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Research progress on fire resistance of concrete-filled aluminum alloy tube columns

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Abstract: As a new type of composite member, concrete-filled aluminum alloy tubular (CFAT) columns combine the dual advantages of low self-weight and excellent corrosion resistance of aluminum alloy with the outstanding compressive performance of concrete, showing broad application prospects in modern building structures. Fire is one of the major hazards faced by building structures. Due to the low melting point of aluminum alloy and the deterioration of concrete properties at elevated temperatures, the fire resistance of such members has become a critical issue that urgently needs to be addressed in engineering applications. This paper systematically reviews the research progress on the fire resistance of CFAT columns at home and abroad. It summarizes the existing research achievements from three dimensions: the mechanical performance of CFAT columns at ambient temperature, the high-temperature properties of aluminum alloy materials, and the fire resistance of aluminum alloy structures. Special emphasis is placed on analyzing the influence of factors such as cross-sectional configuration, material parameters, load ratio, and fire exposure conditions on the fire resistance of the members. The applicability and limitations of existing high-temperature material constitutive models and thermo-mechanical coupling analysis methods are discussed, and the current problems in the research are summarized. Finally, combined with the requirements of engineering applications, future research directions on the fire resistance of CFAT columns are prospected, aiming to provide references for the fire-resistant design and engineering application of such members.

1. Introduction

It is well known that concrete-filled steel tube (CFST) structures possess a series of superior mechanical and constructional advantages, such as high load-carrying capacity, excellent ductility and toughness, convenient construction, good fire resistance, and favorable economic efficiency. Consequently, CFST structures have been widely adopted in building engineering, and numerous scholars have conducted in-depth research on their performance. However, traditional CFST structures suffer from poor corrosion resistance, which limits their application under various extreme environmental conditions, as shown in Fig. 1. Moreover, these structures incur high maintenance costs, and steel tube corrosion may lead to economic losses and even potential safety hazards. Simple anti-corrosion treatments are insufficient to meet the long-term service requirements of CFST structures [1-4].

Fig. 1 Steel corrosion cases

In view of the above shortcomings, CFAT structures have emerged as a promising alternative, the typical cross-sectional forms of CFAT columns are shown in Fig. 2. Compared with steel, aluminum alloy offers distinct advantages, including excellent corrosion resistance, low density, recyclability, and aesthetic appeal. The use of aluminum alloy can reduce steel consumption and lower long-term maintenance budgets, making aluminum alloy structures more cost-effective over their entire life cycle and better aligned with the concept of sustainable development. Furthermore, while replacing steel with aluminum alloy, CFAT structures retain the high load-carrying capacity and superior resistance to local buckling and instability characteristic of CFST structures. A CFAT structure refers to a composite form in which concrete is filled within an aluminum alloy tube, with both components acting together to resist external loads. The fundamental working principle of CFAT structures lies in the synergistic interaction between the aluminum alloy tube and the core concrete under loading: the aluminum alloy tube gradually provides confinement to the core concrete, placing it in a multi-axial stress state, thereby enhancing its compressive strength and improving ductility. Meanwhile, the concrete core provides internal support to the aluminum alloy tube, delaying or preventing local buckling of the tube under compression and enabling the full utilization of the aluminum alloy's strength. Compared with ordinary steel, aluminum alloy also exhibits several inherent drawbacks: its thermal expansion coefficient is approximately twice that of concrete; its elastic modulus, although close to that of concrete, is only one-third of that of ordinary steel; it lacks a distinct yield plateau; the surface oxide layer may weaken interfacial bonding with concrete; and its fire resistance is poor, with a melting point of only about 650 ℃. These factors result in significantly different mechanical behavior of CFAT structures under extreme loads such as fire, compared with traditional CFST structures [5, 6].

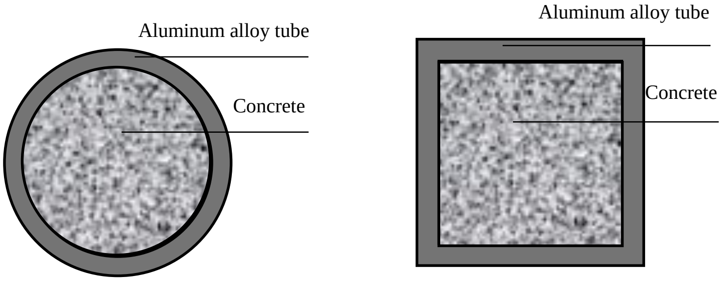

Fig. 2 Typical cross-sections of concrete-filled aluminum alloy tubes

In recent years, bridge fire accidents have occurred frequently, as shown in Fig. 3. High temperatures generated by fires can severely degrade the mechanical properties of aluminum alloy, leading to damage or failure of CFAT bridges under fire conditions. Therefore, to ensure the safe application of CFAT structures in bridge engineering, it is necessary to investigate their fire resistance and improve their fire safety performance. Currently, research on the mechanical behavior of CFAT columns at elevated temperatures remains scarce. Existing related studies are mainly focused on three aspects: the mechanical performance of CFAT columns at ambient temperature, the high-temperature properties of aluminum alloy materials, and the fire resistance of aluminum alloy structures.

Fig. 3 Aluminum alloy materials for engineering applications

2. Mechanical performance of CFAT columns at ambient temperature

Scholars have carried out systematic experimental and numerical simulation studies on the mechanical performance of CFAT columns at ambient temperature, covering basic mechanical behaviors such as compression and bending.

Zhou et al. [7, 8] conducted axial compression tests on short concrete-filled 6061-T6 aluminum alloy tubular columns, and found that the design methods in current American, Australian/New Zealand codes are difficult to accurately match their mechanical characteristics. Jiang et al. [9] also used 6061-T6 as the outer tube, and pointed out that the confining effect of circular sections is superior to that of square sections. Nasser et al. [10] discussed the influences of cross-sectional diameter, diameter-to-thickness ratio and slenderness ratio on the ultimate bearing capacity of circular specimens. Some scholars [11-14] adopted different concrete types such as coral concrete and marine concrete, enriching the test database. Rong et al. [15] carried out tests and finite element analyses on concrete-filled high-strength 7A04-T6 aluminum alloy tubular columns, and modified the design formula, reducing the calculation error by about 10%. Mi et al. [16] studied eccentrically loaded long columns, and found that the eccentricity ratio significantly affects the compression failure characteristics of concrete. In addition, Chen et al. [17-18] systematically carried out flexural performance tests, and proposed design formulas for the in-plane flexural ultimate strength of concrete-filled aluminum alloy tubular members.

In summary, a relatively complete theoretical system has been formed for the mechanical performance and design methods of CFAT compression and flexural members at ambient temperature. However, the solid-section members have large self-weight, making it difficult to meet the special engineering requirements such as large-span and lightweight design. The double-skin concrete-filled aluminum alloy tubular members have gradually become a new research direction due to their light self-weight and excellent mechanical performance.

Zhou et al. [19-20] carried out tests and numerical analyses on two types of double-skin members (outer circular with inner circular, and outer circular with inner square), and proposed ultimate strength design equations. Yan et al. [21] proposed a new confinement coefficient for circular-section double-skin short columns, simplifying the design calculation.

3. High-temperature properties of aluminum alloy materials

As a typical lightweight and high-strength metallic structural material, aluminum alloy has outstanding advantages of low self-weight, high specific strength and excellent corrosion resistance. It possesses remarkable lightweight application value and good engineering adaptability in long-span buildings, large-space public structures and marine engineering under corrosive environments. Different from the mechanical characteristics of traditional structural steel, the stress-strain curve of aluminum alloy does not have an obvious yield plateau, exhibiting significant nonlinear mechanical characteristics throughout the loading process. Therefore, its constitutive model needs to accurately characterize the nonlinear deformation development law. The Ramberg-Osgood model [22] can effectively fit the full-range nonlinear stress-strain response of aluminum alloy and well reflect its core mechanical deformation characteristics, which has been widely applied to the ambient-temperature mechanical performance analysis and refined numerical simulation of various aluminum alloy structural members. The empirical formula for parameter n of this model proposed by Steinhard [23] is widely used in engineering design calculation and finite element numerical simulation due to its concise form, clear physical significance and high fitting accuracy, which can accurately match the actual mechanical deformation law of aluminum alloy materials. The high-temperature mechanical constitutive model of aluminum alloy established in this paper is further developed and parameter modified based on the classic ambient-temperature Ramberg-Osgood model.

In the research field of fundamental high-temperature material properties of aluminum alloy, foreign scholars have carried out extensive basic experimental research and theoretical modeling work. Kaufman [24] systematically tested the tensile mechanical properties, high-temperature creep characteristics and fatigue mechanical properties of various aluminum alloy grades under different elevated temperature conditions, accumulating fundamental and critical test data for the high-temperature material property research of aluminum alloy and providing strong support for the subsequent establishment of high-temperature constitutive models. Considering the non-negligible creep effect of aluminum alloy under fire high temperature, Maljaars [25] established a special high-temperature constitutive model of aluminum alloy suitable for engineering applications and fitted and proposed practical calculation formulas for the high-temperature elastic modulus of different aluminum alloy grades. Eurocode EC9 [26] clearly specifies the reduction coefficients of core mechanical properties and the standard value selection method of elastic modulus for aluminum alloy at elevated temperatures, providing normative basis and reference for the fire-resistant design and numerical simulation parameter selection of aluminum alloy structures.

Domestic researchers have also conducted a series of targeted experimental studies and theoretical analyses on the high-temperature mechanical deterioration law and constitutive relationship of different aluminum alloy grades. Su et al. [27] conducted high-temperature tensile comparison tests on two mainstream aluminum alloy profiles of 6063-T5 and 6061-T6 from room temperature to 600 °C, and proposed high-precision calculation formulas for high-temperature mechanical property reduction coefficients. Compared with the calculation methods of European and American codes, the proposed formulas can better characterize the nonlinear deterioration law of aluminum alloy mechanical properties with increasing temperature. Guo et al. [28] selected four commonly used engineering aluminum alloy grades including 6082-T6, 6N01-T6, 6061-T4 and 6061-T6, and carried out static tensile tests at a constant temperature of 20~300 °C to systematically reveal the influence mechanism of temperature on the strength and ductility of aluminum alloy. Due to the limitation of high-temperature strain measurement accuracy, the high-temperature elastic modulus could not be directly obtained. Subsequently, a well-adapted calculation formula for high-temperature performance reduction coefficients of aluminum alloy was established through nonlinear data fitting. Cui et al. [29] carried out high-temperature material property tests based on 6061-T6 aluminum alloy profile samples, accurately obtained the variation laws of elastic modulus, yield stress and tensile strength of aluminum alloy in the range of 20~500 °C, and fitted the corresponding parameter calculation equations and high-temperature constitutive relationships. Li et al. [30] took 6013-T6 high-strength aluminum alloy as the research object and carried out a series of tests including ambient-temperature monotonic tension, high-temperature static tension and cyclic loading tests. The research showed that the mechanical properties of aluminum alloy deteriorated significantly when the temperature exceeded 200 ℃, and the strength decreased to less than 10% of the ambient-temperature strength at 400 ℃. The traditional two-stage Ramberg-Osgood model was optimized and improved to establish a special high-temperature constitutive model suitable for high-strength aluminum alloy.

4. Fire resistance performance of aluminum alloy structures

Compared with traditional steel structures and concrete structures, the research on the fire resistance of aluminum alloy structures is obviously insufficient. Aluminum alloys feature a low melting point and rapid degradation of mechanical properties at high temperatures, and are prone to instability under fire conditions. Existing studies mostly focus on mechanical properties at ambient temperature, while systematic fire resistance research started late with limited achievements.

Tan et al. [31] pointed out that the ISO 834 standard temperature rise curve is widely adopted in conventional fire resistance research. However, the internal temperature field of large-space buildings presents a non-uniform distribution, and this standard model cannot accurately reflect the actual fire conditions. To address this issue, a three-stage temperature rise model can be adopted. Taking fire load density, fire source diameter, heat release rate and other parameters as inputs, the temperature field distribution at different heights in large spaces can be calculated, and the real temperature rise curves of structural members can be obtained. Furthermore, a thermal-mechanical coupled finite element model of aluminum alloy reticulated shells can be established to evaluate their fire resistance performance. Song et al. [6] adopted a combined experimental and numerical simulation method to study the fire resistance of concrete-filled aluminum alloy tube geopolymer recycled concrete short columns. The research variables included concrete type, tube wall thickness and load ratio, and data of temperature, deformation and fire resistance limit were acquired. A temperature field calculation model was established, and the coefficients of thermal convection and thermal radiation were determined. Based on the existing high-temperature compression constitutive model of steel tube confined geopolymer recycled concrete, considering the confinement difference between aluminum alloy tubes and steel tubes, a constitutive model suitable for aluminum alloy tube confinement was proposed. The reliability of the finite element model was verified through ambient temperature and high-temperature axial compression tests as well as fire resistance tests.

5. Conclusion

This chapter systematically reviews the domestic and international research status of three core research topics: mechanical performance of concrete-filled aluminum alloy tube columns under ambient temperature, high-temperature properties of aluminum alloy materials, and fire resistance behavior of aluminum alloy structures. The state-of-the-art progress, major research achievements and remaining research gaps in this field are summarized.

(1) Research on concrete-filled aluminum alloy tube columns at ambient temperature is well established, covering axial compression, eccentric compression and flexural loading conditions. Circular sections exhibit superior confinement effectiveness compared with square sections. Modifying concrete types or arranging internal steel tubes can effectively improve the load-bearing capacity and ductility. Studies on double-skin aluminum alloy tubular members have preliminarily clarified the effects of key parameters including hollow ratio and tube wall thickness, and corresponding design approaches have been proposed.

(2) The Ramberg-Osgood model is commonly used to characterize the nonlinear mechanical

behavior of aluminum alloys at ambient temperature. Overseas researchers have conducted high-temperature tensile and creep tests on various aluminum alloy grades, and established corresponding constitutive models and elastic modulus equations. Eurocode 9 has formulated temperature reduction factors for structural aluminum alloys.

(3) Research on the fire resistance of aluminum alloy structures commenced relatively late. The ISO 834 standard fire curve and non-uniform temperature rise models are widely applied. Finite element results indicate that aluminum alloys suffer a substantial reduction in load-bearing capacity at elevated temperatures. Local real fire tests and fire protection studies have facilitated the development of performance-based fire design methods. Fire resistance experiments and numerical simulations on geopolymer recycled concrete-filled aluminum alloy tube columns have acquired temperature field distribution and fire endurance data, with calibrated finite element models established accordingly.

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