a modified constitutive model based on the existing Dorn–Harmathy one. Validation was performed using transient tests that simulate realistic fire scenarios for protected aluminium elements, with heating rates ranging from 2.4 °C/min to 11 °C/min and stress levels from 20 N/mm² to 100 N/mm². Investigations by Maljaars et al. [68] led to a modified stress–strain relation model for aluminium alloys exposed to fire under transient thermal conditions, building upon the original models proposed by Dorn and Harmathy. With parameter adjustments specific to each alloy, this extended model by Maljaars was also adopted by Soyal [86], who validated it through transient state tests involving rising temperatures under constant or variable loading. Soyal additionally pointed out differences between welded and unwelded specimens. The disparity in strength between the heat-affected zone (HAZ) and the base material decreases as the temperature rises, but equalises at 300 °C and above. A similar topic was explored by Kandare et al. [87], who followed the original proposals of Maljaars and colleagues to perform analytical validations as a basis for further investigation. They also incorporated additional parameters to refine the model for predicting the failure of aluminium elements under compressive loads in fire conditions. The prediction of temperature and the timing of initial or final column failure was validated using tests on an aluminium plate specimen. However, despite a good match between experimental and analytical results, these findings should be interpreted with caution due to the simplicity of the test setup. Fogle et al. [88] proposed a simplified analytical model for predicting failure in fire-exposed elements, without accounting for the effects of creep or initial imperfections. Their tests were conducted on plates of varying geometry, subjected to compressive loading and constant heat flux exposure.

Building on research into the development of creep deformation in steel, Torić et al. [89] investigated the same phenomenon in aluminium exposed to elevated temperatures. They analysed climb dislocation onto a neighbouring free slip plane as the prime deformation mechanism for high-temperature creep. A rheological model was developed, incorporating all three stages of creep, and was calibrated using examples for steel grade S275 and aluminium alloy 6082-T6. The model is applicable to any metal characterised by high-temperature creep, within the limitations defined in their work.

Zheng and Zhang [90] studied beams made from aluminium alloys 5083-H112 and 6060-T66, investigating both unprotected and protected aluminium beams under ambient and elevated temperature conditions. Based on their models and experimental testing, they highlighted the conservative nature of the critical temperature values calculated in accordance with Eurocode 9. They proposed simplified formulas for estimating temperature rise and, depending on the alloy, for calculating critical temperature. A comparison between the results of the simplified equations and those obtained using ABAQUS showed good agreement (Figure 9.). The simplified equation results were also compared with experimental data, showing similarly good alignment, although the simplified values were somewhat more conservative.

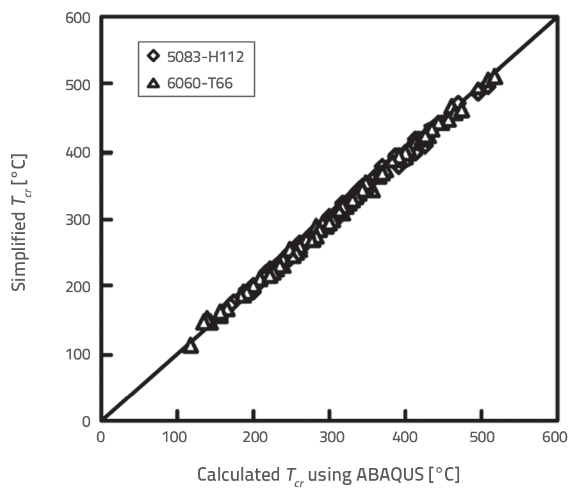

Figure 9. Critical temperature calculations [90]

Megalingam et al. [91] conducted tests at a constant temperature of 250 °C to investigate the creep behaviour of aluminium alloy 7075 under high, constant stress levels and elevated temperatures. The Norton–Bailey equation was employed to describe creep, linking creep strain rate to applied stress, temperature, and material characteristics. A key parameter in predicting creep is the strain exponent, which was determined in this study to be n = 4.6 for a stress range of 30 to 70 MPa at the specified temperature. By modelling the relationship between creep deformation and age hardening under various thermal and mechanical loading conditions [92], a complete set of constitutive models was developed through testing on aluminium alloy 7050. For the first time, these models demonstrate the ability to reliably predict key micro- and macro-scale properties regardless of initial material states and loading history.

Sun et al. [93] conducted extensive testing on the 7075-T6 alloy, determining stress–strain curves and material properties both during and after fire exposure, across a temperature range from 20 °C to 550 °C. A reduction factor for the specified alloy and temper was established, along with a series of models designed to predict the stiffness and strength of high-strength aluminium alloys under and following fire conditions. They concluded that the original

Ramberg–Osgood model was not suitable for capturing the full range of deformation behaviour of aluminium alloys during and after fire exposure. The authors further developed and adapted a model proposed by Yun et al. [94], who, based on a database of over 700 stress–strain curves at ambient temperature, introduced a modified two-stage Ramberg–Osgood model. The experimentally obtained stress–strain curves, representing properties during and after fire exposure, were compared with those predicted by the unified two-stage model. The good correlation observed confirmed the applicability of the model.

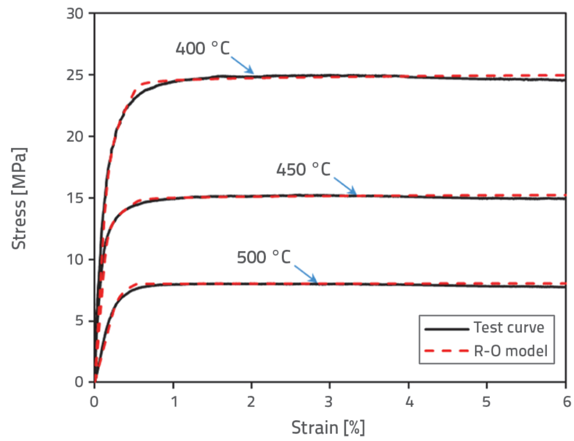

Figure 10. Comparison of measured and model-predicted stress–strain curves during fire [93]

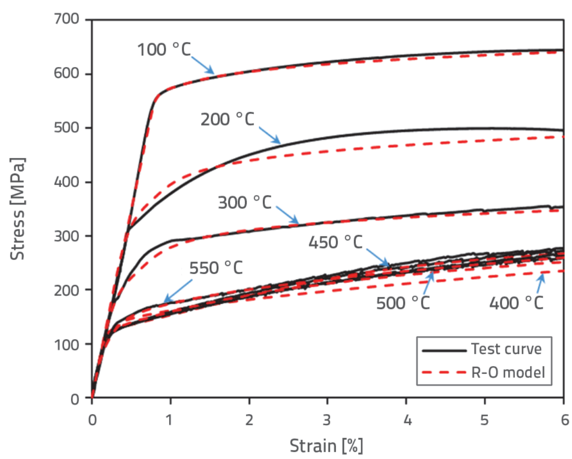

Figure 11. Comparison of measured and model-predicted stress–strain curves after fire [93]

Nabarro [95] conducted a comprehensive review and raised numerous questions and doubts regarding the credibility of creep models developed for pure metals. He identified discrepancies in the conclusions reached by different research groups who had tested similar materials under nearly identical methods and experimental conditions. Nevertheless, one of the theories was further developed by Spigarelli and Sandström [96], who formulated a basic creep model originally designed for copper and austenitic stainless steel, and later applied it to pure aluminium. The model does not contain any adjustable parameters; all variables are predefined, making it entirely predictive. In other words, to estimate creep levels, it is sufficient to experimentally determine the metal's composition, the applied stress, and the temperature. If proven sufficiently reliable, such a model would provide an excellent foundation for further development of creep prediction models for age-hardened aluminium alloys.

3. Rheological modelling of aluminium

The compatibility among various models proposed for predicting material characteristics represents a key step in developing a reliable rheological model. As early as 1973, Helman and Creus [97] recognised this need and, using concrete as a case study, proposed one of the first rheological models to describe nonlinear deformations and load-bearing failure. They developed expressions for both instantaneous and time-dependent deformations under constant stress. Their experimental results were adequately adapted, with model elements validated on series of individual components, resulting in the formulation of a Kelvin model composed of a spring and a damper with associated constants. Chindam et al. [98] carried out cyclic tests on steel at stress levels below the yield strength, observing the influence of heat generated by cyclic processes on the material. For simulating viscoelastic responses, they employed rheological models of the Kelvin–Voigt and Maxwell types. These models consist of a spring and a damper arranged either in series or in parallel, with the spring simulating the material's elastic nature and the damper representing its viscosity. Their findings indicated that the Kelvin–Voigt model more accurately describes the mechanical and thermo-mechanical responses of polycrystalline materials in the elastic loading regime. It is therefore proposed that this model be further validated for application to aluminium.

There are some already proposed models have include series-connected Kelvin–Voigt elements, each representing a specific type of deformation process. Torić and Burgess [99] developed a rheological model composed of two Kelvin–Voigt elements connected in series: the first representing mechanical deformation, and the second capturing viscous creep deformation. The model is capable of representing two out of the three components of total deformation at any temperature. The omitted component is classical thermal deformation, which is dependent solely on temperature. The model was first verified against numerous experimental results from various sources [100], and subsequently against the authors' own tests conducted on S275-grade structural steel and aluminium alloy 6082-T6 [89, 100], with model calibration performed using material

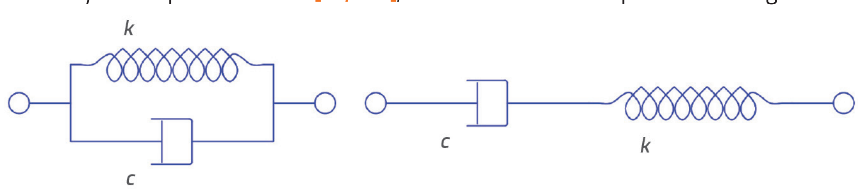

Figure 12. Representation of the Kelvin–Voigt and Maxwell model

properties derived from steel in the range of 400 °C to 600 °C and from aluminium in the range of 200 °C to 300 °C. Provided that the constitutive components are adequately calibrated, this model can be applied to any type and grade of carbon steel (S235–S355). It may also be considered a foundational framework for a universal rheological model applicable to metals that exhibit creep behaviour at elevated temperatures.

4. Discussion

In studying aluminium, it becomes evident that it cannot be regarded as a single, uniform material. Aluminium encompasses groups of alloys with differing properties, and even within the same group, mechanical characteristics vary depending on the specific alloy. Final differences are determined by the associated temper. As a result, researchers are increasingly conducting tests on various alloys under same testing conditions. Montuori et al. [24], through more than 100 experimental investigations (15 conducted by the authors and 86 gathered from the literature) on aluminium alloys 6060-T66, 6082-T6 and 6005A-T6, highlighted the conservative nature of design standards. Guo et al. [57] performed 169 tensile tests on alloys 6082-T6, 6N01-T6, 6061-T6, 6061-T4, and 7020-T6 to examine and compare the changes in their mechanical properties with increasing temperature. These numerous investigations have opened up several new topics that require further exploration:

- Compressive tests on alloys 5083-H111, 6060-T66, and 6063-T5 have revealed some lesser-studied phenomena, such as the increase in Poisson's ratio with rising temperature [60], and the often-overlooked influence of strain hardening in aluminium alloys [62];
- Although previous studies have indicated minimal influence of soak time duration on the mechanical performance of steel elements [56], extended exposure time leads to more pronounced creep development in aluminium. It is therefore necessary to examine the extent to which strength depends on the duration of elevated temperature soak time [29];
- Maljaars and Katgerman argue that the strength values provided by design standards are insufficiently reliable, as they are derived from steady-state tests, which poorly represent real fire scenarios [29]. However, in [55], the yield strength equations were validated against both steady-state and transient test results, and no significant discrepancies in the reduction factors were observed;
- The creep implicitly accounted for in European standards has also been shown to be inadequate for certain fire scenarios [27];
- Eurocode [22] gives reduction factors for properties such as the 0.2 % proof strength and elastic modulus, based on existing experimental data at elevated temperatures. These reduction factors are provided for discrete temperatures, and linear interpolation is required for intermediate values. When compared with experimentally determined data, the accuracy of these factors, particularly for predicting the elastic modulus, is often deemed insufficient.

For an accurate and reliable representation of stress–strain curves, at least three fundamental material parameters are required: yield strength, tensile strength, and elastic modulus. Accordingly, special attention will be given to the latter.

As temperature increases, there is a significant reduction in the load-bearing capacity of aluminium alloys, making it essential to accurately assess the residual mechanical properties both during and after fire exposure. As early as the 1980s, substantial reductions in strength and elastic modulus of aluminium alloys at elevated temperatures were observed. It is also known that, in addition to the variation in stress–strain curve shapes between different alloys, the shape of the curve for a single alloy differs markedly between ambient and elevated temperatures [29, 62].

The elastic modulus, representing the ratio of stress to strain, is a measure of material stiffness, and it is typically illustrated on a stress–strain diagram as the slope of the initial linear part of the curve. This measure is of critical importance in evaluating structural stability and safety.

It is important to emphasise that while design standards provide reduction factors for material properties at elevated temperatures (i.e., during fire exposure), they do not define equivalent factors for post-fire conditions.

All reduction coefficients defined in Eurocode, as well as those experimentally determined in the literature, are illustrated in Figures 13. and 14. Figure 13 presents reduction factors for elastic modulus during fire exposure, obtained from tests on various alloys subjected to elevated temperatures. The results are compared with the reduction curve proposed by Eurocode, revealing differences in the behaviour of individual alloys. A consistent reduction in elastic modulus is observed, implying a continuous loss of stiffness with rising temperature.

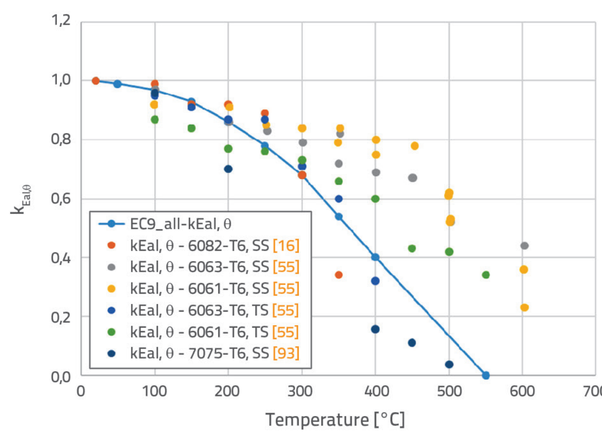

Figure 13. Comparison of the in-fire elastic modulus test results and Eurocode 9

Figure 14 presents a comparison of post-fire reduction factors. It is important to note that there are no significant reductions, except in the case of alloy 6082-T6, which exhibits a maximum reduction of 30 % after exposure to 500 °C. According to the presented results, the ratios remain nearly constant, suggesting that the elastic modulus is not significantly affected by temperature once the structural elements have cooled down.

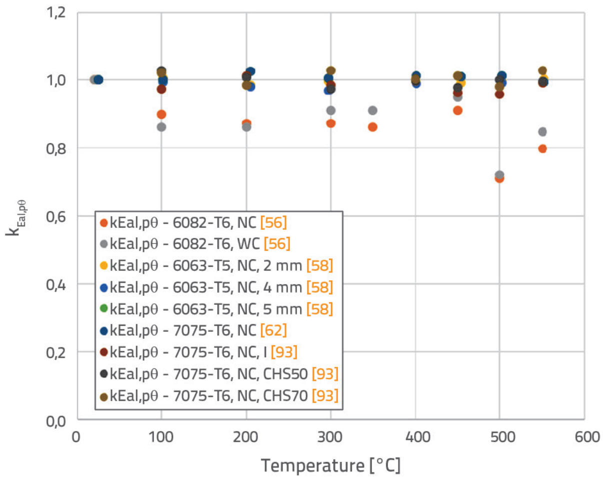

Figure 14. Comparison of the post-fire elastic modulus test results

The results highlight the numerous differences among aluminium alloys suitable for structural applications. Further research is required to address the current limitations in standards for the design of aluminium structures. To investigate the key behavioural parameters under fire conditions, it is essential to conduct numerical analyses that would reduce the need for costly and complex experimental testing. In line with this, there is motivation for the development of a universal rheological model. This motivation stems from the need to integrate analyses of aluminium structures in fire, taking into account all complex and time-dependent deformation components. The aim is to consider all key thermomechanical variables: temperature and temperature rate, stress, and strain rate, which are the main factors governing aluminium's behaviour during fire exposure. Such a detailed and accurate assessment of fire impact on structural performance would significantly enhance our understanding of the complex processes occurring under extreme conditions.

5. Conclusion

Over the past few decades, and particularly in recent years, aluminium has been increasingly used across various engineering disciplines. Its most notable attribute is the high strength-to-weight ratio, coupled with excellent corrosion resistance. Aluminium bridges are being constructed, and its role as a structural material is growing, both on land and in offshore structures. The properties offered by aluminium can significantly reduce inspection and maintenance costs. Therefore, this paper aims to draw the attention of design engineers to its potential. Acknowledging the current lack of information regarding aluminium alloys used as load-bearing structural elements, the paper focuses on analysing their creep behaviour. Given the clearly demonstrated challenges concerning fire resistance in the reviewed studies, particular attention will be dedicated to this issue. To minimise the cost of future testing, a rheological model will be defined based on the experimental analysis of material behaviour. This will enable more accurate assessments of damage extent and residual material properties following exposure to elevated temperatures. Further work will focus on the development of new creep models applicable to specific aluminium alloys, as well as on a generalised model for currently used structural aluminium alloys in civil engineering.

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