Stainless Steel Stub Columns Subject to Combined Bending and Axial Loading

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STAINLESS STEEL STUB COLUMNS SUBJECT TO COMBINED BENDING AND AXIAL LOADING

M. Macdonald\textsuperscript{1} and J. Rhodes\textsuperscript{2}

ABSTRACT

Stainless steel exhibits highly non-linear behaviour, and in the case of short column structural members, this can lead to substantial conservatism in the prediction of load capacity by design codes due to their use of the 0.2\% proof stress as an upper limit of capacity. This paper examines the behaviour of short stainless steel stub columns in which the material follows a Ramberg-Osgood type of stress-strain law. The column length is varied to examine the effects on the load capacity when the column is subjected to varying magnitudes of combined bending and axial compression loading. The loading is applied as eccentric axial loading, with the eccentricity being positive at one end and negative at the other to produce varying moments along the column under load. Two different methods of analysis are employed, (1) the ASCE design code using a Ramberg-Osgood stress-strain law combined with a full section moment capacity within the interaction formula with nominal levels of loading eccentricity, and (2), the same approach, but using the true eccentricity with reference to the unsupported length of the columns. The results are compared with those obtained from a series of compression tests performed on cold formed stainless steel Type 304 stub columns of lipped channel cross-section for the same conditions.

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INTRODUCTION

The mechanical properties of stainless steel structural members are significantly different from those of carbon steel. Stainless steels display a pronounced response to cold working which results in anisotropic, non-linear stress-strain behaviour, and also, low proportional limits. The material properties of various stainless steels have been thoroughly investigated since the 1960s by a number of researchers, e.g. refs. [1], [2], [3], [4]. It has been generally concluded that the stress-strain behaviour of stainless steels can be best described by the Ramberg-Osgood model [5], and Hill's [6] modified form of the Ramberg-Osgood equation is used in the ASCE design specification.

The main design specification for cold formed stainless steel members in the USA is the ASCE specification [7] and in Europe, Eurocode 3: Part 1.4 [8] has been recently developed and is still under examination. The two codes use different approaches when dealing with the mechanical properties of the material. The ASCE code employs the modified form of the Ramberg-Osgood model to describe the stress-strain behaviour of a material, whereas the Eurocode relies for most purposes on the specification of a linear stress-strain law, with the yield strength taken as the 0.2% proof stress. In two recent publications refs. [9], [10], a comparison of the Eurocode and ASCE code load capacity predictions for lipped channel columns is illustrated. The simpler Eurocode analysis has been found to give reasonable estimates of concentrically loaded column strength without taking account into the non-linearity of the stress-strain curve. For eccentrically loaded columns, a general conservatism was found, particularly for shorter stub columns where the eccentricity was of a fixed magnitude. Improvements in correlations of code predictions with test results were obtained by employing the actual full-section stress-strain characteristics as described in ref. [11]. In a further analysis described in ref. [12], a finite element model provided excellent correlations to test results, regardless of the stress-strain model adopted.

MECHANICAL PROPERTIES OF STAINLESS STEEL LIPPED CHANNEL MEMBERS

The properties of cold formed material vary throughout the profile of the cross-section formed where at the formed bends, higher yield and tensile strengths exist, leading to a more complex stress-strain relationship for cold formed members. The level of increase of both yield and tensile strength is highly
dependent on the ratio of corner radius to material thickness \((r/t)\). The cold formed lipped channels under investigation are of stainless steel, of cross-sections with small web, flange and lip dimensions and are considered to be thick and hence four corner bends are formed with small \(r/t\) ratios (<1). The four bends have an effect on the stress-strain response of the material obtained from a full section test.

The ASCE design specification adopts the modified Ramberg-Osgood formula to obtain an accurate stress-strain model up to a value slightly greater than yield, as given by equation (1).

\[
\varepsilon = \frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{\sigma_y} \right)^n
\]

(1)

where \(\varepsilon\) = unit strain, 
\(\sigma\) = unit stress \((\text{N/mm}^2)\), 
\(\sigma_y\) = 0.2% proof stress \((\text{N/mm}^2)\), 
\(E_0\) = initial modulus of elasticity \((\text{N/mm}^2)\), 
and \(n\) = plasticity factor.

The ASCE design code makes use of equation (1), and three points on the stress-strain curve are defined as: (i) the origin; (ii) the point of 0.2% proof stress; (iii) another offset strength (e.g. 0.01%). If these points are substituted into equation (1), then ‘\(n\)’ can be evaluated. The term ‘\(n\)’ is referred to in the ASCE design code as the plasticity factor. The accuracy of the above method is largely based on how well the analytical equation fits the stress-strain relationship of the material. The code lists for particular grades of stainless steel, tables of yield stress, tangent modulus and plasticity factors.

In this investigation, equation (1) is used to model the stress-strain behaviour of virgin stainless steel and the full cold formed lipped channel cross-section stub columns.

LOAD CAPACITY OF STAINLESS STEEL LIPPED CHANNEL STUB COLUMNS SUBJECTED TO COMBINED BENDING AND AXIAL COMPRESSION LOADING
Rhodes et. al. [9], [10], investigated both concentric and eccentric loading of cold formed stainless steel lipped channel section columns. The findings showed that the relevant design codes provided very accurate predictions of load capacity for the concentric loading case using both virgin and full section material properties when compared to experimental results. A finite element analysis also produced a very accurate correlation to both the experimental results and the design code predictions. However, for shorter length eccentrically loaded stub columns, the design codes were very conservative in their prediction of load capacity using both virgin and full section material properties. It was concluded that the design codes' interaction formulae were inadequate in predicting the load capacity of short-to-medium length columns. The ASCE interaction formula is given by equation (2).

\[
\frac{P_u}{P_n} + \frac{P_u e}{M_n \left(1 - \frac{P_u}{P_E}\right)} \leq 1.0
\]  

(2)

where \(P_u\) required axial strength (N)

\[P_n = \varphi A_e F_n\]  

(N) where \(\varphi\) = resistance factor = 0.85

\[M_n = \frac{F_y I_{xx}}{y}\]  

= moment capacity of the cross section (Nmm)

where \(F_y\) = 0.2% proof stress (N/mm²)

\[P_e = \frac{\pi^2 E_a I_{xx}}{L^2}\]  

= Euler buckling capacity (N)

\(e\) = distance from centroid (eccentricity) = ±4, 8, 12 and 16 mm

and all other terms are as defined in ref. [9].

This equation produced very conservative estimates of load capacity and attempts to improve the interaction formula was proposed by Macdonald [11]. A modification to the interaction formula involved replacing the linear moment capacity \(M_n\) with the true or enhanced moment capacity of the lipped channel.
cross-section $M_{\text{exp}}$, obtained from bending tests was made. Hence the ASCE interaction formula was modified as given by equation (3).

$$\frac{P_u}{P_n} + \frac{P_u e}{M_{\text{exp}} \left(1 - \left(\frac{P_u}{P_E}\right)\right)} \leq 1.0 \quad (3)$$

In equation (2), $M_{\text{exp}}$ is the cross-section true moment capacity where the 0.2% proof stress is taken from the full section tensile test results. Another attempt to improve correlations of code predictions to test results was made by excluding the resistance factor $\varphi$ in the axial strength $P_n$ calculation.

**EXPERIMENTAL INVESTIGATIONS**

**Tensile Tests**

Figure 1 shows a typical cross-section of the cold formed stainless steel lipped channel member under investigation. The member is commercially available and was supplied in two different sizes of cross-section and all the specimens were accurately measured at a number of points, with the values averaged to obtain the finished dimensions, and all calculations were based on the mid-line dimensions shown in Table 1. In order to determine the material properties of the sections, tensile tests were set-up where the applied load and gauge specimen elongation were recorded continuously until fracture of the specimen occurred. The measured load and elongation were normalised to give a stress-strain relationship. Due to the anisotropy of stainless steel, a full analysis of the material properties would require tensile tests in the longitudinal and transverse directions, as well as compression tests in the same directions. However, compression tests were not carried out as there would be difficulty in establishing the true material properties of the material due to likely buckling effects. Also, transverse direction tensile tests could not be carried out because of the limitations in the geometry of the sections. Hence tensile testing was limited to the longitudinal direction.

All tensile tests were carried out in accordance with BSEN10002-1 [13]. Standard tensile tests were performed to ascertain the material properties of the stainless steel for the 2 different thicknesses. Coupons were cut from the webs
of the columns and tested to obtain the 0.2% proof stress and the modulus of elasticity.

Tensile tests were also performed on full sections to include the effects of the cold formed corners and from these tests, the 0.2% proof stress and the modulus of elasticity were determined.

For the standard coupons, a total of three specimens were cut from the section web, tested and the average results were noted. For the full section tests, two specimens were tested and again, the average results were noted.

Compression Tests

In the experimental investigation a series of compression tests to failure were made on stainless steel stub columns of the lipped channel cross-section as described above.

The stub column lengths varied from 124 mm to 624 mm in increments of 100 mm. (The slenderness ratio varied from 24 to 120.)

Twenty-eight tests to failure were carried out, with the loading applied at eccentricities of 4, 8, 12 and 16 mm above and below the centroidal axis of the cross-section. For certain stub column specimens, two specimens were tested and the average failure loads were noted.

Each length of stub column tested was cut to the specified length and then milled flat at each end to avoid any possible gripping problems. The end grips were designed such that they would hold the ends of the column and allow the loading to be applied at the required eccentricity through knife edges. The specimens were tested using a Tinius Olsen electro-mechanical testing machine, with the stub column vertical displacement and mid-span horizontal deflection measured during the tests using displacement transducers. Figure 1 shows a simplified drawing of the stub column test configuration.

RESULTS

All results obtained from tensile tests to establish virgin material and full cross-section mechanical properties are detailed in ref. [10] and are shown in Table 2. Table 3 shows the results obtained from the compression tests carried out on the stub columns, with varying nominal levels of eccentricity.

Tables 4, 5, 6 and 7 show the ASCE design code failure load predictions for virgin mechanical properties (with nominal eccentricity), full section mechanical properties and moment capacity (with nominal eccentricity, including the
resistance factor), full section mechanical properties and moment capacity (with true eccentricity, including the resistance factor) and full section mechanical properties and moment capacity (with true eccentricity, excluding the resistance factor) respectively.

Figures 2, 3, 4 and 5 show graphs of Failure Load v. Stub Column Length for the stainless steel stub columns subject to eccentric loading with nominal eccentricities of 4 mm, 8 mm, 12 mm and 16 mm respectively. Figure 2 shows the curves obtained for the test results, the ASCE with the virgin mechanical properties and nominal eccentricities, the ASCE with full section mechanical properties and moment capacity and true eccentricities – including the resistance factor, and, the ASCE with full section mechanical properties and moment capacity and true eccentricities – excluding the resistance factor.

OBSERVATIONS

As shown in Figures 2, 3, 4 and 5, the failure load predictions obtained from the ASCE design code are conservative when compared to the experimental results. Using the basic virgin mechanical properties within the interaction formula provides a very conservative failure load prediction, and the level of conservatism increases with increasing eccentricity. Using the full section mechanical properties combined with the full section moment capacity within the interaction formula shows an improvement on the basic properties. However, when the true level of eccentricity is applied within the interaction formula along with the full section properties, the degree of conservatism is reduced quite significantly, particularly for the shortest of the range of stub columns tested. Also, excluding the 0.85 resistance factor within the calculation of nominal axial strength, then the correlation between the curves obtained for failure loads with true eccentricity applied and the experimental failure loads is actually very good, with highest degree of conservatism being for the 8 mm eccentricity case.

CONCLUSIONS

Using the ASCE interaction formula with the virgin material properties and the linear elastic moment capacity, leads to very high levels of conservatism in predicting the failure loads of cold formed stainless steel stub columns subject to
nominal levels of eccentricity. Improvements are gained by employing the full section mechanical properties along with the section experimental full moment capacity, particularly for loads applied nearer to the centroidal axis. However, generally, applying the true level of load eccentricity provides further improvements when compared to the test results. Intermediate column lengths tested showed conservative results, particularly for greater levels of eccentricity of applied load, which may have been due to experimental error. However, it can be concluded that the ASCE design code requires further investigation with respect to imperfection parameters in particular, when designing stub columns subject to combined bending and axial loading.

ACKNOWLEDGEMENT

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Figure 1: Details of Stub Column Geometry and Load Application

TABLE 1
Average Dimensions of Lipped Channel Cross-Sections

<table>
<thead>
<tr>
<th>Web $b_1$ (mm)</th>
<th>Flange $b_2$ (mm)</th>
<th>Lip $b_3$ (mm)</th>
<th>Thickness $t$ (mm)</th>
<th>Radius $r_1$ (mm)</th>
<th>Radius $r_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.00</td>
<td>14.88</td>
<td>7.45</td>
<td>2.43</td>
<td>1.10</td>
<td>1.10</td>
</tr>
</tbody>
</table>

TABLE 2
Tensile Test Results: Virgin Material and Full Section (FS) Mechanical Properties

<table>
<thead>
<tr>
<th>Thickness $t$ (mm)</th>
<th>Av. Virgin $0.2%$ P.S. (N/mm$^2$)</th>
<th>Av. Virgin UTS (N/mm$^2$)</th>
<th>Virgin $n$ [Eqn.(1)]</th>
<th>Av. FS $0.2%$ P.S. (N/mm$^2$)</th>
<th>Av. FS UTS (N/mm$^2$)</th>
<th>FS $n$ [(Eqn.(1)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.43</td>
<td>480</td>
<td>553</td>
<td>3.80</td>
<td>520</td>
<td>689</td>
<td>5.02</td>
</tr>
</tbody>
</table>
### TABLE 3
Compression Test Results: Failure Loads for Varying Nominal Eccentricity

<table>
<thead>
<tr>
<th>Stub Column Length (mm)</th>
<th>Failure Load (kN) - Experimental</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom.Ecc.=4m</td>
<td>Nom.Ecc.=8m</td>
<td>Nom.Ecc.=12m</td>
<td>Nom.Ecc.=16m</td>
</tr>
<tr>
<td>100</td>
<td>66.80</td>
<td>53.50</td>
<td>49.70</td>
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<td>200</td>
<td>54.70</td>
<td>47.80</td>
<td>33.50</td>
<td>28.30</td>
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<tr>
<td>300</td>
<td>40.00</td>
<td>39.70</td>
<td>34.00</td>
<td>24.80</td>
</tr>
<tr>
<td>400</td>
<td>28.20</td>
<td>26.00</td>
<td>21.20</td>
<td>21.10</td>
</tr>
<tr>
<td>600</td>
<td>16.00</td>
<td>14.80</td>
<td>13.70</td>
<td>13.60</td>
</tr>
</tbody>
</table>

### TABLE 4
ASCE Design Code Results: Failure Loads for Varying Nominal Eccentricity (Virgin Material Mechanical Properties – including Resistance Factor)

<table>
<thead>
<tr>
<th>Stub Column Length (mm)</th>
<th>Failure Load (kN)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom.Ecc.=4m</td>
<td>Nom.Ecc.=8m</td>
<td>Nom.Ecc.=12m</td>
<td>Nom.Ecc.=16m</td>
</tr>
<tr>
<td>100</td>
<td>30.92</td>
<td>20.36</td>
<td>15.21</td>
<td>12.14</td>
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<tr>
<td>200</td>
<td>25.36</td>
<td>17.57</td>
<td>13.52</td>
<td>11.01</td>
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<tr>
<td>300</td>
<td>20.70</td>
<td>14.96</td>
<td>11.84</td>
<td>9.83</td>
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<tr>
<td>400</td>
<td>16.36</td>
<td>12.35</td>
<td>10.06</td>
<td>8.53</td>
</tr>
<tr>
<td>600</td>
<td>9.66</td>
<td>7.89</td>
<td>6.78</td>
<td>5.98</td>
</tr>
</tbody>
</table>
### TABLE 5
ASCE Design Code Results: Failure Loads for Varying Nominal Eccentricity
(Full Section Mechanical Properties and Moment Capacity – including Resistance Factor)

<table>
<thead>
<tr>
<th>Stub Column Length (mm)</th>
<th>Failure Load (kN)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom.Ecc.=4m m</td>
<td>Nom.Ecc.=8m m</td>
<td>Nom.Ecc.=12m m</td>
<td>Nom.Ecc.=16m m</td>
</tr>
<tr>
<td>100</td>
<td>40.02</td>
<td>29.15</td>
<td>23.01</td>
<td>19.04</td>
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<td>32.00</td>
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<td>19.61</td>
<td>16.56</td>
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<td>300</td>
<td>25.05</td>
<td>19.58</td>
<td>16.30</td>
<td>14.05</td>
</tr>
<tr>
<td>400</td>
<td>18.67</td>
<td>15.17</td>
<td>12.99</td>
<td>11.44</td>
</tr>
<tr>
<td>600</td>
<td>10.35</td>
<td>8.95</td>
<td>8.01</td>
<td>7.31</td>
</tr>
</tbody>
</table>

### TABLE 6
ASCE Design Code Results: Failure Loads for Varying True Eccentricity
(Full Section Mechanical Properties and Moment Capacity – including Resistance Factor)

<table>
<thead>
<tr>
<th>Stub Column Length (mm)</th>
<th>Failure Load (kN)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom.Ecc.=4m m</td>
<td>Nom.Ecc.=8m m</td>
<td>Nom.Ecc.=12m m</td>
<td>Nom.Ecc.=16m m</td>
</tr>
<tr>
<td>100</td>
<td>55.51</td>
<td>41.68</td>
<td>39.76</td>
<td>32.16</td>
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<td>37.82</td>
<td>29.05</td>
<td>28.44</td>
<td>23.42</td>
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<tr>
<td>300</td>
<td>28.28</td>
<td>21.92</td>
<td>21.68</td>
<td>18.22</td>
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<tr>
<td>400</td>
<td>20.56</td>
<td>16.31</td>
<td>16.23</td>
<td>14.00</td>
</tr>
<tr>
<td>600</td>
<td>10.86</td>
<td>9.26</td>
<td>9.26</td>
<td>8.32</td>
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</table>
TABLE 7
ASCE Design Code Results: Failure Loads for Varying True Eccentricity
(Full Section Mechanical Properties and Moment Capacity – excluding Resistance Factor)

<table>
<thead>
<tr>
<th>Stub Column Length (mm)</th>
<th>Failure Load (kN)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom.Ecc.=4m m</td>
<td>Nom.Ecc.=8m m</td>
<td>Nom.Ecc.=12m m</td>
<td>Nom.Ecc.=16m m</td>
</tr>
<tr>
<td>100</td>
<td>65.31</td>
<td>49.04</td>
<td>46.78</td>
<td>37.84</td>
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<tr>
<td>200</td>
<td>44.50</td>
<td>34.18</td>
<td>33.46</td>
<td>27.55</td>
</tr>
<tr>
<td>300</td>
<td>33.27</td>
<td>25.79</td>
<td>25.51</td>
<td>21.44</td>
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<tr>
<td>400</td>
<td>24.19</td>
<td>19.19</td>
<td>19.09</td>
<td>16.44</td>
</tr>
<tr>
<td>600</td>
<td>12.78</td>
<td>10.89</td>
<td>10.89</td>
<td>9.79</td>
</tr>
</tbody>
</table>

Figure 2: Graph of Failure Load v. Stub Column Length: (Test Results/ASCE) - e = ±4mm
Figure 3: Graph of Failure Load v. Stub Column Length: (Test Results/ASCE) - e = ±8mm

Figure 4: Graph of Failure Load v. Stub Column Length: (Test ASCE) - e = ±12mm
Figure 5: Graph of Failure Load v. Stub Column Length: (Test Results/ASCE) – e = ±16mm