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Comparative experimental study of hot-rolled and cold-formed rectangular hollow sections

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ABSTRACT

Square and rectangular hollow sections are generally produced either by hot-rolling or cold-forming. Cross-sections of nominally similar geometries, but from the two different production routes may vary significantly in terms of their general material properties, geometric imperfections, residual stresses, corner geometry and material response and general structural behaviour and load-carrying capacity. In this paper, an experimental programme comprising tensile coupon tests on flat and corner material, measurements of geometric imperfections and residual stresses, stub column tests and simple and continuous beam tests is described. The results of the tests have been combined with other available test data on square and rectangular hollow sections and analysed. Enhancements in yield and ultimate strengths, beyond those quoted in the respective mill certificates, were observed in the corner regions of the cold-formed sections—these are caused by cold-working of the material during production, and predictive models have been proposed. Initial geometric imperfections were generally low in both the hot-rolled and cold-formed sections, with larger imperfections emerging towards the ends of the cold-formed members—these were attributed largely to the release of through thickness residual stresses, which were themselves quantified. The results of the stub column and simple bending tests were used to assess the current slenderness limits given in Eurocode 3, including the possible dependency on production route, whilst the results of the continuous beam tests were evaluated with reference to the assumptions typically made in plastic analysis and design. Current slenderness limits, assessed on the basis of bending tests, appear appropriate, though the Class 3 slenderness limit, assessed on the basis of compression tests, seems optimistic. Of the features investigated, strain hardening characteristics of the material were identified as being primarily responsible for the differences in structural behaviour between hot-rolled and cold-formed sections.

1. Introduction

Structural hollow sections are widely used in a range of engineering applications, offering structural efficiency, aesthetic solutions and the possibility of being concrete-filled to achieve greater load-carrying capacity. There are a variety of means of producing square and rectangular hollow sections (SHS and RHS, respectively), the principal two being hot-rolling and cold-forming, with two further, less common alternative techniques involving welding two channel sections tip-to-tip or welding four flat plates at their corners. Cold-formed sections may be subsequently stress relieved. It therefore follows that SHS and RHS of nominally similar geometries may exhibit different structural characteristics owing to the different strain histories and thermal actions that may be experienced during production.

Hot-rolling of structural steel sections is generally carried out above the re-crystallisation temperature of the material (typically around 850 °C) in accordance with EN 10210-1 [1]; the resulting sections have homogeneous material properties, consistent hardness, good ductility and relatively low residual stresses. Tight corner radii, which often facilitate welding between members, can also be achieved [2]. Conversely, cold-formed sections are produced at ambient temperatures in accordance with EN 10219-2 [3], and undergo plastic deformation during forming. Plastic deformation causes cold-working of the material, resulting in enhanced strength, but a corresponding loss of ductility. Non-homogeneity of material properties and variation in hardness around the section typically arise due to the uneven levels of plastic deformation experienced during forming; the corner regions of cold-formed sections, in particular, undergo high levels of cold-work, and larger corner radii are specified in EN 10219-2 to avert corner cracking. Also associated with non-uniform plastic deformation is the formation of residual stresses—in cold-formed structural sections, these generally appear as through-thickness bending residual stresses, as discussed later in this paper.

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Further information on the properties and behaviour of cold-formed sections can be found in [4].

Overall, disparities between hot-rolled and cold-formed hollow sections may be observed in material properties, geometric imperfections, residual stresses, corner geometry and material response as well as the general structural behaviour and load-carrying capacity of the produced sections. A comparative study of these characteristics is presented herein.

Direct comparisons between hot-rolled and cold-formed structural steel sections are relatively scarce, but many of the above properties have been studied in hot-rolled steel sections [5–7], cold-formed steel sections [8–11] and cold-formed stainless steel sections [12–15]. The influence of different production routes on the behaviour of structural carbon steel [16] and structural stainless steel [17–19] members, which tend to display a more pronounced response to cold-work, has also been investigated. In this paper, a series of investigations are described to highlight the distinctions between hot-rolled and cold-formed steel box sections.

2. Experimental investigation

2.1. Test specimens

An experimental programme comprising tensile coupon tests on flat and corner material, measurements of geometric imperfections and residual stresses, stub column tests and simple and continuous beam tests was carried out to investigate the structural behaviour of hot-rolled and cold-formed square and rectangular hollow sections (SHS and RHS, respectively). All tests and measurements were performed in the Structures Laboratory of the Department of Civil and Environmental Engineering at Imperial College London.

A total of ten structural hollow sections were examined—five hot-rolled and five cold-formed of the following nominal section sizes-100 × 100 × 4, 60 × 60 × 4, 60 × 40 × 4, 40 × 40 × 4 and 40 × 40 × 3. The nominal yield strength of the hot-rolled tubes was 355 N/mm^2 while that of the cold-formed tubes was 235 N/mm^2. Ten flat and six corner tensile coupons together with 20 stub columns were tested. Geometric imperfections were measured along the centrelines of the four faces of all 20 stub columns, whilst residual stresses were quantified from the flat and corner coupons, which were subsequently subjected to tensile testing.

2.2. Tensile coupon tests

The basic stress–strain properties of the investigated hot-rolled and cold-formed sections were obtained through tensile coupon tests. These tests were conducted in accordance with EN 10002-1 [20]. For each of the ten SHS and RHS specimens, one flat parallel coupon was machined from the face opposite to the weld. Corner coupons were also extracted and tested for each of the five cold-formed sections in order to examine the influence of the high localised cold-work, and for one of the hot-rolled sections to confirm uniformity of properties. Fig. 1 shows the location of the flat and corner tensile coupons extracted from the hot-rolled and cold-formed box sections for this study, together with the adopted dimension labelling system.

The nominal dimensions of flat coupons were 350 × 15 mm for the smaller cross-section sizes (40 × 40 × 4 mm and 40 × 40 × 3 mm) and 320 × 20 mm for the larger cross-sections. All tensile tests were performed using an Amsler 350 kN hydraulic testing machine. Linear electrical strain gauges were affixed at the midpoint of each side of the tensile coupons and a series of overlapping proportional gauge lengths was marked onto the surface of the coupons to determine the elongation at fracture. Load, strain, displacement and input voltage were all recorded using the data acquisition equipment DATASCAN and logged using the DALITE and DSLOG computer packages.

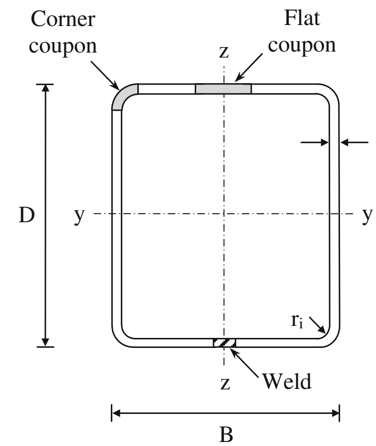

Fig. 1. Section labelling convention and location of flat and corner tensile coupons.

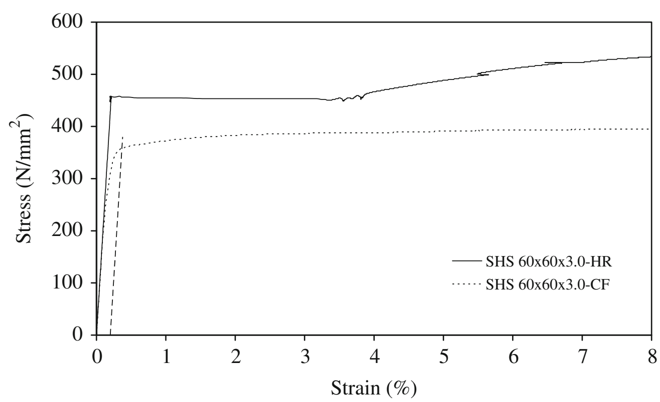

Fig. 2. Typical stress–strain curves from hot-rolled and cold-formed tensile coupons (SHS 60 × 60 × 3).

Typical measured stress–strain curves from hot-rolled and cold-formed material (SHS 60 × 60 × 3-HR and SHS 60 × 60 × 3-CF) are shown in Fig. 2, with the hot-rolled material displaying the anticipated sharply defined yield point, yield plateau and subsequent strain hardening whilst the cold-formed material exhibited a more rounded response. The key results from all tensile coupon tests, together with the corresponding mill certificate (virgin) material properties, are given in Table 1. The specimens were labelled according to their different section geometries and production routes (HR=hot-rolled and CF=cold-formed), while a ‘C’ was appended to the specimen designation to indicate corner coupon. In Table 1, σ_y and σ_u refer to the yield and ultimate strengths of the material, respectively, E denotes Young’s modulus and ε_f is the plastic strain at fracture. For the hot-rolled sections a distinct yield stress was observed (with the lower yield stress being reported in Table 1), but for the cold-formed sections the yield stress was taken as the 0.2% proof stress (as marked in Fig. 2).

2.3. Geometric imperfection measurements

Measurements of local geometric imperfections were performed on all four faces of 20 stub columns—two specimens for each of the ten box sections. The experimental set-up for the