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Stress–strain relationship of cold-formed lean duplex stainless steel at elevated temperatures

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ABSTRACT

A test programme to examine the material properties of a relatively new cold-formed lean duplex stainless steel at elevated temperatures is presented. A total of 80 tensile coupon tests were carried out by both steady state test method and transient state test method for temperatures ranged from 24 to 900°C. The coupons were extracted from square and rectangular hollow sections. Material properties including thermal elongation, 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 and Young [1] for stainless steel. The lean duplex stainless steel is not covered by these design rules. Reliability analysis was carried out to assess the applicability of these existing design rules. It is shown that the material properties of lean duplex stainless steel at elevated temperatures cannot be well predicted by the existing design rules. Modification to the existing design rules for lean duplex stainless steel at elevated temperatures is proposed. The stress–strain curves of the test specimens under different temperatures were plotted and compared with stress–strain curves predicted by the unified equation using modified coefficients. It is shown that the stress–strain curves and other material properties predicted by the modified design rules agree well with the test results.

1. Introduction

Fire is destructive in metal structures including stainless steel structures, due to its significantly reduced strength and stiffness at elevated temperatures. Accurate design rules are required to predict the material properties at 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 in construction industry. However, little research has been carried out on the material properties of lean duplex stainless steel at 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.

Chen and Young [1] investigated the material properties of duplex stainless steel grade EN 1.4462 (S31803) and austenitic stainless steel grade EN 1.4301 (AISI 304) at elevated temperatures. Unified equations to predict the material properties and stress–strain curves at different temperatures were proposed for the duplex stainless steel grade EN 1.4462 and austenitic stainless steel grade EN 1.4301. It is shown that the proposed design rules compared well with the test results. Gardner et al. [2] summarized test results on material properties of various stainless steel alloys at elevated temperatures, including the lean duplex stainless steel. Reduction factors of strength and stiffness for different types of stainless steel were proposed according to the available data.

Kouhi et al. [3] investigated the suitability of austenitic stainless steel grades EN 1.4571 and EN 1.4301 being used in buildings as load-bearing structures without fire protection. Tensile coupon tests at elevated temperatures were carried out, and the test results were compared with the existing design rules. It is found that the austenitic stainless steel is generally suitable to be used in constructions without fire protection. To and Young [4] investigated the performance of stainless steel tubular columns at elevated temperatures by carrying out finite element analysis. Two different design rules were proposed to determine the failure loads of cold-formed stainless steel tubular columns at elevated temperatures. Both methods were shown to be reliable and conservative based on reliability analysis. Feng and Young [5] performed numerical investigation on duplex EN 1.4462, high strength austenitic, and austenitic EN 1.4301 stainless steel in tubular joints at elevated temperatures. The existing design rules were assessed by comparing with the numerical results, and a new design equation was proposed by introducing a temperature factor.

In this study, a test programme to examine the material properties of cold-formed lean duplex stainless steel (EN 1.4162) at elevated temperatures using steady state test method and transient state test method is carried out. Tensile coupon tests were conducted for cold-formed lean duplex stainless steel specimens extracted from square and rectangular hollow sections. In the steady state tests, the test specimens were heated to a specified temperature and then imposed tensile stress to the

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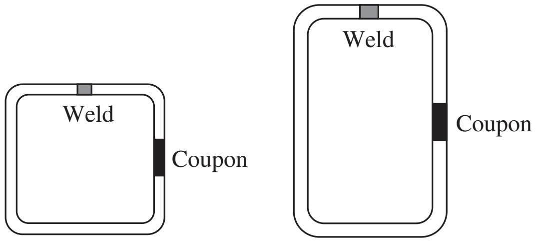

Fig. 1. Location of coupon and weld in hollow sections.

specimens until failure; whereas in transient state tests, a constant tensile stress is applied to the specimens and then the temperature rises until the specimens fail. The nominal temperatures used in the coupon tests ranged from 24 to 900°C, while the stress levels applied to the specimens in transient state tests were from 0 to 750MPa. The test results were compared with the design values given by EC3 [6] and Chen & Young [1]. It should be noted that these design rules do not cover lean duplex stainless steel. Therefore, the duplex stainless steel (EN 1.4462) was used for comparison in this study. Reliability analysis was also performed 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 at elevated temperatures. A set of coefficients for the unified equation in Chen and Young [1] was calibrated against the test data obtained from the lean duplex stainless steel. The design predictions were compared with the steady and transient state tests obtained from this study as well as compared with the available test data [2]. It is shown that the material properties predicted by the modified design rules conform well to the test results.

2. Experimental investigation

2.1. General

Coupon tests were conducted at 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, and t are the depth, width, and thickness in millimetre of the cross-sections, respectively. The coupons were taken from the centre of the face at 90° angle from the weld for all specimens, as shown in Fig. 1. The dimensions of coupon specimens conformed to the Australian Standard AS 2291 [7] and the American Standard ASTM E 21 [8] for the tensile testing of metals at elevated temperatures using a 6mm wide coupon and a gauge length of 25mm, as shown in Fig. 2.

The test set-up is shown in Fig. 3. An MTS testing machine was used to conduct the coupon tests. The MTS high temperature furnace with a maximum temperature of 1400°C was used to specify the required temperatures during testing, with an accuracy of 1°C. There are three heating elements located at the upper, middle and lower parts on each of the two sides of the furnace. Three internal thermal couples were located inside the furnace to measure the air temperature, and one external thermal couple was attached at the mid-length of the coupon specimen to measure the temperature of the specimen. The calibrated extensometer of 25mm gauge length with the range limitation of ±2.5mm was mounted onto the specimens to measure the longitudinal strain during the tests. For specimens with large elongation 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.

The specimens were labelled such that the test method, dimension of cross-section from which coupon specimens were extracted and the nominal temperature could be identified. For example, in the label $S50\times50\times1.5T800^{\#2}$, the first letter indicates the test method, where "S" represents steady state test method and "T" represents transient state test method. The coupon specimen was extracted from cross-section of nominal dimension 50×50×1.5 and was tested under nominal temperature of 800°C. If the location of fracture is outside the gauge length of a specimen, meaning that the extensometer could not capture all of the strain near failure. Hence, the strain at ultimate strength and fracture could not be accurately measured and these values were not reported. These specimens are labelled using a superscript # followed by a number to identify the specimens failed outside the gauge length of the coupon specimens.

2.2. Steady state tests

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°C with an interval of 100°C. Firstly, the upper end of the specimen was gripped, and the lower end of the specimen is free to expand during the heating process until it reaches a specified temperature. When the temperature on the specimen, which is measured by the external thermal couple, is stabilized at the specified temperature for 10min, 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 0.5mm/min until it fails. The strain rate of the tests measured by the extensometer conformed to the Australian Standard AS 2291 [7] and American Standard ASTM E 21 [8]. A total of 44 coupon specimens were tested using steady state test method.

2.3. Transient state tests

In the transient state tests, a specimen is subjected to a specified tensile stress while the temperatures increase until the specimen fails. The nominal stress levels in this test programme were 0, 100, 200, 300, 400, 500, 550, 600, 650, 700 and 750MPa. Load control was used in the transient state tests so that a specified stress level can be maintained during the test. The air temperatures in the furnace increased in the rate of 15°C/min until the specimen fails. The specimen temperatures were measured by the external thermal couple throughout the test. The test results of the transient state tests were converted to the stress–strain curves of the specimens at different specimen temperatures. The load level of 0MPa is to measure the thermal elongation of the specimens at elevated temperatures. The lower end of the specimen was free to expand, while the temperature increased from 24 to 1000°C in the rate of 15°C/min. The thermal elongation is recorded by the extensometer

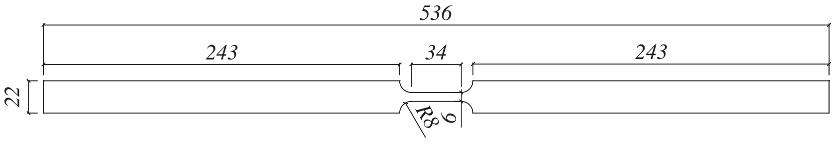

Fig. 2. Dimensions of coupon specimen.