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M. MacDonald

J. Rhodes

G. T. Taylor

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Compressional Behaviour of Stainless Steel Short Struts

by

M. Macdonald[1], J. Rhodes[2] and G. T. Taylor [3]

1.Department of Engineering, Glasgow Caledonian University, Glasgow, UK

2.Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK

3.Department of Energy and Environmental Technology, Glasgow Caledonian University, Glasgow, UK

SUMMARY

The effects of cold forming on both carbon steel and stainless steel structural members has been the subject of extensive research since the early 1940's. Design code specifications for carbon steel members have been published in many countries around the world, including BS 5950, Part 5 in the UK (1) the AISI Specification in the USA (2), and the new Eurocode 3, Part 1.3 (3). For stainless steel members there are fewer design code specifications available, and those that are available, which include the ANSI/ASCE in the USA (4) and the new Eurocode 3, Part 1.4 (5), do not give such detailed design recommendations as the carbon steel specifications.

This paper describes the results obtained from a series of axial compression tests performed on short strut members of plain channel cross section cold formed from Type 304 stainless steel sheet. The corner radius and the material thickness are varied to examine the effects of cold forming on the load capacity of the channels in compression and the results are compared to those obtained from the relevant design specifications. Conclusions are drawn on the basis of the comparisons.

INTRODUCTION

Cold formed sections are widely used for building structures, storage racking and domestic equipment. This is due to various characteristics such as their high strength to weight ratio, their ease of manufacture and the fact that a wide range of cross-sections can be formed from many different materials.

An advantage which is obtained from cold forming structural members is the increase in yield strength gained due to the cold working involved. Such cold working causes strain hardening of the material which affects its mechanical properties, and consequently the material properties of a formed section may be markedly different from those of the virgin sheet material from which it was formed. In general, this strain hardening increases both the yield strength and the ultimate tensile strength. This is certainly true for mild steel as reported by Karren (6) and Karren and Winter (7). However, for a material such as stainless steel, these increases may not be the same as for mild steel and the ratio of the ultimate tensile strength to the yield strength may also be different. Karren and Winter demonstrated with their tensile test approach on carbon steel that the effect that cold forming has on structural sections is generally confined to the areas of formed bends and it is in these areas that increases in yield and ultimate strength are located. Research by Van Den Berg and Van Der Merwe (8) which modified the AISI carbon steel design code specification for various types of stainless steels including Type 304, arrived at a simple equation to predict the increase in mechanical properties gained at corner sections and their effect on the whole cross-section. Further research by Macdonald et al (9, 10) using a hardness test approach, confirmed this type of behaviour for carbon steel and also examined similar behaviour for stainless steel cold formed members.

The localised effect of cold forming is now investigated further by examining its consequence on the axial compression behaviour of short struts with plain channel cross sections manufactured from Type 304 stainless steel sheet with relatively small bend radius/material thickness (r/t) ratios.

No UK design code exists for cold formed stainless steel members, but two widely used design codes are the ANSI/ASCE specification (4) and the new Eurocode 3, Part 1.4 specification (5). These codes give many design recommendations which include methods of computing the load capacity of short structural members subjected to axial compressive loading, often termed "stub columns"

AXIAL COMPRESSION LOAD CAPACITY OF STAINLESS STEEL PLAIN CHANNEL SHORT STRUTS - DESIGN CODE RECOMMENDATIONS

In the formation of a profiled section, the cold working occurs in localised areas, with the material at the bends being strain hardened to a much greater degree than the material in the flat elements. Therefore the properties of the material vary throughout the cross-section where at the formed bends, a higher yield strength will exist. The effect that the areas of high strength have on the load capacity of short struts of plain channel cross-section is considered here for Type 304 stainless steel. The plain channel cross-sections have constant flange widths and web depth with the length of the strut also being constant. To vary the amount of cold forming, the cold formed corners were manufactured with various sizes of inside bend radius and also the materials used were of three different thicknesses hence providing a range of r/t ratios. The r/t ratios were kept small varying from approximately 2.5 to 8.5. The design codes make the assumption that cold formed bends with r/t < 5t can be treated as sharp corners. Hence one of the aims of this investigation was to determine if an increase in load capacity in compression could be gained for plain channel sections with variation in r/t.

The lengths of the struts were kept short such that failure by Euler type buckling would be eliminated and that failure would occur due to local buckling effects only. Further details of the experimental investigation are described later.

The load capacity for short struts subjected to axial compression loading for stainless steel cold formed members according to the relevant design codes are calculated as follows:

ANSI/ASCE-8-90:

Design Axial Strength, $P_n = A_e f_y$ (N) (1)

where A_e = effective cross-sectional area (mm^2)
and f_y = virgin material 0.2% proof stress (N/mm^2)

Eurocode 3, Part 1.4:

Design Buckling Resistance, $N_{b,Rd} = \chi \beta_A A_g f_y$ (N) (2)

where χ = reduction factor equal to unity for the struts examined.
β_A = ratio of A_{eff}/A_g,
A_g = gross cross-sectional area (mm^2)
and f_y = virgin material 0.2% proof stress (N/mm^2)

The effective area in both codes is determined on the basis of effective widths of the elements which are related directly to the initial elastic modulus, and do not take any account of the degradation of E as loading progresses.

The results obtained from the above equations will be used for comparison with the results obtained from the axial compression tests described later.

AXIAL COMPRESSION TEST EXPERIMENTAL INVESTIGATION

A total of 29 plain channel section short strut specimens were cold formed from stainless steel sheet of three different thicknesses - nominally 0.7mm, 0.9mm and 1.2mm. The inside radius of the corner bends of the plain channels were varied with sizes of 3mm, 5mm and 6mm to give a small range of r/t ratio. The cross-section dimensions were kept constant with the flange being of nominal width 30mm and the web being of nominal depth 60mm. The length of the short strut specimens was also kept constant at a nominal 180mm. Three specimens were manufactured for each specimen of a given thickness and bend radius so that an average load capacity could be used for comparison to design code specification predictions. One specimen was manufactured for each thickness with sharp corners to give a radius as close as possible to zero so that the load capacity for sections with formed corners could be compared to that obtained for no formed corners.

The specimens were formed from flat sheet into plain channel sections with varying thicknesses and corner bend radii. This was done by using a mechanically-operated bending machine with slight variations in the setting of the material to account for different sizes of corner bend radius. However, due to different material thicknesses and machine settings, the bending process generated fluctuations in the overall dimensions for the specimens with the only exception being the specimen length which was maintained at approximately 180mm. Figure 1 shows a plain channel section short strut column with all the nominal dimensions shown. All the specimens were accurately measured to obtain the finished dimensions and all calculations were based on the actual dimensions measured.

t = 0.7, 0.9 and 1.2mm; B_1 = 30mm (constant)
r = 3, 5 and 6mm; B_2 = 60mm (constant)
L = 180mm (constant)

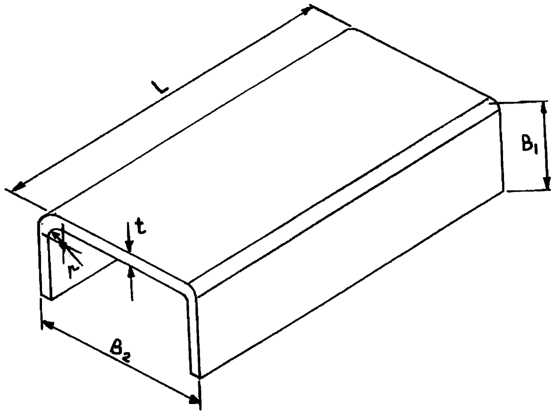

Figure 1: Nominal Dimensions of Short Strut Plain Channel Cold Formed Sections.

The ends of the specimens were ground to ensure flatness and the specimens were compressed uniformly to failure between flat plattens in a Tinius Olsen Electro-mechanical testing machine, with the load-end compressive displacement path being recorded.

RESULTS

The specimen details and the experimental and design specification predictions for the axial compressive load capacity of the stainless steel short struts are shown in Table 1. The table shows a comparison of the experimental load capacities obtained with the load capacities obtained from the ANSI/ASCE and Eurocode 3, Part 1.4 design specifications. Figure 2 shows a graph of the failure loads for short struts plotted against the r/t ratio for each different thickness of material. Figure 3 shows the variation of A_{eff}/t^2 at failure with variation in r/t ratio for the different material thicknesses.

OBSERVATIONS

Figure 2 indicates that the stainless steel strut test results are in good agreement with the ultimate load predictions of Eurocode 3: Part 1.4 and the ANSI/ASCE design code. Both design codes are very similar in their treatment of stub column capacity, and the results only differ very slightly because of minor differences in the specifications, such as the value of the Elasticity Modulus. In the case of 0.7mm thick material the failure loads obtained experimentally, and those of the design codes, did not show any significant variation with change in r/t ratios for the corners. It should be mentioned here that analysis to the codes assumed square corners so that the fact that the experimental results followed the same pattern suggests that (i)- although the high-yield corner area is increased in relation to the flat area by increasing the r/t ratio, this does not seem to affect the strength, and (ii) – the buckling resistance of the elements seems to be well described using the full width between intersections of elements rather than just the flat width.

In the case of the 0.95mm material the section with sharp corners took substantially less load than those with radii, both from test and using the design codes. This is largely because the thickness was rather far from the nominal value. Other than this the variation in radii did not seem to affect the strength to any great extent. A similar conclusion can be drawn for the 1.19mm material.

Figure 3 shows the variation in the ratio of total effective area to thickness squared at failure for the stub columns tested, and again plots the results against r/t for each of the different thicknesses investigated. The design code predictions are, as in Figure 2, very similar and have been incorporated in the figure mainly as a control to ensure that any variations in individual specimen dimensions or properties which could have significantly affected the results would be seen. As may be observed this quantity (i.e $\Sigma b_{eff} .t / t^2$) is approximately 70 for all specimens regardless of the r/t ratio, being slightly greater (71-75) for the thinner specimens, and slightly less (approximately 68) for the thicker specimens. The quantity is actually the sum of b_{eff}/t taken over the complete section, and with one stiffened element and two unstiffened elements the sum of effective widths should be approximately 70 at failure. The tests back up the design code predictions in this respect. It is, however, obvious from the test results that the corners do not have any significant influence on the strength, and that evaluation of the properties, particularly the local buckling properties, on the basis of mid-line dimensions assuming square corners gives a good approximation to the test results.

CONCLUSIONS

The main conclusion from the work is that the new Eurocode for stainless steel members, and the ANSI/ASCE specification, give accurate predictions of the stub column strength of plain channel sections. The neglect of the changes in E as loading progresses does not seem to have resulted in any substantial errors in the evaluation of axial load capacity.

The variation in capacity with variation in corner radii is small, and inconsistent, and for members with corner r/t ratios as examined here the assumption of mid-line dimensions and square corners is perfectly satisfactory.

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Table 1

Compression Test Results: Stainless Steel Plain Channel Section Short Struts
(Nominal Dimensions: Flange-30mm; Web-60mm; Length-180mm)

Specimen Ref.	Bend Radius, r (mm)	Thickness t (mm)	r/t	Whole C.S.A., A (mm^2)	Virgin 0.2% P.S. (N/mm^2)	Exp. Load Capacity,P_{exp} (kN)	Eurocode 1.4 $N_{b\,Rd}$ (kN)	ANSI/ASCE P_n (kN)
Sharp Corner Specimens:								
CTSSSC1	N/A	0.69	N/A	89.89	304.50	11.05	10.79	10.66
CTSSSC2	N/A	0.84	N/A	109.41	319.10	15.81	16.04	15.85
CTSSSC3	N/A	1.13	N/A	146.63	304.10	28.13	26.85	26.55
Formed Corner Radius Specimens:								
CTSS1A	3.00	0.70	4.290	90.88	304.50	10.88	11.09	10.96
CTSS1B	3.00	0.70	4.290	90.52	304.50	10.52	11.08	10.95
CTSS2A	5.00	0.69	7.250	88.65	304.50	11.10	10.79	10.66
CTSS2B	5.00	0.69	7.250	87.27	304.50	10.92	10.78	10.64
CTSS2C	5.00	0.69	7.250	89.19	304.50	11.10	10.80	10.67
CTSS3A	6.00	0.70	8.570	90.19	304.50	10.84	11.10	10.96
CTSS3B	6.00	0.74	8.108	95.72	304.50	10.70	12.32	12.17
CTSS3C	6.00	0.74	8.108	96.53	304.50	10.97	12.34	12.19
CTSS4A	3.00	0.95	3.160	123.79	319.10	18.64	19.58	19.89
CTSS4B	3.00	0.93	3.226	121.41	319.10	18.95	19.36	19.14
CTSS4C	3.00	0.93	3.226	121.57	319.10	18.59	19.37	19.15
CTSS5A	5.00	0.93	5.380	121.02	319.10	18.64	19.38	19.15
CTSS5B	5.00	0.93	5.380	120.46	319.10	18.82	19.36	19.13
CTSS5C	5.00	0.92	5.435	118.90	319.10	18.64	18.96	18.74
CTSS6A	6.00	0.93	6.452	121.43	319.10	18.59	19.39	19.17
CTSS6B	6.00	0.92	6.522	120.22	319.10	18.68	19.01	18.79
CTSS6C	6.00	0.93	6.452	121.58	319.10	18.33	19.40	19.17
CTSS7A	3.00	1.19	2.520	156.97	304.10	28.32	29.52	29.20
CTSS7B	3.00	1.20	2.500	157.92	304.10	27.91	29.90	29.58
CTSS7C	3.00	1.19	2.521	156.78	304.10	27.82	29.46	29.14
CTSS8A	5.00	1.19	4.200	156.17	304.10	27.87	29.49	29.17
CTSS8B	5.00	1.20	4.167	157.79	304.10	27.96	29.97	29.65
CTSS8C	5.00	1.19	4.200	155.33	304.10	27.91	29.44	29.12
CTSS9A	6.00	1.22	4.920	162.78	304.10	27.96	31.03	30.70
CTSS9B	6.00	1.22	4.918	161.29	304.10	28.54	30.93	30.60
CTSS9C	6.00	1.22	4.918	159.71	304.10	27.60	30.81	30.48

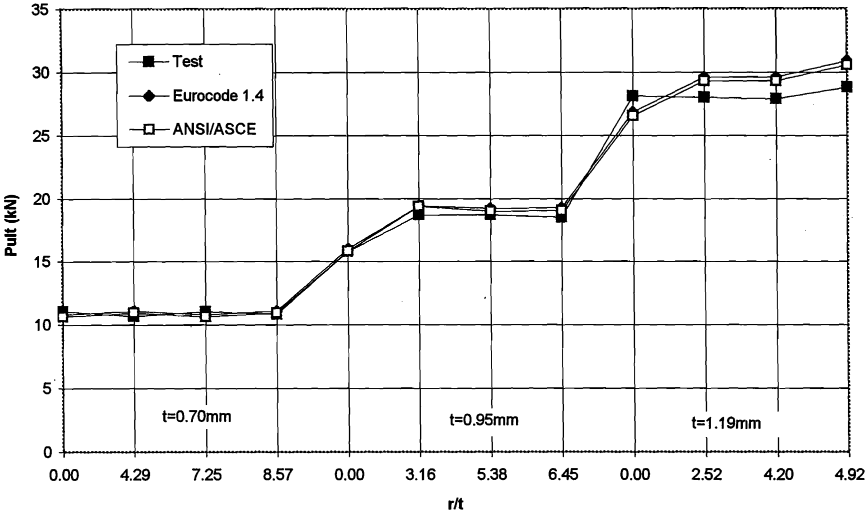

Figure 2 - Variation of Failure Load with r/t ratio for specimens of all thicknesses

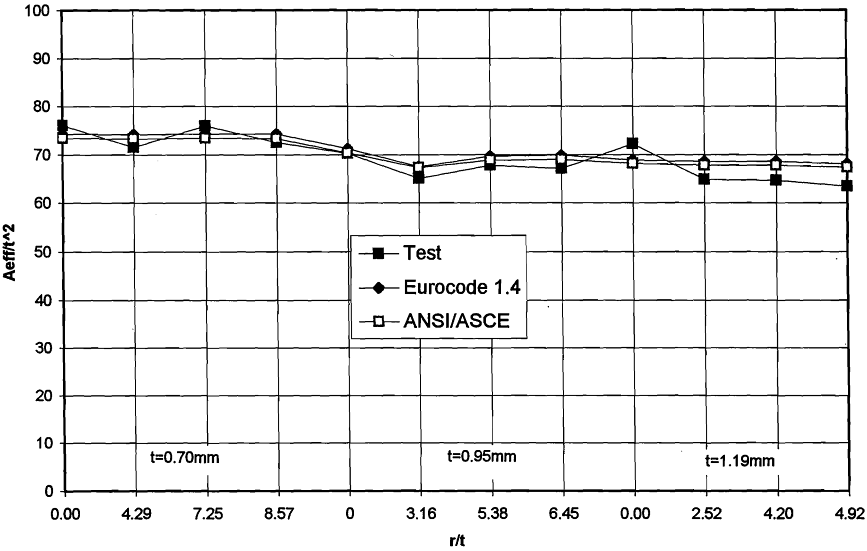

Figure 3 - Variation of A_{eff}/t^2 with r/t ratio for specimens of all thicknesses