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Experimental and numerical study of stainless steel I-sections under concentrated internal one-flange and internal two-flange loading

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ABSTRACT

The behaviour and design of stainless steel I-section beams under concentrated transverse loading are investigated in this study. Twenty-four experiments on stainless steel I-sections, formed by the welding of hot-rolled plates, were performed. The tests were conducted under two types of concentrated transverse loading – internal one-flange (IOF) and internal two-flange (ITF) loading. The experimental set-up, procedure and results, including the full load-displacement histories, ultimate loads and failure modes, are reported. A complementary nonlinear finite element modelling study was also carried out. The models were first validated against the results of the experiments. A parametric investigation into the influence of key parameters such as the bearing length, web slenderness and level of coexistent bending moment, on the structural response was then performed. Finally, an assessment of current design provisions for the resistance of stainless steel welded I-sections to concentrated loading is presented. The results show that the current design formulae yield safe-sided, but generally rather scattered and conservative capacity predictions, with considerable scope for further development.

1. Introduction

Structural steel members under concentrated transverse loading are encountered in a wide range of situations – examples include primary girders at bearing supports, primary beams under roof purlins, columns in beam-to-column connections [1] and bridge girders during their launching phase [2,3]. Members under concentrated transverse loading are subjected to non-uniform stress distributions, complex edge restraint conditions between the web and flanges, and local yielding beneath the load [4]. Taken together, these render the development of analytical formulations able to predict accurately the ultimate resistances of members under concentrated loading non-trivial. Even analytical models for the key reference points of the elastic buckling load and plastic collapse load [5,6], which can be used to predict ultimate resistance, are still complex, and numerical techniques are often necessary for their accurate determination [7,8].

Experimental investigations carried out to determine the ultimate bearing resistances of steel members under concentrated transverse loading date back to 1946, when the first tests on cold-formed carbon steel members were reported by Winter and Pian [9]. Such tests have since been performed on cold-formed carbon steel members with different cross-section shapes, including I-sections, C-sections, Z-sections, hat-sections, deck sections, and hollow sections [10–14], on members with and without flange restraints [15–18], and web openings [19–21], and on cold-formed stainless steel members [22–25]. Numerical studies on cold-formed stainless steel members have also been performed [23,26–28]. Tests on cold-formed members are often referred to as *web crippling tests* due to the failure mode exhibited during the experiments. A substantial number of tests has also been carried out on hot-rolled and welded I-section members with slender [29,30] and stocky webs [31], considering different bearing lengths [32–34] coincident bending moments [35,36] and including sections made of high strength steel [37]. There exist, however, very few tests on welded stainless steel I-section members subjected to concentrated transverse loading [38].

The structural performance of stainless steel members under concentrated transverse loading is the focus of the present study. Two types of concentrated transverse loading are considered: (i) internal one-flange loading resulting in failure beneath a single concentrated load away from the beam end, and (ii) internal two-flange (ITF) loading, leading to failure between two concentrated loads applied at opposite flanges away from the beam end. An experimental investigation involving twenty-four physical tests to

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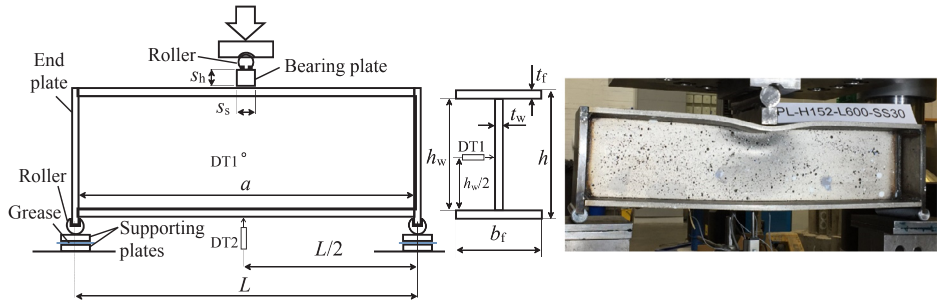


(a) Schematic setup (b) Test setup

Fig. 1. Experimental setup for IOF specimens.

examine the influence of different bearing lengths and bending moments on the ultimate resistance of stainless steel beams under IOF and ITF loading is first presented. Following this, numerical models, validated against the results of the physical experiments, are used to generate further data across a broad range of practical cases. Finally, the experimental and numerical results are employed to assess the accuracy of existing design provisions [39,40] for the design of stainless steel members under concentrated transverse loading.

2. Experimental investigation

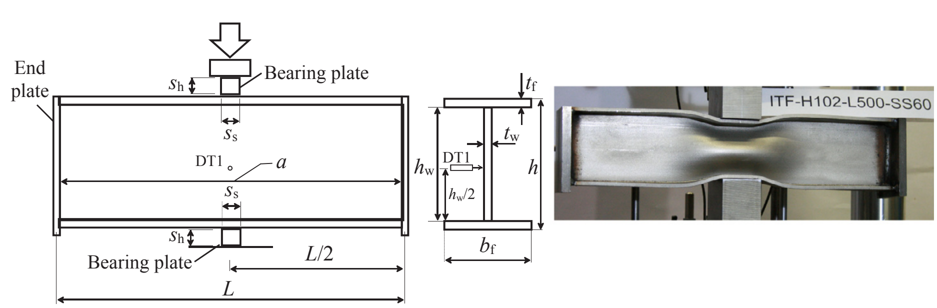
Sixteen internal one-flange (IOF) loading tests and eight internal two-flange (ITF) loading tests were carried out to assess the web bearing strengths of stainless steel I-section members. The specimens were fabricated from hot-rolled stainless steel plates which were laser-welded in accordance with EN ISO 13919-1 [41]; the quality level was Class B (stringent). Four cross-section sizes were examined: (i) I 102 × 68 × 5 × 5, (ii) I 152 × 160 × 6 × 9, (iii) I 150 × 75 × 7 × 10, and (iv) I 160 × 82 × 10 × 12. The cross-sections were formed from austenitic stainless steel of different grades: Grade EN 1.4571 for the first two cross-sections, Grade EN 1.4404 for the third and Grade EN 1.4307 for the fourth. The IOF tests, the setup for which is shown in Fig. 1, were performed on three different cross-section sizes with different bearing lengths and a range of spans, while the ITF tests, the setup for which is depicted in Fig. 2, were carried out on two different cross-section sizes with different bearing lengths. Both test series were designed to cover a range of structural responses and isolate the influence of the key parameters. The adopted test labelling system identifies the loading type (IOF or ITF), and the nominal cross-section height (102 mm, 150 mm, 152 mm, or 160 mm), specimen length (from 300 mm to 750 mm) and bearing length s_s (from 5 mm to 100 mm); for example, IOF-H102-L500-SS20 indicates a member under IOF loading with a cross-section height of 102 mm, a length of 500 mm and a bearing length of 20 mm. In the following subsections, the member tests, together with the accompanying material coupon tests and geometric imperfection measurements, are reported.

2.1. Material testing

A comprehensive characterization of the tensile stress-strain properties of the cross-sections tested herein can be found in Gardner et al. [42]; in this section, a brief summary is provided. All the tensile coupon tests were performed according to EN ISO 6892-1 [43], using an Instron 8802 250 kN hydraulic testing machine. The coupons were extracted from the longitudinal direction of the members. For cross-sections comprising plates of the same thickness, a single coupon test was performed, while for those fabricated from plates of different thicknesses, two coupon tests (one from the web and one from the flanges) were carried out. A summary of the measured tensile material properties for each cross-section size is given in Table 1, where E is the Young's modulus, f_y is the 0.2% proof stress, $f_{1.0}$ is the 1% proof stress, f_u is the ultimate tensile stress, ε_u is the strain the at ultimate stress, and ε_f is the strain at the fracture, measured over the standard gauge length.

2.2. Geometric dimensions and imperfection measurements

Prior to the member tests, the dimensions and geometric imperfections of the specimens were measured. The initial imperfection measurements were taken using the setup shown in Fig. 3, following a similar procedure to that employed by Schafer and Pekoz [44] and Zhao et al. [45]. A Linear Variable Displacement Transducer (LVDT) was attached to the head of a milling machine, while the specimens were secured to the moving machine bed. The LVDT was utilised to measure the variation in the out-of-plane



(a) Schematic setup (b) Test setup

Fig. 2. Experimental setup for ITF specimens.