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Post-fire behaviour of ferritic stainless steel material

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HIGHLIGHTS

- Investigation on ferritic stainless steel post-fire mechanical properties was performed.
- Effects of exposed temperature up to 1000 °C, soak time and cooling rate were investigated.
- Existing design rules were assessed by comparing test results.
- Design rules to predict residual mechanical properties were proposed.
- Constitutive model to predict stress-strain curves after fire exposure was proposed.

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ABSTRACT

Ferritic stainless steel has a high potential to be used as structural material, as it has a desirable mechanical properties and a relatively low price compared with other stainless steel materials. However, the post-fire mechanical properties of ferritic stainless steel have not been investigated up to now. This paper presents an experimental investigation on mechanical properties of ferritic stainless steel after exposed to high temperatures up to 1000 °C. Residual mechanical properties and microstructure of the specimens are examined. The ferritic stainless steel specimens were cooled down by four different cooling methods, namely cool-in-chamber, cool-in-air, cool-in-air-with-fan and cool-in-water. It is shown that different cooling rates have minor effects on the strengths of ferritic stainless steel, but it affects the strain and Ramberg-Osgood parameter (n) in a certain temperature range. It is shown that the design equations in literature cannot provide accurate predictions for the post-fire mechanical properties of ferritic stainless steel materials. Therefore, a unified design equation is proposed to predict the post-fire mechanical properties, and a stress-strain model is also proposed to predict the post-fire stress-strain relationship of specimens which are cooled down in chamber from up to 1000 °C. Reliability analysis has also conducted to assess the reliability of the proposed design rules. It is shown that the modified stress-strain models compare well with the experimental results throughout the full range of stress-strain curves.

1. Introduction

Stainless steel has a high corrosion resistance compared with carbon steel. It has been increasingly used in recent years as a structural material especially in medium-to-high corrosion applications, due to its aesthetic appearance and ease in future maintenance as well as a longer life cycle. Ferritic stainless steel has a high strength-to-cost ratio, and thus it has a high potential to be widely applied in construction industry to reduce the construction and life-long cost. Ferritic stainless steel has been used as construction material in buildings, houses, roofing of large-span structures and bridges in Europe, Japan and South Africa [1]. Fire is a potential hazard in these applications. Further structural applications of ferritic stainless steels have been investigated in a Research Fund for Coal and Steel (RFCS) project of "Structural Applications of Ferritic Stainless Steels (SAFSS)" [2], which develops design guidelines and technical information sheet for engineers and architects to use ferritic stainless steel in structural components. Therefore, it is important to evaluate the structural performance of stainless steel structures after exposed to fire hazards, considering the high initial cost of stainless steel structures. The objectives of this research are to provide new test data and also propose design equations to predict the residual factors of mechanical properties and stress-strain relationship after exposed to fire. The investigation on their post-fire mechanical properties provides evidence in repair and

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Nomenclature

Notation			
a	coefficient used in proposed unified equation	n_o	Ramberg-Osgood parameter at room temperature
B	width of cross-section	n_T	Ramberg-Osgood parameter at elevated temperature T °C
b	coefficient used in proposed unified equation	P_m	mean value of tested-to-predicted load ratio
COV	coefficient of variation	p	parameter in the proposed stress-strain model
c	coefficient used in proposed unified equation	T	temperature in °C
D	depth of cross-section	t	thickness of cross-section
d	coefficient used in proposed unified equation	U_T	total mechanical energy per unit volume
E_o	initial Young's modulus at room temperature	V_F	coefficient of variation of fabrication factor
$E_{p,T}$	initial modulus of elasticity at the onset of strain hardening	V_p	coefficient of variation of tested-to-predicted load ratio
E_T	initial Young's modulus at temperature T °C	V_{um}	coefficient of variation of material factor for ultimate strength
F_{um}	mean value of fabrication factor for ultimate strength	V_{ym}	coefficient of variation of material factor for yield strength and Young's modulus
F_{ym}	mean value of fabrication factor for yield strength and Young's modulus	β_0	reliability index
f	stress	β_1	reliability index
$f_{u,o}$	ultimate strength at room temperature	χ	residual factor
$f_{u,T}$	ultimate strength at temperature T °C	χ_d	residual factor calculated from proposed design rule
$f_{0.01,T}$	strength at 0.01% strain at temperature T °C	χ_t	residual factor obtained from test results
$f_{0.2,o}$	yield strength at room temperature	ε	strain
$f_{0.2,T}$	yield strength at temperature T °C	$\varepsilon_{f,T}$	tensile strain at fracture at temperature T °C
$f_{0.5,T}$	strength at 0.5% strain at temperature T °C	$\varepsilon_{p,T}$	strain at the onset of strain hardening
$f_{1.5,T}$	strength at 1.5% strain at temperature T °C	$\varepsilon_{u,o}$	tensile strain at ultimate strength at room temperature
$f_{2.0,T}$	strength at 2.0% strain at temperature T °C	$\varepsilon_{u,T}$	tensile strain at ultimate strength at temperature T °C
HV	Vickers hardness value	ϕ	resistance factor
M_m	mean value of material factor	ϕ_0	resistance factor
m_T	parameter in stress-strain model	ϕ_1	resistance factor

reinforcement of stainless steel structures after fire hazards, and thus reduce economic losses of fire and improve sustainability of the built environment. The relevant results and analytical models can be referred to in the fire engineering design of stainless steel structure.

Residual mechanical properties of steel materials in post-fire condition have been investigated by previous researchers, including high strength structural steel of grade S460, S690 and S960 [3,4], structural steel and reinforcing steel [5], cold-formed steel of grades G300, G500 and G550 [6], NiTi shape memory alloy [7], and austenitic stainless steel [8]. After a steel structure is exposed to fire, the steel members can be cooled down at a wide range of cooling rates. It is impossible to control or predict these cooling rates in the real fire situations. The effect of cooling rate on carbon steel has been investigated by previous researchers [5,9,10]. It has shown that the stress-strain curves of carbon steel specimens that are cooled in furnace, cooled in blanket and cooled in air are almost the same. The yield strength of the post-fire specimens increase significantly when they are cooled in water. Previous researches [11,12] suggested that the soak time has negligible effect on post-fire mechanical properties for carbon steel and austenitic stainless steel. However, there is no available research on post-fire mechanical properties of ferritic stainless steel. Therefore, the effect of the exposed high temperatures, cooling rate and soak time on the mechanical properties of ferritic stainless steel materials are remain unknown to the engineers.

On the other hand, numerous stress-strain models to predict the full stress-strain behaviour for stainless steel material have been proposed by previous researchers. The Ramberg-Osgood equation [13] has been widely used for a rounded stress-strain curve. In recent years, some researches [14–16] were conducted to improve the Ramberg-Osgood model, where 2-stage models were used for a more accurate prediction. The model proposed by Rasmussen [15] has been widely used for stainless steel. Later on, the two-stage model was further modified to a three-stage model [17,18], in which an intermediate point at 2.0% proof stress was used. Stress-strain model for cold-formed steel with yield plateau was proposed by Mander [19], and further modified by Tao et al. [5].

Experimental investigation on post-fire mechanical properties of ferritic stainless steel has been conducted and presented in this paper. A total of 58 ferritic stainless steel specimens have been tested. The ferritic stainless steel are cooled down with four different cooling methods from the specified elevated temperature to room temperature, namely cool-in-chamber (CIC), cool-in-air (CIA), cool-in-air-with-fan (CAF) and cool-in-water (CIW). Therefore, the influence of various cooling rates can be investigated. It is showed that different cooling rates have negligible effect on the post-fire mechanical properties of ferritic stainless steel. The residual factors of the Young's modulus, yield strength, ultimate strength, Ramberg-Osgood parameter, strain at the ultimate strength, hardness, and energy absorption have been obtained and reported. The ferritic stainless steel exhibits a unique post-fire mechanical behaviour, as its ultimate strength increased significantly after exposed to an elevated temperature higher than 700 °C. The microstructure of the ferritic stainless steel specimens after exposed to fire has been investigated using scanning electron microscope (SEM), in order to understand the post-fire mechanical behaviour of these two materials. The residual mechanical properties of steel materials are compared with the predicted values calculated by the existing equations. It is shown that the design equations in literature are not capable of providing accurate predictions for ferritic stainless steel. Design equations are proposed to predict the post-fire mechanical properties, which was then assessed by reliability analysis.