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Mechanical properties of lean duplex stainless steel at post-fire condition

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ABSTRACT

This paper reports an experimental investigation of the mechanical properties of cold-formed lean duplex stainless steel after exposure to high temperatures up to 1000 °C. The test specimens were extracted from rectangular and square hollow sections that were cold-rolled from flat plates of lean duplex stainless steel. The mechanical properties, Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter and strain at ultimate strength of lean duplex stainless steel, are reported. The residual mechanical properties of steel materials are compared with the predicted values calculated by the existing equations. It is shown that the existing equations cannot provide accurate predictions for the post-fire mechanical properties of lean duplex stainless steel materials. Thus, a unified equation is proposed to predict residual mechanical properties for lean duplex stainless steel specimens in post-fire conditions. A constitutive model is also proposed to predict the stress-strain relationship of the test specimens after exposure to high temperatures up to 1000 °C. A reliability analysis was conducted for the proposed equation. The proposed equation compared favourably with the experimental results, and was found to be reliable for predicting lean duplex stainless steel mechanical properties after exposure to high temperatures.

1. Introduction

Lean duplex stainless steel (EN 1.4162), which is a relatively new type of steel material, has been used increasingly in construction in recent years. It has a high strength-to-cost ratio compared with other types of stainless steel materials, due to a low nickel (Ni) content of 1.5%, compared with over 5% in other duplex and austenitic stainless steel materials. It has an excellent corrosion resistance, which leads to an aesthetic appearance, ease in future maintenance, and long life cycle. Fire hazards are normally destructive for steel structures, as both stiffness and strength of steel materials decrease dramatically at elevated temperatures. Generally, stainless steel materials have a better fire resistance than carbon steel materials. The investigation of their post-fire mechanical properties provides evidence about the repair and reinforcement of stainless steel structures after exposure to fire hazards, which can reduce economic loss due to fire and improve sustainability of the built environment. The post-fire mechanical properties of lean duplex stainless steel have not been reported in literature. Hence, there was an eminent need to investigate the deterioration and residual mechanical properties of lean duplex stainless steel after exposure to high temperatures.

Previous researchers have investigated residual mechanical property factors of steel materials after fire, including high strength structural steel of grade S460, S690 [1] and S960 [2], structural steel and reinforcing steel [3], cold-formed steel of grades G300, G500 and G550 [4], and austenitic stainless steel of grade EN 1.4301 [5]. However, there is no available research on post-fire mechanical properties of lean duplex stainless steel. Therefore, the effect of the high temperatures on the mechanical properties of lean duplex stainless steel materials remain unknown to engineers and researchers. On the other hand, numerous stress-strain models to predict the full stress-strain behavior for stainless steel material at room temperature have been proposed by previous researchers. The Ramberg-osgood equation [6] has been used widely for a rounded stress-strain curve, and several 2-stage models have been modified from the Ramberg-osgood equation [7–9] for a more accurate prediction for stainless steel materials. The two-stage model was modified further to three-stage models [10,11]. Stress-strain models for austenitic and duplex stainless steel materials at elevated temperatures have also been proposed by Chen and Young [12] and Huang and Young [13]. It should be noted that there is no equation to predict stress-strain relationship of lean duplex stainless steel in post-fire conditions.

An experimental investigation of the post-fire mechanical properties of lean duplex stainless steel was conducted and is presented in this paper. A total of 17 lean duplex stainless steel specimens was tested. The residual mechanical property factors of the Young's modulus, yield

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NOTATION

The following symbols are used in this paper:

B	width of cross-section;
D	depth of cross-section;
E_o	initial Young's modulus at room temperature;
E_T	initial Young's modulus at temperature T °C;
f	stress
$f_{0.2,o}$	yield strength at room temperature;
$f_{0.2,T}$	yield strength at temperature T °C;
$f_{u,o}$	ultimate strength at room temperature;
$f_{u,T}$	ultimate strength at temperature T °C;
$f_{0.01,T}$	strength at 0.01% strain at temperature T °C;
$f_{0.5,T}$	strength at 0.5% strain at temperature T °C;
$f_{1.5,T}$	strength at 1.5% strain at temperature T °C;
$f_{2.0,T}$	strength at 2.0% strain at temperature T °C;
n_o	Ramberg-Osgood parameter at room temperature;
n_T	Ramberg-Osgood parameter at elevated temperature T °C;
T	temperature in °C;
t	thickness;
U_T	total mechanical energy per unit volume absorbed by the material during tensile testing;
ε	strain;
$\varepsilon_{f,T}$	tensile strain at fracture at temperature T °C;
$\varepsilon_{u,o}$	tensile strain at ultimate strength at room temperature; and
$\varepsilon_{u,T}$	tensile strain at ultimate strength at temperature T °C.
a	coefficient used in modified equations;
b	coefficient used in modified equations;
COV	coefficient of variation;
c	coefficient used in modified equations;
d	coefficient used in modified equations;
$E_{p,T}$	initial modulus of elasticity at the onset of strain hardening
F_{um}	mean value of fabrication factor for ultimate strength;
F_{ym}	mean value of fabrication factor for yield strength and Young's modulus;
f_u	ultimate strength;
$f_{u,d}$	ultimate strength predicted by Vickers hardness value;
HV	Vickers hardness value;
M_m	mean value of material factor;
m_T	parameter in stress-strain model;
N	coefficient used in Chen and Young (2006) equations;
P	parameter in the proposed stress-strain model;
P_m	mean value of tested-to-predicted load ratio;
V_F	coefficient of variation of fabrication factor;
V_p	coefficient of variation of tested-to-predicted load ratio;
V_{um}	coefficient of variation of material factor for ultimate strength;
V_{ym}	coefficient of variation of material factor for yield strength and Young's modulus;
β	reliability index;
β_0	reliability index;
β_1	reliability index;
χ	residual mechanical property factor;
χ_d	residual mechanical property factor calculated from proposed design rule;
χ_t	residual mechanical property factor obtained from test results;
$\varepsilon_{p,T}$	strain at the onset of strain hardening;
ϕ	resistance factor;
ϕ_0	resistance factor; and
ϕ_1	resistance factor.

strength, ultimate strength, Ramberg-osgood parameter, strain at the ultimate strength, hardness, and energy absorption were obtained and are reported here. The lean duplex stainless steel specimens were cooled down in the furnace from the specified elevated temperature to room temperature. The microstructure of the lean duplex stainless steel specimens before and after exposed to fire was investigated using a scanning electron microscope (SEM). The residual mechanical properties of lean duplex stainless steel after exposure to high temperatures were compared with the predicted values calculated by the existing equations for other types of steel materials. It should be noted that lean duplex stainless steel was not covered in the existing equations. It was found that the existing equations generally are not capable of providing accurate predictions for lean duplex stainless steel. A set of new equations is proposed, therefore, to predict the post-fire mechanical properties. A reliability analysis was performed to assess the reliability of the proposed equations.

Table 1
Post-fire mechanical properties of lean duplex stainless steel.

Specimen	T (°C)	Thermal expansion (%)	E_T (GPa)	$f_{0.2,T}$ (MPa)	$f_{0.5,T}$ (MPa)	$f_{1.5,T}$ (MPa)	$f_{2.0,T}$ (MPa)	$f_{u,T}$ (MPa)	$\varepsilon_{u,T}$ (%)	$\varepsilon_{f,T}$ (%)	n_T	U_T (MPa)	HV30 (kgf/mm^2)
L1T24	24.0	–	208.8	648.1	676.2	748.1	753.0	805.4	21.7	33.4	7.1	251.3	260.0
L1T200s20	202.5	0.71	212.3	634.5	634.4	673.8	683.6	791.9	23.8	34.7	10.9	260.2	269.0
L1T300s20	304.1	0.29	216.3	632.4	632.2	668.7	679.1	781.1	20.5	34.1	11.8	252.8	277.0
L1T400s20	404.8	1.89	212.7	629.7	630.0	666.9	676.6	782.8	19.4	29.3	15.7	217.2	270.0
L1T500s20	505.9	2.50	214.5	638.2	637.4	659.9	673.3	802.3	18.7	33.5	11.5	253.1	271.0
L1T600s0	624.1	1.66	215.1	607.4	608.6	652.7	667.9	800.6	19.6	33.0	13.9	249.0	260.0
L1T600s20	604.6	5.3	209.8	616.2	616.8	668.3	681.3	800.2	19.9	33.2	12.7	251.7	275.0
L1T600s60	599.7	1.73	214.8	561.2	560.9	635.6	655.2	803.0	19.7	32.0	6.4	244.2	271.0
L1T600s180	594.1	0.90	215.2	538.9	549.5	640.8	658.2	793.3	28.4	39.1	4.7	299.4	264.0
L1T700s20	697.0	3.93	209.5	517.0	531.2	610.4	630.5	814.2	39.5	43.9	4.5	335.0	268.0
L1T800s20	795.0	4.06	217.3	509.6	526.1	613.9	633.7	851.2	39.5	44.6	3.7	346.4	265.0
L1T900s20	889.8	8.76	218.2	462.8	486.2	567.0	586.5	818.1	41.7	49.1	3.7	366.6	264.0
L1T1000s20	990.7	8.45	211.8	467.9	488.3	568.5	586.5	758.1	27.9	43.6	4.3	310.9	235.5
L2T24	24.0	–	198.7	682.4	666.5	748.8	753.7	828.1	20.2	30.6	6.4	243.2	280.0
L2T300s20	307.4	0.35	209.2	697.62	693.4	726.9	738.1	817.6	18.8	30.4	12.6	238.3	279.0
L2T500s20	509.1	0.70	212.8	703.84	694.5	731.7	742.7	855.9	19.0	30.9	9.4	251.6	274.0
L2T700s20	701.0	1.12	215.8	524.3	542.8	659.9	679.6	853.5	39.5	47.1	3.8	378.8	274.0

Note: L1 and L2 are extracted from sections 150 × 50 × 2.5 and 50 × 50 × 1.5, respectively.