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Numerical modelling and design of hot-rolled and cold-formed steel continuous beams with tubular cross-sections

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A B S T R A C T

The structural behaviour and design of hot-rolled and cold-formed steel continuous beams with square and rectangular hollow sections are studied in the present paper, with a focus on the beneficial effects of material strain hardening and moment redistribution. Finite element (FE) models were first developed and validated against existing test results on hot-rolled and cold-formed steel square and rectangular hollow section continuous beams. Upon validation against the experimental results, parametric studies were carried out to expand the available structural performance data over a range of cross-section geometries, cross-section slendernesses, steel grades and loading conditions. Representative material properties and residual stress patterns were incorporated into the FE models to reflect the two studied production routes – hot-rolling and cold-forming. The experimental results, together with the parametric numerical results generated herein, were then used to evaluate the accuracy of the design provisions of EN 1993-1-1 (2005) as well as the continuous strength method (CSM) for indeterminate structures, the latter of which is extended in scope in the present study. It was shown that the current provisions of EN 1993-1-1 (2005) for the design of hot-rolled and cold-formed steel continuous beams are rather conservative, while the proposed CSM yields a higher level of accuracy and consistency, due to its rational consideration of both strain hardening at the cross-sectional level and moment redistribution at the global system level. Finally, statistical analyses were carried out to assess the reliability level of the two design methods according to EN 1990 (2002).

1. Introduction

Square and rectangular hollow sections (SHS and RHS, respectively) are widely used across a range of applications within the construction industry, owing principally to their favourable structural properties, inherent aesthetic advantages and ease of prefabrication and mass production. These sections are manufactured following one of two main production routes: hot-rolling and cold-forming. Hot-rolled hollow sections are produced or finished at temperatures above the recrystallization temperature, while cold-formed hollow sections are manufactured at room temperature and undergo significant plastic deformation during the fabrication process. The different production routes lead to significant differences in both the material stress-strain characteristics and residual stresses that arise in the final cross-sections. Hot-rolled steel sections typically exhibit linear elastic material behaviour up to the yield stress and a yield plateau before strain hardening is encountered [2], while cold-formed steel sections have a more rounded stress-strain response with an increased yield strength over the unformed material, but reduced ductility [3]. Residual stresses in hot-rolled hollow sections are generally of low magnitude due to the relatively uniform cooling associated with the regular geometry and constant thickness of tubular sections. For cold-formed hollow sections, the formation of residual stresses is largely associated with non-uniform plastic deformation during the section production process, causing predominantly through-thickness bending residual stresses around the cross-section. Detailed information on the mechanical properties, residual stress distributions and structural performance of hot-rolled and cold-formed SHS and RHS can be found in [4–8].

For cross-section design, hot-rolled and cold-formed SHS and RHS are generally treated in the same manner in existing steel design specifications (e.g. EN 1993-1-1 [1] and AISC 360-16 [9]) using an elastic-perfectly plastic material model, without considering the differences in their material properties. The current design codes adopt the concept of cross-section classification, and classify cross-sections into discrete behavioural classes based upon the susceptibility of the most slender plate element in the cross-section to local buckling. For the design of indeterminate steel structures, the European code EN 1993-1-1 [1] considers moment redistribution by allowing plastic design to be used for

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structures with Class 1 cross-sections, which are assumed to have sufficient rotation capacity required from plastic analysis without reduction of their resistances, but plastic design is not currently permitted for structures with higher cross-section classes. The existing design approaches are often found to be conservative in estimating the cross-section resistances of stocky hot-rolled and cold-formed steel SHS and RHS [4,10–14], due to the neglect of the beneficial strain hardening effect, and also create discontinuous steps in the capacity predictions of indeterminate structures at boundaries between different classes, owing to the limitations of the conventional classification system (e.g. limiting the cross-section bending resistance to the plastic moment capacity M_{pl} for Class 1 or Class 2 sections and the elastic moment capacity M_{el} for Class 3 sections, and allowing full moment redistribution for structures with Class 1 sections but no moment redistribution for structures with higher class sections). It is therefore considered necessary to develop more efficient and accurate design approaches for indeterminate structures that can rationally account for strain hardening effects at the cross-sectional level and moment redistribution at the global system level.

The continuous strength method (CSM) is a deformation based design approach that provides an alternative treatment to cross-section classification and enables the effective exploitation of strain hardening [15]. The CSM has recently been extended to the design of stainless steel and aluminium alloy continuous beams [16–19], and shown to provide more accurate and consistent capacity predictions. The purpose of the present paper is to investigate the feasibility of applying the CSM to hot-rolled and cold-formed steel continuous beams, based on the recent CSM proposals for hot-rolled and cold-formed steel cross-sections under isolated loading (i.e. pure compression and pure bending) [11,12]. Finite element (FE) models, considering the different characteristics (i.e. material stress-strain properties and residual stress patterns) of hot-rolled and cold-formed steel sections, were first developed and validated against the results of the hot-rolled and cold-formed steel continuous beam tests conducted by Gardner et al. [4]. Secondly, an extensive parametric study was carried out to generate additional structural performance data for hot-rolled and cold-formed steel continuous beams with a range of cross-section geometries, cross-section slendernesses, steel grades and loading conditions. The design provisions of EN 1993-1-1 [1] and the proposed CSM for indeterminate structures were then assessed based on the results of the parametric study, together with the collected experimental data. Finally, the applicability and reliability of the proposed CSM for hot-rolled and cold-formed steel continuous beams are evaluated by means of statistical analyses.

2. Summary of previous experimental investigation

The experimental investigation conducted by Gardner et al. [4], which reported a total of 12 test results on hot-rolled and cold-formed steel continuous beams with square and rectangular hollow sections (SHS and RHS, respectively), is summarized in this section and used for validation of the finite element (FE) model and the assessment of design proposals in Sections 3–5. The experimental programme consisted of 12 continuous beam tests on specimens with three different nominal cross-section sizes; for each cross-section size, two hot-rolled and two cold-formed specimens were tested. Table 1 summarizes the measured geometric properties of the test specimens using the symbols illustrated in Fig. 1, where H is the height of the section, B is the width of the section, t is the thickness of the section, r_i is the inner corner radius and $h = H - 2t - 2r_i$ and $b = B - 2t - 2r_i$ are the flat width of flange and web, respectively. In Table 1, the specimens are labelled according to their cross-sectional shape, cross-sectional dimensions, production routes and specimen number. For example, the label RHS 60 × 40 × 4 HR1 defines an RHS with nominal cross-sectional dimensions of height H (60 mm) × width B (40 mm) × thickness t (4 mm), and it is the first of the two hot-rolled (HR) test specimens. Note that the letters “CF” in the labels indicate a cold-formed specimen.

The material properties of the investigated hot-rolled and cold-formed sections were determined by tensile coupon tests. Flat coupons were taken from the centre of the face opposite to the weld in the longitudinal direction of all specimens. For the cold-formed sections, corner coupons were also extracted and tested in order to characterize the material properties in the corner regions, where strength enhancements arise due to the large plastic deformations experienced during the manufacturing process. A summary of the measured tensile material properties for each cross-section size is given in Table 2, where E is the Young's modulus, f_y is the material yield strength (taken as the 0.2% proof stress for the cold-formed steel), f_u is the ultimate tensile strength and ε_f is the strain at fracture measured over the standard gauge length. As expected, a sharply defined yield point, followed by a yield plateau and a moderate degree of strain hardening, was observed in the hot-rolled steel coupon tests, while a rounded stress-strain response with no sharply defined yield point was observed for the cold-formed material.

The beam specimens were 2400 mm in length and were continuously supported over two equal spans of 1100 mm each (i.e. equal to $L_1 + L_2$), as shown in Fig. 2. The loads were applied symmetrically at two points through steel loading plates within the span, using a spreader beam (see Fig. 2). According to the position of the applied loads along the continuous beam specimens, two five-point bending test configurations were employed in the experimental programme. The first five-point bending configuration is designated “1/3 Span” in Table 1, where the concentrated loads were applied at a distance of one-third of the span from the centre support (i.e. $L_1 = 733.3$ mm and $L_2 = 336.7$ mm), while in the second configuration, designated “1/2 Span” in Table 1, the continuous beams were subjected to concentrated mid-span loads (i.e. $L_1 = L_2 = 550$ mm). The different loading conditions were adopted in order to evaluate the influence of moment gradient, sequence of hinge formation and different plastic hinge rotation demands, on the performance of hot-rolled and cold-formed steel continuous beams. Steel rollers were employed beneath steel loading plates to allow free rotation about the axis of bending at the beam ends and central support, and wooden blocks were inserted into the tubular specimens at the loading points and central support to prevent web crippling due to the localised point loading. The applied load, vertical displacement at the loading points and rotations at the beam ends and central support were measured and detailed in Gardner et al. [4].

3. Numerical investigation

A numerical modelling study of hot-rolled and cold-formed steel SHS and RHS continuous beams was also conducted, using the nonlinear FE analysis package ABAQUS [20]. The results of the 12 continuous beam tests summarized in the previous section were initially used to validate the developed FE models, which were subsequently employed in a comprehensive parametric study to expand the available experimental database over a wider range of cross-section geometries, cross-section slendernesses, steel grades and loading configurations. Finally, the data generated through the parametric study together with the experimental results were used to evaluate the accuracy of existing and proposed design approaches for continuous beams.

3.1. Modelling assumptions

The four-noded doubly curved shell element with reduced integration and finite membrane strains, designated S4R [20], was selected as the element type in the present study, which has been successfully employed in previous numerical studies on hot-rolled and cold-formed steel tubular sections [11,12]. A mesh convergence study was carried out to obtain an optimum mesh size which provides reliable FE results at reasonable computational costs. Consequently, an element size equal to one twentieth of the width of the most slender plate (i.e. the