EXPERIMENTAL INVESTIGATIONS INTO INTERACTIVE BUCKLING OF ULTRA-LIGHT GAUGE STEEL STORAGE RACK UPRIGHTS

ADAM TROUNCKER
KIM JR RASMUSSEN

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ABSTRACT

This report 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 has been given to longer specimens that fail by flexural-torsional 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 report details the observed failure modes, the recorded ultimate strengths and load-deflection responses.

KEYWORDS

Interactive Buckling, Cross-sectional Imperfections, Local Buckling, Distortional Buckling, Flexural-Torsional Buckling, Cold Formed Steel, Ultra-Light Gauge Steel, Storage racks.
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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 or distortional buckling may be followed by a significant post-buckling reserve, the deformations and redistribution of stresses that are associated with the post-buckling reserve strength change the global buckling response and strength of a member (Ziemian 2010). The interaction between these buckling modes makes a prediction of the member strength of these sections more complex.

While a large amount of research has been conducted on singular buckling modes (local, overall and distortional) for light-gauge steel sections (Hancock 2003, Schafer 2011) and the interaction between distortional and overall buckling (Yap & Hancock 2006), little attention has been given to the interaction between all three buckling modes and the subsequent effect on member strength (Basaglia et al. 2009).

An experimental investigation into the behaviour of ultra-light gauge steel storage rack uprights subjected to compression was conducted. Two different types of ultra-light gauge steel storage rack members with varying lengths were tested. A total of 20 tests were completed at the Civil Engineering Structures Laboratory at the University of Sydney using 'The J.W. Roderick Laboratory for Materials and Structures'. The two types of sections used were the 90mm wide rear-flange (RF90.1) and standard upright sections (SD90.1), both of which were specially rolled for these experiments and were nominally 1.0 mm thick. Both types of sections were cold-rolled from G550 galvanised strip with a guaranteed minimum proof stress of 550MPa. The 20 tests are divided into three sub-categories according to the specimen's length and failure mode; stub/local, distortional and flexural-torsional.

For all of the tests, load was applied concentrically through the centroid of the cross-section. The length of the specimens and the support conditions of each of the experiments were designed so that the specimens would fail in the desired failure mode. For the flexural-torsional specimens, three different lengths were used to investigate the combined effects of local, distortional and overall buckling.

While the combined effects of local and distortional buckling were investigated, special attention was given to longer specimens that fail by flexural-torsional buckling. Deformations experienced during testing by all specimens were measured and observations regarding failure modes were documented. In addition, the geometric imperfections of each member were measured before testing, as were the material properties of sections and the virgin steel from which the sections were formed. This report details the experimental set-up, observed failure modes, the recorded ultimate strengths, and load-deflection responses including the correlation between the measured geometric imperfections for each of the members and the measured displacements.

MATERIAL PROPERTIES

Coupon tests were conducted on coupons cut from both the sheets and also coupons cut directly from the members after cold-forming. Figure 1 shows where in the cross-section coupons were cut from members after cold-forming. This was done to determine the difference in material properties due to cold-forming.

![Figure 1. Location of where coupons were cut from member](image)
TENSILE PROPERTIES OF FLAT

Three coupons were cut longitudinally from a length of each flat steel coil and another three were cut from the flange of the formed uprights. All the coupons were tested to failure using a 40mm gauge extensometer and also fitted with strain gauges on each face of the narrow parallel strip. 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 MTS Sintech testing machine with a strain rate of 2.78 x10⁻⁴ /s.

<table>
<thead>
<tr>
<th>Thickness of .SD Coupons (mm)</th>
<th>Thickness of RF Coupons (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.99</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 1. Measured Coil Thickness

Table 2 summarises the static and dynamic yield stress \( f_y \) and ultimate strengths, where the former was obtained from the curves as the 0.2% proof stress. Dynamic values refer to the readings taken when the test was running, whereas static values were obtained by pausing the test for two minutes at the time that yield stress and ultimate strength was reached. Values of Young’s Modulus obtained from fitting strain gauges to the third coupon of each coil may be seen in Table 3.

<table>
<thead>
<tr>
<th>Coil</th>
<th>Upright Type</th>
<th>Coupon Number</th>
<th>Dynamic Yield Stress (MPa)</th>
<th>Static Yield Stress (MPa)</th>
<th>Dynamic Ultimate Strength (MPa)</th>
<th>Static Ultimate Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SD90.1</td>
<td>1</td>
<td>678.6</td>
<td>655.1</td>
<td>686.0</td>
<td>658.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>676.2</td>
<td>652.4</td>
<td>681.2</td>
<td>652.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>677.4</td>
<td>653.8</td>
<td>683.6</td>
<td>655.5</td>
</tr>
<tr>
<td>B</td>
<td>RF90.1</td>
<td>1</td>
<td>685.1</td>
<td>666.3</td>
<td>694.5</td>
<td>674.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>687.2</td>
<td>669.2</td>
<td>690.6</td>
<td>662.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>686.2</td>
<td>667.8</td>
<td>692.6</td>
<td>668.4</td>
</tr>
</tbody>
</table>

Table 2. Tensile Coupon Test Results

Figure 2. Tensile Coupon Stress Strain Curves a) Coil A b) Coil B
Table 3. Coupon Test Results for Young's Modulus

<table>
<thead>
<tr>
<th>Coil</th>
<th>Upright Type</th>
<th>Coupon Number</th>
<th>Young's Modulus, E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SD90.1</td>
<td>1</td>
<td>220,646</td>
</tr>
<tr>
<td>A</td>
<td>SD90.1</td>
<td>2</td>
<td>220,164</td>
</tr>
<tr>
<td>A</td>
<td>SD90.1</td>
<td>Average</td>
<td>220,405</td>
</tr>
<tr>
<td>B</td>
<td>RF90.1</td>
<td>1</td>
<td>222,197</td>
</tr>
<tr>
<td>B</td>
<td>RF90.1</td>
<td>2</td>
<td>220,661</td>
</tr>
<tr>
<td>B</td>
<td>RF90.1</td>
<td>Average</td>
<td>221,429</td>
</tr>
</tbody>
</table>

COMPRESSIVE MATERIALS OF FLAT

Compression coupon tests on flat sections of the two types of uprights were also completed. The tests were conducted to determine if there was any difference in stress-strain behaviour derived from the tensile coupon tests. A similar method for performing the compression coupons had previously been used by Lecce and Rasmussen (2006).

Three coupons were manufactured from the flat part of the flange of each of the SD and RF uprights. The coupons had nominal dimensions; 63 mm long, 19.5 mm wide and 6 mm thick. In order to obtain the 6 mm of thickness, 6 individual coupons cut from the 1.0 mm SD and RF uprights were glued together and subsequently machined square. Once the coupons had been assembled, 3 mm wide strain gauges were applied to both sides of the thickness of the coupons at mid-height. A small amount of lubrication was then added to the largest faces of the coupons. Once ready, the coupons were carefully placed in the compression jig and the bolts were hand-tightened. The reason for only hand tightening and adding lubrication was to prevent friction in the jig and to allow Poisson’s expansion to occur essentially unrestrained. This test setup allowed the coupon to have continuous lateral support and prevented buckling about the minor axis. The coupons were also 2 mm taller than the jig, meaning that results for the stress-strain curve could be achieved up to approximately 1% strain. A photograph of the test rig may be seen in Figure 3.

Before the test began, the coupons were pre-loaded with a very small force. This was completed so that the base of the rig could be slightly adjusted to ensure the top of the coupon was sitting flush on the loading plate. The difference in strains recorded from the two sides of the coupon was used as a guiding indicator. After adjusted, the bolts in the bottom plate were tightened and locked in place. The force was subsequently released and the MTS Sintech testing machine started to test at a displacement rate of 0.1 mm/s. Results for each of the coupons may be seen in Table 4 where the yield stress was obtained as the 0.2% proof stress. An example of the stress-strain curve derived from each of the two sections is also shown in Figure 4. Comparing these results to the tensile coupon tests shows that there is only a minor variation in both the yield stress and Young’s Modulus of each section. These results from the compression coupon tests will form the foundation of the material properties later used in the Finite Element Analysis.

Figure 3. Compression Coupon Test Rig
### Table 4. Flat Compression Coupon Test Results

<table>
<thead>
<tr>
<th>Upright Type</th>
<th>Coupon Number</th>
<th>Static Yield Stress (MPa)</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF90.1</td>
<td>1</td>
<td>655.2</td>
<td>224,160</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>650.5</td>
<td>225,235</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>653.6</td>
<td>222,111</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>653.1</td>
<td>223,835</td>
</tr>
<tr>
<td>SD90.1</td>
<td>1</td>
<td>642.6</td>
<td>215,133</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>640.2</td>
<td>219,025</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>639.2</td>
<td>218,265</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>640.7</td>
<td>217,474</td>
</tr>
</tbody>
</table>

#### Figure 4. Compression Coupon Stress-Strain Curves a) SD-1 b) RF-1

### SECTION DESIGN AND GEOMETRY

#### GEOMETRY OF SECTION

The uprights consisted of nominally 1.0 mm thick, 90 mm wide rear-flange (RF90.1) and standard upright (SD90.1) sections. These sections were cold-rolled from G550 galvanised strip with a guaranteed minimum proof stress of 550 MPa. Typically, these uprights only come in 1.5, 1.9 or 2.4 mm thicknesses. However, these specimens were specially rolled at Dematic with a nominal 1.0 mm thickness, ensuring prominent local and distortional buckling would occur during full scale testing. Both uprights have 42.4 mm diamond perforations running down the web of the section for beam connections and 10.4 mm diameter perforations on the flange used for bolted diagonal connections. A diagram of the two sections and their nominal dimensions may be seen in Figure 5 and Figure 6 respectively.

#### Figure 5. Upright Specimens Used
SPECIMEN LENGTHS

For each of the tests being conducted, an appropriate length of upright was carefully selected. The objective of this procedure was to ensure that each upright failed in the desired buckling mode for the test being conducted.
Stub columns for each of the specimens were kept equal at 300 mm in length, which was no less than three times the width of the widest side, and no more than twenty times the least radius of gyration, as specified in Clause 8.1.2 of AS/NZS 4600 (2005). This ensured that the stub columns would reach their ultimate load without suffering overall instability and fail locally. For the distortional buckling tests, the critical distortional buckling half-wavelength of the cross-sections dictated the length of the specimens. ThinWall was used to determine the distortional buckling half-wavelength for all the specimens.

ThinWall (Papangelis & Hancock 1995) was developed at the University of Sydney and is a software program which implements the finite strip buckling analysis for elastic materials. After the user enters the cross-sectional information of the specimen, ThinWall calculates and subsequently plots the elastic buckling stress versus the buckling half-wavelength. A ‘typical’ elastic buckling stress vs half-wavelength curve features two distinct minima. The first minimum at short buckling half-wavelengths corresponds to the local critical buckling half-wavelength whereas the second minimum is associated with the critical distortional half-wavelength. After this second half-wavelength the asymptotic curve for longer half-wavelengths takes over which signifies overall buckling. Graphs for the elastic buckling stress vs buckling half-wavelengths may be seen in Figure 7 for both the SD and RF cross-sections.

For both the sections displayed, the experimental values of Young's modulus and nominal cross-section dimensions were used in the calculation. However, it must be noted that section perforations were not incorporated into this analysis and Thin Wall assumed pinned boundary conditions at both ends. As can be clearly seen in Figure 7, the critical distortional buckling half-wavelength for the SD sections is quite prominent between 500-600 mm, whereas for the RF section, the minimum is less defined between 500-700 mm. As distortional buckling tests were completed between idealised fixed boundary conditions, the effective length of the section is half that of pinned. For this reason, and for simplicity, the length of distortional buckling specimens for both of the upright tests was taken as 1000 mm.

A different criterion was used to determine the lengths of the uprights that were to fail by overall buckling. In order to determine the effects of interactive buckling and imperfections on the ultimate load of the uprights, a number of different specimen lengths were tested. Three separate lengths of each upright type were tested under pinned boundary conditions with respected to bending about their major axis of symmetry, so that each would fail by overall buckling. In this instance, for both types of uprights, flexural-torsional buckling is the dominant overall buckling mode. The three nominal lengths for each type of uprights was selected so that they would roughly correspond to slenderness ratios \( \left( \frac{\sigma_y}{\sigma_{cr,o}} \right) \) of 0.5, 1 and 1.5, where \( \sigma_{cr,o} \) is the minimum of the elastic flexural and flexural-torsional buckling stresses, of which the latter was critical. Care was also taken to ensure that significant distortional and local buckling half-wavelengths could develop before the ultimate load was reached in some of the global buckling tests. By selecting uprights of these varying lengths, interactive buckling could be investigated, along with the effects that geometric imperfections had on the ultimate load of specimens with different slenderness ratios. Table 5 shows the nominal and actual lengths of each of the tests completed.
Experimental Investigations into interactive buckling of ultra-light gauge steel storage rack uprights

Figure 7. Buckling Stress vs. Half-wavelength

a) SD Upright

b) RF Upright

Figure 7. Buckling Stress vs. Half-wavelength
**Table 5. Specimens Lengths Tested**

<table>
<thead>
<tr>
<th>Upright Type</th>
<th>Test Type</th>
<th>Test Number</th>
<th>Nominal Length (mm)</th>
<th>Measured Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stub</td>
<td>SD-S-300-1</td>
<td>300</td>
<td></td>
<td>299.5</td>
</tr>
<tr>
<td>Stub</td>
<td>SD-S-300-2</td>
<td>300</td>
<td></td>
<td>298.5</td>
</tr>
<tr>
<td>Distortional</td>
<td>SD-D-1000-1</td>
<td>1000</td>
<td></td>
<td>1000.5</td>
</tr>
<tr>
<td>Distortional</td>
<td>SD-D-1000-1</td>
<td>1000</td>
<td></td>
<td>1001</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-625-1</td>
<td>625</td>
<td></td>
<td>626</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-625-2</td>
<td>625</td>
<td></td>
<td>624.5</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-1345-1</td>
<td>1345</td>
<td></td>
<td>1345</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-1345-2</td>
<td>1345</td>
<td></td>
<td>1343</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-1950-1</td>
<td>1950</td>
<td></td>
<td>1947</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>SD-FT-1950-2</td>
<td>1950</td>
<td></td>
<td>1946</td>
</tr>
<tr>
<td>SD90.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stub</td>
<td>RF-S-300-1</td>
<td>300</td>
<td></td>
<td>298</td>
</tr>
<tr>
<td>Stub</td>
<td>RF-S-300-2</td>
<td>300</td>
<td></td>
<td>298.5</td>
</tr>
<tr>
<td>Stub</td>
<td>RF-S-300-3</td>
<td>300</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Distortional</td>
<td>RF-D-1000-1</td>
<td>1000</td>
<td></td>
<td>996.5</td>
</tr>
<tr>
<td>Distortional</td>
<td>RF-D-1000-1</td>
<td>1000</td>
<td></td>
<td>999</td>
</tr>
<tr>
<td>RF90.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-600-1</td>
<td>600</td>
<td></td>
<td>600.5</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-600-2</td>
<td>600</td>
<td></td>
<td>601</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-1275-1</td>
<td>1275</td>
<td></td>
<td>1277.5</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-1275-2</td>
<td>1275</td>
<td></td>
<td>1274.5</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-1950-1</td>
<td>1950</td>
<td></td>
<td>1948</td>
</tr>
<tr>
<td>Flex.-Tor.</td>
<td>RF-FT-1950-2</td>
<td>1950</td>
<td></td>
<td>1951</td>
</tr>
</tbody>
</table>

**LABELLING AND CONVENTIONS**

Each of the tests completed were 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, D and FT refer to stub, distortional and flexural-torsional test types. For example, specimen SD-D-1000-2 refers to the second distortional test of a nominally 1000 mm length standard flange upright. Figure 8 also displays the sign conventions used for the top and bottom rotations, lateral overall displacements and local displacements of the web and the flange. Similar to the imperfection measurements, positive local displacements were always away from the centroid of the cross-section. Further to this, Figure 9 displays the definition used for different parts of the cross-section and Figure 10 displays the positive x-axis and y-axis sign conventions used when describing displacements of the cross-section.
a) End Rotations and Lateral Displacements

b) Local Displacements

Figure 8. Sign Conventions used for Testing
GEOMETRIC IMPERFECTIONS

IMPERFECTION MEASUREMENT

In order to characterise the imperfections present in the test specimens, and to have an appreciation of their shape and magnitude longitudinally and transversely, measurements need to be taken on the edges and centrelines of component plates at closely spaced points along the member for all of the buckling test specimens. A summary of this process as it relates to the shorter single uprights is described below.

A laser rig was constructed which measured 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 3mm from corners and perforations. Diagrams detailing the location and number of each of the laser lines may be seen in Figure 11 for both the RF and SD sections.

The position of each of these lines was carefully selected to ensure the imperfections could be broken down into the critical eigenmodes. 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.

For speed, efficiency and accuracy, a laser rig was designed which housed all eight electronic laser optical displacement sensors, allowing all eight devices to electronically read the distance to the specimen using...
interference of a reflected laser beam. All eight lasers were connected to a Vishay data logger collecting data using StrainSmart software. The laser housing frame was constructed using 3 mm gal sheet and reinforced with flat bar to ensure vibrations were minimized. Each of the lasers were bolted to 3 mm gal sheet brackets which connected to the laser housing frame, holding them in position. Figure 12 shows a photo of the actual housing frame and lasers used.

The housing frame was mounted on a trolley which was pulled along 25 mm diameter high-precision bars at a constant speed by a small electric step motor. The motor was connected to Kremford-Hyperdrive Programmable Stepper Motor Controller, which was commanded using Terra Term software. For each of the tests conducted, the translation speed of the laser housing frame was set at 10 mm/s, while the sampling rate was kept constant at 10 Hz. A reading was therefore recorded every millimetre along the length of each upright.

Due to the small magnitudes of the imperfections, it was important to ensure that the test rig was perfectly straight and level. Two supports were fabricated and positioned near the ends of each specimen. Pictures of the supports can be seen in Figure 13. The supports were constructed for both speed and accuracy of testing. Each support was fabricated using a screw jack and a custom made specimen holder. The screw jack could be adjusted to take into account any inconsistencies in the floor height while the custom-made specimen holder secured the specimen so it would not move during testing. Each specimen sat over the top of supports with the inside web seated comfortably on the custom made holder.
Before the measurement of each test specimen, the upright was secured in the base supports and its verticality checked using a level. The specimen was also cleaned and wiped down with Shellite to ensure any dirt or grit would not affect the results. Tests then began 5 mm from the end of each specimen and the results were recorded for each of the eight laser lines. Two runs of the laser rig along the full length of each of the specimen were conducted.

IMPERFECTION RESULTS

After measurements from the optical displacement sensors were collected by the Vishay data logger, results were exported to text (.txt) files for each of the specimens. Using this data, a python program was developed for each RF and SD specimen to plot and analyse the raw data. A python script titled 'SD/RF_RawData_Analysis.py' was produced to analyse the raw data using a Fast Fourier Transform and obtain the amplitudes for each laser line for each half-wavelength. For each of the specimens, the data from each laser line was zeroed relative to the start and end of each member. While flaring was observed at the start and ends of each of the specimens, the imperfection measurements were taken as the deviation relative to these points at either end of the specimen.

After running the SD/RF_RawData_Analysis for each of the members, graphs of the imperfection data were plotted for each laser line. Results for each of the specimens may be seen in Appendix A. While there are some small variations between points due to the vibration of the system, the data shows accurate and stable readings. However, to reduce the contribution of the high-frequency vibrations of the system, the Fourier series was truncated after 150 terms. To ensure this did not affect results, the shortest wavelength was selected well beyond the critical local buckling half-wavelength. To confirm the results from the Fourier transform matched the measured data, the imperfection data corresponding to the deviation from the perfect geometry was then plotted on the same graph as the Fourier transform results. An example of this may be seen in Figure 14 where the blue and red lines represent the measured data and Fourier transform respectively. From this graph, it is clearly evident that the Fourier transform replicates a near perfect fit.
Figure 14. Imperfection Measurements and Fourier Transform For SD-1000 Section

After plotting the imperfection data against the longitudinal location of the beam, the Fourier coefficients against the half-wavelengths for each of the laser lines was then plotted, as exemplified in Figure 15. Graphs for all the laser lines in each of the SD and RF sections may be seen in Appendix A. Observations from test results indicate that the maximum magnitudes of imperfections range from 3mm in the flange and 2.5 mm in the web for the SD sections and 2.8 mm in the lip and 2.3 mm in the web for RF sections. Comparing the specimens, it can be seen that the local imperfection measurements for the SD sections are larger than those in the RF section, due to the fact that the SD sections do not have flange stiffeners.
COLUMN BUCKLING TESTS

PREPARATION OF SPECIMENS FOR TESTING

Once the specimens had been cut, milled to length and measured for imperfections, they were then prepared for testing. In order to ensure the concentric load was being applied evenly across the cross-section at either end of the specimen so that localised failure did not occur at these points, a special Pattenstone mould was used for each of the members. For this to occur, two custom moulds were fabricated for the storage rack uprights. A levelling table was used to make sure that the moulds were always sitting flat and the Pattenstone would be distributed evenly.

Grease was first wiped over the inside of each of the models, allowing the Pattenstone to be removed easily after testing. Each specimen was then carefully adjusted and placed in the mould, ensuring that the major principal axis was aligned perfectly with the centre. A mixture of 32 ml of water to 100 g of Pattenstone H (ultra-hard gypsum) with a compressive strength of 70 MPa and maximum setting expansion of 0.24% was then poured into the mould and allowed to set for 30 mins. After this time, the specimen was flipped and the
identical process was conducted for the other end of the specimen. For the longer members, the 'transducer cage' (explained later in the Flexural Torsional Test Setup Section) was attached to the specimen before the second mould was poured. Photographs of this process may be seen in Figure 16.

An important observation to note is that the top Pattenstone mould for the longer specimens did not necessarily perfectly align with the bottom mould for the longer sections. Due the ultra-thin nature of these storage rack uprights, although both ends were milled flat and perpendicular to the longitudinal axis of the specimen, some of the longer specimens had a slight twist. This means that the major principal axis at the top and base of the cross-section were not perfectly aligned. Figure 17 explains this process. In these instances, the line of best fit was taken for each of the specimens and the error was halved between both moulds. While these initial 'twist' imperfections were partially captured in the measured imperfections of the specimen, they were assumed to have a negligible effect on ultimate loads and observed results.

**STUB COLUMN TESTS**

**Introduction**

To investigate the effects of local buckling and to determine the axial capacity of the cross-sections, stub column tests were completed as part of this investigation. A total of five stub column tests were completed, two from the SD90.1 uprights and three from the RF90.1 uprights. Before testing each of the specimens, the net minimum area of each specimen, $A_{net-min}$, was accurately calculated by determining the gross area, $A_{gross}$, and subtracting the maximum hole area $A_{holes}$. The gross area $A_{gross}$ was found by multiplying the measured coil thickness by the measured flat coil width. The maximum hole area was determined by measuring the maximum width of the perforations and multiplying it by the coil thickness. All of the SD90.1 uprights were
cold-formed from Coil 1, whereas the RF90.1 uprights were formed from a separate coil, Coil 2. Table 6 summaries the measured dimensions and areas for each specimen. It must also be noted that the galvanising layer was removed before the thickness of the coils were measured.

<table>
<thead>
<tr>
<th>Coil</th>
<th>Upright Type</th>
<th>Measured Base Coil Thickness (mm)</th>
<th>Measured Flat Coil Width (mm)</th>
<th>Gross Area (mm²)</th>
<th>Maximum Area of Holes (mm²)</th>
<th>Net Minimum Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>RF90.1</td>
<td>0.98</td>
<td>260</td>
<td>254.8</td>
<td>28.0</td>
<td>226.8</td>
</tr>
<tr>
<td>B</td>
<td>SD90.1</td>
<td>0.98</td>
<td>235</td>
<td>230.3</td>
<td>28.0</td>
<td>202.3</td>
</tr>
</tbody>
</table>

Table 6. Stub Column Test Specimen Characteristics

**Test Set-up**

Each of the specimens was tested using a 300 kN capacity MTS Sintech testing machine. The ends of the stub column were milled flat to a tolerance of 0.025mm, perpendicular to the longitudinal axis of the upright. The axial load was applied with the Sintech machine, which had a top end platen mounted on the movable cross-head and a bottom end platen mounted on a half-spherical bearing. The half-spherical bearing meant the bottom end platen could initially rotate, ensuring that there was always full contact between the platen and the ends of the specimen. To ensure that the specimen was flat and vertical in the test rig, a small load was first applied and then the bolts surrounding the half-sphere at the base of the specimen were locked in place. As discussed previously, a Pattenstone mould was applied to both ends of all of the specimens to prevent distortion at the ends and maintain an even load distribution across the cross-section. During testing, a cross head speed of 0.1 mm/min was used to apply load to the test specimens. A photo of the testing machine and boundary conditions and loading application may be seen in Figure 18.

After the specimen had been placed in the testing machine, five LVDTs (Linear Variable Displacement Transducers) and three Micro-Epsilon OptoNCDT-1700/20 Laser Displacement Sensors were placed around the specimen. The LVDTs and Laser displacement sensors measured the cross-sectional deformations of the critical points of the cross-section as the load was being applied. Three Laser Displacement sensors with a measuring range of 20mm were placed on the web, while five LVDT’s were placed around different locations of the flanges for the two types of cross-section. Sensors T1 and T8 (T7 for the SD Section) measured the local deformations, sensors T2, T4 and T7 (only T2 and T4 for the SD section) measured the distortional deformations and lasers T3, T5 and T6 measured the global translational movement of the cross-section during testing. As all of the sensors were not attached to the member, the difference between the relevant local or distortional deformations from the global movements of the specimen can be calculated to determine the pure cross-sectional deformations of the cross-section. Figures 19 and 20 display the location of the sensors for both the SD90.1 and RF90.1 sections.

Due to the short nature of the stub columns, there was no room to include transducers to measure the axial shortening of the cross-section, so this data was taken directly from the test machine. Once this was complete and all the sensors had been set-up, testing began and axial load was applied by an axial displacement rate of 0.1 mm/min of the cross-head.
Experimental Investigations into interactive buckling of ultra-light gauge steel storage rack uprights

a) Fixed Lower Platen On Half-Spherical Bearing

b) Test Setup for RF and SD Stub Column Sections

Figure 18. Stub Column Test Setup
Figure 19. Photos of Transducer and Laser Setup

Figure 20. Locations of LVDT's and Lasers around Cross-Section
Observations and Test Results

The complete set of test results for both the SD and RF stub column tests may be seen in Appendix B. Representative results are presented in this section.

SD Sections

Two stub column tests were completed for the SD cross-sections, both of which had very similar ultimate loads and failure patterns. A summary of the ultimate loads may be seen in Table 7. During testing, both local and distortional buckling of the cross-section occurred quite prominently which began to reduce the rigidity of the cross-section. The local and distortional buckling of both the web and the flange can be seen in the data captured by the transducers shown in Figure 21 for SD-S-300-2, where the positions of the transducers in the cross-section are shown in Figure 20.

As axial load was applied to the SD stub column, local buckling of the flange tip began to occur. As seen from Transducers 1 and 7 in Figure 21, the flange of the SD section began to move inward towards the centroid of the cross-section. In addition to this local buckling, distortional buckling deformations also started around a load of about 40 kN and interaction of both local and distortional buckling occurred. Distortional buckling is characterised by a rotation of the flanges of the sections as well as the movement of the web, as captured by transducers 2 and 4. This distortional buckling of the cross-section meant that the flange progressed even further inwards towards the cross-sections centroidal axis. Photos of this process may be seen in Figure 22.

As the test continued, local and distortional buckling deformations increased until the ultimate load was reached. For both specimens, a symmetrical local and distortional buckling failure occurred in the flanges of the cross-section close to mid height. Photographs of this may be seen in Figure 23. By this stage significant outward movement of the web had occurred at a similar height. It should also be noted that a similar pattern of failure through the diamond perforations in the web also occurred. For the majority of the tests a bulge occurred at the top outside edge of the diamond perforation at failure. After the ultimate load the section rigidity greatly reduced and displacements began to occur at a more rapid pace, as seen in Figure 21.
Three different stub columns for the rear flanged section were tested in the Sintech testing machine. Similar to the SD stub column tests, a number of failure patterns and observations emerged which were consistent with all of the tests. Due to the extra lip on the flange, local and distortional buckling was less pronounced than for the SD sections, however still occurred well before the ultimate loads. The ultimate load for each of the test
specimens was within 2% of each other. Results from the RF stub columns are summarised in Table 7. Figure 24 depicts the transducer data captured from the RF-S-300-3 test. As seen from transducers 1 and 8, local buckling of the flange tips developed quite early and gradually moved inward. Unlike the SD sections, local buckling was less prominent and harder to observe. For each of the buckling tests, transducers 2 and 7 rested on the flange a reasonable distance from the web for the RF sections. It is quite evident from transducers 2, 7 and 4 that distortional buckling also began to influence the RF upright, similar to the SD section. The direction of this distortional buckling was different for each of the tests. For RF-S-300-3 and RF-S-300-2, the distortional buckling caused both flanges to move symmetrically inwards towards the centroid, both before and after the ultimate load was reached. However, for RF-S-300-1, distortional buckling occurred asymmetrically and the two flanges at mid-height moved in different directions. The inside portion of the web also gradually moved outwards away from the centroid of the cross-section. Pictures of these local and distortional deformations may be seen in Figure 25.

The final failure pattern for the three RF stub columns was very similar to that of the SD columns. All reached ultimate loads very close to 120 kN and the failure was due to a local failure of the side flange, similar to the SD sections. In addition to this failure, a number of smaller local failures occurred symmetrically on the stiffed flange very close to the top and bottom of the specimen. Moreover, a failure pattern emerged on the perforations of the web. Figure 26 shows the failed specimen for each of the RF stub column tests.

![Figure 24. Transducer Data from RF-S-300-3](image_url)
Figure 25. Local and Distortional Buckling During Testing

Figure 26. Failed RF Stub Column Specimens
DISTORTIONAL BUCKLING TESTS

Introduction

Distortional buckling tests were completed to determine the ultimate capacity of the sections failing by distortional buckling. As previously discussed, the distortional buckling specimens were cut to 1000 mm, which is very close to twice the critical distortional buckling half-wavelength for each of the two types of storage rack uprights. The procedure for completing the distortional buckling tests was identical to that of the stub column tests, as discussed below.

Test Set-up

All of the distortional buckling tests were completed between fixed ends using the 300 kN capacity MTS Sintech testing machine. All of the specimens were first milled flat, set in Pattenstone and placed in the Sintech Testing Machine between a fixed upper platen and a fixed lower platen mounted on a half-sphere bearing. To ensure there was always full contact between the platen and the end of the specimens, an initial load was applied before the screws were tightened on the half sphere bearing. Five LVDTs and three Micro-Epsilon OptoNCDT-1700/20 Laser Displacement Sensors were placed around the specimen in the same locations for each of the specimens, as displayed in Figure 20. Load displacement data from each test was also taken and recorded directly from the Sintech Machine to the Vishay datalogger.

Similar to the stub column tests, axial load was applied through a 0.1 mm/min displacement rate of the upper platen for each of the tests. Photographs of the distortional buckling test setup for both the SD90.1 and RF90.1 specimens may be seen in Figure 28.

Observations and Test Results

The complete set of load vs. end shortening and load vs. transducer displacement graphs may be seen in Appendix C for each of the test specimens. A summary of the ultimate loads of the four specimens tested may also be seen in Table 8.

Table 7. Stub Column Test Results

<table>
<thead>
<tr>
<th>Upright Type</th>
<th>Test Number</th>
<th>Measured Length (mm)</th>
<th>Static Ultimate Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD90.1</td>
<td>SD-S-300-1</td>
<td>299.5</td>
<td>88.5</td>
</tr>
<tr>
<td></td>
<td>SD-S-300-2</td>
<td>298.5</td>
<td>88.6</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>88.5</td>
</tr>
<tr>
<td>RF90.1</td>
<td>RF-S-300-1</td>
<td>298.0</td>
<td>123.1</td>
</tr>
<tr>
<td></td>
<td>RF-S-300-2</td>
<td>298.5</td>
<td>119.4</td>
</tr>
<tr>
<td></td>
<td>RF-S-300-3</td>
<td>300.0</td>
<td>119.8</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>120.7</td>
</tr>
</tbody>
</table>
Figure 27. Distortional Buckling Test Setup

Figure 28. Distortional Buckling Test Setup Photographs
RF Sections

For both of the nominally 1000 mm long RF sections tested, one distortional buckle formed as axial load was applied and the specimen failed by distortional buckling. Before the ultimate load was reached, local buckling of the stiffened flange also occurred. Figure 29 shows the transducer measurements from the RF-D-1000-1 test.

As clearly indicated by transducer 4 in Figure 29, as the axial load was increased, the centre of the web began to move inwards towards the centroid of the cross-section. Simultaneously, after 30 kN was reached, transducers 2 and 7 began to measure positive displacements, indicating that the side flanges were starting to move outwards. While transducer 6 measured some small movements of the flange near the web from the start, this should be attributed to the large deformations of the cross-section due to distortional buckling, rather than lateral movement of the cross-section due to overall buckling. During the increase in axial load, small local buckling deformations of the flange also occurred, as measured by transducers 1 and 8. These transducers then slipped off the rear flange and no longer recorded data, as seen in the photographs in Figure 31. As the ultimate load of the cross-section drew closer, distortional deformations in the shape of the lowest buckling mode were amplified. Once the ultimate load was reached, failure occurred quite suddenly and there was a sharp drop in the applied load. Significant distortion around the circular and diamond perforations at mid height could also be seen at this point and appear to have triggered the sharp drop in load. Photographs of the process may be seen in Figures 30 and 31.

![Figure 29. LVDT Displacements Results for RF-D-1000-1](image-url)
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Figure 30. Photographs of RF Distortional Buckling Tests

a) Test Beginning

b) Distortional Buckling Starting to Occur
Similar to the RF uprights, both 1000 mm nominally long SD uprights failed by distortional buckling where one buckle in the cross-section’s lowest mode was formed. The largest deformations for both specimens tested occurred just below mid height. Unlike the RF sections, the SD uprights do not have the added rigidity of a flange lip stiffener. For this reason, local and distortional deformations were much larger in the SD sections and occurred at a lower axial load. Figure 32 shows the transducer measurements from the different points around the cross-section for the SD-D-1000-1 test.

**SD Sections**
From Figure 32, it is clearly evident that significant local and distortional buckling occurred during testing. Transducers 1 and 7, which were located on the outermost points of the flanges, recorded significant deformations from 10 kN and above as the local buckling caused the inwards deformation of the outer flange. It was also observed that buckling was not completely symmetrical in both of the flanges, highlighted by the minor differences in displacements from transducers 1 and 7 and transducers 2 and 6. The initial imperfections of the cross-section may be the reason for this slight unsymmetrical behaviour.

As the axial load reached 34 kN, distortional buckling began to occur. The lowest distortional buckling eigenmode forced the flange inwards, while the web distorts outwards away from the centroid of the SD cross-section. Transducers 2 and 6 measured the deformation in the flange, while transducer 4 measured the distortion in the web. As the axial load continued to increase well above 50 kN, distortions in the web became very large and transducers 1 and 7 ran off travel and went out-of-range. At this point, the flange had displaced inwards so far both sides were only a few millimetres away from each other. The ultimate load was reached soon after and significant deformations around perforations were seen along with the local failure on both flanges. After reaching the ultimate load, deformations continued to increase until both flanges were firmly touching each other. After a 15% drop in ultimate load, the test was concluded and the axial load was released. Figures 33 and 34 show detailed photographs of the progression of the test. Table 8 summaries the ultimate loads of the SD specimens.
FLEXURAL-TORSIONAL BUCKLING TESTS

Introduction

Flexural-torsional buckling tests were completed for three separate lengths for each of the two cross-sections. Each test was also repeated meaning that a total of 12 tests were completed in this series of tests. Details of the specific lengths for each of the tests completed may be seen in Table 5. The different lengths of the uprights were selected so that the effects of interaction between local, distortional and flexural-torsional (overall column) buckling could be investigated. All specimens were tested between pinned ends about the specimen’s major axis and fixed about the minor axis, as seen in Figure 35.

![Figure 35. Boundary Conditions of Flexural Torsional Tests](image)

Test Set-up

All of the flexural-torsional buckling tests were completed between pinned ends conditions about the specimen’s major principal axis and fixed about the minor axis in a 2000 kN maximum capacity Dartec testing machine in the Civil Engineering Structures Laboratory at the University of Sydney. Concentric axial load was applied to each of the specimens through an axial displacement of the top head at a rate of 0.1 mm/min.

![Figure 36. Pinned Boundary Conditions about Major Axis](image)
Figure 37. Axial Shortening Transducers on Pattenstone
Similar to the stub columns and distortional buckling tests, Pattenstone moulds were used at the top and bottom supports for each specimen to prevent distortion at the loaded edges. The specimens were oriented so that their major centroidal axis was positioned perfectly over the centre of the Pattenstone moulds. A line scribed through the centre of the moulds allowed this to be achieved to an accuracy of 1mm. Centre lines were also scribed on the side of the Pattenstone moulds and on the platens of the two hinge joints in the Dartec testing machine. Great care was taken to make sure that the Pattenstone moulds and centroidal axis of each specimen were perfectly aligned with the hinge axes. The distance between the centre of each pin and the base of the specimen within the Pattenstone was measured to be 60 mm for both the top and base. Therefore, the effective length of each of the specimens for bending about the axis of symmetry may be calculated by adding an additional 120 mm to the member length. Figure 36 shows the pinned hinge assemblies used at the top and base of the specimen.

For the short 600 mm sections, axial shortening of the section was taken directly from the Dartec machine stroke as there was not enough room to install transducers at the top and bottom of each specimen. However, for the longer mid-range sections, two LVDTs (titled T1, T2, B1 and B2) were placed on top of the Pattenstone at the top and bottom of the sections to measure the axial shortening of the specimen. While this proved reasonably adequate, the results still displayed some initial non-linear 'settling in' due to the initial contraction of the Pattenstone. For this reason, for the nominally 1950 mm members, two specially designed web fasteners were fabricated and bolted to the web and flange of the specimen as close to the base and top as possible. Resting the axial displacement LVDTs on the brackets attached to the specimen rather than the Pattenstone proved to give significantly more accurate results. In addition to axial shortening, these transducers also allowed the end rotation of the bearings for each test to be calculated. Photographs of the two different set-ups used may be seen in Figure 37 and Figure 38.

In addition to the transducers measuring the axial shortening and end rotations, a further thirteen transducers were used to measure the global movements of the member and cross-sectional deformations as the load was applied. Ten of the transducers used were measuring displacement at five critical points around the cross-sections at two different elevations. A custom fabricated transducer frame was made so that these transducers could be attached to each test specimen and would fit around each type of upright. Spring-loaded hooks and adjustable screws on the transducer frame held it in place, while a two-sided counterweight system allowed it to be suspended perfectly at mid-height of the specimen. These features allowed the transducer frame to move with the cross-section as overall buckling occurred. Subsequently, the transducers held on this frame were measuring only the pure cross-sectional deformations due to local and distortional buckling. The locations of the transducers mounted around each cross-section on the frame may be seen in Figure 39 and 40. Figure 41 also shows photographs of the full test set-up while Figure 42 depicts the counterweight system.

Similar to the stub column and distortional buckling tests, transducers T1 and T5 captured the local deformations whereas transducers T2, T3 and T4 captured distortional buckling deformations of the cross-
section. In addition to these five transducers around the cross-section at mid height elevation, an additional five transducers were fastened 100 mm below them on the transducer frame. These additional 5 transducers (labelled T6-T10) captured the exact same buckling deformations, just at a lower height. This ensured that local deformations could still be determined even if the inflection point of local buckling happened to occur at mid-height. Furthermore, these extra transducers also provided another valuable set of data which could be analysed and compared to the numerical studies conducted. Photos of the transducers housed by the transducer holder may be seen in Figure 43.

Further to the transducers measuring the cross-sectional deformations, three other transducers were used to measure the translation and twisting of the cross-section as overall buckling occurred. As seen in Figure 44, transducers T11 and T12 were positioned on the back of the transducer holder to measure the out of plane movement and twist rotation of the member. Similarly, transducer T13 was positioned on the right hand side of the transducer box to measure the in-plane movement due to overall bucking. These transducers were fastened to the Dartec testing machine.

After the specimen had been placed in the testing machine and the transducers had been correctly set up, the top head of the Dartec was slowly lowered until it was 50 mm above the top Pattenstone mould. Another separate batch of Pattenstone was then mixed up and placed on top of this top Pattenstone mould. The head of the ram was then slowly lowered until it made contact and an even spread of the Pattenstone had been achieved, as seen if Figure 45. The purpose of this additional Pattenstone layer between the top of the specimen's Pattenstone mould and the top pin joint was to ensure that they were perfectly flush against each other so there was an even load distribution and no eccentricities. This Pattenstone was then left to set for an additional 30 mins. After this time, the test was ready to begin. A small load was applied and the chocks under
the bottom pin were removed. Axial load was then concentrically applied to the specimen using a displacement rate of 0.1 mm/min. All the transducer and load data was captured using two Vishay data loggers and a number of tests were filmed using a high speed Cannon EOS 1100D digital camera.

Figure 40. Transducer Location for RF and SD Sections
Figure 41. Full Flexural-Torsional Buckling Test Setup
Figure 42. Counterweight System

Figure 43. Transducer Housing for SD and RF Sections
Figure 44. Transducers Measuring Global Movement

Figure 45. Pattenstone Between Upright and Top Pin Connection
Observations and Test Results

As previously noted, flexural-torsional buckling tests were completed for three different lengths of both RF and SD uprights. All the load vs. displacement results for both axial and translational directions, along with transducer measurements for each of the specimens may be found in Appendix D. A summary of the ultimate loads for each of the tests may also be seen in Table 9.

Due to the nature of the buckling tests and pinned boundary conditions for the major principal axis, regardless of the length of the specimen tested, overall buckling was the dominant failure mode. For the shorter sections, both local and distortional buckling typically occurred well before overall buckling, meaning that there was an interaction between the buckling modes which lead to a reduction in the upright's axial stiffness. For longer sections, this buckling interaction was not seen as prominently. For brevity, the discussion below about the flexural-torsional buckling behaviour will be based around the RF-FT-1950-1 and SD-FT-1950-1 tests completed.

RF Uprights

In order to effectively capture observations as the tests ran and load was applied, a high speed Canon Digital SLR camera was mounted on a tripod and programmed to take HD pictures at 5 second intervals. A script was then written which stitched the images together to create a movie. A video of both the RF-FT-1950-1 and RF-FT-1950-2 tests may be seen in Appendix E.

In addition to the above video, Figure 46 displays the load vs axial displacement and load vs. translational displacement as measured by the attached transducers for RF-FT-1950-1. From Figure 46 and the video footage of the experiment, it can be seen that initially as the load is applied, there is only modest displacement or distortion in the cross-section. Gradually as load increased, transducers 1, 5, 6 and 10 on the stiffened flange started to record an outwards displacement from the centroid of the cross-section. As load reached 30 kN, the transducers 2, 4, 7 and 9 on the side flanges of the cross-section also started to measure an outwards displacement of the flange, meaning that distortional buckling was beginning to occur.

![Figure 46. Overall Member Displacements RF-FT-1950-1](image-url)
Figure 47. Cross Sectional Displacements RF-FT-1950-1 Mid-Height

Figure 48. Cross Sectional Displacements RF-FT-1950-1 150mm below Mid-height
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While considerable distortional and local displacements occurred before reaching the ultimate load in the shorter specimens (as seen by the results in Appendix D), for these longer specimens, the displacement caused by local and distortional buckling is small in comparison to the overall y-axis displacement of the cross-section, recorded by transducer 13. This is also reflected by the fact that the gradient of the load vs axial shortening curve in Figure 46 did not change and consequently there was no reduction in the section's axial rigidity. As the load continued to increase above 30 kN, the upright continued to displace in the positive y-direction and simultaneously began to rotate, seen in the twist rotation curve in Figure 46. Displacements continued to increase until the ultimate load was reached at 54kN. After the ultimate load, the axial load gradually dropped and horizontal and axial displacements began to dramatically increase. This continued until the axial displacements had reached 5 mm, at which point a failure of the flange occurred and the load started to drastically decrease. The test was then stopped after a 20% load reduction from ultimate had occurred. The video footage of both the RF-FT-1950 tests provides the best records of these observations.

SD Uprights

Similar to the RF tests, an HD quality video was also recorded for the SD-FT-1950-2 test. However, unfortunately the camera was only just able to capture up to the ultimate load. This video may also be viewed at: http://tiny.cc/SD-1950-2 (password = 'buckling').

Unlike the RF uprights, the SD section does not have a rear flange stiffener and as such, local and distortional buckling was prevalent in all the lengths of the uprights well before the ultimate load was reached. As seen in Figures 49 and 50 from test SD-FT-1950-1, as load starts to increase the member starts very gradually to move in the positive y-direction, as recorded by Transducer 13. When the loads reaches 10 kN, transducers 1 and 5 begin to record small displacements at the tip of the flanges. The readings were positive indicating the flanges moved outwards, a result of local buckling creating short half-wavelength deformations. The web also began to move inwards due to this local buckling, as indicated by transducer 3. These displacements continued to increase and were then amplified by the distortional buckling of the cross-sections which occurred above 20 kN. At this point the flanges of the cross-section slowly began to rotate outwards at the flange-web corners at mid-height, as seen by the positive recording from transducers 2 and 4.

![Figure 49. Overall Member Displacements SD-FT-1950-1](image-url)
Once the axial load passed 30 kN, the local and distortional deformations started to occur at a faster rate. It is now evident that the interaction between the buckling modes were reducing the axial rigidity of the section, observed by the reduced gradient of the axial load vs axial shortening and twist initiated in the cross-section, as shown in Figure 49. The second order effects meant that there was an increase in the horizontal displacements of the cross-section and a faster rate of twist of the cross-section around 35 kN. Transducers 11 and 12 showed that the cross-section was now rotating in a clockwise direction while the member was simultaneously displacing in a negative y-direction, a sign that flexural-torsional buckling was starting to occur. Flexural-torsional buckling continued until the specimen reached its ultimate load at 42kN and subsequently failed in this mode.

After the ultimate load has been reached, displacements continued to rapidly increase and the upright continued to twist and displace in the negative y-direction at an increasing rate. Finally, after the axial load had dropped to 37 kN, a localised failure in the flange occurred and there was a rapid decrease in load and section capacity. Similar to the other specimens, a failure of the flange occurred at mid-height and there was significant distortion through the diamond perforations of the web. Figures 51 and 52 show this progression and failure during Test SD-FT-1950-1. Graphs and data from all the other tests may also be seen in Appendix D.
Figure 51. Local and Distortional Buckling Before Ultimate Load SD-FT-1950-1
CONCLUSIONS

An experimental investigation into the behaviour of ultra-light gauge steel storage rack uprights subjected to compression was conducted. A total of 20 ultra-light gauge steel storage rack sections were tested in the Civil Engineering Structures Laboratory at the University of Sydney. While the combined effects of local and distortional buckling were investigated, special attention was given to longer specimens that failed by flexural-torsional buckling. All flexural-torsional buckling test specimens were conducted between pinned end conditions with an axial load applied concentrically using a Dartec testing machine. Two different types of ultra-light-gauge steel storage rack uprights were tested, RF90.1 and SD90.1. Before testing, the geometric
imperfections in each of the members were measured, as were the material properties of the sections and the virgin steel from which the sections were formed.

All the tests conducted at the University of Sydney were successful in displaying and capturing the interactive buckling effects of local, distortional and overall buckling. Deformations experienced during testing by all specimens were measured and observations regarding failure modes were documented. Results from nominally identical tests were in good agreement. These tests are the first to provide valuable data that will help to provide an understanding of the effect of tri-modal interactive buckling on the ultimate capacity and observed failure mode of thin-walled steel sections.

Given the imperfection-sensitive nature of interactive buckling, precise imperfection measurements were also recorded using laser displacement sensors for each of the specimens. This data will form the basis for ongoing research into the verification of finite element models for parametric studies, which will help with the characterisation of imperfections and determination of their effect on the ultimate strength of sections.

REFERENCES


D.C.P. Yap and Hancock G. J. Post-buckling in the distortional mode and buckling mode interaction of cold-formed thin-walled sections with edge stiffeners. In 18th International Specialty Conference on Cold-Formed steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction, pages 71-788, 2006.

APPENDIX

APPENDIX A- GEOMETRIC IMPERFECTION MEASUREMENTS

General

Please refer to Figure 11 to see the locations of the laser displacement sensors around the cross sections used for the geometric imperfection measurements.

SD Specimens

Figure 53. SD-S-300-1 Imperfection measurements
Figure 54. SD-S-300-1 Imperfection amplitudes vs half-wavelength
Figure 55. SD-S-300-2 Imperfection measurements
Figure 56. SD-S-300-2 Imperfection amplitudes vs half-wavelength
Figure 57. SD-D-1000-1 Imperfection measurements
Figure 58. SD-D-1000-1 Imperfection amplitudes vs half-wavelength
Figure 59. SD-D-1000-2 Imperfection measurements
Figure 60. SD-D-1000-2 Imperfection amplitudes vs half-wavelength
Figure 61. SD-FT-625-1 Imperfection measurements
Figure 62. SD-FT-625-1 Imperfection amplitudes vs half-wavelength
Figure 63. SD-FT-625-2 Imperfection measurements
Figure 64. SD-FT-625-2 Imperfection amplitudes vs half-wavelength
Figure 65. SD-FT-1345-1 Imperfection measurements
Figure 66. SD-FT-1345-1 Imperfection amplitudes vs half-wavelength
Figure 67. SD-FT-1345-2 Imperfection measurements
Figure 68. SD-FT-1345-2 Imperfection amplitudes vs half-wavelength
Figure 69. SD-FT-1950-1 Imperfection measurements
Figure 70. SD-FT-1950-1 Imperfection amplitudes vs half-wavelength
Figure 71. SD-FT-1950-2 Imperfection measurements
Figure 72. SD-FT-1950-2 Imperfection amplitudes vs half-wavelength
RF Specimens

Figure 73. RF-S-300-1 Imperfection measurements
Figure 74. RF-S-300-1 Imperfection amplitudes vs half-wavelength
Figure 75. RF-S-300-2 Imperfection measurements
Figure 76. RF-S-300-2 Imperfection amplitudes vs half-wavelength
Figure 77. RF-S-300-3 Imperfection measurements
Figure 78. RF-S-300-3 Imperfection amplitudes vs half-wavelength
Figure 79. RF-D-1000-1 Imperfection measurements
Figure 80. RF-D-1000-1 Imperfection amplitudes vs half-wavelength
Figure 81. RF-D-1000-2 Imperfection measurements
Figure 82. RF-D-1000-2 Imperfection amplitudes vs half-wavelength
Figure 83. RF-FT-600-1 Imperfection measurements
Figure 84. RF-FT-600-1 Imperfection amplitudes vs half-wavelength
Figure 85. RF-FT-600-2 Imperfection measurements
Figure 86. RF-FT-600-2 Imperfection amplitudes vs half-wavelength
Figure 87. RF-FT-1275-1 Imperfection measurements
Figure 88. RF-FT-1275-1 Imperfection amplitudes vs half-wavelength
Figure 89. RF-FT-1275-2 Imperfection measurements
Figure 90. RF-FT-1275-2 Imperfection amplitudes vs half-wavelength
Figure 91. RF-FT-1950-1 Imperfection measurements
Figure 92. RF-FT-1950-1 Imperfection amplitudes vs half-wavelength
Figure 93. RF-FT-1950-2 Imperfection measurements
Figure 94. RF-FT-1950-2 Imperfection amplitudes vs half-wavelength
APPENDIX B- STUB COLUMN TEST RESULTS

SD Specimens

Figure 95. SD-S-300-1 Transducer Measurements
Figure 96. SD-S-300-2 Transducer Measurements
RF Specimens

Figure 97. RF-S-300-1 Transducer Measurements
Figure 98. RF-S-300-2 Transducer Measurements
Figure 99. RF-S-300-3 Transducer Measurements
APPENDIX C- DISTORTIONAL BUCKLING TEST RESULTS

SD Specimens

Figure 100. SD-D-1000-1 Transducer Measurements

Figure 101. SD-D-1000-2 Transducer Measurements
RF Specimens

Figure 102. RF-D-1000-1 Transducer Measurements
Figure 103. RF-D-1000-2 Transducer Measurements
APPENDIX D - FLEXURAL-TORSIONAL TEST RESULTS

SD Specimens

- [Graphs showing load-displacement curves for SD Specimens with labels Axial Disp., T7, T9, T5, T4, T3, T6, T10, and T8]
Figure 104. SD-FT-625-1 Transducer Measurements
Figure 105. SD-FT-625-1 Transducer Measurements
Figure 106. SD-FT-1345-1 Transducer Measurements
Figure 107. SD-FT-1345-2 Transducer Measurements
Figure 108. SD-FT-1950-1 Transducer Measurements
Figure 109. SD-FT-1950-2 Transducer Measurements
RF Specimens
Figure 110. RF-FT-600-1 Transducer Measurements
Figure 111. RF-FT-600-1 Transducer Measurements
Figure 112. RF-FT-1275-1 Transducer Measurements
Figure 113. RF-FT-1275-2 Transducer Measurements
Experimental Investigations into interactive buckling of ultra-light gauge steel storage rack uprights

Figure 114. RF-FT-1950-1 Transducer Measurements
APPENDIX E- FLEXURAL-TORSIONAL VIDEO FOOTAGE

SD Specimens

For footage of the experiment SD-FT-1950-2, please visit the link below and use the password “buckling” to access the video.

http://tiny.cc/SD-1950-2

RF Specimens

For footage of the experiments RF-FT-1950-1 and RF-FT-1950-2, please visit the respective links below and use the password “buckling” to access the videos.

http://tiny.cc/RF-1950-1