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LEAN DUPLEX STAINLESS STEEL MATERIAL TESTS
At Elevated Temperatures Using Steady State Method

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Abstract

A test program to investigate the material properties of a relatively new cold-formed lean duplex stainless steel under elevated temperatures is presented. A total of 44 tensile coupon tests were carried out by steady state method for temperatures ranged from 24 to 900 ºC. Material properties including Young's modulus, yield strength, ultimate strength and ultimate strain were obtained. The test results and available data were compared with the design values in the European Code as well as a unified equation by Chen & Young for stainless steel. The lean duplex stainless steel is not covered in these existing design rules. It is shown that the material properties of lean duplex stainless steel under elevated temperatures cannot be well predicted by the existing design rules.

Keywords: elevated temperatures, fire resistance, lean duplex, material properties, stainless steel, steady state tests

INTRODUCTION

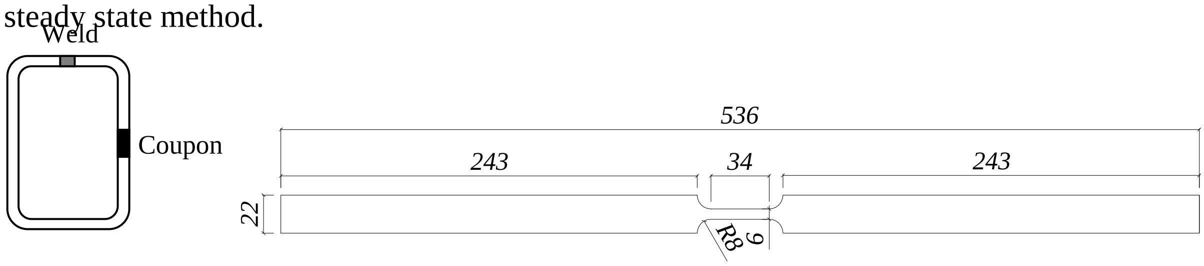
Fire is destructive for stainless steel structures, due to its significantly reduced strength and stiffness under elevated temperatures. Accurate design rules are required to predict the material properties under elevated temperatures, which is important in structural design. Cold-formed lean duplex stainless steel (EN 1.4162), a recently developed high strength stainless steel with a relatively low price, has a great potential to be used in construction. However, little research has been carried out on the material properties of lean duplex stainless steel under elevated temperatures, and this material is not covered in the existing design specifications for stainless steel structures. Therefore, it is necessary to investigate the material properties of cold-formed lean duplex stainless steel.

A test program to investigate the material properties of cold-formed lean duplex stainless steel (EN 1.4162) at elevated temperatures using steady state method is carried out. The test specimens were heated to a specified temperature then imposed tensile stress to the specimens until failure. Tensile coupon tests were conducted for cold-formed lean duplex stainless steel specimens extracted from three different sections, which are under different level of residual stresses due to the cold-forming process. The nominal temperatures used in the test program were ranged from 24 – 900 ºC. The test results were compared with the design values by EC3 (2005) and Chen & Young (2006). It should be noted that these two design rules do not cover the lean duplex stainless steel. Therefore, the duplex stainless steel (EN 1.4462) was used for comparison. Reliability analysis was also conducted to assess the design rules for lean duplex stainless steel. It is shown that the EC3 generally provides unconservative prediction, which may lead to an unsafe design of structures, while the unified equation provides generally conservative prediction to lean duplex stainless steel material properties under elevated temperatures.

1 STEADY STATE TESTS

Coupon tests were conducted under elevated temperatures to determine the material properties of the coupon specimens. The specimens were extracted from cold-formed lean duplex stainless steel rectangular hollow sections (RHS) and square hollow section (SHS) with

nominal dimension ($D \times B \times t$) 50×30×2.5, 50×50×1.5, and 150×50×2.5, where D, B, t are the depth, width, and thickness in millimetre of the cross-section, respectively. The coupons were taken from the centre of the face at 90º angle from the weld for all specimens. The dimensions of coupon specimens conformed to the Australian Standard AS 2291 (1979) and the American Standard ASTM E 21 (1992) for the tensile testing of metals at elevated temperatures using a 6 mm wide coupon and a gauge length of 25 mm. The location of coupon and weld in cross-section as well as dimensions of the coupon specimens are shown in Fig. 1.
The test set-up is shown in Fig. 2. An MTS testing machine was used to conduct the coupon tests. The MTS high temperature furnace with a maximum temperature of 1400 ºC was used to specify the required temperatures during testing, with an accuracy of 1 ºC. There are six heating elements located at the upper, middle and lower part of each side of the furnace. Three internal thermal couples were located inside the furnace to measure the air temperature, and one external thermal couple was attached on the specimen surface to measure the temperature of the specimen. The calibrated extensometer of 25 mm gauge length with the range limitation of ± 2.5 mm was mounted onto the specimens to measure the longitudinal strain during the tests. For specimens with large deformation under high temperatures, the strain may exceed the range limit of the extensometer. The extensometer was reset manually when it approached approximately 80% of the range limit during testing to avoid any damage to the apparatus.
In the steady state tests, a specimen is heated up to a specified temperature and then loaded until it fails. The temperature is maintained when the tensile load is applied during testing. Coupons extracted from each hollow section are loaded under 10 different nominal temperatures from 24 to 900 ºC with an interval of 100 ºC. Firstly, the lower end of the specimen is free to expand during the heating process until it reaches the specified temperature. When the temperature on the specimen, which is measured by the external thermal couple, is stabilized at the specified temperature for 10 minutes, the lower end of the specimen is then gripped. Secondly, tensile load is applied to the specimen by displacement control with a constant loading rate of 0.5 mm/min until it fails. The strain rate of the tests measured by the extensometer conformed to the Australian Standard AS 2291 (1979) and American Standard ASTM E 21 (1992). A total of 44 coupon specimens were tested using steady state method.



(a)

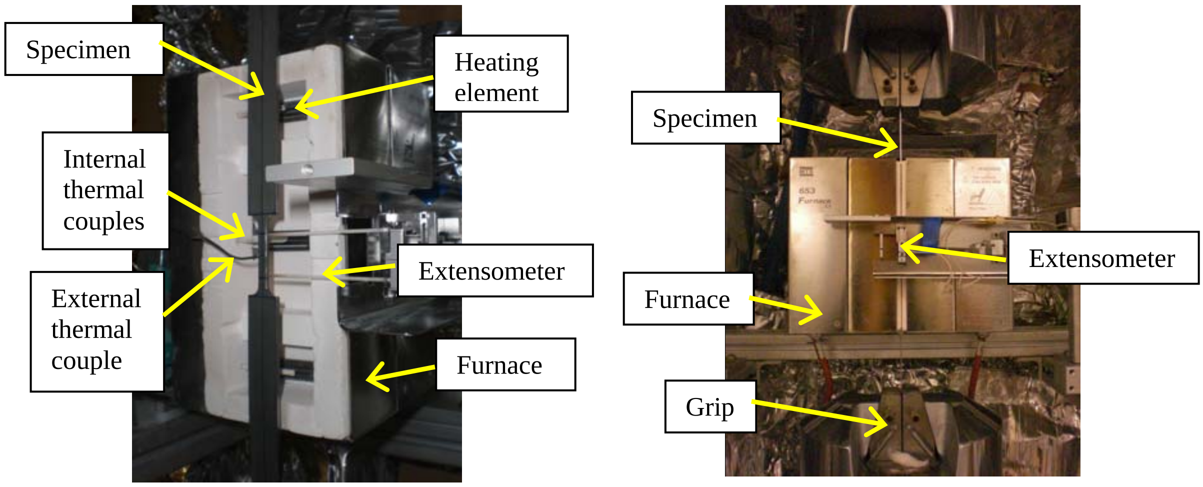
(b)

Fig.1: (a) Location of coupon and weld in hollow section (b) Dimensions of coupon specimens

2 TEST RESULTS

The material properties measured at room temperature including Young's modulus (E_o), 0.2% yield strength (f_y), which is also known as the 0.2% proof stress, ultimate tensile strength (f_u), elongation at ultimate strength (ε_u) and fracture (ε_f) of a gauge length of 25 mm, and the Ramberg-Osgood parameter (n) using the Ramberg-Osgood expression $n = \ln(0.01/0.2)/\ln(f_{0.01}/f_y)$ are summarized in Tab. 1. The 0.2% yield strength and 0.01% stress ($f_{0.01}$) are the intersection points on the stress-strain curve, which are the proportional lines off-set by 0.2% and 0.01% strains, respectively. It is well known that the material properties reduce as the temperature increases. The reduction factors of Young's modulus (E_T/E_o), 0.2%

yield strength ($f_{y,T}/f_y$), ultimate strength ($f_{u,T}/f_u$) and ultimate strain ($\varepsilon_{u,T}/\varepsilon_u$) determined from the ratio of material properties under elevated temperatures to those at room temperature are shown in Fig. 3. Some specimens were failed outside the measuring range of the extensometer, and therefore the ultimate strains for these specimens are not reported. The actual specimen temperature was obtained by the average value of the specimen temperatures measured by the external thermal couple at the beginning, middle and the end of each test. The actual specimen temperatures are close to the nominal temperatures with the maximum difference of 6.6%. The reduction factors of Young's modulus (E_T/E_o), 0.2% yield strength ($f_{y,T}/f_y$), ultimate strength ($f_{u,T}/f_u$) and ultimate strain ($\varepsilon_{u,T}/\varepsilon_u$) are plotted against the actual specimen temperatures in Figs 3(a), (b), (c), (d), respectively.



(a) One of the two sides of the furnace and a coupon specimen

(b) Test set-up during testing

Fig. 2: Typical test set-up of a coupon specimen

Tab. 1 Material properties obtained from coupon tests at room temperature

Specimen	T (ºC)	E_o (GPa)	f_y (MPa)	f_u (MPa)	ε_u (%)	ε_f (%)	n
50×30×2.5T24	24.6	203	722.1	829.7	16.4	27.2	5.9
50×50×1.5T24	24.2	199	682.4	828.1	21.5	30.6	6.4
150×50×2.5T24	25.0	199	693.0	830.4	21.7	33.0	6.9

3 COMPARISON OF TEST RESULTS WITH DESIGN PREDICTIONS

A total of 11 data of the reduction factors of 0.2% yield strength (0.2% proof stress) and ultimate strength for lean duplex stainless steel sheets under transient state tests were reported by Gardner et. al. (2010). Test results of lean duplex stainless steel material properties under elevated temperatures obtained from this study and the available data are compared with design values by European Code (2005) and unified equations (Chen & Young, 2006). For the European Code, the reduction factors of Young's modulus, 0.2% yield strength and ultimate strength under elevated temperatures for various stainless steel grades are provided in Tab. C.1 of the Code. However, the lean duplex stainless steel of Grade 1.4162 is not covered by the Code. Therefore, the reduction factors of duplex stainless steel (EN 1.4462) are used to compare with the test results to assess its suitability for lean duplex stainless steel (EN 1.4162). The reduction factors in European Code are provided for discrete temperatures only, thus linear interpolation was required to obtain the reduction factors corresponding to the actual temperatures on the test specimens. Chen & Young (2006) proposed four unified equations to predict the reduction factors of Young's modulus, 0.2% yield strength, ultimate strength and ultimate strain for stainless steel under elevated temperatures. Two sets of coefficients are calibrated for stainless steel types EN 1.4462 (Duplex) and EN 1.4301 (AISI 304). The unified equations with coefficients for stainless steel type EN 1.4462 (Duplex) are used to compare with the test results in this study and the available data, in order to assess its suitability for lean duplex stainless steel.

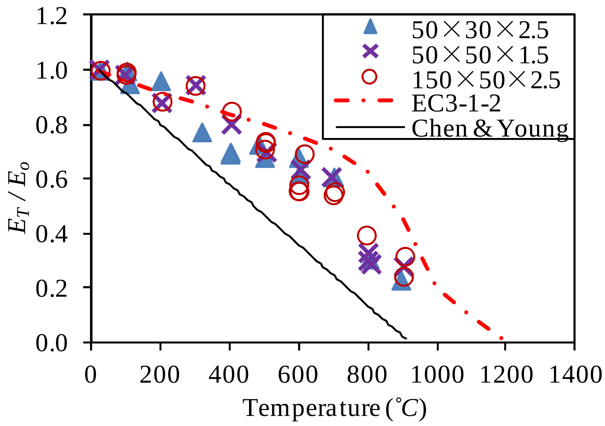
The reliability of the design rules to predict the lean duplex stainless steel material properties under elevated temperatures was evaluated using reliability analysis, which is detailed in the Commentary of the ASCE (2002). However, target reliability index (β_0) and the resistance factor (ϕ_0) for stainless steel material property are not suggested by the design specification. Therefore, the target reliability index of 2.50 for stainless steel material property is adopted in this study. The resistance factors of the two design rules corresponding to this target reliability index 2.50 are calculated by Eq. 6.2-2 of the ASCE Specification (2002). The load combinations of 1.35DL+1.5LL and 1.2DL+1.6LL, as specified in the EC3 (2005) and ASCE (2002) respectively, were used in calculating the resistance factors (ϕ_0) for EC3 and the unified equations (Chen & Young, 2006), where DL = dead load and LL = live load. For the purpose of direct comparison, a load combination of 1.2DL + 1.6LL as specified in the ASCE was used to calculate the resistance factors (ϕ_1), as shown in Tab. 2.

The reduction factors of Young's modulus of the test specimens under elevated temperatures are compared with those predicted by EC3 (2005) and unified equation for Young's modulus (Chen & Young, 2006) for duplex stainless steel of Grade EN 1.4462. The comparison of the reduction factors are shown in Tab. 2 and Fig. 3(a), where $k_{E,Test}$, $k_{E,EC3}$, and $k_{E,Chen\&Young}$ are the reduction factors of Young's modulus obtained from the test results, prediction values by EC3 and prediction values by the unified equation, respectively. It is observed that the predictions by EC3 are unconservative for the test specimens, which may lead to an unsafe design. However, the unified equation provides quite conservative and scattered predictions to the Young's modulus of lean duplex stainless steel under elevated temperatures. It is found that these two design rules cannot provide accurate predictions of Young's modulus for lean duplex stainless steel under elevated temperatures, and thus further research on this topic is required.

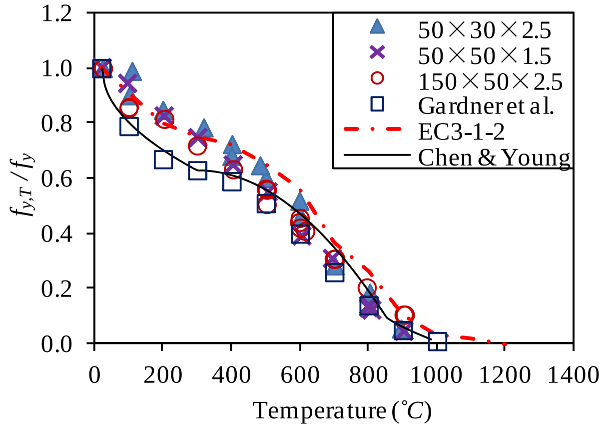
The reduction factors of yield strength of the test specimens and the available data under elevated temperatures are also compared with the design values by the two design rules, as shown in Tab. 2 and Fig. 3(b), where $k_{y,Test}$, $k_{y,EC3}$, and $k_{y,Chen\&Young}$ are the reduction factors of 0.2% yield strength obtained from the test results, prediction values by EC3 and prediction values by the unified equation for yield strength (Chen & Young, 2006), respectively. Once again, the EC3 is unconservative in predicting the reduction factors of 0.2% yield strength of lean duplex stainless steel under elevated temperatures. On the other hand, the predictions by the unified equation for yield strength provide a conservative prediction. The mean value of $k_{y,Test}/k_{y,Chen\&Young}$ equals to 1.02, with the COV of 0.203. The target reliability of 2.50 can be achieved by adopting the resistance factor of 0.75. It is shown that the unified equation is generally capable to predict the reduction factor of yield strengths of lean duplex stainless steel under elevated temperatures, by adopting the resistance factor of 0.75.

Comparison between the reduction factors of ultimate strength of the test specimens and the available data with the design values are shown in Tab. 2 and Fig. 3(c), where $k_{u,Test}$, $k_{u,EC3}$, and $k_{u,Chen\&Young}$ are the reduction factors of ultimate strength obtained from the test results, prediction values by EC3 (2005) and prediction values by the unified equation for ultimate strength (Chen & Young, 2006). It is shown that the predictions by both design rules are generally unconservative. Therefore, it is recommended that further research should be carried out for lean duplex stainless steel ultimate strength under elevated temperatures.

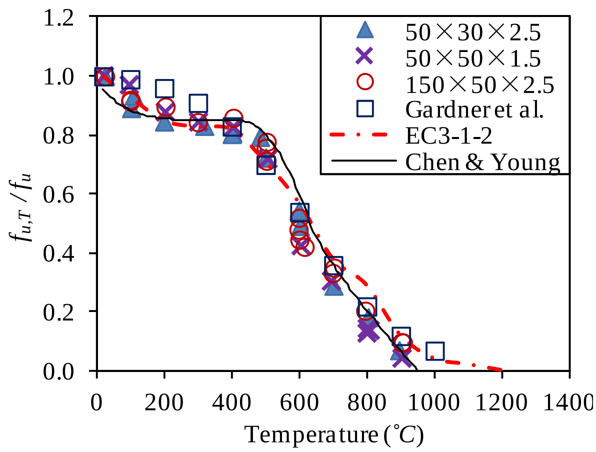
Chen & Young (2006) proposed an equation to predict the reduction factor of ultimate strain ($\varepsilon_{u,T}/\varepsilon_u$) for duplex stainless steel EN 1.4462. Such predictions are compared with the test results, as shown Fig. 3(d). The design rule provides a generally conservative prediction to the reduction factor of the ultimate strain of the lean duplex stainless steel under elevated temperatures. Therefore, the design equation for duplex stainless steel (EN 1.4462) is also recommended for lean duplex stainless steel (EN 1.4162) in predicting the ultimate strain under elevated temperatures.



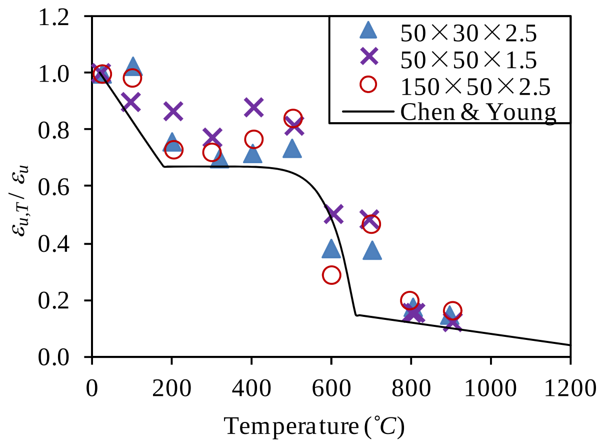
(a) Young's mudulus



(b) 0.2% yield strength



(c) Ultimate strength



(d) Ultimate strain

Fig. 3: Comparison of material properties obtained from design rules and test results

Tab. 2 Material properties obtained from coupon tests at room temperature

	$\frac{k_{E,Test}}{k_{E,EC3}}$	$\frac{k_{E,Test}}{k_{E,Chen\&Young}}$	$\frac{k_{y,Test}}{k_{y,EC3}}$	$\frac{k_{y,Test}}{k_{y,Chen\&Young}}$	$\frac{k_{u,Test}}{k_{u,EC3}}$	$\frac{k_{u,Test}}{k_{u,Chen\&Young}}$
# of data	44	44	55	55	55	55
Mean (P_m)	0.84	1.60	0.85	1.02	0.90	0.87
COV (V_p)	0.209	0.318	0.193	0.203	0.200	0.186
Resistance factor (ϕ_o)	0.59	0.95	0.61	0.75	0.68	0.70
Reliability index (β_o)	2.50	2.50	2.50	2.50	2.50	2.50
Resistance factor (ϕ_1)	0.61	0.95	0.64	0.75	0.71	0.70
Reliability index (β_1)	2.50	2.50	2.50	2.50	2.50	2.50

4 CONCLUSIONS

An experimental investigation of material properties of lean duplex stainless steel at elevated temperatures has been presented. The test specimens are extracted from three square and rectangular hollow sections of type EN 1.4162. Coupon tests using steady state method at different temperatures ranging from 24 to 900 ºC were conducted. Material properties including Young's modulus, yield strength, ultimate strength and ultimate strain under elevated temperatures were obtained. The test results obtained in this study together with available data were compared with design values by current design rules. It is shown that the ultimate strain of lean duplex stainless steel under elevated temperatures can be well predicted using the unified equation proposed by Chen & Young (2006), in which the lean duplex stainless steel material was not covered by the proposed equation. It is also shown that the EC3 provides generally unconservative predictions to the Young’s modulus, yield strength and ultimate strength. The unified equations provide quite conservative predictions for Young’s modulus, conservative predictions for yield strength, but unconservative predictions for ultimate strength. It is apparently shown that the current design rules are generally inappropriate to be used for lean duplex stainless steel under elevated temperatures. It is suggested that further research is required for lean duplex stainless steel under elevated temperatures for both steady and transient state tests.

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