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FINITE ELEMENT MODELLING OF STAINLESS STEEL COLUMNS WITH VARIATION IN MECHANICAL PROPERTIES

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SUMMARY

This paper describes the results obtained from a finite element investigation into the column capacity of Type 304 stainless steel column members of lipped channel cross-section. Stress-strain curves derived from tests were incorporated into non-linear finite element analyses of eccentrically loaded stainless steel columns. The results obtained are compared with test results on stainless steel channel columns with the same properties and dimensions, and also with design code predictions.

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, 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 design specifications.

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 three 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

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strength without taking account of the non-linearity of the stress-strain curve. As part of a previous investigation ref. [11], a series of tensile tests were carried out on coupons cut from stainless steel lipped channel sections, and also on full sections, and the stress-strain characteristics are examined in this paper and incorporated into a non-linear finite element analysis.

MECHANICAL PROPERTIES OF STAINLESS STEEL LIPPED CHANNEL MEMBERS

In the formation of a profiled section, the cold working occurs in localised areas, with the material at the bends being strain hardened. Therefore the properties of the material vary throughout the cross-section where at the formed bends, higher yield and tensile strengths exist, leading to a more complex stress-strain relationship for cold formed members, and in particular, for 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 thick and hence four corner bends are formed with small r/t ratios (<1). These four 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.

The ASCE design specification adopts the modified form of the Ramberg-Osgood formula given by equation (1). It is a three-parameter equation for expressing the relationship between the stress and strain for stresses up to a value slightly greater than the yield strength of the material.

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^n \qquad (1)$$

where ε = unit strain

σ = unit stress (N/mm^2)

E = modulus of elasticity (N/mm^2)

K and n are constants for a given curve, which are evaluated through two secant yield strength values for slopes of 0.7E and 0.85E. Equation (1) was modified by Hill [6], and, instead of using secant yield strengths, K and n can be evaluated in terms of two yield strength values: (i) σ_1 at an offset ε_1; (ii) σ_2 at an offset ε_2.

Using the most common offset of 0.002 for the yield stress (σ_2) and assuming that the modulus of elasticity E is equal to the initial value Eo, equation (1) becomes:

$$\varepsilon = \frac{\sigma}{E_o} + 0.002\left(\frac{\sigma}{\sigma_y}\right)^n \tag{2}$$

The ASCE design code makes use of this modified equation 2, and the 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 (2), 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.

The results obtained for the stress-strain relationship from both virgin material and full section tensile tests will be used for comparison with the results obtained from the above ASCE Ramberg-Osgood approach and by a trial and error 'best fit' method using the experimental stress-strain curves. These will then be incorporated into a non-linear finite element analysis of eccentrically loaded stainless steel columns.

LOAD CAPACITY OF STAINLESS STEEL LIPPED CHANNEL 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 [7], [8] 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 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 [7] interaction formula to determine the axial strength P_u is given by equation (3).

$$\frac{P_u}{P_n} + \frac{P_u e}{M_n\left(1 - \left(\frac{P_u}{P_E}\right)\right)} \leq 1.0 \tag{3}$$

where $P_n = 0.85AF_n$ (N)

$M_n = \frac{F_y I_{xx}}{\bar{y}}$ = moment capacity of the cross section (Nmm)

$P_e = \frac{\pi^2 E_o I_{xx}}{L^2}$ = Euler buckling capacity (N)

e = distance from centroid (eccentricity) = 8 mm

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

The Eurocode (8) interaction formula to determine the axial strength N_{sd} is given by equation (4).

$$\frac{N_{Sd}}{\chi f_y\left(\frac{A}{\gamma_{M1}}\right)} + \frac{\kappa N_{Sd} e}{\left(\frac{M_n}{\gamma_{M1}}\right)} \leq 1 \qquad (4)$$

where e = distance from centroid (eccentricity) = 8 mm,

M_n = moment capacity = $\frac{f_y I_{xx}}{\bar{y}}$ (Nmm),

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

Both equations produced very conservative estimates of load capacity and an attempt to improve the interaction formulae was proposed by Macdonald ref. [12]. This modification to the interaction formulae involved replacing the linear moment capacity M_n with the true moment capacity of the lipped channel cross-section M_{exp} obtained from bending tests. Hence the ASCE interaction formula was modified as given by equation (5).

$$\frac{P_u}{P_n} + \frac{P_u e}{M_{\exp}\left(1 - \left(\frac{P_u}{P_E}\right)\right)} \leq 1.0 \qquad (5)$$

The Eurocode interaction formula was modified as given by equation (6).

$$\frac{N_{Sd}}{\chi f_y\left(\frac{A}{\gamma_{M1}}\right)} + \frac{\kappa N_{Sd} e}{\left(\frac{M_{\exp}}{\gamma_{M1}}\right)} \leq 1 \qquad (6)$$

In both equations (5) and (6), M_{exp} is the cross-section true moment capacity and the 0.2% proof stress is taken from the full section tensile test results, and all other terms are defined in ref. [12] The results obtained from equations (5) and (6) for the load capacity of the eccentrically loaded columns are shown in Table 4.

FINITE ELEMENT ANALYSIS

Finite element analysis results for concentrically loaded columns showed excellent correlation with both test results and design code predictions as shown by Figures 3 and 4 for THN and THK sections respectively. A finite element analysis was performed using the ANSYS software package to determine the load capacity of eccentrically loaded columns. Two types of buckling analyses are available within the ANSYS package – eigenvalue analysis and non-linear analysis. Both types of analyses were used, however, the eigenvalue analysis was used only to verify that the finite element model boundary conditions (i.e. column pin ends and eccentric loading) were accurate, as this type of analysis takes no account of material non-linearity. A full non-linear analysis was conducted using shell elements (ANSYS 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 ANSYS 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; (iii) ASCE (Ramberg-Osgood) approach (varying 'n' factors); (iv) 'best fit' stress-strain curves.

The non-linear solution breaks the load up into a series of load increments that can be applied over several load steps. At the completion of each incremental solution, the program adjusts the stiffness matrix to reflect the non-linear changes in the structural stiffness before proceeding to the next load increment. For a non-linear buckling analysis to be accurate using ANSYS, it is necessary to set an initial imperfection in the structure 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 5 for THN columns and Table 6 for THK columns.

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 mid-line dimensions. The details are given 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. Indeed, provision is made in the ASCE design code to enable use to be made of them in specific applications. 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 initial modulus of elasticity were determined.

For the standard coupons, a total of three thin (THN) specimens and six thick (THK) specimens were tested and the average results were noted. For the full section tests, two THN and two THK specimens were tested and again, the average results were noted. It should be mentioned here that the thick sections have wider webs than the thin sections, and in the graphs reference is often made to 'W' sections (which are THK specimens) and 'T' sections (THN specimens).

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 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.

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.

RESULTS

Tensile tests

All results obtained from tensile tests to establish virgin material and full cross-section mechanical properties are detailed in ref. [11] and are shown in Table 2.
The results obtained for the plasticity factors n from the ASCE design code, i.e. the modified form of the Ramberg-Osgood equation given by equation (2), are also detailed in ref. [11] and shown in Table 3. Also shown in Table 3 are the plasticity factors obtained from a comparative plots/trial and error ('best fit') process using the stress-strain curves obtained from the tensile tests, as reported in ref. [11].

Compression tests

Figures 3 and 4 show the graphs of Load Capacity v. Column Length for concentrically loaded THN and THK section columns respectively, showing curves for the test results, the Eurocode and ASCE design code predictions (for both virgin material properties and full section properties) and also finite element predictions, and are detailed in ref. [12].

The results obtained for the load capacity of eccentrically loaded lipped channel section columns are shown in Table 4. Also shown are the predictions obtained from the design codes based on virgin and full section material properties, and on the modification to the design code interaction formulae given by equations (5) and (6).

Figures 5 and 6 show the graphs of Load Capacity v. Column Length for eccentrically loaded THN and THK section columns respectively, showing curves for the test results and the Eurocode, ASCE, modified Eurocode and modified ASCE design code predictions.

Finite element analysis

Tables 5 and 6 show the results for column load capacity obtained from finite element modelling of eccentrically loaded, cold formed, stainless steel lipped channel THN and THK columns respectively, incorporating the four different stress-strain curves into the non-linear analyses.

OBSERVATIONS

Figures 3 and 4 show the results obtained for the load capacity of concentrically loaded THN and THK stainless steel lipped channel section columns from tests, design codes (using virgin material properties and full section properties) and from finite element analysis. The design code and finite element predictions show excellent correlation with the test results for all but the shortest of the THK columns as was reported in ref. [12].

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, design codes (using virgin material properties and full section properties) and from modifications to the design codes as described by equations (5) and (6). 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 7 and 8 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 8, 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.

CONCLUSIONS

It has been shown in this paper that finite element analysis can be used with a high level of confidence in predicting the load capacity of concentrically and eccentrically loaded cold formed stainless steel, short-to-medium length columns of lipped channel section. This has been shown to be true for various stress-strain curves including that obtained from virgin material tensile tests. Using the virgin material properties in Eurocode 1.4, and the ASCE design code by using the modified Ramberg-Osgood model, leads to very conservative estimations of load capacity, particularly for eccentrically loaded columns.

Appendix.-References

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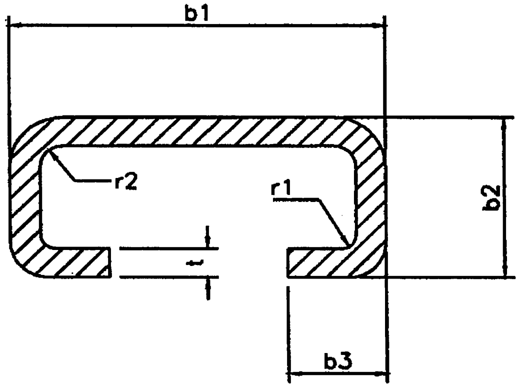


Figure 1: Typical Lipped Channel Section

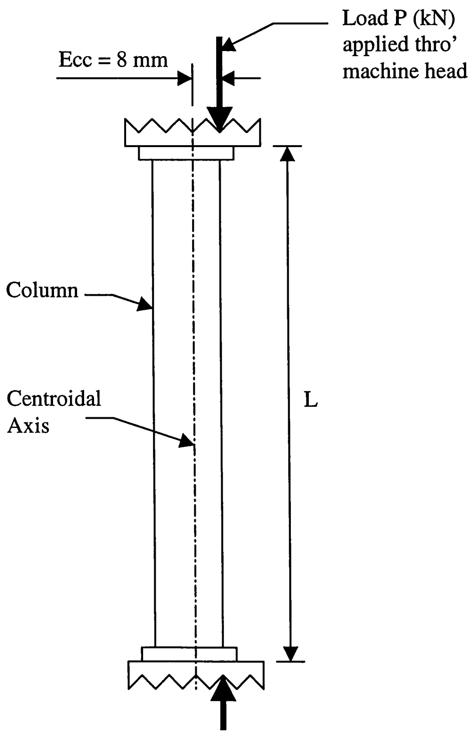


Figure 2: Schematic Diagram of Eccentrically-Loaded Column Test

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

TABLE 2

Tensile Test Results: Virgin Material 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

TABLE 3

Plasticity Factors

Tensile Test	n (ASCE)	n (Best Fit)
Coupon – THN (T)	3.80	6.22
Coupon – THK (W)	4.66	7.50
Full Section – THN (T)	5.02	6.65
Full Section – THK (W)	3.62	6.00

TABLE 4

Eccentrically Loaded THN and THK Section Columns: Test Results and Design Code Predictions

Specimen Ref.	Column Length L (mm)	Test Load P_{exp} (kN)	ASCE (Virgin) P_n (kN)	ASCE (FS) P_n (kN)	Euro.1.4 (Virgin) $N_{b,Rd}$ (kN)	Euro.1.4 (FS) $N_{b,Rd}$ (kN)	ASCE (M_{exp},FS) P_n (kN)	Euro.1.4 (M_{exp},FS) P_n (kN)
THN1	1222	3.261	2.739	2.774	3.270	3.326	3.078	3.676
THN2	1122	3.691	3.141	3.186	3.709	3.780	3.605	4.279
THN3	1022	4.352	3.638	3.695	4.230	4.322	4.255	5.000
THN4	922	4.954	4.258	4.332	4.852	4.972	5.116	5.977
THN5	822	6.182	5.042	4.141	5.595	5.753	5.976	6.932
THN6	722	7.402	6.055	6.188	6.478	6.690	7.465	8.442
THN7	622	9.218	7.379	7.567	7.520	7.804	9.084	10.000
THN8	522	11.457	9.112	9.404	8.719	9.103	12.209	12.500
THN9	422	14.759	11.238	11.753	10.033	10.547	15.538	15.000
THN10	322	18.703	13.476	14.278	11.433	11.995	19.767	18.210
THN11	222	24.299	15.687	16.716	13.778	14.593	24.143	21.514
THK1	1222	6.933	5.620	5.806	6.403	6.687	6.666	7.143
THK2	1122	7.771	6.421	6.654	7.215	7.572	8.023	8.352
THK3	1022	9.117	7.397	7.687	8.166	8.622	8.714	9.524
THK4	922	10.990	8.616	8.994	9.283	9.870	10.400	11.473
THK5	822	13.160	10.132	10.623	10.591	11.354	11.905	13.429
THK6	722	15.177	12.068	12.730	12.109	13.110	15.253	16.179
THK7	622	18.388	14.537	15.438	13.844	15.164	18.571	19.048
THK8	522	22.749	17.591	18.884	15.761	17.501	23.969	23.441
THK9	422	31.886	20.775	22.804	17.738	20.013	29.048	27.619
THK10	322	40.853	23.799	26.826	20.370	22.834	35.888	32.933
THK11	222	53.595	26.767	30.949	23.609	27.043	42.143	37.619

TABLE 5

Eccentrically Loaded THN Section Columns: Test Results and Finite Element Predictions (FEA)

Specimen Ref.	Column Length L (mm)	FEA (Virgin) P_{vir} (kN)	FEA (FS) P_{fs} (kN)	FEA (n=3.80 - ASCE) P_{asce} (kN)	FEA (n=6.22 - Best Fit) $P_{best\ fit}$ (kN)	Test Load P_{exp} (kN)
THN1	1222	2.900	3.358	3.000	3.000	3.261
THN2	1122	3.375	3.878	3.606	3.500	3.691
THN3	1022	4.000	4.598	4.000	4.350	4.352
THN4	922	4.750	5.400	4.850	4.850	4.954
THN5	822	5.625	6.458	5.800	6.302	6.182
THN6	722	7.125	7.500	7.000	7.500	7.402
THN7	622	8.700	9.500	8.700	9.305	9.218
THN8	522	10.900	11.858	10.850	11.350	11.457
THN9	422	14.405	15.500	14.350	14.700	14.759
THN10	322	19.000	20.350	19,000	19.350	18.703
THN11	222	25.128	27.000	26.700	25.710	24.299

TABLE 6

Eccentrically Loaded THK Section Columns: Test Results and Finite Element Predictions (FEA)

Specimen Ref.	Column Length L (mm)	FEA (Virgin) P_{vir} (kN)	FEA (FS) P_{fs} (kN)	FEA (n=4.66–ASCE) P_{asce} (kN)	FEA (n=7.50 – Best Fit) $P_{best\ fit}$ (kN)	Test Load P_{exp} (kN)
THK1	1222	6.500	6.800	6.500	6.900	6.933
THK2	1122	7.800	8.000	7.800	8.000	7.771
THK3	1022	8.900	9.000	8.900	9.400	9.117
THK4	922	10.500	10.800	10.500	10.900	10.990
THK5	822	12.454	12.000	12.500	13.282	13.160
THK6	722	14.900	15.600	14.900	15.800	15.177
THK7	622	18.000	19.000	18.000	19.141	18.388
THK8	522	22.500	24.000	22.500	23.400	22.749
THK9	422	28.500	30.900	28.500	28.900	31.886
THK10	322	36.000	40.180	36.500	36.450	40.853
THK11	222	45.978	53.000	47.800	46.500	53.595

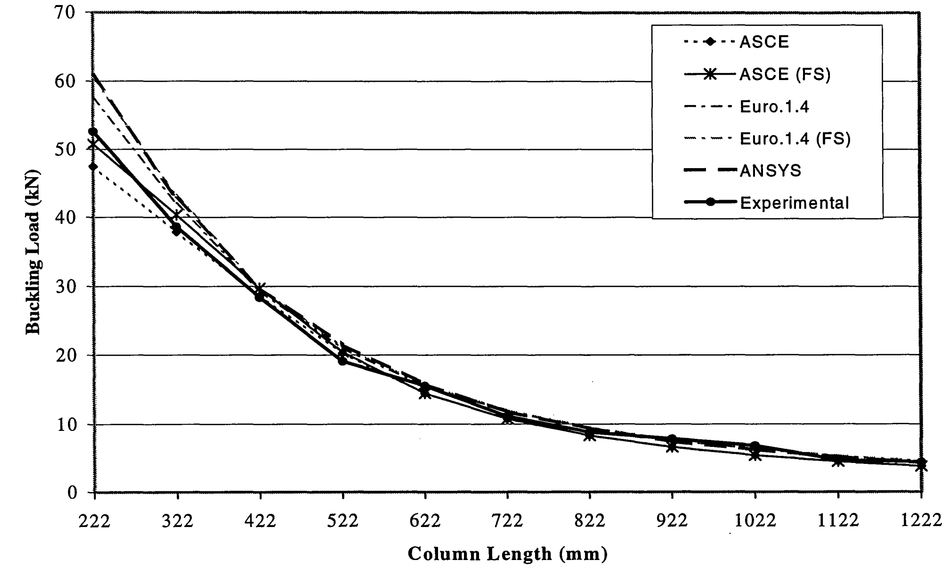
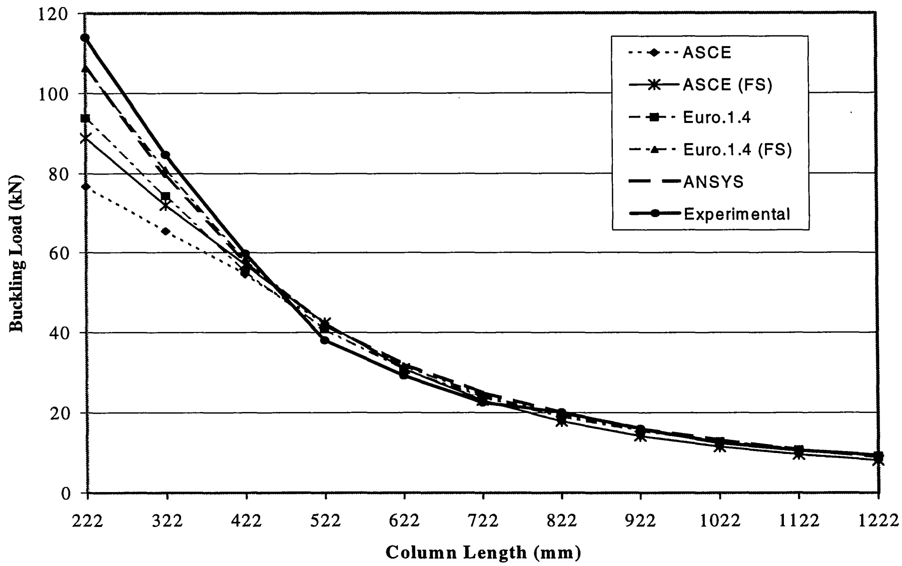
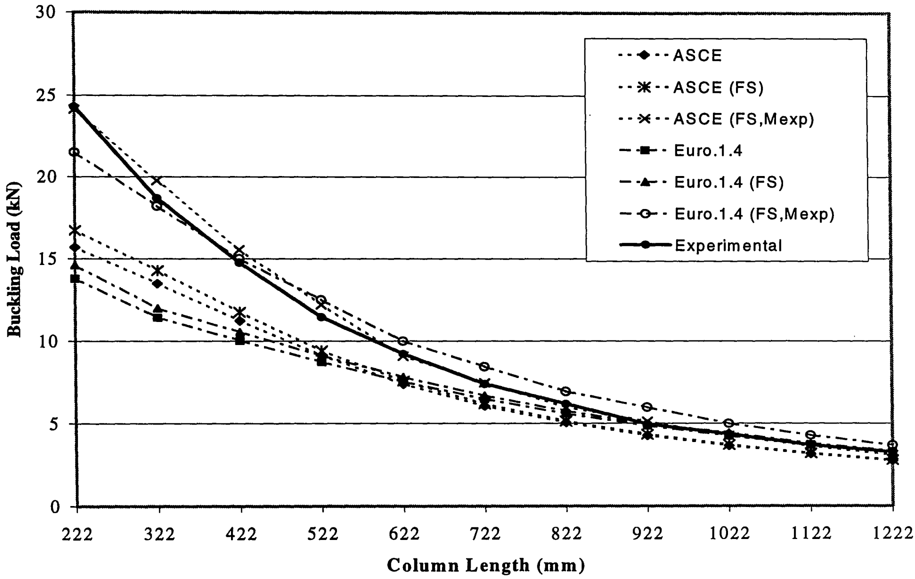


Figure 3: Graph of Load Capacity v. Column Length: Concentric Loading–THN Sections



(Test/Design Codes/Finite Element Analysis)

Figure 4: Graph of Load Capacity v. Column Length: Concentric Loading–THK Sections



(Test/Design Codes/Finite Element Analysis)

Figure 5: Graph of Load Capacity v. Column Length: Eccentric Loading–THN Sections (Test/Design Codes)

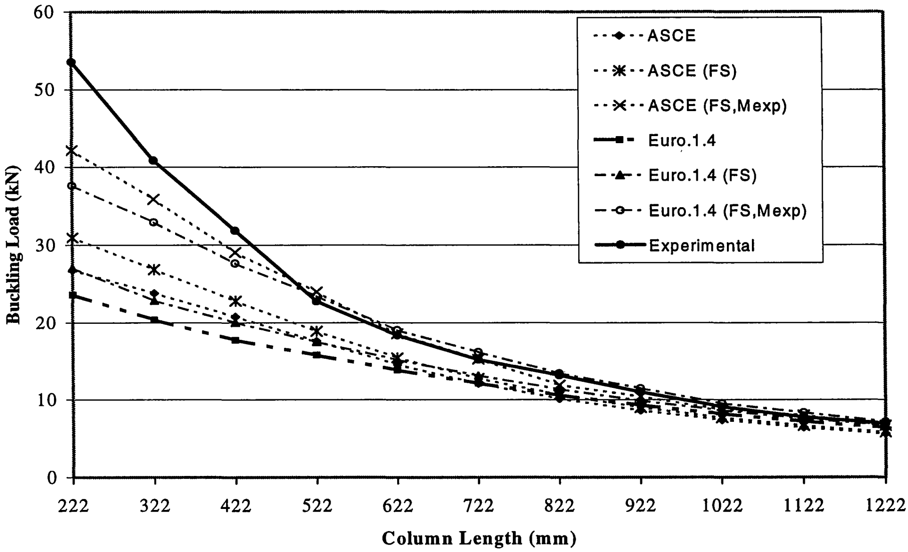


Figure 6: Graph of Load Capacity v. Column Length: Eccentric Loading–THK Sections (Test/Design Codes)

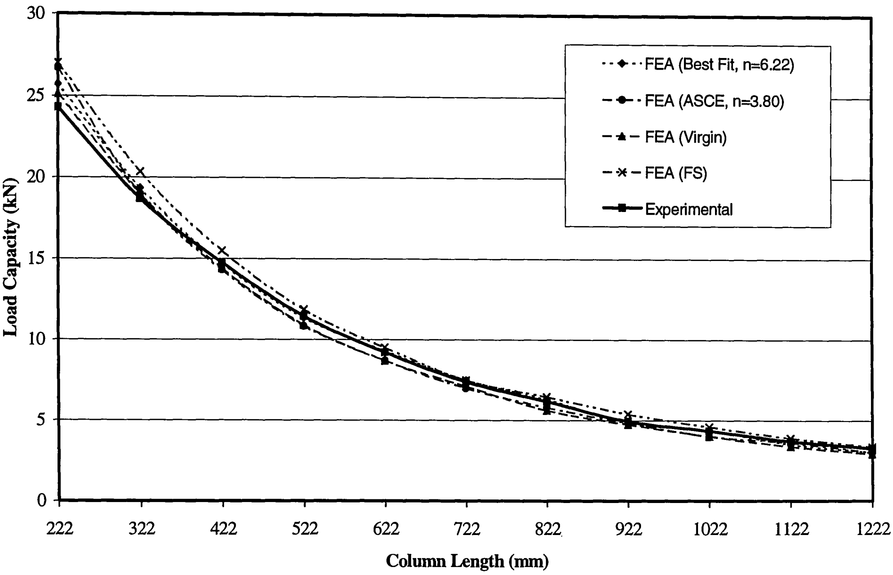


Figure 7: Graph of Load Capacity v. Column Length: Eccentric Loading–THN Sections (Test/Finite Element Analysis)

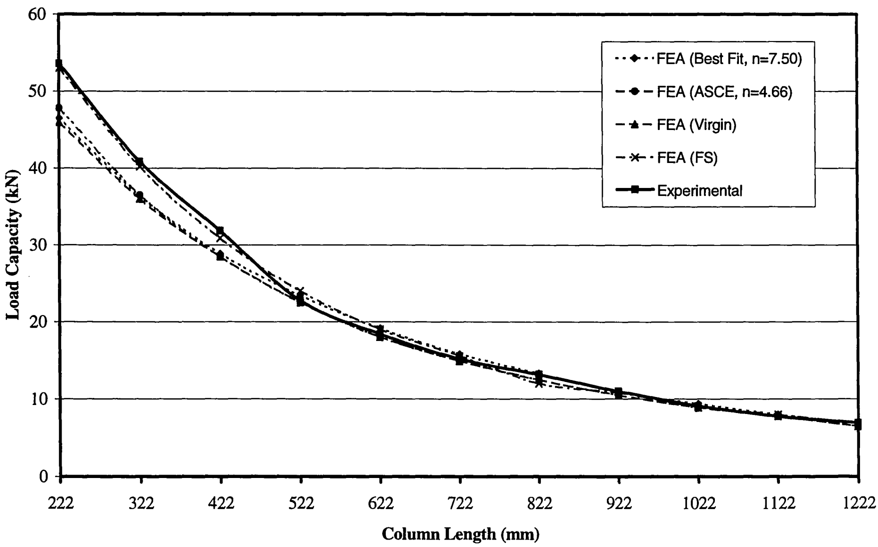


Figure 8: Graph of Load Capacity v. Column Length: Eccentric Loading–THK Section (Test/Finite Element Analysis)