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Structural fire behaviour of aluminium alloy structures: Review and Outlook

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Abstract:

Aluminium alloys are gaining increasing use in the construction industry, underpinned by extensive research and the growing availability of codified structural design rules at room temperature. More recently, considering that the material properties of aluminium alloys degrade significantly at elevated temperatures, a substantial number of studies have also been conducted to investigate the behaviour and design of aluminium alloy structures exposed to fire. This paper presents a review of recent studies on the mechanical characteristics of aluminium alloys in fire and after fire, as well as the structural behaviour of aluminium alloy structures in fire conditions, considering members, connections, joints and overall systems. In addition, possible passive and active fire protection measures for aluminium alloy structures are introduced and discussed. Lastly, recommendations for future work on the structural fire behaviour of aluminium alloy structures are set out, providing insight into aspects that require further investigations to promote the more widespread use of aluminium alloys in structural applications.

Keywords: Aluminium alloys; Applications; Elevated temperatures; Mechanical properties; Structural performance; Fire; Fire protection measures.

1. Introduction

The use of aluminium alloys in the construction industry is becoming increasingly popular owing to their favourable mechanical properties such as high strength-to-weight ratio, excellent corrosion resistance, appealing appearance, good recyclability, ease of fabrication and nonmagnetic characteristic. Recent years have witnessed the wide application of aluminium alloys in long-span structures, marine and offshore structures, movable light gauge structures and prefabricated systems, examples of which are shown in Fig. 1, namely the Beijing Daxing International Airport (Fig. 1a) [1], the Arvida Bridge in Quebec (Fig. 1b) [2], a German military bridge (Fig. 1c) [3] and a prefabricated office building in Hong Kong (Fig. 1d) [4]. The growth in the use of aluminium alloys in structural applications has been matched by a growth in research activities. Specifically, a large number of studies have been performed over the past few decades to investigate the material properties of aluminium alloys [5,6], as well as the structural performance of aluminium alloy elements [7-26], connections and joints [27-30] and systems [31] at ambient temperature. To date, four international standards [32-35] have been developed for the design of aluminium alloy structures.

(a) Beijing Daxing International Airport [1] (b) Arvida Bridge in Quebec [2]

(c) German military bridge [3] (d) Prefabricated office building in Hong Kong [4]

Fig. 1. Typical structural applications of aluminium alloys.

Fire represents one of the most serious hazards to engineering structures, and, if not well managed, can result in great loss to human life and property. Fire causes elevated temperatures, resulting in deterioration of the material properties. Compared to carbon steels, aluminium alloys have a lower melting point and exhibit a more severe degradation of mechanical properties with increasing temperatures [36], consequently leading to a serious reduction in the fire resistance of members, joints and structures; thus, investigations into the structural behaviour of aluminium alloy structures in fire are necessary and significant. The present paper aims to provide a comprehensive review of advances in research on the fire behaviour of aluminium alloys at various levels: materials, structural components and systems. Following the methodology section, which states how this paper identified and selected relevant research work, the thermal and mechanical properties of aluminium alloys in and after fire are first discussed in Section 3, serving as the basis for understanding the fire behaviour of aluminium alloy structural members, joints and systems, studies on which are reviewed in Sections 4-6, respectively. Research into passive and active fire protection measures for aluminium alloy structures is outlined in Section 7, with a view to improve the fire-resistant performance of aluminium alloy structures. Finally, an outlook, with recommendations for future work on the structural fire behaviour of aluminium alloy structures, is set out in Section 8.

2. Research methodology

The aim of this review article is to provide a critical review of existing literature on aluminium alloy structures in fire at various levels and indicate the future research paths and efforts to improve the fire performance of aluminium alloy structures.

A comprehensive literature review has been conducted including published journal and conference articles, books as well as dissertations on aluminium alloys in fire. Many of the articles that feature in this review were identified based on the combined knowledge and experience of the authors. Additional publications were identified through a literature search, conducted in the manner described below. Literature available in Scopus and Web of Science (WoS) was first identified by searching terms “alumin*um” and “fire” combined with the Boolean operator ‘‘AND”, resulting in a total of 4670 literature elicited. Three categories of keywords: (1) mechanical properties, (2) members and structures, and (3) fire protection were then added to refine the search. Each category contains a block of keywords and the keywords within each search block were combined using the Boolean operator ‘‘OR”. The search was conducted utilizing the advanced search facility in Scopus and queried the title, abstract and keywords of publications, while in WoS, the topic was queried; this resulted in 2587 literature. The extracted literature was then filtered through removal of duplicates and selecting publications in English and Chinese languages; following this, 2341 articles were identified. After evaluation of the relevance and abstracts of the extracted literature, 47 publications were selected. The flow chart of the search process and results is shown in Fig. 2.

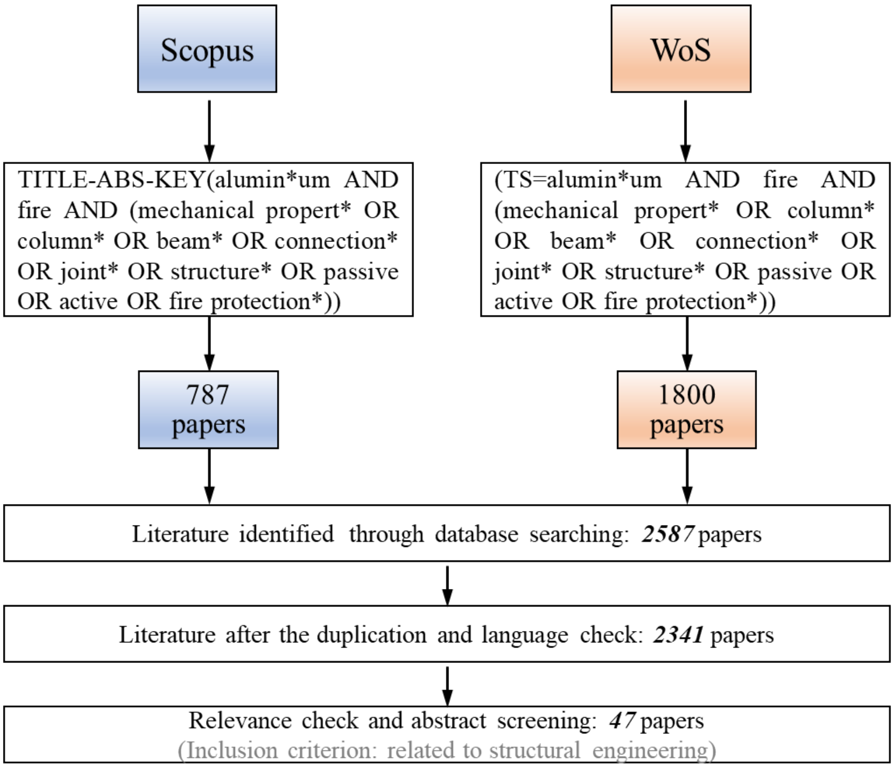


Fig. 2. Flow diagram of the search process and results.

3. Thermal and mechanical properties in and after fire

A comprehensive understanding of the thermal and mechanical properties of a material at elevated temperatures is crucial to understand the response of a structure composed of that material in fire. Studies into the thermal and mechanical properties of aluminium alloys both in and after fire are reviewed in this section.

3.1. Thermal properties

Typical values of the key physical and thermal properties of aluminium alloys are compared with those of carbon steels and stainless steels in Table 1 and discussed below. The melting point of commonly used aluminium alloys is around 600 °C [33], which is less than half that of the steels [37]. According to CSA S157-17 [38] and EC3 1-2 [37], the density of structural aluminium alloys and (stainless) steels can be assumed to be independent of temperature, and taken as 2700 and 7850 kg/m^3, respectively.

Table 1 Comparison of key physical and thermal properties of aluminium alloys, carbon steels and stainless steels.

Metal type	Melting point (°C)	Density (kg/m^3)	Emissivity ε_m	Coefficient of thermal expansion α (10^{-6}/°C)	Thermal conductivity λ_a (W/m°C)	Specific heat c_a (J/kg°C)
Aluminium alloys	590-650	2700	0.3	22.9	142-191	911
Carbon steels	1425-1540	7850	0.7	12.2	53	440
Stainless steels	1375-1510	7850	0.4	16.1	15	455

Material emissivity (ε_m) is a dimensionless value between zero and one and is defined as the ratio of the energy radiated from the surface of a material to that radiated from a blackbody (ε_m = 1). Although the emissivity is influenced by the angle of the radiation, wavelength of the radiant energy and even the temperature, it may be considered to be constant for a given surface of material in structural fire engineering calculations [39,40]. Lower emissivity values slow the rate of heat transfer and hence the development of temperature in fires.

The thermal elongation of a member depends on the coefficient of thermal expansion (α) of the material and the change in temperature (ΔT). Although the value of α is commonly assumed to be constant in simple calculations, aluminium alloys, carbon steels and stainless steels in fact elongate at different rates at different temperatures, as shown in Fig. 3 [37,41]. The higher thermal expansion of aluminium alloys may result in higher forces being induced in axially or rotationally restrained members in fires, which may require some consideration in design [42,43].

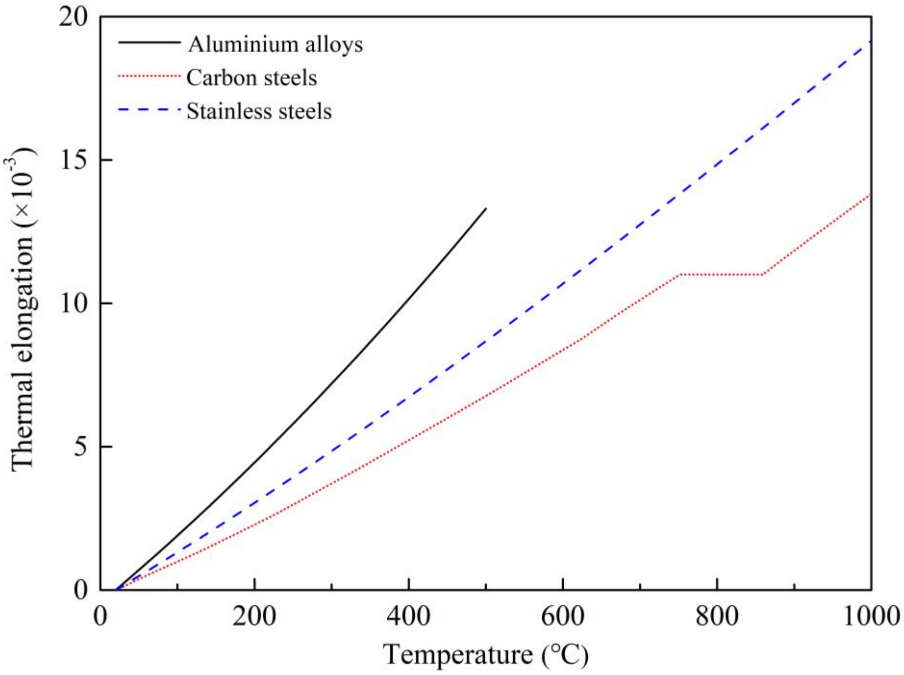


Fig. 3. Thermal elongation of aluminium alloys, carbon steels and stainless steels.

The thermal conductivity of aluminium alloys is substantially higher than that of carbon steels and stainless steels at elevated temperatures, as displayed in Fig. 4 [37,41]. Among the different families of aluminium alloys, the thermal conductivities of the 3000 and 6000 series alloys are the highest [44]. Thermal conductivity mainly affects the temperature distribution within a structural member or a structural system. Although the high thermal conductivity of aluminium alloys can reduce the development of the high localised temperature concentrations within structural components in the initial stages of fire exposure [45], it may also lead to the increased transfer of heat to structural components more remote from the heat source [46].

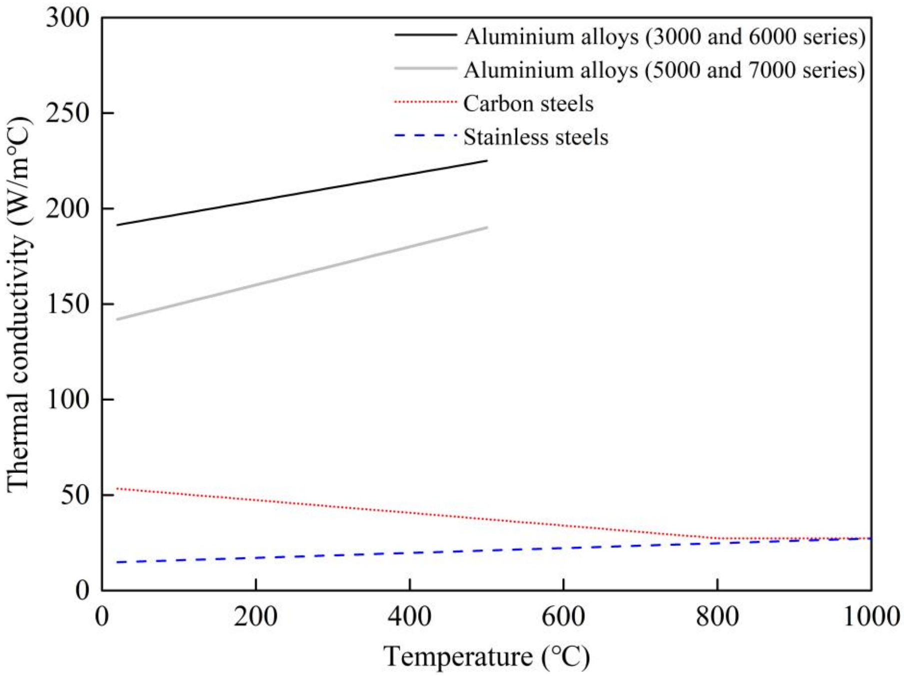


Fig. 4. Thermal conductivity of aluminium alloys, carbon steels and stainless steels.

Specific heat (c_a), also termed as specific heat capacity, quantifies the amount of heat that has to be added to one unit mass of a material in order to raise its temperature by 1 °C. The variation of the specific heat of aluminium alloys, carbon steels and stainless steels with temperature is shown in Fig. 5. It can be seen that, prior to reaching the melting point, the specific heat capacity of aluminium alloys is significantly higher than that of carbon steels and stainless steels; this has the beneficial effect of requiring a larger input of heat per unit mass to raise the temperature of aluminium alloy elements [40,45].

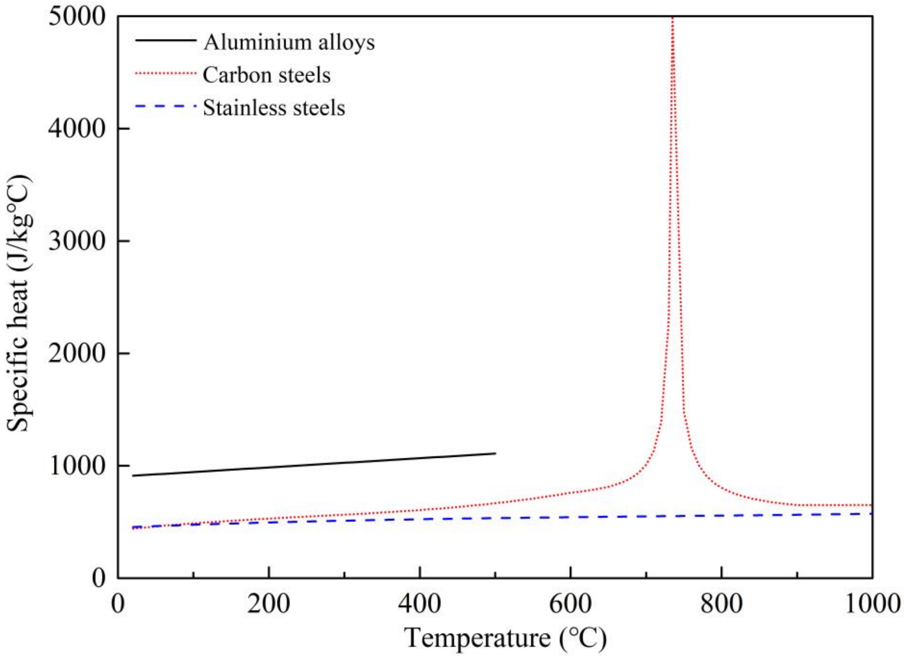


Fig. 5. Specific heat of aluminium alloys, carbon steels and stainless steels.

3.2. Mechanical properties in fire

The mechanical properties of commonly used structural aluminium alloys degrade faster than those of carbon steels and stainless steels, as shown in Figs. 6-9, where the elevated temperature reduction factors for Young's modulus $k_E = E_\theta/E$, where E is the Young's modulus at room temperature and E_θ is the Young's modulus at elevated temperature θ, yield (0.2% proof) strength $k_{0.2} = f_{y,\theta}/f_y$, where f_y is the yield strength at room temperature and $f_{y,\theta}$ is the yield strength at elevated temperature θ, ultimate strength $k_u = f_{u,\theta}/f_u$, where f_u is the ultimate strength at room temperature and $f_{u,\theta}$ is the ultimate strength at elevated temperature θ, and ultimate strain $k_{\varepsilon u} = \varepsilon_{u,\theta}/\varepsilon_u$, where ε_u is the ultimate strain at room temperature and $\varepsilon_{u,\theta}$ is the ultimate strain at elevated temperature θ, for different aluminium alloys [47-50], carbon steels and stainless steels [37,51] are compared.

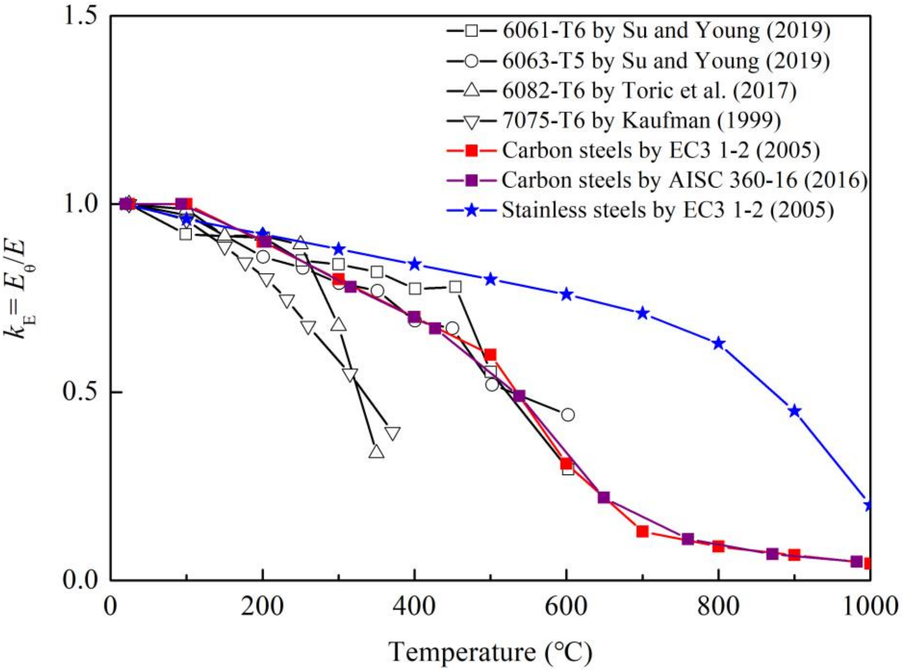


Fig. 6. Comparison of Young's modulus reduction factor k_E for different aluminium alloys and carbon and stainless steels at elevated temperatures.

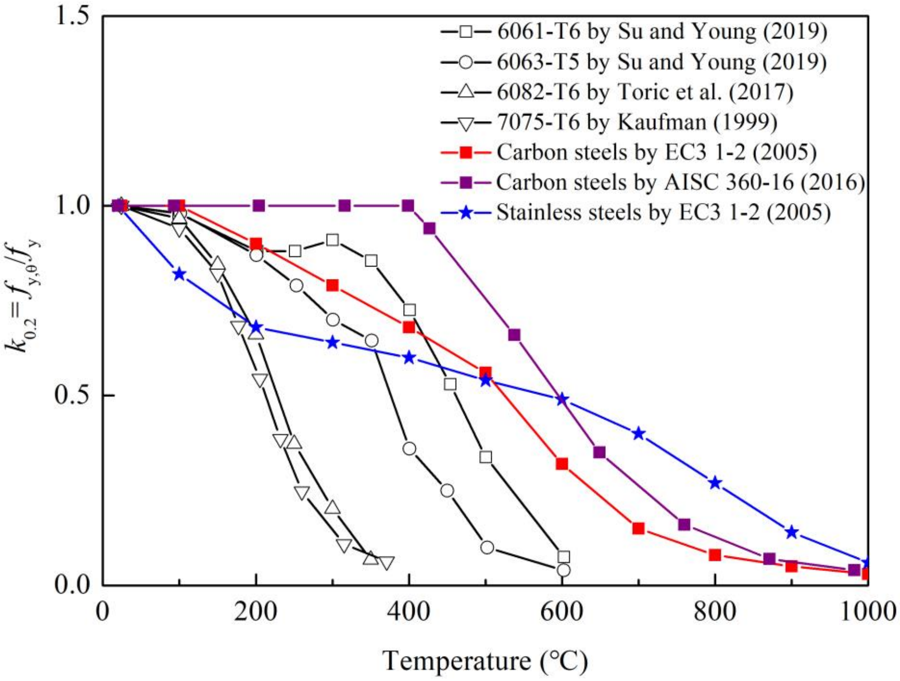


Fig. 7. Comparison of yield strength reduction factor $k_{0.2}$ for different aluminium alloys and carbon and stainless steels at elevated temperatures.

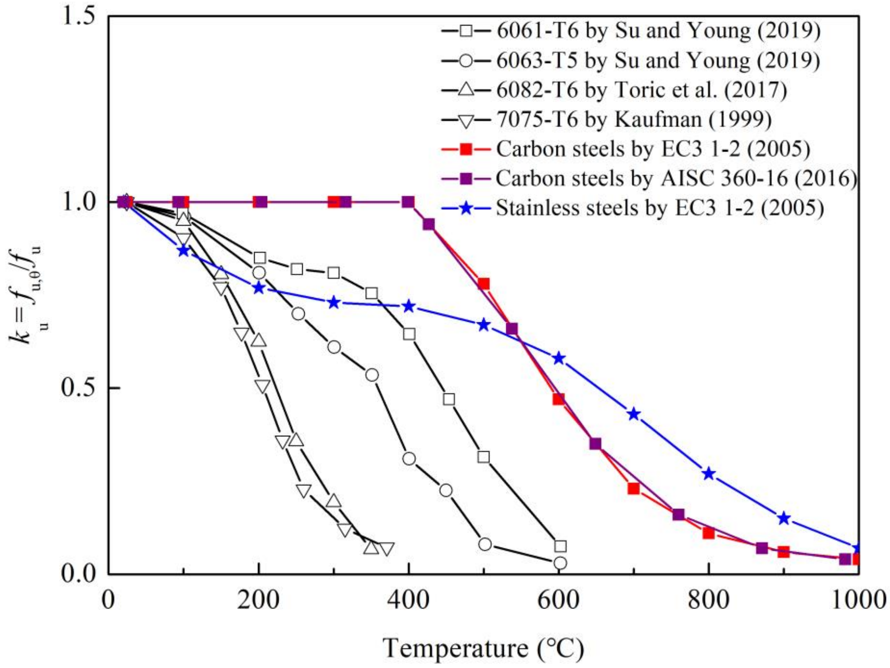


Fig. 8. Comparison of ultimate strength reduction factor k_u for different aluminium alloys and carbon and stainless steels at elevated temperatures.

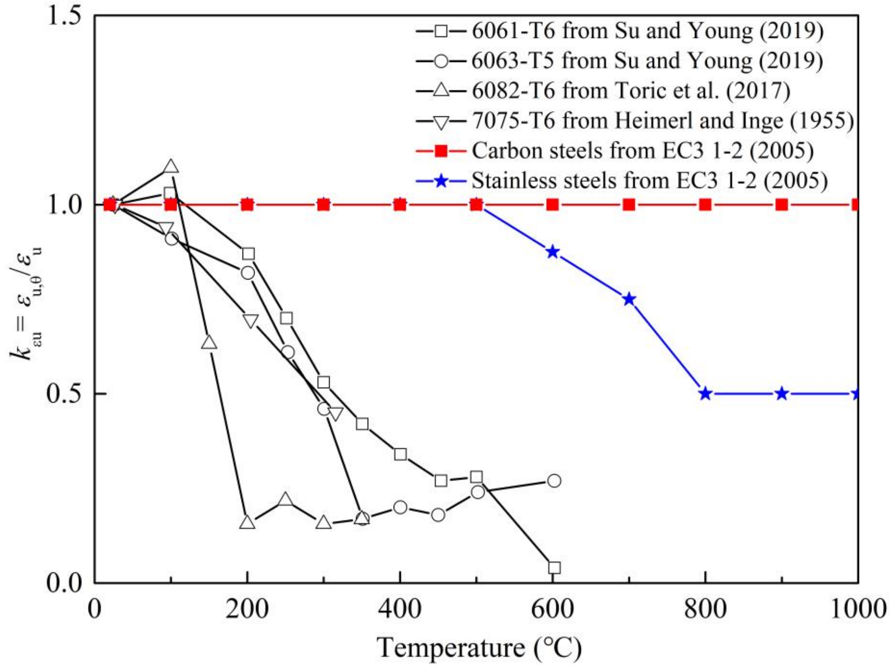


Fig. 9. Comparison of ultimate strain reduction factor $k_{\varepsilon u}$ for different aluminium alloys and carbon and stainless steels at elevated temperatures.

In recent decades, a large number of research studies have been conducted to investigate the mechanical properties of aluminium alloys under fire conditions; these are summarised in Table 2 and further discussed in this subsection. Kaufman [49] investigated the mechanical properties of eight series of aluminium alloys (from 1000 to 8000 series) at elevated temperatures by carrying out a range of steady-state experiments. Su and Young [47] performed both steady- and transient-state tests to study the mechanical properties of 6063-T5 and 6061-T6 aluminium alloys at elevated temperatures and put forward a set of empirical equations for calculating the elevated temperature reduction factors for the key mechanical properties discussed above, as given by Eq. (1),

$$k_{\mathrm{E/0.2/u/}\varepsilon\mathrm{u}} = a_1 - \frac{\theta - b_1}{c_1} \tag{1}$$

where θ is the elevated temperature in Celsius, and a_1, b_1 and c_1 are coefficients determined based on experimental results. Peng et al. [52] and Guo et al. [53-55] carried out steady-state tests on different aluminium alloys including 6082-T6, 6N01-T6, 6061-T4, 6061-T6 and 7020-T6, and proposed predictive expressions for determining the reduction factors for the mechanical properties of the investigated aluminium alloys at elevated temperatures; the predictive expressions are given in the form of Eq. (2), where a_2, b_2 and c_2 are coefficients determined on the basis of the test results.

$$k_{\mathrm{E/0.2/u}}\left(\theta\right) = a_2\theta^2 + b_2\theta + c_2 \tag{2}$$

Fire-resistant aluminium alloys are being increasingly used in the mechanical engineering sector due to their substantially improved mechanical properties at elevated temperature compared to the traditional aluminium alloys [56,57]. These alloys, however, have not been widely applied in the field of structural engineering; the fire-resistance behaviour of structural elements made of fire-resistant aluminium alloys should be further investigated in the future, as detailed in Section 8.2 of the present paper.

Although extensive experimental studies have been conducted previously to investigate the mechanical properties of aluminium alloys at elevated temperatures, investigations into the constitutive modelling of aluminium alloys at elevated temperatures are still rather limited. Figgiano et al. [58] extended the Ramberg-Osgood model, which has been commonly used for the description of the stress-strain response of a range of aluminium alloys at ambient temperature [6,32], for aluminium alloys at elevated temperatures, as shown in Eq. (3),

$$\varepsilon = \frac{\sigma}{E_{\theta}} + 0.002\left(\frac{\sigma}{f_{\mathrm{y},\theta}}\right)^{n} \tag{3}$$

where ε and σ are strain and stress of aluminium alloys, respectively, and n is the strain hardening exponent. Figgiano et al. [58] found that n varies significantly between different aluminium alloy grades and is dependent on temperature; this observation was confirmed by Su et al. [47].

The creep behaviour of aluminium alloys at elevated temperatures has been investigated in a number of studies. Hepples and Wale [59] and Langhelle [60] proposed different creep models based on creep test results on 6082-T6 aluminium alloy, which take into account the primary and secondary creep phases. In addition, Toric et al. [48] proposed an analytical creep model for 6082-T6 aluminium alloy at elevated temperatures underpinned by a series of constant stress-rate and stationary creep tests; this model was shown to yield good agreement with the experimental results, accurately capturing all three distinctive creep phases (i.e. primary, secondary and tertiary). On the basis of the classical creep model developed by Dorn [61] and Harmathy [62], Maljaars et al. [63] proposed a modified constitutive model that incorporated the tertiary creep stage for aluminium alloys at elevated temperatures; this model was validated against transient-state tests on two representative aluminium alloys – 5083-H111 and 6060-T66, and deemed suitable for use in the simulation of insulated aluminium alloy members exposed to fire. Maljaars et al.'s model was further developed by Kandare et al. [64].

Table 2 Summary of research studies on mechanical properties of aluminium alloys in fire.

Reference	Aluminium alloy grade	Details
Su and Young [47]	6063-T5, 6061-T6	Steady-state tests (24-600 °C)/ Transient-state tests
Toric et al. [48]	6082-T6	Steady-state tests (20-350 °C)/ Creep tests (150-300 °C)
Peng et al. [52]	6061-T6	Steady-state tests (14.1-552.1 °C)
Guo et al. [53]	6082-T6, 6N01-T6, 6061-T4, 6061-T6	Steady-state tests (20-300 °C)
Guo et al. [54]	7072-T6	Steady-state tests (-120-300 °C)
Guo et al. [55]	6082-T6, 6N01-T6, 6061-T4, 6061-T6, 7072-T6	Steady-state tests (-100-300 °C)
Figgiano et al. [58]	3003-O, 3003-H14, 5052-O, 5052-H34, 5083-O, 5454-O, 5086-O, 5086-H32, 6061-T6, 6063-T6, 7075-T6	Theoretical analysis
Hepples et al. [59], Langhelle [60]	6082-T6	Steady-state tests
Maljaars et al. [63]	5083-O, 5083-H111, 6060-T6	Transient-state tests/ Creep tests (200-340 °C)
Kandare et al. [64]	5083-H116	Transient-state tests/ Creep tests (300-400 °C)

3.3. Mechanical properties after fire

With regards to the post-fire mechanical properties of aluminium alloys, Summers et al. [65] carried out a series of uniaxial tensile coupon tests on 5083-H116 and 6061-T651 aluminium alloys to investigate their residual mechanical properties after exposure to elevated temperatures, revealing that the residual mechanical properties are dependent on both the heating rate and the maximum temperature attained in the prior heating history. Based upon the findings, empirical models were developed to determine the residual yield strength of the investigated aluminium alloys after a fire considering their time-temperature dependent characteristics. Rippe et al. [66] experimentally investigated the post-fire material properties of 6061-T651 aluminium alloy; the obtained findings accorded with those reported by Summers et al. [65]. Rippe et al. [66] also established finite element (FE) models that featured the use of the maximum exposure temperature as an input parameter to simulate the post-fire behaviour of aluminium alloy beams; the developed models were shown to be able to accurately capture the post-fire mechanical behaviour of aluminium alloy structural components. Considering the combined effects of the maximum exposure temperature and duration, Rippe and Lattimer [67] proposed a kinetics-based model based on the Arrhenius equation [68] to predict the degradation of mechanical properties. More recently, Chen et al. [69] studied the effects of exposure temperature and cooling methods (i.e. natural cooling and water cooling) on the post-fire mechanical properties of 6061-T6 and 7075-T73 aluminium alloys through experimentation and proposed predictive equations for the estimation of the post-fire mechanical properties. A similar study on the post-fire mechanical properties of 6082-T6 aluminium alloy was undertaken by Liu et al. [70]. To study the hysteretic properties of 6061-T6 aluminium alloy after fire, Liu et al. [71] conducted both monotonic tensile tests and cyclic loading tests, considering different fire exposure times and cooling methods, to obtain the residual mechanical properties. A further study was performed by Chen et al. [72] to investigate the influence of multiple fire exposures on the post-fire mechanical properties of 6061-T6 and 7075-T73 aluminium alloys. The research investigations into the post-fire behaviour of aluminium alloys are summarised in Table 3.

Table 3 Summary of previous studies on mechanical properties of aluminium alloys after fire.

Reference	Aluminium alloy grade	Heating rate (°C/min)	Temperature range (°C)	Duration (min)	Cooling method
Summers et al. [65]	5083-H116, 6061-T651	5/20/25/250	100-500	-	Water
Rippe et al. [66]	6061-T651	-	-	5, 10, 20	Water
Rippe et al. [67]	6061	-	-	5, 10, 20	Water
Chen et al. [69]	6061-T6, 7075-T73	15	100-550	-	Air, Water
Liu et al. [70]	6082-T6	20	100-550	-	Air, Water
Liu et al. [71]	6061-T6	-	100-500	30, 180	Air, Water
Chen et al. [72]	6061-T6, 7075-T73	15	100-550, 200-500	-	Air, Water

3.4. Discussion on material properties in and after fire

With regards to the material behaviour of aluminium alloys in fire, accurate constitutive models are essential to link the extensive material test results with structural fire analyses at higher levels, i.e. members, connections/joints and structural systems. However, research work into the constitutive modelling of aluminium alloys in fire remains scarce. The only existing material model for aluminium alloys at elevated temperatures was proposed by Figgiano et al. [58], as described in Section 3.2 and shown in Fig. 10. It can be seen that the predictive model, on the basis of the Ramberg-Osgood (R-O) model, fails to accurately predict the full-range stress-strain curves of aluminium alloys in fire. A possible solution is to use the R-O model in a two-stage form. The two-stage R-O model has been shown to provide an accurate description of the stress-strain responses of cold-formed steels at ambient temperature [73], aluminium alloys at ambient temperature [6] and stainless steels at both ambient [74] and elevated temperatures [75-77]. It is therefore anticipated that the model could also be extended to aluminium alloys at elevated temperatures; however, the extension requires further experimental and theoretical investigations. Another key aera regarding the mechanical properties of aluminium alloys in fire is creep and its corresponding theoretical models. Creep behaviour is dependent on the duration of heating, stress and temperature; it can generally be neglected at ambient temperature but is more significant at elevated temperatures for aluminium alloys [46]. As can be seen from Table 2, only a limited number of grades of aluminium alloys have been investigated to clarify their creep behaviour, while the behaviour of other commonly used structural aluminium alloys (e.g. 6061-T6 and 6063-T5) requires exploration, and the applicability of existing creep models [48,59,60,63,64] needs to be verified. It should be noted that the differences in mechanical properties of aluminium alloys obtained from steady-state tests and transient-state tests [63] are primarily associated with the high-temperature creep. However, further research is needed to investigate the interplay between the different mechanical properties obtained from the two test approaches and the influence of creep [47,63]. The research gaps indicated above highlight the need to carry out additional experimental studies on a wider range of aluminium alloy grades and theoretical investigations to clarify the effects of the key influencing factors (e.g. the duration of heating, stress and temperature) on the creep behaviour of aluminium alloys.

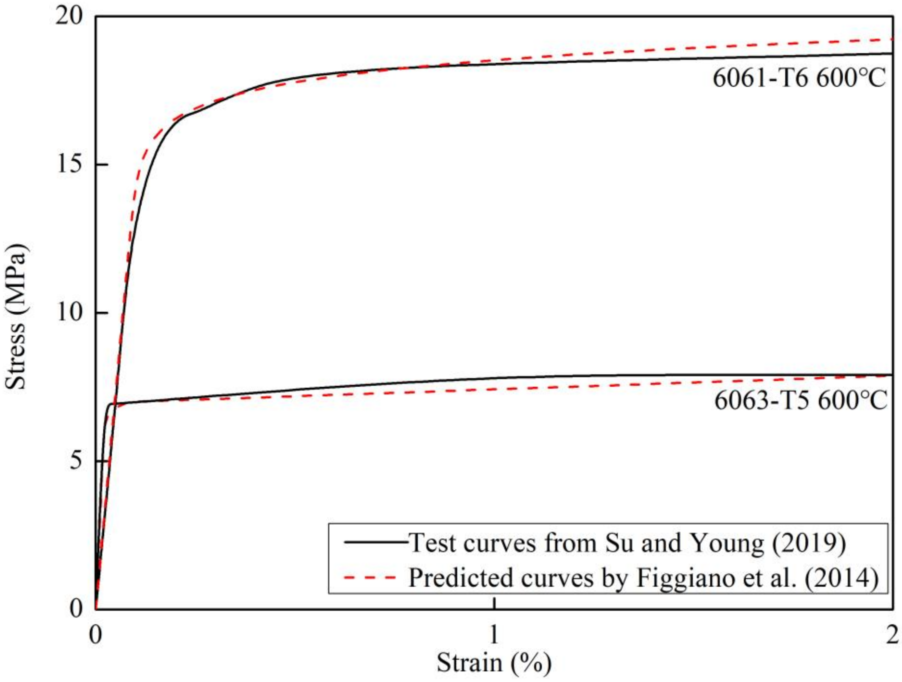


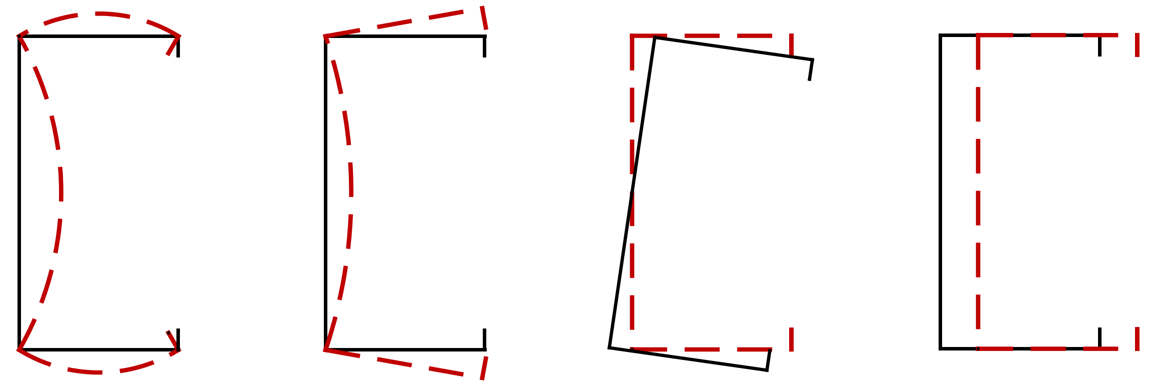
Fig. 10. Comparisons between experimental stress-strain curves and predicted curves by Figgiano et al. [58].

The previous investigations into the post-fire mechanical properties of aluminium alloys provide a basis for the evaluation of the residual load-carrying capacity and repair needs of aluminium alloy structures after fire. As can be summarised from Section 3.3, the post-fire mechanical properties of aluminium alloys are influenced by the maximum exposure temperature, the cooling method, the number of fire exposure events and the heating rate. Although the influence of different heating parameters (e.g. rate, number and maximum temperature) on the post-fire mechanical properties of aluminium alloys has been comprehensively investigated in previous studies, little attention has been paid to the influence of different cooling methods [78] on the residual mechanical properties of aluminium alloys. It has been found in [72] that the residual strength of aluminium alloys does not always decrease with an increase in exposed temperature and that the decreasing trend reverses at around 400 °C; this contradicts with conventional conceptions and requires future investigations. A more comprehensive understanding may be obtained through observation of the microstructure of post-fire materials after exposure to different temperatures. The post-fire cyclic behaviour of aluminium alloys has also been studied [70,71], but post-earthquake fire (PEF) is a more likely scenario [79]; hence consideration should be given to this in future research. Finally, it can be seen from Table 3 that the majority of studies have been focused on the post-fire material behaviour of normal strength aluminium alloys (i.e. 6000 and 5000 series), while research studies on high strength aluminium alloys (i.e. 7000 series) are rather limited, thus requiring further investigations.

4. Structural members in fire

4.1. Columns

Columns are generally considered to be the most important components that influence the overall structural performance of buildings in fire conditions [80]. Buckling is the dominant failure mode of aluminium alloy columns in fire, which may lead to the collapse of the whole structural system [81]. The degraded mechanical properties of aluminium alloys as well as the increased creep deformations and internal forces resulting from thermal expansion accelerate column buckling at elevated temperatures. The three basic modes are: local, distortional and Euler (i.e. global) buckling [82], as shown in Fig. 11. To manage the high structural safety risk associated with column buckling at elevated temperatures, recent decades have seen a number of research studies into the structural behaviour of aluminium alloy columns exposed to fire, in which the influence of aluminium alloy, cross-section shape and fire conditions have been investigated. These studies are summarised in Table 4 and discussed further in this section.



(a) Local (b) Distortional (c) Global (torsional) (d) Global (flexural)

Fig. 11. Different buckling modes of an aluminium lipped channel section column in fire.

4.1.1. Local buckling

The conventional concept of cross-section classification is adopted in current design specifications, e.g. EN 1999-1-2 [37] and AA 2015 [33], for the treatment of local buckling in aluminium alloy structural elements in fire. The design rules set out in these specifications for aluminium alloy sections in fire essentially mirror those at ambient temperature, reflecting a scarcity of studies on the local buckling behaviour of aluminium alloy structural elements at elevated temperatures. Responding to this knowledge gap, Maljaars et al. [83] carried out an experimental investigation into the local buckling of aluminium alloy sections in compression at elevated temperatures. Steady-state and transient-state fire tests on a total of 55 slender square hollow section (SHS) and angle section stub columns made of two different aluminium alloys (5083-H111 and 6060-T66) were reported [83]. Following the experimental programme, Maljaars et al. [84] conducted further numerical analysis, from which the key parameters that influence the local buckling behaviour of aluminium alloy sections in fire, such as the width-to-thickness ratio and boundary conditions of the plates and the elevated temperature reached, were investigated. It was found that the Class 3 slenderness limits for both outstand and the internal aluminium alloy plates in compression at elevated temperatures, as set out in EN 1999-

1-2 [37], were generally safe but conservative; improved slenderness limits were thus proposed [84]. Maljaars et al. [85] also proposed a new design model that takes into account the nonlinear stress-strain characteristics of aluminium alloys at elevated temperatures. The proposed method was shown to yield more accurate local buckling resistance predictions for fire exposed aluminium alloy columns [85]. Suzuki et al. [86] carried out a series of transient-state tests on both unprotected and protected aluminium alloy columns and proposed formulae to determine the critical temperature at which local and global buckling occurred. Fogle et al. [87] performed an experimental study to investigate the effects of varying geometries (i.e. plate thickness, width and height), fire exposure conditions and load levels on the local buckling behaviour of compressed plate elements made of 5083-H116 and 6082-T651 aluminium alloys and found that the use of the critical temperature as the only criterion is not sufficient for evaluating the performance of aluminium alloy structural elements in fire. An empirical model for predicting the resistances of fire exposed aluminium alloy plates, which explicitly accounts for all the influencing parameters, was also proposed. Kandare et al. [64] presented a creep-based modelling approach utilising the constitutive model proposed by Maljaars et al. [63] to predict the deformation and creep-induced buckling failure of compression-loaded aluminium alloy plates exposed to fire. Feih et al. [88] also developed an FE modelling approach capable of predicting critical fire exposure times considering elastic, plastic and creep softening effects. Liu et al. [89] numerically investigated the interaction between local and distortional buckling in irregular-shaped aluminium alloy columns in fire and concluded that the Direct Strength Method (DSM) is able to provide more accurate buckling resistance predictions for such columns compared to the existing codified design rules in EN 1999-1-2 [37].

4.1.2. Global buckling

The global buckling response of aluminium alloy columns at elevated temperatures has been investigated in a number of studies over the past few decades. Jiang et al. [90] conducted steady-state experiments on 6061-T6 aluminium alloy rectangular hollow section (RHS) columns; the obtained test results were used to examine the accuracy of the existing codified design methods [32,35], indicating that the current EN 1999-1-2 [37] leads to rather conservative buckling resistance predictions for 6061-T6 aluminium alloy columns at elevated temperatures, especially when the temperature is higher than 300 °C. Guo et al. [91] performed a numerical investigation into the behaviour and design of 6061-T6 aluminium alloy columns of different cross-section shapes at elevated temperatures, and proposed a modified formula, based on the Perry-Robertson concept [92] and thus compatible with the existing design rules in EN 1999-1-2 [37], to estimate the buckling reduction factor χ:

$$\chi = \frac{1}{2\bar{\lambda}^2}\left[\left(\bar{\lambda}^2 + \eta(\theta) + 1\right) - \sqrt{\left(\bar{\lambda}^2 + \eta(\theta) + 1\right)^2 - 4\bar{\lambda}^2}\right] \tag{4}$$

where $\bar{\lambda}$ is the relative slenderness at room temperature and $\eta(\theta)$ is the imperfection coefficient that depends upon temperature, as given by:

$$\eta(\theta) = \alpha(\theta)\left[\bar{\lambda} - \bar{\lambda}_0(\theta)\right] \tag{5}$$

in which $\alpha(\theta)$ and $\bar{\lambda}_0(\theta)$ are the temperature-dependent imperfection factor and limiting slenderness, respectively. Building on this study, Jiang et al. [93] and Ma et al. [94] conducted further systematic experimental and numerical investigations, and extended the design proposals of Guo et al. [91] to cover different aluminium alloys and tempers, as detailed in Table 4. More recently, Zhu et al. [95] numerically investigated the buckling performance of 6061-T6 and 6063-T5 aluminium alloy open section (i.e. lipped channel section and plain channel section) columns and concluded that the current codified methods for aluminium alloy columns at ambient temperature, as set out in EN 1999-1-1 [32], AA 2015 [33] and AS/NZS 1664.1 [34], are also applicable to the design of columns in fire provided that suitable elevated temperature material properties are employed. However, EN 1999-1-1 [32] was reported to yield unconservative buckling resistance predictions for 5083-O/H111 and 6060-T66 aluminium alloy columns in fire [96]; thus, a new design model, which takes account of the particular stress-strain characteristics of aluminium alloys at elevated temperatures, was proposed and shown to provide accurate buckling resistance predictions [96]. It should be noted that the design model proposed by Maljaars et al. [96] requires knowledge of the transient-state stress-strain response of the considered aluminium alloy; the scope is therefore limited by data availability. Liu et al. [97,98] conducted an extensive numerical investigation into the behaviour of irregular-shaped thin-walled aluminium alloy columns at elevated temperatures and proposed modifications to EN 1999-1-2 [37], improving the accuracy thereof.

Table 4 Summary of previous studies on aluminium alloy columns in fire.

Reference	Aluminium alloy grade	Methodology	Cross-sectional shape	Failure mode
Maljaars et al. [83]	6060-T66, 5083-H111	Steady-state tests (20-400 °C)/ Transient-state tests	SHS, L-	Local buckling
Maljaars et al. [84]	6060-T66, 5083-H111	FE	SHS, L-	Local buckling
Maljaars et al. [85]	-	Analytical	-	Local buckling
Suzuki et al. [86]	5083-H112, 5083-O	Transient-state tests (ISO-834)/ Analytical	SHS, I-	Local buckling Global buckling
Liu et al. [89]	6082-T6	FE	Irregular	Local-distortional buckling
Jiang et al. [90]	6061-T6	Steady-state tests (20-450 °C)	RHS	Global buckling
Guo et al. [91]	6061-T6	FE	RHS, CHS, L-, C-, I-, T-, Z-	Global buckling
Jiang et al. [93]	6061-T6, 6063-T6, 6061-T4, 6063-T5	Steady-state tests (20-400 °C)/ FE	RHS, CHS, L-,C-, I-, T-, Z-	Global buckling
Ma et al. [94]	6082-T6	Steady-state tests (20-400 °C)/ FE	RHS, CHS, I-	Global buckling

Reference	Aluminium alloy grade	Methodology	Cross-sectional shape	Failure mode
Zhu et al. [95]	6061-T6, 6063-T5	FE	SHS, L-, C-	Local buckling, Global buckling, Local-global buckling interaction
Maljaars et al. [96]	6060-T66, 5083-H111, 5083-O	FE/ Analytical	SHS, I-	Global buckling
Liu et al. [97,98]	6060-T66, 6063-T5, 6061-T6	FE	Irregular	Local buckling, Global buckling, Local-global buckling interaction

4.2. Beams

To date, investigations into the structural performance of aluminium alloy beams at elevated temperatures have been rather scarce, and the current design provisions for these members in fire largely follow the design rules at ambient temperature, with the primary difference being in the adopted material properties. Huang and Jiang [99] studied the lateral-torsional stability of I-section and channel section beams made of 6061-T6 aluminium alloy at elevated temperatures numerically and suggested a revised lateral-torsional buckling curve; the revised curve adopted the general form of the Perry-Robertson formulation [92] as given in Eqs. (4) and (5), and was calibrated against the generated numerical results. Suzuki et al. [86] conducted a series of non-loaded uniform heating tests on 5083-H112 aluminium alloy H-section beams to ascertain the temperature rise in these members; following this, the members were loaded and analytical expressions to predict critical temperatures (i.e. the temperature at which the member or structure fails to sustain the applied load) were proposed. Wang et al. [100] investigated numerically the influence of a series of key parameters, including boundary conditions, load level and load distribution, on the critical temperatures of 6061-T6 aluminium alloy I-section beams, while more recently, Zheng and Zhang [101] developed FE models to investigate the lateral-torsional buckling behaviour of unprotected and protected 5083-H112 and 6060-T66 aluminium alloy I-section beams exposed to fire on three sides; practical design equations for estimating their critical temperatures, taking into account the influence of the load level, the beam span as well as the thickness and thermal conductivity of the protective fireboard, were proposed [101].

A number of studies have been carried out aiming to improve the accuracy of the existing design approaches for aluminium alloy beams in fire. van der Meulen et al. [102] highlighted the conservatism of adopting the room temperature classification of cross-sections (EN 1999-1-1 [32]) for the design of aluminium alloy beams at elevated temperatures (EN 1999-1-2 [37]), and proposed modified classification limits which account for the variation of stiffness and strength of aluminium alloys at elevated temperatures. van der Meulen et al. [103] also carried out both steady- and transient-state tests on 6060-T66 aluminium alloy SHS beams under three point bending; the experimental results were subsequently used to validate FE models and to underpin the development of new design rules that adopted the general format of those set out in EN 1999-1-2 [37], for the local buckling of aluminium alloy beams in fire conditions [104]. It was shown that the proposed design rules [104] provided safe-sided resistance predictions that were more accurate than those obtained using the existing EN 1999-1-2 design rules [37]. In addition, Su et al. [105] carried out FE analyses to investigate the structural fire behaviour of 6061-T6 and 6063-T5 aluminium alloy beams, and extended the Continuous Strength Method (CSM) [106] to the design of aluminium alloy beams at elevated temperatures. The proposed CSM was shown to offer improved accuracy relative to the existing design rules set out in EN 1999-1-1 [32], AA 2015 [33] and AS/NZS 1664.1 [34]. The above mentioned studies on aluminium alloy beams at elevated temperatures are summarised in Table 5.

Table 5 Summary of previous studies on aluminium alloy beams in fire.

Reference	Aluminium alloy grade	Methodology	Cross-sectional shape	Failure mode
Suzuki et al. [86]	5083-H112, 5083-O	Transient-state tests (ISO-834)/ Non-loaded heating tests	I-	Local buckling
Huang and Jiang [99]	6061-T6	FE/Analytical	I-, C-	Lateral-torsional buckling
Wang [100]	6061-T6	FE/Analytical	I-	Local buckling
Zheng and Zhang [101]	6060-T66, 5083-H112	FE	I-	Lateral-torsional buckling
van der Meulen et al. [102]	-	Analytical	-	Local buckling
van der Meulen et al. [103], van der Meulen [104]	6060-T66	Steady-state tests (20-300 °C)/ Transient-state tests (2.5/10 °C/min)/ FE	SHS	Local buckling
Su et al. [105]	6061-T6, 6063-T5	FE	SHS	Local buckling

4.3. Beam-columns

A limited number of studies have been conducted into the structural fire behaviour of aluminium alloy beam-columns; these are summarised in Table 6 and reviewed in this subsection. Specifically, Guo et al. [107] and Zhu et al. [108] performed experimental and numerical studies on eccentrically loaded H-section members made of 6063-T5 or 6061-T6 aluminium alloy at elevated temperatures to investigate their flexural-torsional stability. The study highlighted the conservative nature of the design method set out in EN 1999-1-2 [37] and proposed a new linear interaction curve for the flexural-torsional buckling design of aluminium alloy beam-columns at elevated temperatures. Hou [109] extended the investigation to 6082-T6 aluminium alloy H-section beam-columns at elevated temperatures, confirming the applicability and accuracy of the design proposal of Guo et al. [107] and Zhu et al. [108].

Table 6 Summary of previous studies on aluminium alloy beam-columns in fire.

Reference	Aluminium alloy grade	Methodology	Cross-sectional shape	Failure mode
Guo et al. [107] and Zhu et al. [108]	6061-T6, 6063-T5	Steady-state tests (20-300 °C)/ FE	I-, T-	Global buckling
Hou [109]	6082-T6	Steady-state tests (20-400 °C)/ FE	I-	Global buckling

4.4. Discussion on structural members in fire

Extensive investigations have been carried out into the buckling behaviour of aluminium alloy members at elevated temperatures through experimental, numerical and analytical methods. Two aspects, however, require additional attention, namely the distortional buckling behaviour of compression members and the buckling behaviour of beam-columns in fire. These should therefore be the subject of future research.

With regards to the investigations into the local and global buckling behaviour of columns and beams, there also exist some shortcomings. For the local buckling behaviour of aluminium alloy columns and beams in fire, the experimental data are still very limited and most are from the same institute [83,104]. Besides, the existing studies have mainly focused on cross-sections with constituent plates of equal width (i.e. SHS and equal-leg angle section); element interaction [110,111] between adjoined plates under fire conditions has therefore not been extensively studied. On the basis of the above-mentioned limitations, it is recommended that additional experimental investigations on a wider range of cross-section shapes, such as I-sections, RHS and CHS, are conducted. From the perspective of the buckling behaviour of aluminium alloy plate elements in fire, the literature indicates that the cross-section slenderness limits for aluminium alloy plate elements vary with temperatures, primarily owing to the different rates of deterioration of the Young's modulus and the yield strength of aluminium alloys at elevated temperatures; this highlights the need for the development of more accurate classification criteria for aluminium alloy plates, as well as advanced design methods (e.g. the Continuous Strength Method (CSM) [106]) that are capable of providing continuous strength predictions with varying cross-section slenderness. It is also worth noting that the more rounded stress-strain characteristics [85] and the increased creep deformations of aluminium alloys at elevated temperatures [103] have an adverse influence on local buckling behaviour in fire.

For the global buckling behaviour of aluminium alloy members in fire, existing studies have mainly focused on columns, though studies into the torsional and flexural-torsional buckling behaviour of aluminium alloy columns in fire still remain scarce. With regards to the global buckling behaviour of aluminium alloy beams in fire, there are currently no test data available in the literature, highlighting the need for research activity in this aera. Catenary action in beams is widely exploited to enhance fire design efficiency in steel construction; further research into the development of catenary action in aluminium alloy beams in fire [42] is also required.

5. Connections and joints in fire

The performance of connections and joints at elevated temperatures has a significant influence on the response of whole structures in real fires [112,113], the failure of which may result in progressive collapse of the whole structure [114]; investigations into the fire performance of joints and connections have risen after the "9/11" event. According to EN 1999 1-1 [32], a "connection" is defined as a structural component which mechanically fastens a given member to another and should be distinguished from a "joint", which comprises the connection(s) plus the corresponding interaction zone between the connected members. Studies into the behaviour of aluminium alloy connections and joints at elevated temperatures are summarised in Table 7 and reviewed in this section.

5.1. Connections

Previous research on aluminium alloy connections has mainly focused on bolted arrangements, since welded connections are less commonly used in construction due to the poor weldability of the structural aluminium alloys, such as 6061-T6 and 6063-T5. The structural performance and design of aluminium alloy bolted connections at elevated temperatures have been investigated by a number of researchers during the past decade. Guo et al. [115] performed numerical analyses on aluminium alloy double-shear connections with a single stainless steel bolt at elevated temperatures, and observed that some connections that failed by bolt shear fracture at room temperature may fail by plate bearing at elevated temperatures due to the higher rate of strength and stiffness deterioration of aluminium alloys compared to that of stainless steels. It was also found that the design equations specified in EN 1999-1-2 [37] provide conservative resistance predictions for aluminium alloy shear connections. Subsequently, Guo et al. [116] extended their investigations to aluminium alloy double-shear connections with two stainless steel bolts (arranged in the loading direction) at elevated temperatures and proposed empirical equations for predicting bearing resistance. Liu et al. [117] carried out thorough experimental and numerical investigations into the elevated temperature mechanical performance of aluminium alloy single-shear connections with single or multiple stainless steel bolts, examining the key influencing parameters, including the geometries of the aluminium alloy plates and the arrangement, pretension and diameter of the bolts. Maljaars and De Matteis [118] performed tests and numerical simulations on 6060-T66 aluminium alloy T-stubs connected by galvanised steel bolts at elevated temperatures, and proposed theoretical models based on yield line mechanisms [119] for determining the critical temperature.

With regard to the structural fire behaviour of welded connections, Maljaars and Soetens [120] conducted steady- and transient-state uniaxial tensile tests on welded (fillet welded and butt welded) and unwelded 5083-H111, 6061-T66 and 6082-T6 aluminium alloy coupons at elevated temperatures. It was observed that the differences between the strengths of the heat affected zone (HAZ) and the parent metal are largely alleviated at elevated temperatures.

5.2. Joints

Aluminium alloy gusset (AAG) joints, an example of which is shown in Fig. 12, have been gaining increasing use in reticulated shell structures. Following an experimental investigation into the load-bearing response of AAG joints at ambient temperature [121], Guo et al. [122] performed numerical analyses to investigate their structural performance at elevated temperatures, verifying that the failure modes in fire were similar to those observed at ambient temperature. Zhu et al. [123] and Guo et al. [124] subsequently conducted steady-state tests on 6063-T5 and 6061-T6 AAG joints at varying elevated temperatures and developed numerical models with the objective of investigating their out-of-plane flexural behaviour in fire. Guo et al. [124] also proposed theoretical formulae for determining the stiffness and strength of AAG joints at elevated temperatures. The behaviour and resistance of aluminium alloy bolt-sphere joints in fire have been studied by Liu et al. [125], where experiments and calibrated design formulae were presented.

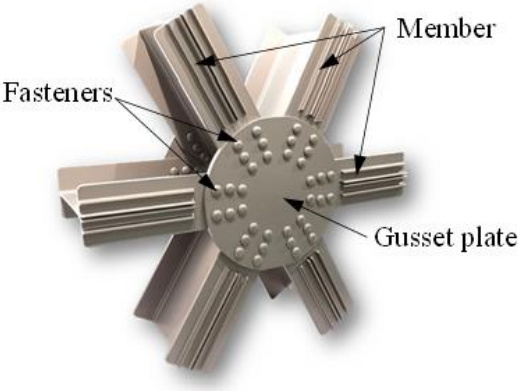


Fig. 12. Aluminium alloy gusset (AAG) joint [121].

Table 7 Summary of previous studies on aluminium alloy connections and joints in fire.

Reference	Connection or joint type	Aluminium alloy grade	Methodology	Bolt grade/ weld type
Guo et al. [115]	Bolted	6061-T6	FE	Stainless steel A2-70
Guo et al. [116]	Bolted	6061-T6	Steady-state tests (20-300 °C)/ FE	Stainless steel A2-70
Liu et al. [117]	Bolted	6061-T6	Steady-state tests (10-400 °C)/ FE	Stainless steel 304HC
Maljaars and De Matteis [118]	Bolted	6060-T66	Steady-state tests (20-290 °C)/ Transient-state tests/ FE/ Analytical	Grade 8.8
Maljaars and Soetens [120]	Welded	5083-H111, 6060-T66, 6082-T6	Steady-state tests (20-300 °C)/ Transient-state tests	Fillet, butt welded
Guo et al. [122]	AAG	6061-T6	FE	Stainless steel A2-70
Guo et al. [123,124]	AAG	6061-T6, 6063-T5	Steady-state tests (20-300 °C)/ FE	Stainless steel A2-70
Liu et al. [125]	Bolt-sphere	-	Steady-state tests (20-500 °C)/ Analytical	Stainless steel

5.3. Discussion on connections and joints in fire

Compared with studies on members, investigations into the structural fire behaviour of aluminium alloy connections and joints are rather limited. Aluminium alloy connections are commonly composed of at least two different materials (e.g. aluminium alloy plates and stainless steel bolts, or aluminium alloy plates and welding material), which normally exhibit different mechanical properties at high temperatures; this may lead to different failure modes in aluminium alloy connections. Further investigations should be performed into the structural behaviour of aluminium alloy connections to underpin more accurate design methods for such connections at elevated temperatures. Compared to room temperature conditions, welded aluminium alloy connections exhibit more comparable structural performance to their bolted counterparts at elevated temperatures [120], but the design of welded aluminium alloy connections at elevated temperatures remains relatively unexplored and requires further investigation in this field.

Existing investigations on aluminium alloy joints in fire have mainly focused on AAG joints, while other commonly used joint types, such as hub joints, cast aluminium alloy joints and beam-to-column joints, have yet to be studied. Furthermore, all studies to date [122-125] have been focused on the joint resistance and stiffness, while rotation capacity (i.e. ductility) has yet to be systematically examined. Sufficient rotation capacity of aluminium alloy joints can be achieved through the application of certain construction details at ambient temperature [126], but should be quantified and carefully considered at elevated temperatures due to the large deformations of structural elements in fire [114]; this highlights the need for further experimental investigations into the full-range behaviour of aluminium alloy joints in fire. Another issue that has not been addressed in previous studies to date is the varying influence of axial forces in members connected to the joint during the heating or cooling phases in fire; hence, investigations into aluminium alloy joint behaviour in fire under combined bending moments and axial forces are suggested in the future research. Finally, it can be concluded from

Section 5.2 that studies to date on the fire behaviour of beam-to-column joints have been rather limited; thus, further experimental and numerical investigations are needed to facilitate the development of more rational and reliable design rules for aluminium alloy beam-to-column joints in fire.

6. Structural systems in fire

As summarised in the previous sections, extensive studies have been conducted on the structural behaviour of individual aluminium alloy components (i.e. beams, columns, beam-columns, connections and joints) in fire. These studies, however, fail to account for the changing distributions of forces and moments in a real structure exposed to fire [127]. Modern structural design approaches, such as performance-based design [128] and design by advanced analysis [129,130], emphasize the need for considering the structure as a whole, leading to more efficient and safer designs. The development of such system-based approaches for aluminium alloy structures in fire requires investigations of their fire performance at the structural system level. Responding to this need, a number of studies have been carried out aiming at understanding the real fire behaviour of aluminium alloy structures, as summarised in Table 8.

Maljaars and Soetens [127] carried out an experimental study comprising three transient-state tests on aluminium alloy sub-frames. For each of the tested sub-frames, a 6060-T66 extruded SHS was used for the beams while a 6060-T66 extruded I-section was used for the column; end plates made of 5083-O/H111 aluminium alloy were employed for the joints between the column and the beams. The experimental investigation was followed by a numerical simulation study, where FE models were created and validated against the test results, showing good agreement. The results showed that the effects of member interaction and thermal expansion on the fire resistance of aluminium alloy systems were non-negligible. A fire engineering approach that considers the structure as a whole and takes the true fire conditions into account, was therefore recommended for the design of aluminium alloy structures in fire. Faggiano et al. [58] numerically studied the influence of using different constitutive models on the structural behaviour of aluminium alloy structures in fire and concluded that the strain hardening characteristics of aluminium alloys at elevated temperatures can have a strong effect on the global response. Arangio et al. [131] performed numerical analyses of a 6082-T6 aluminium alloy truss under standard ISO-834 fire conditions; the truss underwent substantial deformations due to the rapid degradation of the mechanical properties in fire, highlighting that special attention should be paid to the fire safety of aluminium alloy structures. In view of the fact that aluminium alloys are increasingly being used in spatial structures, Guo et al. [132] and Zhu et al. [133] carried out non-destructive and destructive fire tests on single-layer 6063-T5 aluminium alloy reticulated shells with gusset plate joints, respectively, to study their fire behaviour. The former study investigated the influence of different fire locations (at the centre or corner of the shell), fire intensity and ventilation conditions (windows open or closed) on the global fire response of the structures; the test results showed that the temperature field in aluminium alloy reticulated shells in fire was non-uniform and two analytical approaches were developed to predict the non-uniformity. Following this study, destructive tests were conducted by Zhu et al. [133] to further explore the structural fire performance of reticulated shells in the non-uniform temperature fields. Zhu et al. [133] found that the non-uniform temperature field can have a significant effect on the internal member forces within spherical shells, due to the high thermal expansion of aluminium alloys at elevated temperatures. More recently, Yin et al. [134] conducted both experimental and numerical analyses of a full-scale cylindrical aluminium alloy reticulated roof structure under localised fire and proposed a predictive model to estimate the near-roof temperature field. It is worth noting that despite the above investigations, studies into the fire behaviour of aluminium alloy structures remain scarce; further research is therefore needed in this area. It is recommended that future research considers further the interaction among different aluminium alloy structural elements, the influence of the non-uniform temperature fields on the structural fire performance and the development of performance-based design methods.

Table 8 Summary of previous studies on aluminium alloy structures in fire.

Reference	Structural type	Aluminium alloy grade	Methodology
Faggiano et al. [58]	Frame	3003-O/3003-H114/5052-O/5052-H34/5083-O/5086-O/5454-O/5454-H32/6061-T6/6063-T6/7075-T6	FE
Maljaars and Soetens [127]	Frame	6060-T66/5083-O/5083-H111	Transient-state tests/ FE
Arangio et al. [131]	Truss	6082-T6	FE
Guo et al. [132]	Reticulated shell	6063-T5	Steady-state tests/ FE
Zhu et al. [133]	Reticulated shell	6063-T5	Steady-state tests/ FE
Yin et al. [134]	Reticulated shell	6061-T6	Transient-state tests/ computational fluid dynamics simulation

7. Fire protection

Aluminium alloys are generally less resistant to elevated temperatures compared to other structural materials, such as carbon steels, stainless steels and reinforced concrete; thus, greater attention should be paid to the fire protection of aluminium alloy components and structures.

This section reviews different fire protection approaches that may be applied to aluminium alloy structures to enhance their fire resistance; these approaches can be categorised into two groups: passive fire protection (PFP) and active fire protection (AFP).

7.1. Passive fire protection (PFP)

The application of passive fire protection aims to reduce the temperature development and hence loss of mechanical properties in structural elements during fires. PFP approaches that can be applied to aluminium alloy structures include coatings, thermal insulation boards and flexible blanket systems [135].

7.1.1. Coatings

Intumescent coatings are often used for the fire protection of steel structures and are also suitable for aluminium alloy structures. Intumescent coatings are easy to apply to any surfaces and have negligible influence on the properties of the substrate. When exposed to fire, the intumescent coatings swell and foam into a highly porous, thick and thermally stable char layer with very low thermal conductivity (acting as a thermal barrier to insulate the substrate) through an endothermic decomposition reaction [136]. Spray-applied fire-resistive materials (SFRM), such as inorganic fibre and cementitious materials, possess the merits of easy execution and low cost and have been widely used in steel structures; these materials are also deemed appropriate for the fire protection of aluminium alloy structures. However, it should be noted that the following issues must be taken into consideration when using coatings to achieve effective fire protection for aluminium alloys: (1) the time required for intumescent coatings to form an insulation layer should be short for aluminium alloy structures due to the rapid deterioration of the mechanical properties, and (2) some cement-based coating materials, which are acidic, may damage the passivation layer and reduce the corrosion resistance of aluminium alloys [36]. In addition, the cohesivity of insulation materials with aluminium alloy structures should be ensured in practical applications, as specified in Chinese standard T/CECS 756-2020 [137]. When using SFRM as protective coatings, galvanized steel wire mesh (GSWM) [137] is suggested to be set between the coatings and the aluminium alloy to improve the adhesion strength. EN 1999-1-2 [41] specifies that the cohesivity properties of the protection materials should be verified by tests, the procedure of which can be found in ENV 13381-4 [138]. There is still a research gap regarding the fire performance of aluminium alloy structures insulated with coatings; thus, further evaluations on topics such as the required coating thickness and the time to form an insulation layer are essential for applying coatings as fireproof materials to aluminium alloy structures.

7.1.2. Thermal insulation boards

The use of thermal insulation boards, which are rigid and suitable for members or structures with simple shapes [139], is considered to be an effective way of increasing the fire resistance of metal structures. There are a variety of materials that are suitable for use as thermal insulation boards, such as mineral wool, ceramic fibres, calcium silicate, vermiculite and gypsum [36]. According to the recent studies on the functionally graded materials (FGMs) [140,141], FGM boards may also be applied as thermal insulation for aluminium alloy structures owing to the low thermal conductivity provided by the constituent ceramic materials and the high strength provided by the metal components. In [86], thermal insulation boards made of calcium silicate were employed to protect aluminium alloy members (see Fig. 13), showing excellent heat-insulating performance, delaying the development of temperature, as indicated in Fig. 14. Cracking and detachment of the insulation boards that have been observed in previous tests should be avoided in practical applications following requirements mentioned in Section 7.1.1.

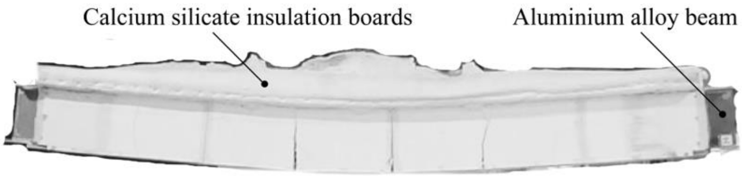


Fig. 13. Aluminium alloy beam insulated using calcium silicate insulation boards [86].

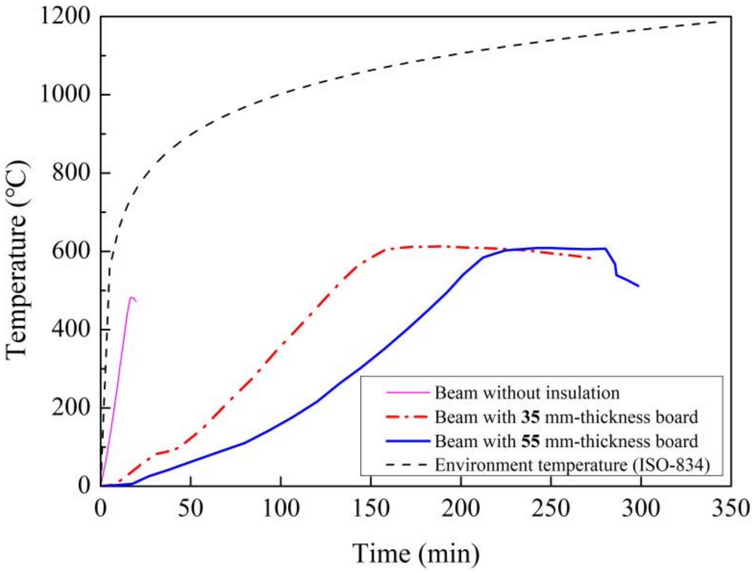


Fig. 14. Comparison of temperature-time curves for aluminium alloy beams with and without calcium silicate insulation boards subjected to elevated temperatures [86].

7.1.3. Flexible blanket system

Flexible blankets made of, e.g., fibreglass, mineral wool, ceramic fibre or aerogel [142], can be designed for metal insulation applications, providing a cost-effective and reliable system to delay the temperature rise in structural elements. The flexible blanket system provides a good option for the thermal insulation of objects with complex shapes, such as joints and structural members with irregular-shaped cross-sections that are commonly seen in extruded aluminium alloy structural elements [142]. Moreover, some promising high performance thermal insulation materials, such as aerogels, possessing lightweight, low thermal conductivity and translucent properties, have shown significant potential for the thermal insulation of aluminium alloy structures [143].

7.2. Active fire protection (AFP)

The purpose of an active fire protection (AFP) system is to detect and alert, extinguish or contain a fire. An integrated AFP system generally includes a fire detection system, a fire suppression system and a smoke management system [144]. Among the three systems, fire suppression systems act on structures directly and is promising for wide application in aluminium alloy structures for the reasons presented in Section 7.3; such systems are therefore discussed in this subsection.

There are several distinct types of fire suppression system, including sprinkler systems (by using e.g. water spray, water mist or foam), gaseous agent systems and chemical agent systems, among which the sprinkler systems, as shown in Fig. 15 for a typical water-based fire sprinkler system, are the most frequently used fire suppression systems for controlling or extinguishing fires in protected areas of buildings. Outinen and Vaari [145] found that sprinkler systems are able to efficiently cool down steel columns in different fire scenarios, and thus are deemed capable of providing reliable fire protection for aluminium alloy structures. However, studies on the application of sprinkler systems in aluminium alloy structures are lacking, and the fire performance of aluminium alloy structural elements in sprinklered buildings is not yet fully understood. Thus, research on the effectiveness of sprinkler systems for the fire protection of aluminium alloy structures is recommended. In addition, further investigations on the layout of the sprinkler system within aluminium alloy structures are needed since the rapid cooling of specific members, especially the columns, may have negative effects on their load-carrying performance [146]. It should also be noted that the time required for sprinkler systems to be activated is crucial to aluminium alloy structures due to the rapid deterioration of the mechanical properties of aluminium alloys in fire; this highlights the needs for suitably sensitive fire detection systems.

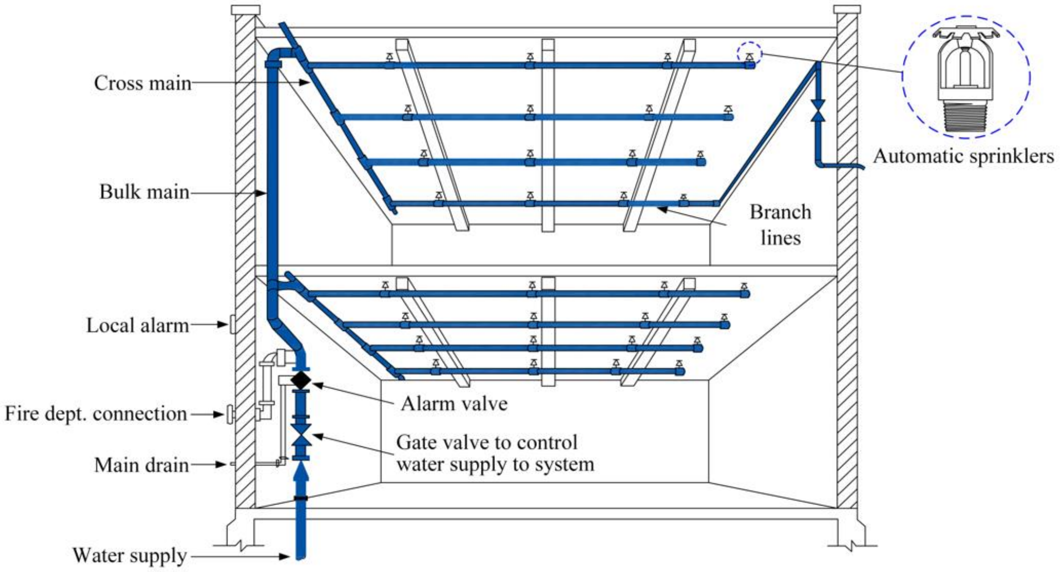


Fig. 15. Fire sprinkler systems [147].

7.3. Comparison between PFP and AFP measures

Engineers should strike the right balance between passive and active fire protection measures when designing an effective fire protection system [148]. With regards to aluminium alloy structures, the use of traditional coatings (PFP approach) may have a negative influence on their aesthetic appearance and recyclability, while the emergence of aerogels, as discussed in the previous subsection, provides possible alternative solutions. Compared with PFP, AFP is more efficient in keeping the aluminium alloy members at relatively low temperatures and the action that results from AFP will help contain, suppress or extinguish a fire before it causes harm. To date, a very limited number of studies [149,150] have focused on the fire behaviour of aluminium alloy structures protected by PFP and/or AFP measures; this is an area that would benefit from further research.

8. Outlook

The use of aluminium alloys has become increasingly widespread in structural engineering, but their elevated temperature performance may act as a barrier to their wider application. Building on the existing studies on the structural fire performance of aluminium alloys, an outlook for future research and methods for improving the fire resistance of aluminium alloy structures is presented in this section.

8.1. Aluminium alloy-based hybrid structures

The hybrid use of aluminium alloys with other structural materials has the potential to achieve enhanced fire performance. For example, aluminium alloy members joined by means of stainless steel connection components, as shown in Fig. 16 [29], have been found to have improved fire-resistance compared to fully aluminium alloy solutions. Moreover, analogous to concrete-filled steel tubular (CFST) cross-sections, innovative timber-filled aluminium alloy tubular (TFAAT) cross-sections, utilising aluminium alloys for the outer tube as shown in Fig. 17, may be used to exploit the favourable properties of the constituent materials by preventing the timber core from combustion and burning and delaying local buckling of the aluminium alloy tube. In addition, the combined use of newly developed FGM boards and aluminium alloy members/structures represents a promising composite structural system [140,141,151], in which the FGM boards provide enhanced load-carrying capacity and fire protection at elevated temperatures. Other forms of aluminium alloy-based hybrid structures merit further exploration, with the aim of improving both the room temperature performance and fire resistance, as well as the overall cost-effectiveness of the system.

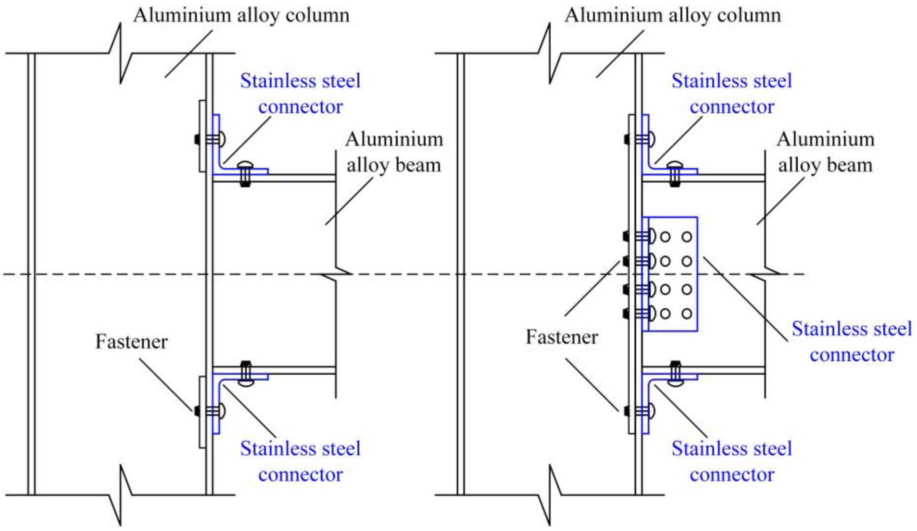
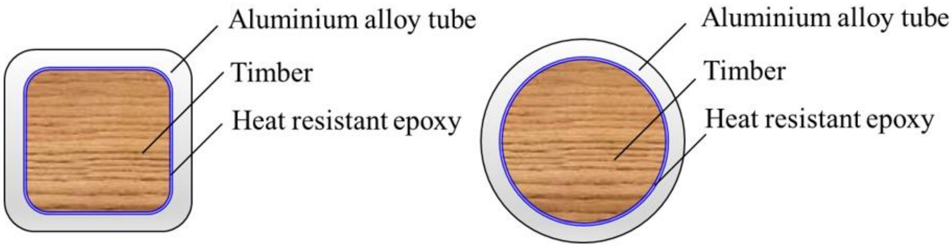


Fig. 16. Beam-to-column joints composed of aluminium alloy members and stainless steel connectors [29].



(a) Square cross-section

(b) Circular cross-section

Fig. 17. Timber-filled aluminium alloy tubular (TFAAT) cross-sections.

8.2. Fire-resistant aluminium alloys

Recently developed fire-resistant aluminium alloys [56,57,152,153] have been shown to have markedly enhanced strength retention properties at elevated temperatures compared to those of conventional structural aluminium alloys. The mechanical properties of the fire-resistant aluminium alloys at elevated temperatures were enhanced through the precipitation of intermetallic compounds and the addition of dispersion or reinforcing particles [153,154] (e.g. Al_2O_3, SiO_2 or ceramics). The control of dendrite arm spacing (DAS), rapid solidification, and thermo-mechanical treatment also have beneficial influences on the high temperature performance of the alloys [152]. However, there exists significant scope for further investigations into the mechanical properties of fire-resistant aluminium alloys at both ambient and elevated temperatures as well as the structural performance and design of members, connections and joints made of such materials, with the aim to promote their wider use in structural applications.

9. Conclusions

Aluminium alloys are being increasingly used in structural applications due to their high strength-to-weight ratio, excellent corrosion resistance, ease of fabrication and maintenance and aesthetic appearance. However, a major concern for aluminium alloy structures is their fire performance. This paper presents a review of reported studies on aluminium alloys at elevated temperatures, including their mechanical properties in and after fire, the fire performance of members, connections, joints and structural systems, as well as different fire protection approaches. At the material level, reduction factors and constitutive models that account for the influence of creep in aluminium alloys at high temperatures have been summarised. Considering that the material properties of aluminium alloys degrade significantly at elevated temperatures, special attention should be given to the design of aluminium alloy structures at the member, joint and structural levels, as well as to the fire protection of aluminium alloy structural systems. At the structural member and connection/joint levels, differences in behaviour and failure mechanisms at ambient and elevated temperatures have been highlighted. Although joints clearly play a crucial role in maintaining the integrity of a structure in fire, rather few studies have been conducted to date and further research is needed on this topic. At the system level, studies have shown that the non-uniform temperature fields that can arise within a structure exposed to a fire can have a significant impact on the distribution of internal member forces owing to the high coefficient of thermal expansion of aluminium alloys. Various fire protection approaches that are suitable or have potential for use in aluminium alloy structures have also been described. Overall, while there has been substantial progress in understanding and improving the performance of aluminium alloy structures in fire, there remains scope for further research and development in this crucial area to promote the wider application of aluminium alloys in the construction industry.

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