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Experimental investigation of locally and distortionally buckled portal frames

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ABSTRACT

The paper presents an experimental investigation into the structural performance of cold-formed steel pitched portal frames subject to local and distortional buckling prior to global sway failure. The columns and rafters were constructed from back-to-back lipped channel sections, and the apex and eave joints comprised brackets bolted to both the webs and flanges of the channel sections. Three frames were tested, subjected to different combinations of horizontal and vertical loads. In all tests, lateral and torsional restraints effectively constrained the frames to deform in their own plane. Local buckling developed at a relatively early stage of loading while distortional buckling occurred when the loads were near ultimate. The occurrence of local and distortional buckling reduced the horizontal stiffness and ultimate load significantly. Failure occurred when a spatial plastic hinge formed at the top of the columns in the vicinity of the eave joints. Component tests, including tests on tension coupons and apex and eave joints, were also conducted to obtain the material and connection properties of the frames. A critical appraisal is made of the accuracy of existing design guidelines to predict the ultimate strength of the frames tested experimentally, including the interactive effect of local, distortional and overall sway buckling.

1. Introduction

Cold-formed steel sections are widely used in many applications such as structural frames, scaffolding systems, purlins and roofing systems as well as storage racks. In particular, cold-formed steel portal frames can be an alternative to conventional hot-rolled steel portal frames for industrial, rural and residential applications. The advantages of using cold-formed steel solutions include higher strength to weight ratios, and reduced material, erection and transportation costs.

As the demand for and cost of steel increase, industry is under pressure to produce increasingly light structures. Accordingly, the overriding trend over the last several decades has been to decrease the thickness of structural sections and increase the yield stress. In recent decades, cold-reduced galvanized G550 steel with high yield stress of 550 MPa and 1.0 mm thickness or less has been widely adopted in Australia for structural products. The inevitable consequence of this trend is that instability of the cross-section is becoming increasingly common. Therefore, there is a need to study the structural behaviour of structures with slender sections.

Over the past three decades a number of researchers [1–5] have undertaken tests on cold-formed steel portal frames. The tests mainly focused on the behaviour of joints, and employed relatively stocky sections. Hence, they provided little insight into the effects of cross-sectional instability on the overall stability of the frame.

Unlike conventional hot-rolled steel portal frame joints, which are usually designed to be rigid or pinned, most joints of cold-formed steel portal frames are semi-rigid. Various researchers [3,6–9] have conducted tests on joint configurations that can be used for the apex and eave joints of cold-formed steel portal frames, featuring mainly joints that were formed through brackets bolted to channel sections.

In this paper, a series of coupon, joint and portal frame tests are presented. The main purpose of the research was to study the effect of cross-sectional instability on the two-dimensional sway failure of cold-formed steel portal frames. The experimental strengths are compared with design strength predictions obtained using the current Australian and American specifications for cold-formed steel structures and conclusions are drawn about their accuracy when applied to pitched portal frames with slender cross-sections.

2. Scope of study

The experimental program investigated the structural behaviour of locally and distortionally buckled steel portal frames. It included six material (coupon) tests, four component (apex and eave joint) tests, and three full-scale portal frame tests. The main purpose of the component tests was to obtain the moment-rotation relationship of each joint, and to ensure that the joints would not fail prematurely in the portal frame tests. The material used to construct the columns and rafters

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Table 1
Measured tensile material properties.

Material	E_o (GPa)	$\sigma_{0.01}$ (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	n
Column	210	470	562	583	16.8
Rafter	195	510	545	549	45.1

was G500 Z275 Zinc-Hi-Ten and G450 Z350 Galvaspan [10,11] respectively, which was sourced from BlueScope Steel [12]. Other plates (base plates and connection brackets) were Grade 350 steel to Australian Standard AS 3678 which had a nominal yield stress of $f_{yn} = 350$ MPa and a nominal ultimate tensile strength of $f_{un} = 450$ MPa. Sheets of G500 and G450 steel were press-braked into sections specifically designed for this project.

Complete details of the experimental program are available in [13].

3. Material tests

The material investigation of the steel used for the columns and rafters was essential for the design of suitable sections and for calibrating numerical models. Tensile coupons cut from flat parts of the columns and rafters in the longitudinal direction of the members were machined and tested to Australian Standard AS1391 [10]. Three specimens for each member were tested in a 300 kN capacity MTS Sintech machine using a displacement rate of 1.0 mm/min. The coupon tests were paused regularly for about 2 min to allow stress relaxation to occur and thus obtain static values of the stress-strain curve. All coupons were instrumented with an extensometer to measure the elongation of the specimen during testing. Strain gauges were also installed at the mid-height of selected specimens for the accurate determination of the initial Young's modulus.

High strength cold-formed steel has usually undergone cold reduction during the manufacturing process, and so does neither exhibit a sharp yield point, nor a distinct yield plateau. The 0.2% proof stress is commonly used to define the yield stress of metals with a gradual transition from the elastic to plastic states, and is determined as the stress corresponding to 0.2% plastic strain. The Ramberg-Osgood expression shown in Eq. (1) is well-established for modelling the stress-strain behaviour of metals featuring gradual yielding,

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n. \tag{1}$$

In Eq. (1), E_0 is the initial Young's modulus, $\sigma_{0.2}$ is the 0.2% proof stress and n characterises the roundness of the stress-strain curve. The n-parameter can be calculated using the equation,

$$n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \tag{2}$$

where $\sigma_{0.01}$ is the 0.01% proof stress, often taken as the proportionality limit. The curve displays a rounder shape with a lower value of n.

The average static values of the coupon test results are given in Table 1, including the initial Young's modulus (E_o), the proportionality stress ($\sigma_{0.01}$), the 0.2% proof stress ($\sigma_{0.2}$), the ultimate tensile strength (σ_u), the n-parameter and the elongation after fracture. The stress-strain curves for the column and rafter sections are shown in Figs. 1 and 2, respectively.

4. Component tests

4.1. Configuration of joint tests

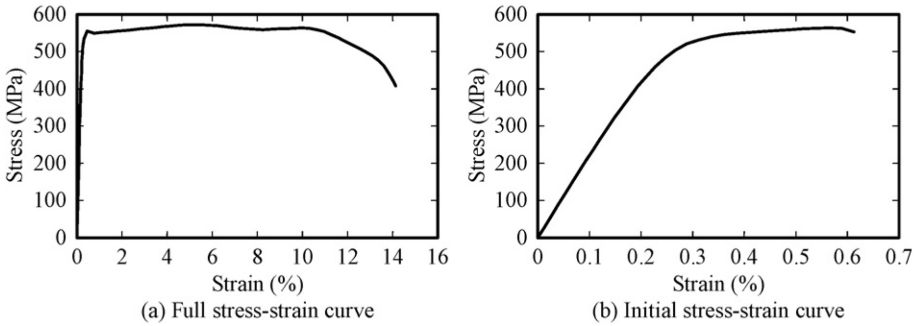
Two component test series with a total of four tests were carried out on apex and eave joints.

The apex and the eave joints comprised 6 mm G350 mild steel brackets bolted to both the webs and flanges of the back-to-back channel section. The apex brackets were cut at a 152° angle and the eaves brackets were cut at a 104° angle. The nominal diameters of the bolts and bolt holes were 16 mm and 18 mm for the webs, and 8 mm and 10 mm for the flanges. Grade 8.8 M16 and Grade 8.8 M8 bolts were used for the webs and flanges, respectively. Figs. 3–5 show the nominal and measured dimensions of the column and rafter cross-sections, and the geometry of the apex and the eave joints. They also show the lengths and widths of the bolt groups used for the apex and eave joints.

4.2. Tests on apex joint

The aim of the apex joint tests was to determine the behaviour of the apex joint under the actions likely to be experienced in the portal frame tests. Hence, the design of the test rig was targeted at producing similar internal actions (axial force, shear force, bending moment) as those developing in the portal frame tests. Evidently, the influence of bending moment on the rotational behaviour of the joint is more pronounced than that of axial force and shear force. Therefore, the design focused on replicating the bending moment distribution. Fig. 6 shows the bending moment diagram of the portal frame under a pair of vertical loads where the bending moment is almost constant near the apex connection. The apex joint test was therefore designed to be symmetrical in geometry, and a pair of symmetrical point loads was applied to produce a constant moment in the connection. A schematic diagram of the apex joint test set-up is shown in Fig. 7.

A spreader beam was used to distribute the applied downward load equally to the two rafters. Two stiffening plates were bolted to the webs of the rafters at the vertical loading points, as shown in Detail 1 of Fig. 7. At each loading point, a pin was inserted through holes drilled in the stiffening plates and the webs of the rafter. The applied load was passed to the specimen through the stiffening plates using an arrangement that ensured only vertical loads were transferred through the pins. The load was applied through the shear centre of the double C-section to minimize twisting. At the supports, each rafter was bolted to a vertical end



(a) Full stress-strain curve
(b) Initial stress-strain curve

Fig. 1. Stress-strain curve of column section.