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Material properties of cold-formed high strength steel at elevated temperatures

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ABSTRACT

This paper presents the material properties of cold-formed high strength steel at elevated temperatures. Material properties at elevated temperatures have a crucial role in fire resistance design of steel structures. The fire resistances of steel structures in the existing international standards are mainly based on experimental data of hot-rolled mild steel. However, investigation of high strength steel at elevated temperatures is limited. Therefore, a test program has been carried out to investigate the material properties of cold-formed high strength steel at elevated temperatures. The coupon specimens were extracted from cold-formed high strength steel square and rectangular hollow sections with nominal yield stresses of 700 and 900 MPa at ambient temperature. The coupon tests were carried out through both steady and transient state test methods for temperatures up to 1000 °C. Material properties including thermal elongation, elastic modulus, yield stress, ultimate strength, ultimate strain and fracture strain were obtained from the tests. The test results were compared with the design values in the European, American, Australian and British standards. The comparison results revealed the necessity of proposing specified design rules for material properties of cold-formed high strength steel at elevated temperatures. New design curves to determine the deterioration of material properties of cold-formed high strength steel at elevated temperatures are proposed. It is shown that the proposed design curves are suitable for high strength steel materials with nominal yield stresses ranged from 690 to 960 MPa at ambient temperature.

1. Introduction

In recent years, high strength steel products with yield stress up to 1400 MPa are available in the market with the development of metallurgical and manufacturing technologies. Due to its superior strength-to-weight ratio that could lead to lighter and elegant structures, high strength steel is becoming increasingly attractive in structural and architectural applications such as bridges and high-rise buildings. The steel grade S355 with the nominal yield stress of 355 MPa, which was once considered as high strength steel, is widely used in structural engineering. In the present study, high strength steel is defined as yield stress of the material greater than 460 MPa that implied in the context of the Eurocode EN 1993-1-12 [1], where specified design rules for steel structures with steel grade greater than 460 MPa and up to 700 MPa are provided.

The stiffness and strength of steel structural members may reduce in fire. The material properties at elevated temperatures have a crucial role in fire resistance design of steel structures. Material properties at elevated temperatures are provided in international specifications for steel structures such as the European Code (EC3) [2], American Specification (AISC Specification) [3], and Australian Standard (AS 4100) [4]. However, the material properties at elevated temperatures in these specifications are mainly based on experimental data of hot-rolled carbon steel with normal strength [5]. The investigation on material properties of high strength steel or cold-formed steel at elevated temperatures is limited. Chen et al. [5] investigated the material properties of hot-rolled high strength steel sheet BISPLATE 80 (measured 0.2% proof stress of 789 MPa at ambient temperature) at elevated temperatures using steady and transient state test methods, and the test results were compared with predictions from the American, Australian, British and European standards. Chen and Young [6] studied the behaviour of high strength steel columns at elevated temperatures using finite element analysis, and lower bond equations were proposed to predict the material properties of hot-rolled high strength steel at elevated temperatures. Qiang et al. [7–9] carried out experimental investigation on material properties of high strength steel grades S460, S690 and S960 with nominal yield stresses of 460, 690 and 960 MPa at ambient temperature, respectively, at elevated temperatures, and the

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Notation

E	elastic modulus at ambient temperature;
E_T	elastic modulus at temperature T °C;
$f_{0.2}$	0.2% proof stress at ambient temperature;
$f_{0.2,T}$	0.2% proof stress at temperature T °C;
$f_{0.5}$	stress at 0.5% strain at ambient temperature;
$f_{0.5,T}$	stress at 0.5% strain at temperature T °C;
$f_{1.5}$	stress at 1.5% strain at ambient temperature;
$f_{1.5,T}$	stress at 1.5% strain at temperature T °C;
$f_{2.0}$	stress at 2.0% strain at ambient temperature;
$f_{2.0,T}$	stress at 2.0% strain at temperature T °C;
f_u	ultimate strength at ambient temperature;
$f_{u,T}$	ultimate strength at temperature T °C;
k_E	retention factor for elastic modulus;
$k_{0.2}$	retention factor for 0.2% proof stress;
$k_{0.5}$	retention factor for stress at 0.5% strain;
$k_{1.5}$	retention factor for stress at 1.5% strain;
$k_{2.0}$	retention factor for stress at 2.0% strain;
k_u	retention factor for ultimate strength;
$k_{\varepsilon u}$	retention factor for ultimate strain;
$k_{\varepsilon f}$	retention factor for fracture strain;
ε_u	ultimate strain at ambient temperature;
$\varepsilon_{u,T}$	ultimate strain at temperature T °C;
ε_f	fracture strain at ambient temperature;
$\varepsilon_{f,T}$	fracture strain at temperature T °C.

test coupon specimens conducted by Qiang et al. [7–9] were all cut from 5 mm thick hot-rolled steel sheets. Coupon tests were also conducted by Wang et al. [10], Heidarpour et al. [11], Choi et al. [12], Chiew et al. [13] and Xiong and Liew [14] to study the material properties of high strength steel at elevated temperatures. The material properties of cold-formed steel at elevated temperatures were investigated by Outinen [15], Outinen and Mäkeläinen [16], Chen and Young [17,18], Ranawaka and Mahendran [19], Kankanamge and Mahendran [20], Chen and Ye [21], Kesawan et al. [22], McCann et al. [23] and Craveiro et al. [24]. However, investigation on material properties of cold-formed high strength steel with steel grade greater than 550 MPa at elevated temperatures is limited, which is the focus of the present study.

In this study, research efforts are focused on the material properties of cold-formed high strength steel at elevated temperatures. An experimental investigation to study the material properties of cold-formed high strength steel at elevated temperatures was conducted at the University of Hong Kong using both steady and transient state test methods. A total of 83 coupon specimens were extracted from cold-formed high strength steel square and rectangular hollow sections with measured 0.2% proof stresses ranged from 703 to 1024 MPa at ambient temperature. Tensile coupon specimens were loaded under 14 different nominal temperatures from ambient temperature up to 1000 °C in the steady state tests, while transient state tests were applied at various stress levels ranged from 0 (for the measurement of thermal elongation) to 1000 MPa. Material properties including thermal elongation, elastic modulus, yield stress, ultimate strength and ultimate strain obtained from the tests were compared with the design values in the existing design rules. Design curves to determine the deteriorationof material properties of cold-formed high strength steel at elevatedtemperatures are proposed in this study.

2. Experimental investigation

2.1. Test apparatus

An MTS 810 material testing machine was used to carry out the tensile coupon tests. An MTS Model 653.04 high temperature furnace which can heat specimens at a maximum rate of 100 °C/min up to 1400 °C was used as the heating device for the coupon tests at elevated temperatures as shown in Fig. 1. Heat was generated by three pairs of independent-controlled heating elements. Three internal thermocouples were located in three heating elements to measure the air temperature in the furnace. Two external thermocouples were mounted on the surface of the test specimens, one near each end of the reduced sections as required by the ASTM E 21 [25], to measure the real-time temperature of the specimens. For the tensile coupon tests at elevated temperatures, a calibrated MTS Model 632.54F-11 high temperature extensometer of 25 mm gauge length was used to measure the longitudinal strain of the coupon specimens. A data acquisition system was used to record the load, strain and temperatures at regular intervals during testing.

2.2. Test specimens

Tensile coupon specimens were extracted from three different cold-formed high strength steel square and rectangular hollow sections, namely, H50 × 100 × 4, H140 × 140 × 6 and V120 × 120 × 4. The letter "H" indicates the nominal 0.2% proof stress of the material at ambient temperature is 700 MPa, while the letter "V" indicates the nominal 0.2% proof stress at ambient temperature is 900 MPa. The nominal dimensions ($D \times B \times t$) of the sections are 50 × 100 × 4, 140 × 140 × 6 and 120 × 120 × 4, where D, B and t are the depth, width and thickness in millimetre of the cross-sections, respectively. The tensile coupon specimens were taken from the centre of the face at 90 degree angle from the weld, as shown in Fig. 2. The shapes and dimensions of coupon specimens were prepared in accordance with the ASTM E 21 [25] for tensile testing of metallic materials at elevated temperatures using 6 mm wide coupon of 25 mm gauge length as shown in Fig. 3 with units in millimetre.

The test specimens are labelled such that the test method, nominal 0.2% proof stress at ambient temperature, nominal thickness, and applied nominal temperature or stress level could be identified, as

Fig. 1. Test setup.