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Elevated temperature material properties of cold-formed steel hollow sections

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ABSTRACT

Elevated temperature material tests on cold-formed steel coupons cut from circular, rectangular and square hollow sections have been conducted, including both steady-state and transient-state tests. The experimental apparatus, methods of testing and results obtained are fully described. Temperature dependent retention factors for stiffness, strength and ductility were determined and compared to those provided in the European Standard EN 1993-1-2:2005 and the Australian Standard AS 4100:1998. It was found that the codified retention factors, despite being derived on the basis of tests on hot-finished material, are also applicable to cold-formed hollow sections. A design proposal from the literature for the prediction of ultimate strain has been also shown to be suitable for application to cold-formed hollow sections. A new expression for predicting strain at fracture has been proposed that provides a lower bound estimate of the test results derived in the current study.

1. Introduction

In recent years, a significant amount of research has been conducted into the behaviour and performance of steel structures in fire conditions. Reviews have been carried out of fire engineering research on columns and beams [1], composite structures [2], connections [3] and design approaches [4]. Findings arising from the research have been used to formulate and extend design codes such as the European Standard EN 1993-1-2 [5] and the Australian Standard AS 4100 [6].

Fire is now generally treated as a specific limit state for which a structure must be designed, as opposed to simply applying a prescribed level of fire protection [7]. A key effect that must be gauged when conducting analysis and design of steel, or composite steel-concrete, structures in fire is the loss of stiffness and strength of the material with increasing temperature, along with changes in ductility. Accurate assessment of elevated temperature material properties is essential for use in numerical parametric studies and in underpinning the development of fire design codes. In the present study, the full-range elevated temperature stress–strain response of cold-formed steel hollow sections is studied. In particular, although it is known that the mechanical properties of steel at room temperature are influenced by cold-work [8], it is not clear whether the elevated temperature properties of typical cold-formed steel hollow sections can still be presented as constant proportions of the room temperature values using the same retention factors as for hot-finished material. This will be explored for all key mechanical properties (i.e. relating to strength, stiffness and ductility).

There is extensive literature concerning the elevated temperature testing of steel material and structural elements. A variety of cold-formed steel products and grades, including S355 circular hollow sections (CHS) and rectangular hollow sections (RHS) were tested by [9,10]. Tests on cold-formed specimens of grades G450 and G550 steel were conducted by [11,12], while high-strength steel (S690) specimens were examined by [13]. A study [14] of the effects of elevated temperature on cold-formed Q345 steel provided empirical equations for retention factors for modulus of elasticity, yield strength and ultimate strength. A comparison between the results of the test programmes conducted by [9] and [12], together with the predictive models provided in EN 1993-1-2 [5], the ASCE manual [15] and proposed by [16], was made by [17]. A significant spread of experimental results, as well as some differences between the models themselves, was observed. In the present study, comparisons are made with the results of [9–11] since these tests were also performed on cold-formed material.

2. Experimental study

2.1. Introduction

In this section, an experimental study is described in which coupons cut from cold-formed S355 steel circular, square and rectangular

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Symbols

Latin script symbols

A_o original cross-sectional area
E_θ modulus of elasticity at temperature θ
$f_{0.2,\theta}$ 0.2% proof stress at temperature θ
$f_{2.0,\theta}$ stress at 2% strain at temperature θ
$f_{u,\theta}$ ultimate tensile strength at temperature θ
L gauge length
k_X retention factor for material property X

Greek script symbols

$\varepsilon_{f,\theta}$ fracture strain at temperature θ
$\varepsilon_{u,\theta}$ ultimate strain at temperature θ
θ temperature

hollow section (CHS, SHS and RHS, respectively) members have been tested at elevated temperatures. Two testing methods were employed – steady-state (isothermal) and transient-state (anisothermal). In the steady-state tests, the coupons were heated to a target temperature that was held constant while the coupon was subjected to an increasing axial tensile load until fracture. In the transient-state tests, the coupons were loaded with a tensile stress that was maintained constant while the coupon was heated until fracture. Steady-state tests enable stress–strain curves, which are suitable for use in numerical models, to be obtained directly, while transient-state tests more closely mimic the conditions to which material would be subjected to in a structure under fire conditions, i.e. static load followed by increasing temperature. Values were obtained for the following temperature-dependent material properties, where θ is temperature,

- Modulus of elasticity, E_θ
- Yield strength (0.2% proof strength), $f_{0.2,\theta}$
- Strength at 2% strain, $f_{2.0,\theta}$
- Ultimate stress, $f_{u,\theta}$
- Ultimate strain, $\varepsilon_{u,\theta}$
- Strain at fracture, $\varepsilon_{f,\theta}$

These properties are illustrated in Fig. 1. From the test results, temperature-dependent retention factors were calculated for each of the material properties, which are compared later in Section 5 with existing experimental results, code provisions and predictive models from the literature.

2.2. Test apparatus

The test apparatus, located in the Structures Laboratory of the Department of Civil and Environmental Engineering at Imperial College London, is shown in Fig. 2. It comprised an Instron 750 hydraulic testing machine, an electric furnace capable of heating to temperatures up to 1100 °C, a heat control unit with temperature probes which were inserted into the furnace, thermocouples attached to the test specimens, rock-wool insulation at either end of the furnace and an extensometer. The extensometer, shown in Fig. 3, comprised two clamps fixed to the specimen with pointed bolts, two invar rods, a contact plate and a linear variable differential transducer (LVDT). The machine load, machine displacement, LVDT displacement and thermocouple readings were recorded using the DATASCAN data acquisition equipment and logged using the DSLOG computer package at a frequency of 1 Hz.

2.3. Test specimens

The test specimens were all extracted from cold-formed grade S355J2H steel hollow section members produced according to EN 10219-1 [18]. The cross-sections of the members and the number of tests conducted are summarised in Table 1.

Each coupon had an overall length of 800 mm, with the central 600 mm having a nominal width of 20 mm. In order to ensure that the coupons failed within the gauge length (thus providing full stress–strain curves up to fracture), the test pieces were narrowed by a further 2 mm in this region. The extensometer was aligned with the centre of the furnace to ensure that the length of coupon being measured coincided with the region of the furnace at the target test temperature. Standard gauge lengths of $L = 5.65\sqrt{A_o}$, where A_o is the original cross-sectional area of the coupons in the narrowed region, were also marked onto the specimens for the calculation of the fracture strain after testing.

2.4. Testing methods

As mentioned in Section 2.1 and described in the following sub-sections, two complementary elevated temperature material testing methods were employed in the programme. All tests were conducted in accordance with ISO 6892 Parts 1 and 2 [19,20], following the prescribed heating rates and loading rates.

2.4.1. Steady-state (isothermal) tests

In the steady-state tests, the specimens were heated up to the target temperature at a rate of 10 °C/min. Typically, a period of 10 to 15 min was allowed after the heating phase for the temperature to settle. The target temperatures ranged from room temperature to

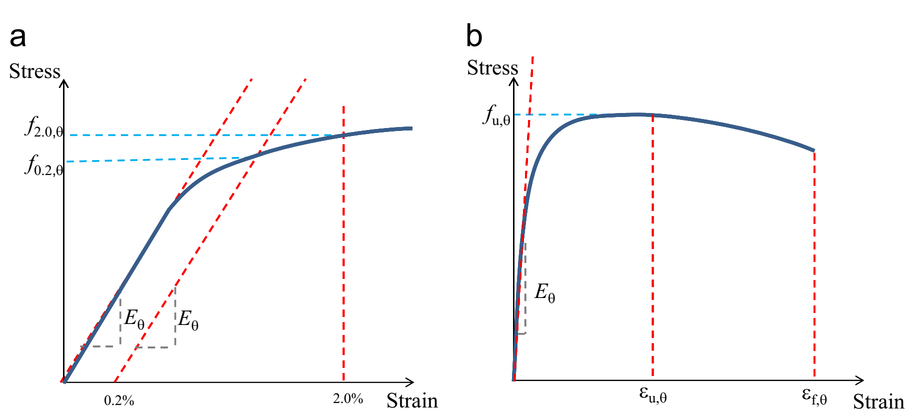

Fig. 1. Definition of measured elevated temperature material properties.