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Flexural–torsional buckling of ultra light-gauge steel storage rack uprights

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ABSTRACT

This paper presents an experimental investigation into the behaviour of ultra light-gauge steel storage rack uprights subjected to compression. Two different types of members with varying lengths are tested and while the combined effects of local and distortional buckling are investigated, special attention is given to longer specimens that fail by flexural–torsional buckling in combination with local and distortional buckling. Deformations experienced during testing by all of the specimens were measured and observations regarding failure modes have been documented. In addition, the geometric imperfections of each member were measured before testing, as were the material properties of the cold-rolled sections and the virgin steel from which the sections were formed. This paper details the observed failure modes, the recorded ultimate strengths and the load-deflection responses. Design capacities calculated from AS/NZS 4084 (2012) [1], RMI (2012) [2] and EN 15512 (2009) [3] specifications are then evaluated and compared to the experimental results obtained.The evaluation of international specificationsdetermined that EN 15512 (2009) [3] is more accurate in predicting ultimate loads of sections undergoing interactive buckling than both AS/NZS 4804 (2012) [1] and RMI (2012) [2].

1. Introduction

Thin-walled cold-formed steel sections are increasingly being used as structural members in light-gauge steel structures due to their high strength-to-weight ratio and efficient use of material. However, due to their reduced wall thickness, thin-walled cold-formed steel sections are prone to local and distortional buckling as well as overall buckling. Although local and/or distortional buckling may be followed by a significant post-buckling reserve, the deformations and redistribution of stresses associated with the post-buckling reserve strength changes the global buckling response and strength of the member [4]. The interaction between these buckling modes makes the prediction of the member strength more complex.

While a large amount of research has been conducted on single buckling modes (local, overall and distortional) for light-gauge steel sections [5,6] and the interaction between distortional and overall buckling [7], little attention has been given to the interaction between all three buckling modes and the subsequent effect on member strength [8]. Furthermore, while a number of researchers [9–11] have conducted experimental studies or numerical analysis [12–14] on cold-formed steel storage rack uprights and systems [15–17], none of these have been on ultra light-gauge sections that fail by the interaction of all three buckling modes. Ultra light-guage sections may be defined as members that have a thickness of less than or equal to 1 mm.

This paper aims to make experimental data available on thin-walled cold-formed steel sections which fail by the interaction of local, distortional and overall buckling. As a result, this data will provide the basis for further research into the effects of interactive buckling across all three modes, verification of finite-element models for parametric studies and an investigation into the characterisation of imperfections and their effect on the section strength.

Two different types of ultra light-gauge steel storage rack members with varying lengths were tested. The two types of sections tested were the 90 mm wide rear-flange (RF90.1) and standard (SD90.1) upright sections both of which were specially rolled for these experiments and were nominally 1.0 mm thick. A total of 16 tests were completed at the University of Sydney using ‘The J.W. Roderick Laboratory for Materials and Structures’.

For each of the two types of uprights, three different lengths were tested that approximately corresponded to overall section slenderness ratios of 0.5, 1 and 1.5 about the major *x*-axis. These slenderness values were chosen to ensure that local and distortional buckling would occur well before overall buckling occurred so the effect of buckling mode interaction could be determined for various slenderness ratios. Based on the experimental data collected, ultimate design capacities from the AS/NZS 4084 [1], RMI [2] and EN 15512 [3] international design specifications have been compared and evaluated.

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2. Section geometry and material properties

2.1. Specimen geometry

The uprights consisted of nominally 1.0 mm thick, 90 mm wide rear-flange (RF90.1) and standard (SD90.1) upright sections. The sections were cold-rolled from G550 galvanised strip with a guaranteed minimum proof stress of 550 MPa. These uprights are typically only commercially available in 1.5, 1.9 or 2.4 mm thicknesses. However, the specimens were specially rolled at Dematic [18] with a nominal 1.0 mm thickness, ensuring prominent local and distortional buckling would occur before overall buckling was intiated. The measured thickness of the SD and RF sections after the galvanising layer had been removed was 0.99 mm and 0.98 mm respectively. Both uprights had pairs of 14.3 mm wide, 42.4 mm long diamond perforations running vertically down the web of the section for beam connections and 10.4 mm diameter circular perforations on the flange used for bolted diagonal connections. Fig. 1a and b below details all the nominal dimensions of both uprights while Fig. 1c shows the perforation details. More information regarding the sections' geometric properties may be found in [19].

2.2. Labelling and conventions

Each of the tests completed was given a unique identifier. Specimens were first identified by their type of upright, followed by the type of test that was being completed, their nominal lengths and finally by the number of tests being completed. The upright types 'Standard Flange' and 'Rear Flange' are identified using SD and RF respectively. Likewise, for the type of test being completed, S and FT refer to stub and flexural–torsional test types. For example, specimen SD-S-300-2 refers to the second stub column test of a nominal 300 mm length standard flange upright.

Fig. 2a displays the sign conventions used for the top and bottom rotations and lateral overall displacements. For local displacements, movement away from the centroid of the cross-section was always positive. Fig. 2b displays the terms used for different parts of the cross-section and Fig. 2c indicates the postive x-axis and y-axis sign conventions used when describing displacements of the cross-section.

2.3. Material properties of flat plate

In order to accurately determine the properties of the material, both compression and tension coupon tests were conducted in accordance with AS 4600 [20] and AS/NZS 1391 [21]. Compression coupon tests were conducted to determine if there was any difference in stress–strain behaviour derived from the tensile coupon tests. A similar method for the compression coupons had previously been used by Lecce and Rasmussen [22]. Full details of the coupon tests may be found in [19].

Two tensile coupons were cut longitudinally from a flat length of each steel coil and another three were cut from the flange of the formed uprights. All the coupons were tested to failure using a 40 mm gauge extensometer and also fitted with strain gauges on each side of the narrow parallel length. The strain gauges were used to accurately measure Young's modulus by loading and unloading the coupon twice in the elastic range. All the coupons were tested in a 300 kN capacity MTC Sintech testing machine with a strain rate of 2.78×10^{-4}/s. Table 1 summarises the ultimate tensile strength (f_u), Young's modulus (E) and yield stress (f_y), the latter obtained as the 0.2% proof stress for the tensile tests completed from coupons cut from the virgin sheet. Static material properties are reported, obtained by pausing the test for a minimum of two minutes at the yield and ultimate tensile stresses. Comparing the tension and compression coupon test results, there is only a minor variation (less than 4%) in both the yield stress and Young's modulus of each section. A similar minor difference was found between the values of yield stress and Young's modulus obtained for the virgin flat steel coupons and the coupons cut from the formed sections, [19].

The effect of 'bending' residual stresses were implicitly considered when the stress strain curve was obtained from the coupon tests. As each coupon was clamped straight into the jaws of the testing machine, the bending residual stresses were effectively re-introduced into the coupons during material testing. On the other hand, experiments [23,24] have shown that 'membrane' residual stresses introduced by cold-forming are small, and generally ignored in analytical studies [25,26]. For this reason, the residual stresses introduced during the forming (rolling) processes were ignored in the current study.

2.4. Stub column tests

The perforations in storage rack uprights reduce their bending and axial capacities. The majority of guidelines for steel storage racks [1,2,3] therefore require compression testing of stub columns. Stub column tests in this investigation were designed to adhere with AS/NZS 4600 [20].

Three SD90.1 and RF90.1 upright specimens were tested using a 300 kN capacity MTS Sintech testing machine. The ends of the stub column were milled flat to a tolerance of 0.025 mm, perpendicular to the longitudinal axis of the upright. The axial load was applied by the Sintech machine, which had a fixed lower platen and a cross-head mounted on a half-sphere bearing. The half-sphere bearing meant the cross-head could rotate, ensuring that there was always full contact between the platen and milled ends of the specimen. For each of the tests, a cross-head speed of 0.1 mm/min was used to determine the static peak loads.

Table 2 shows the ultimate static loads supported by each specimen as well as the Q-factor calculated as the ratio between the ultimate load (P_u) and the minimum net area ($A_{net-min}$). Average Q-factors of 0.686 and 0.823 were determined for the SD90.1 and RF90.1 uprights respectively.

3. Imperfection measurements

3.1. Imperfection laser rig

As imperfections have a profound effect on the capacity of sections undergoing interactive buckling, accurate imperfection measurements were taken for each of the specimens. To characterise the imperfections, and to have an appreciation of their shape and magnitude longitudinally, measurements were taken on the edges and centrelines of component plates at closely spaced points along the member.

A laser rig was constructed to measure imperfections along eight lines parallel to the longitudinal axis for each of the RF and SD specimens. For both types of specimens, readings were taken on flat sections at least 3 mm from corners and perforations. Fig. 3 details the location and number of each of the laser lines for both the RF and SD sections.

The position of each of the laser lines was carefully selected to ensure the imperfections could be broken down into the critical buckling modes. Lasers 3 and 5 were used to determine the global vertical translation of the section in the plane of symmetry. Laser 6 indicated a global horizontal translation of the section while Laser 4 was used to determine the inward or outward local imperfections of the web. Lasers 2 and 7 captured the distortional rotation of the flanges while Lasers 1 and 8 measured the local imperfections at the tips of the flanges.