BEHAVIOUR OF STAINLESS STEEL COLUMNS UNDER COMBINED BENDING AND AXIAL COMPRESSION LOADING

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The behaviour and load capacity of Type 304 stainless steel columns of lipped channel cross-section, subjected to pure compression loading was presented by Macdonald, Rhodes and Kotelko in 2000 [1].This paper describes the results obtained from an investigation into the behaviour and load capacity of eccentrically loaded Type 304 stainless steel columns of the same lipped channel cross-section. The test results obtained are compared with those obtained from Eurocode 3, Part 1.4 and, the applicability of the Polish carbon steel code PN-90/B-03200 is investigated. Finally, all test and code results are compared to those obtained from finite element analysis. Conclusions are drawn on the basis of the comparisons.

1. INTRODUCTION

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

In Europe, Eurocode 3: Part 1.4 [5] has been recently developed and is still under examination. The simpler Eurocode analysis has been found to give reasonable estimates of concentrically loaded column strength without taking account of the non-linearity of the stress-strain curve as was reported in [1].

In Poland no design code exists for the design of cold formed stainless steel members, however, for this investigation the carbon steel code PN-90/B-03200 [6] will be investigated for its applicability to stainless steel members.

The work reported in this paper focuses on eccentric loading of short-to-medium length columns of lipped channel cross-section. The cross-section dimensions and the column length are varied to examine the effects on the buckling load capacity of the columns. Also, two different stress-strain curves are studied.

2. LOAD CAPACITY OF STAINLESS STEEL LIPPED CHANNEL COLUMNS SUBJECTED TO COMBINED BENDING AND AXIAL COMPRESSION LOADING

In the formation of a profiled section, cold working occurs in localised areas, with material at bend regions being strain hardened. Therefore the properties of the material vary throughout the cross-section and at formed bends, higher yield and tensile strengths exist, leading to complex stress-strain relationships for a cold formed stainless steel members. The level of increase of both yield and tensile strength is 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 fully effective. The four formed corners will have an effect on the stress-strain response of the material obtained from a full section test, which could then be compared to that obtained for virgin material from a standard tensile test. Also, most commercially available finite element programs allow for a non-linear analysis and hence the inclusion of the actual stress-strain data obtained from tensile testing and from existing theories.

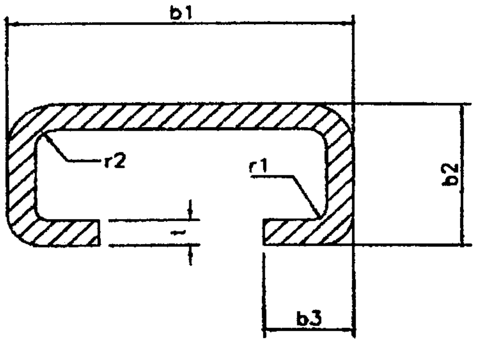

Fig.1. Typical lipped channel section

Eurocode 3, Part 1.4 [5]

This design code provides a bending and compression interaction formula to calculate the maximum compression load P applied at a fixed position of eccentricity e for a fully effective member cross-section and is given by equation (1).

$$\frac{P}{\chi f_y\left(\frac{A}{\gamma_{M1}}\right)}+\frac{\kappa Pe}{\left(\frac{M_n}{\gamma_{M1}}\right)}\leq 1 \tag{1}$$

The Eurocode interaction formula as modified by Macdonald [7] as given by equation (2).

$$\frac{P}{\chi f_y\left(\frac{A}{\gamma_{M1}}\right)}+\frac{\kappa Pe}{\left(\frac{M_{\exp}}{\gamma_{M1}}\right)}\leq 1 \tag{2}$$

In equation (2), M_{exp} is the cross-section true moment capacity obtained from bending tests and the 0.2% proof stress is taken from the full section tensile test results, and all other terms in both equations are defined in [7].

Polish Code PN-90/B-03200, Section 4 [6]

The formula provided by the Polish design code for structural steel members (there is no specific code for stainless steel structures) subject to simultaneous action of compression and bending is basically similar to (1) and for one-plane bending takes form

$$\frac{N}{\varphi N_{R_c}} + \frac{\beta M_{max}}{\varphi_L M_R} \leq 1 \tag{3}$$

where N=P, ϕ is the global buckling reduction factor corresponding to χ in (1), N_{Rc} is the stub column load-capacity and M_R is the bending moment capacity of the member's cross-section. The co efficient ϕ_L counts for the reduction of the bending moment capacity due to lateral buckling and for the case under investigation equals to 1. Thus, using the notation applied in (1) the design formula (3) takes form

$$\frac{P}{\varphi A f_d} + \frac{\beta P e}{M_R} \leq 1 \tag{3a}$$

where $M_R = Z f_d$ and f_d is the material design strength. It should be underlined here that the Polish code recommends to take the design strength less than the material yield stress with the reduction factor depending on a type of the material ($f_d < f_y$).

3. FINITE ELEMENT ANALYSIS

Using the ANSYS finite element package, a full non-linear analysis was performed using shell elements (SHELL181) which are four-noded elements with six degrees of freedom at each node, i.e. translations in x, y and z directions, and rotations about x, y and z axes.

The non-linear material properties of the stainless steel were defined in using the initial elastic modulus, Poisson's ratio and stress-strain data obtained from: (i) coupon tensile tests on material cut from section webs; (ii) full-section tensile tests.

For a non-linear buckling analysis to be accurate, it was necessary to set an initial imperfection in the column being modelled. This was achieved by modelling a mid-span deflection which produced a very large radius of curvature for the lipped channel columns which would approximate any actual imperfections.

A parametric model was constructed by defining positions of keypoints to allow for easy alterations to the model for the two different column lipped channel section thicknesses and for the variation in column length. A half-model of a column was modelled using appropriate symmetry commands that helped to reduce the considerable computer processing time. The boundary conditions were applied and the results are shown in Table 3.

4. EXPERIMENTAL INVESTIGATIONS

4.1 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 as detailed in Table 1. All calculations were based on mid-line dimensions. In order to determine the material properties of the sections, tensile tests to failure were set-up and 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.

Coupons were cut from the webs of the columns, and full sections were tested (to include the effects of cold forming) to obtain the 0.2% proof stress and the modulus of elasticity.

4.2 COMPRESSION TESTS

In the experimental investigation a series of compression tests to failure were made on stainless steel columns of the lipped channel cross-section as described above. The compression loading was applied at a fixed eccentricity position. The specimen parameters investigated were as follows:

1) Column lengths varied from 222 mm to 1222 mm in increments of 100 mm. (The slenderness ratios varied from 42 to 234 for the THN sections and from 38 to 207 for the THK sections.
2) Two thicknesses of lipped channel section, of small cross-section, were examined. The channels of 2.43 mm thickness were denoted 'THN' while those of 3.05 mm thickness were denoted 'THK'.
3) Thirty-three tests to failure (2 sets of THN columns and 1 set of THK columns) were carried out with the loading applied 8 mm eccentric to the centroid of the cross-section.

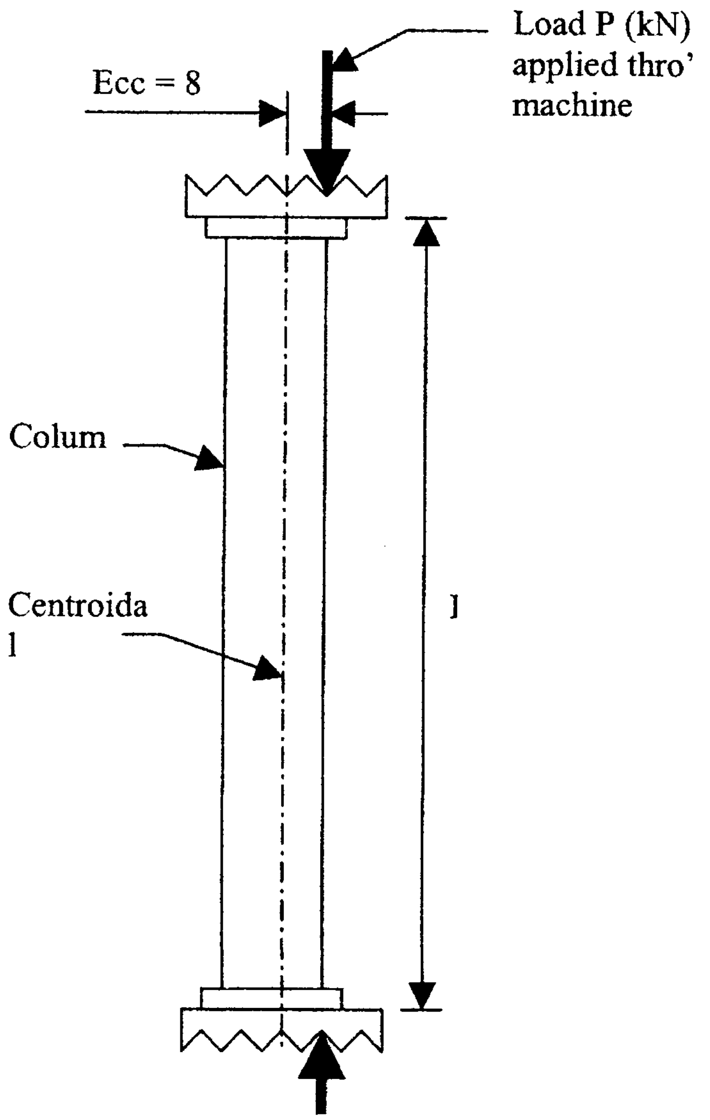

Fig. 2. Schematic Diagram of Eccentrically Loaded Column Test

Table 1. Average Dimensions of Lipped Channel Cross-Sections

Section Ref:	Web, b_1, (mm)	Flange, b_2, (mm)	Lip b_3, (mm)	Thickness t, (mm)	Radius, r_1, (mm)	Radius, r_2, (mm)
THN (T)	28.00	14.88	7.45	2.43	1.10	1.10
THK (W)	38.00	17.19	9.99	3.05	0.735	2.255

Each length of 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 column vertical displacement and mid-span horizontal deflection measured during the tests using displacement transducers. Figure 2 shows a schematic diagram of the column test configuration.

Table 2. Tensile Test Results: Virgin and Full Section (FS) Mechanical Properties

Material Ref:	Thickness t (mm)	Av. Virgin 0.2% P.S. (N/mm^2)	Av. Virgin UTS (N/mm^2)	Av. FS 0.2% P.S. (N/mm^2)	Av. FS UTS (N/mm^2)
THN (T)	2.43	480	553	520	689
THK (W)	3.05	460	541	540	744

5. RESULTS

All results obtained from tensile tests to establish virgin material and full cross-section mechanical properties are detailed in [6] and are shown in Table 2.
The results obtained for the load capacity of eccentrically loaded lipped channel section columns are shown in Table 3. Also shown are the predictions obtained from Eurocode 1.4 based on virgin and full section material properties using equation (1), the modification to the Eurocode 1.4 interaction formulae given by equation (2), the Polish code given by equation (3) and from finite element analysis.
In the calculations conducted due to the Polish code the following design strengths were taken into account:

- for THN $f_d = \dfrac{\sigma_{ult}(virgin)}{1.25} = 442\,MPa$,
- for THK $f_d = \dfrac{\sigma_{ult}(virgin)}{1.25} = \dfrac{R_{0.2}(F.S.)}{1.25} = 432\,MPa$

Figures 3 and 4 show the graphs of Load Capacity v. Column Length for eccentrically loaded THN and THK section columns respectively, showing curves for the test results, Eurocode 1.4, modified Eurocode 1.4 and the Polish code. Figures 5 and 6 show the curves obtained from the tests compared to the finite element predictions.

6. OBSERVATIONS

Figures 3 and 4 show the results obtained for the load capacity of eccentrically loaded THN and THK stainless steel lipped channel section columns from tests, design codes (using virgin material properties and full section properties) and from modifications to the design codes as described by equations (1) and (2). All design code predictions show conservatism in prediction of load capacity for the shorter range of columns with improvements gained when full section properties are used and further improvements are gained in using the modified forms. The best correlation obtained was for THN section columns where the modified design codes predicted accurate load capacities for all column lengths. For the THK section columns, the modified design codes provided accurate predictions of load capacity for all but the shortest columns.
Figures 5 and 6 show the results obtained for the load capacity of eccentrically loaded THN and THK stainless steel lipped channel section columns from tests and from finite element analysis using the various stress-strain curves described earlier. The predictions of the finite element analysis show an excellent correlation to the test results and a real

improvement on the predictions of the design codes. For the THK section columns shown in Figure 6, the stress-strain curve obtained from the full section tensile test and incorporated into the non-linear finite element analysis shows a curve that is almost identical to the test curve. However, for both graphs, any differences between finite element predictions and test results are very slight and occur mainly for very short length columns. The Polish code displays also some conservatism for shorter columns and a good agreement with both experimental and FE results for long, slender columns. The results obtained from the Polish code are situated between results of Eurocode 1.4 and modified design code.

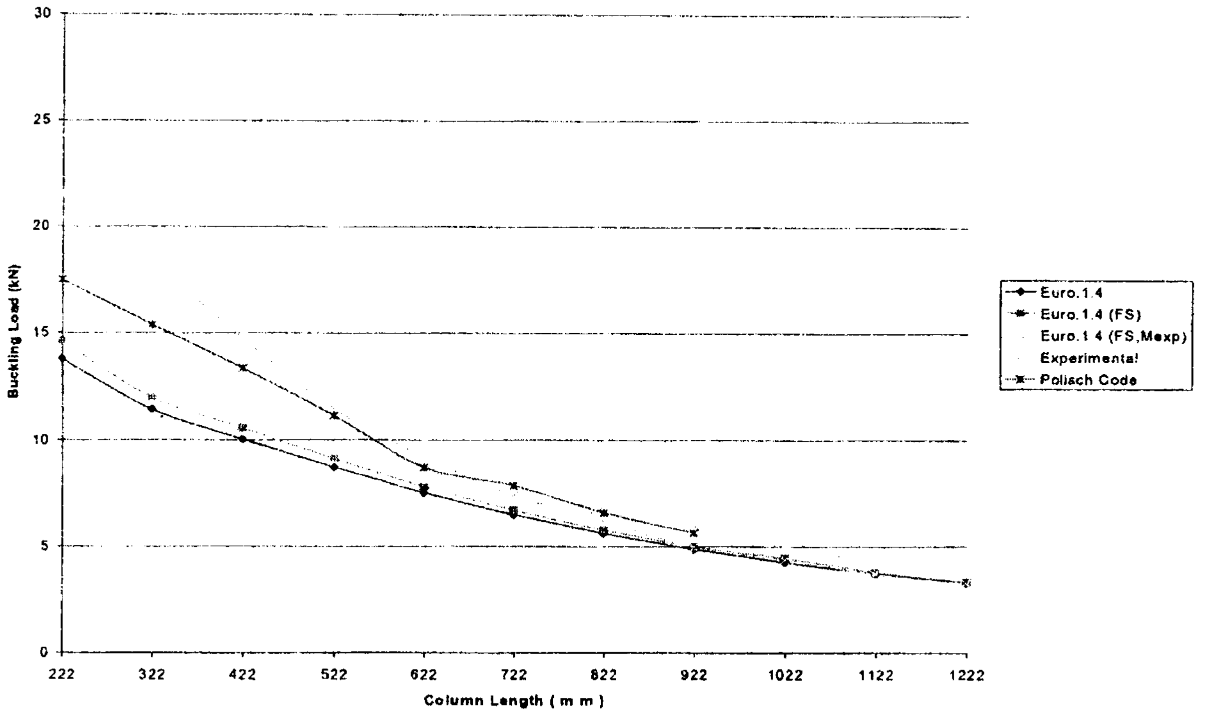

Fig. 3. Graph of Load Capacity v. Column Length: –THN Sections (Test/Design Codes)

7. CONCLUSIONS

This paper has shown that the interaction formula provided by Eurocode 1.4 [equation (1)] shows a high level of conservatism for the shorter length columns using virgin and full section material properties. The modified form of the interaction formula [equation (2)] shows an improved correlation to the test results but it is still conservative. The same concerns the Polish code, but for shorter columns it is less conservative than the Eurocode 1.4, although it overestimates the moment capacity in a significant way. It has also been shown in this paper that finite element analysis can be used with a high level of confidence in predicting the load capacity of eccentrically loaded cold formed stainless steel, short-to-medium length columns of lipped channel section. This has been shown to be true for stress-strain curves obtained from virgin material and full section tensile tests.

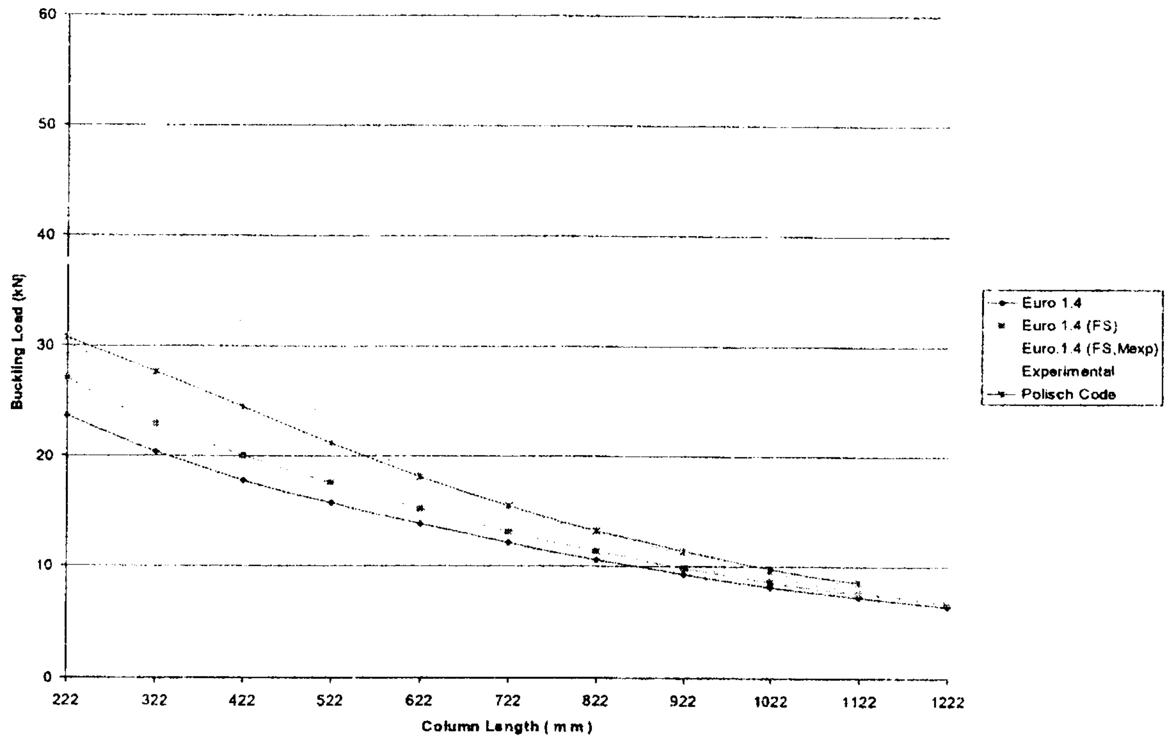

Fig 4. Graph of Load Capacity v. Column Length: –THK Sections (Test/Design Codes)

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