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by

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SUMMARY

This paper describes the results obtained from a series of compression tests performed on cold formed stainless steel Type 304 columns of lipped channel cross-section. The cross-section dimensions, the column length and the eccentricity of the applied compressive load are varied to examine the effects on the buckling load capacity of the columns. The results obtained are compared to those obtained from the relevant design specifications in America and in Europe, and conclusions are drawn on the basis of the comparisons.

INTRODUCTION

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. While design code specifications for carbon steel members have been published in many countries around the world, for example the AISI Code in the USA (1), BS5950: Part 5 in the UK (2) and now Eurocode 3, Part 1.3 (3), covering most of Europe, for stainless steel members there are fewer design specifications available. The main design code in the past for stainless steel members has been that produced by the ASCE in the USA (4). In Europe Eurocode 3, Part 1.4 (5) has been introduced recently and is currently under examination in the member countries of the EEC. The Eurocode has taken a substantially different viewpoint on some aspects of design than that adopted by the ASCE. One such design aspect is the evaluation of column capacity. While the non-linearity of the stress/strain law is taken into account in the ASCE code in the determination of the column capacity, the Eurocode uses the initial elastic modulus and assumes an imperfection parameter larger than that assumed for a similar carbon steel column in determining the column failure load. By this means the weakening effects of reduction in the material stiffness as the stress increases are hopefully catered for by the adoption of the otherwise over-conservative imperfection magnitude.

In dealing with combined axial loads and bending moments the differences between the Eurocode and the ASCE code are compounded by virtue of the different interaction formulae used.

In view of these differences it was felt that an examination of the effects of concentric and eccentric compressive loading on the buckling behaviour and load capacity of stainless steel columns and comparison of the predictions of the ASCE Codes and Eurocode 3, Part 1.4 with experiments would be informative. This paper reports on part of an ongoing investigation of stainless steel columns, and concentrates on cold formed lipped channel columns of rather stocky cross section.

DESIGN CODE RECOMMENDATIONS

The buckling behaviour and load capacity of short to medium length columns of lipped channel cross-section is considered here for Type 304 stainless steel. Two different load conditions are considered, for comparison with the test results. In the first load case the loading is compressive and is applied through the section centroid (concentric loading). In the second load case loading is applied through a point at a fixed distance from the centroid (eccentric loading). This investigation was set up to compare the design code predictions for buckling load capacity for both loading conditions with experimental results. In addition to the different load conditions the effects of different tensile test properties is considered. Tensile tests were carried out on full cross sections of the columns to obtain full section material properties, and also on coupons cut from flat portions of the column specimens to obtain virgin material properties. Design code predictions based on both sets of properties are investigated.

The lipped channel cross-section dimensions were such that the cross-section could be considered to be fully effective against local buckling effects. Details of the experimental investigation are described later.

The design rules given in the ASCE code and in Eurocode 3: Part 1.4, set in a form directly applicable to the particular loading conditions examined experimentally are given below. In dealing with the Eurocode, Part 1.4 does not directly give details of bending/axial load interaction, but by default reference is made to Part 1.3 or Part 1.1.

ASCE

Concentric Loading:

For concentric loading the approach used in the ASCE code is as follows:-

Design Axial Strength, $P_n = 0.85AF_n$ (N) (1)

where A = gross cross-sectional area (mm^2)

and F_n = flexural buckling stress = $\dfrac{\pi^2 E_t}{\left(\dfrac{KL}{r}\right)^2}$ (N/mm^2)

with K = buckling coefficient = 1 for pinned ends

L = column length (mm)

r = cross-section radius of gyration (mm)

and E_t = tangent modulus = $\dfrac{E_o F_y}{F_y + 0.002nE_o\left(\dfrac{\sigma}{F_y}\right)^{n-1}}$ (N/mm^2)

in which n = plasticity factor = 6.216

E_o = initial elastic modulus (N/mm^2)

F_y = virgin or full section 0.2% proof stress (N/mm^2)

and σ = F_n (N/mm^2)

Eccentric Loading:

For eccentrically applied loading the interaction formula used is as follows, in the case of a load of constant eccentricity the maximum eccentric load, *P*, applied at an eccentricity *e* from the neutral axis is given by:-

$$\frac{P}{P_n} + \frac{P\,e}{M_n(1-\dfrac{P}{P_e})} \le 1 \qquad (2)$$

where $M_n = \dfrac{F_y I_{xx}}{\bar{y}}$ is the moment capacity of the cross section

and $P_e = \dfrac{\pi^2 E_o I_{xx}}{L^2}$ is the Euler buckling capacity

Eurocode 3, Part 1.4

Concentric Loading:

In the case of concentric loading the Eurocode uses the same general rules as for carbon steel members, so that

Design Buckling Resistance, $P_n = \chi A f_y$ (3)

where χ is a reduction factor due to overall buckling effects

A is the cross-sectional area of the member

and f_y is the virgin or full section 0.2% proof stress (N/mm^2)

The evaluation of the reduction factor is not detailed here, but this uses a Perry-Robertson approach to take account of overall buckling, yielding and imperfections. As mentioned previously a higher than normal Perry imperfection factor, corresponding to that of European column curve "c" is used for the stainless steel specimens.

Eccentric Loading:

In the case of an eccentrically applied load, with constant eccentricity *e*, and having fully effective cross section, the relevant interaction formula from which the maximum load can be obtained can be written as follows:-

$$\frac{P}{\chi f_y \dfrac{A}{\gamma_{M1}}} + \frac{\kappa P e}{M_n / \gamma_{M1}} \leq 1 \qquad (4)$$

where γ_{M1} is the material factor (equal to 1.1) and the factor κ is given by

$$\kappa = 1 - \frac{\mu_y P}{\chi f_y A} \quad but \quad \kappa \leq 1.5$$

with

$$\mu_y = \bar{\lambda}_y (2\beta_{My} - 4) \quad but \quad \mu_y \leq 0.9$$

In the above $\bar{\lambda}_y = \sqrt{\dfrac{f_y A}{P_e}}$ and β_{M1} is the equivalent moment factor, equal to 1.1 for uniform eccentricity.

Note that although they have been given the same symbols for continuity purposes the moment capacity and axial load capacity given in the ASCE code and Eurocode 3:Part 1.4 are not the same. In the application of the above formulae the values obtained for each individual code have been calculated independently.

The results obtained from the above design code equations will be used for comparison with the results obtained from a series of concentric and eccentric compression tests carried out on small lipped channel section members as described in the following section.

EXPERIMENTAL INVESTIGATION

In the experimental investigation a total of 77 column tests to failure were made on small lipped channel stainless steel columns. The specimen parameters investigated are as follows:

1. The column lengths varied from 222 mm to 1222 mm.

2. Two thicknesses of lipped channel section, of small cross section, were examined. The channels of approximately 2.4mm thickness were denoted "THN" while those of 3mm thickness were denoted "THK".

3. Forty four tests were carried out with concentric loading and thirty three tests were carried out with loading applied at 8 mm eccentric to the centroid of the cross section.

Figure 1 shows the lipped channel cross-section considered with all the measured dimensions given in Table 1. 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 measured mid-line dimensions. Note that the THN and THK specimens have different cross sectional dimensions. The slenderness ratios tested varied from 38 to 207 for the THK sections and from 42 to 234 for the THN sections.

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 cross sections sections to include the effects of cold formed corners.

Eleven different lengths of column were tested. All specimens were cut to the specified length and then milled flat at their ends to avoid any possible gripping problems. The end grips were designed such that they would hold the ends of the column, and allow loading to be applied at a given eccentricity through knife edges. The specimens were tested in a Tinius Olsen electro-mechanical testing machine, with the vertical displacement and column mid-span horizontal deflection measured during the tests using displacement transducers. Figure 2 shows a schematic diagram of the column test configurations.

RESULTS

All results obtained from tensile tests to establish virgin material and full cross-section mechanical properties are shown in Table 2. The results obtained from the standard tensile tests on the column web material showed that the 0.2% proof stress varied from 475 N/mm^2 to 487.5 N/mm^2 for THN material with the average being 480 N/mm^2. For THK material, the 0.2% proof stress varied from 446.79 N/mm^2 to 483.8 N/mm^2 with an average of 460 N/mm^2.

From the full section tensile tests, the 0.2% proof stress for the THN specimens ranged from 518 N/mm^2 to 522 N/mm^2 with the average being 520 N/mm^2. For the THK specimens, the 0.2% proof stress varied from 536.5 N/mm^2 to 543.5 N/mm^2 with an average of 540 N/mm^2.

Table 3 shows the results obtained from the compression tests carried out on concentrically loaded columns along with the ASCE and Eurocode predictions. Each of the experimental results given in this table is obtained from the average of two tests carried out on identical specimens. Table 4 shows the results obtained from the compression tests carried out on eccentrically loaded columns along with the ASCE and Eurocode predictions. In this case each of the experimental results for the THN specimens is the average of two tests. For the THK specimens only one test was carried out for each different length, as it had been recognised that there was very little variation in each pair of tests.

Figures 3 and 4 show the graphs of Buckling Load v. Column Length for concentrically and eccentrically loaded thin (THN) section columns respectively, showing curves for the test results and the ASCE and Eurocode predictions. Figures 5 and 6 show the graphs of Buckling Load v. Column Length for concentrically and eccentrically loaded thick (THK) section columns respectively, showing curves for the test results and the ASCE and Eurocode predictions.

OBSERVATIONS

Figure 3 shows the test results for concentrically loaded THN columns together with the ASCE and the Eurocode predictions. The design codes agreed reasonably well with the test results, with the ASCE design code being slightly conservative for low slenderness ratios while the Eurocode predictions are slightly non-conservative at low slenderness ratios, although the overall accuracy is very good. For the same columns loaded with a fixed eccentricity of 8mm, the code predictions underestimate the experimental capacities substantially, by approximately 40%. It is of interest in this respect that a load of 26.5 kN applied at 8mm eccentricity is sufficient to develop a moment equal to the theoretical moment capacity without taking account of axial load effects. If the 0.2% proof stress obtained from tensile tests on full cross sections is used instead of that obtained from the coupon tests the code predictions are slightly greater, but still substantially less than the experimental failure loads for the eccentric loading case. In actuality the moment capacity of the cross section is very much larger than is given by any approach which uses the 0.2% proof stress together with limited inelastic reserve, and this is the cause of the high degree of conservatism. For the cross sections examined the fully plastic bending capacity is approached, and the stresses acting are closer to the ultimate strength than the 0.2% proof strength. In a parallel series of tests the bending behaviour of these members was examined and the member bending capacity of both types of specimen was found to be slightly more than twice the theoretical capacities determined on the basis of the codes, due to the combination of very substantial post-elastic capacity and enhancement of the stresses beyond the 0.2% proof point before the bending capacity is attained. Substitution of the actual experimentally obtained moment capacities into the interaction equations results in very good agreement between code predictions and experiment for the eccentric loading case.

Figures 5 and 6 show the graphs of Buckling Load v. Column Length for the THK section columns and again the design codes provide rather accurate results for the centroidal loading case, but substantially conservative results, particularly for lower slenderness ratios, for the eccentric loading situation.

CONCLUSIONS

The main conclusions from this investigation is that the new Eurocode for stainless steel members, and the ASCE design specification, give accurate predictions of the buckling load of columns of fully effective lipped channel cross-section under concentric compression, but are conservative in the examination of eccentrically compressed columns of the same geometry.

For concentrically loaded columns, the design codes were accurate in their predictions of the buckling loads for all but the lowest slenderness ratios examined (<75). In this range, the ASCE predictions were more conservative than the Eurocode.

For eccentrically loaded columns, the design codes were found to be less accurate in their predictions of the buckling loads than for concentrically loaded columns, for the specific members examined. It is known that the bending capacity of these members is substantially greater than the code analysis procedures suggest, and this is the main reason for the over conservatism. It is, however, highly unlikely that the underestimation of bending capacity will be found for members with more slender cross sections, so that this conclusion should not be taken as generally applicable for stainless steel columns.

REFERENCES

1. American Iron and Steel Institute, **"Specification for the Design of Cold-Formed Steel Structural Members".** 1996

2. BS 5950, **"Structural Use of Steelwork in Building" - Part 5: "Code of Practice for the Design of Cold Formed Sections".** 1990.

3. ENV 1993-1-3, Eurocode 3: Design of Steel Structures; Part 1.3: **"General Rules - Supplementary Rules for Cold Forming Thin Gauge Members and Sheeting".** February 1996. (Edited Draft).

4. ANSI/ASCE-8-90, **"Specification for the Design of Cold-Formed Stainless Steel Structural Members".** 1991.

5. ENV 1993-1-3, Eurocode 3: Design of Steel Structures; Part 1.4: **"General Rules - Supplementary Rules for Stainless Steel".** July 1996.

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	28.00	14.88	7.45	2.43	1.10	1.10
THK	38.00	17.19	9.99	3.05	0.735	2.255

(Column Lengths: Varying from 222 mm to 1222 mm in Increments of 100 mm)

Table 2.
Tensile Test Results: Virgin Material and Full Section Mechanical Properties

Material Ref.	Thickness t (mm)	Average Virgin 0.2% P.S. (N/mm^2)	Average Virgin UTS (N/mm^2)	Average Full Section 0.2% P.S. (N/mm^2)	Average Full Section UTS (N/mm^2)
THN	2.43	480	553	520	689
THK	3.05	460	541	540	744

Table 3.
Buckling Load Results: Concentric Loading

Specimen Ref.	Column Length L, (mm)	ASCE (Virgin) P_n (kN)	ASCE (Full Section) P_n (kN)	Eurocode 1.4 (Virgin) P_n (kN)	Eurocode 1.4 (Full Section) P_n (kN)	Experimental Buckling Load P_{exp} (kN)
THN1	1222	3.758	3.755	4.515	4.533	4.355
THN2	1122	4.455	4.456	5.302	5.325	4.685
THN3	1022	5.371	5.373	6.314	6.343	6.820
THN4	922	6.600	6.603	7.643	7.683	7.825
THN5	822	8.300	8.303	9.437	9.494	8.789
THN6	722	10.755	10.759	11.934	12.019	11.156
THN7	622	14.462	14.481	15.537	15.674	15.554
THN8	522	20.260	20.430	20.948	21.193	19.102
THN9	422	28.641	29.701	29.336	29.846	28.391
THN10	322	37.862	40.380	42.030	43.281	38.640
THN11	222	47.469	50.777	57.599	60.498	52.640
THK1	1222	8.069	8.072	9.190	9.285	9.350
THK2	1122	9.575	9.578	10.772	10.894	10.661
THK3	1022	11.545	11.537	12.796	12.957	12.513
THK4	922	14.173	14.177	15.443	15.663	15.984
THK5	822	17.841	17.827	18.988	19.302	20.092
THK6	722	23.095	23.078	23.886	24.341	22.509
THK7	622	30.961	30.877	30.776	31.552	29.131
THK8	522	42.305	42.401	40.806	42.220	38.006
THK9	422	54.599	56.958	55.313	58.253	59.777
THK10	322	65.438	72.054	74.376	80.951	84.713
THK11	222	76.799	88.901	93.890	106.230	114.033

Table 4.
Buckling Load Results: Eccentric Loading

Specimen Ref.	Column Length L, (mm)	ASCE (Virgin) P (kN)	ASCE (Full Section) P (kN)	Eurocode 1.4 (Virgin) P (kN)	Eurocode 1.4 (Full Section) P (kN)	Experimental Buckling Load P_{exp} (kN)
THN1	1222	2.739	2.774	3.270	3.326	3.261
THN2	1122	3.141	3.186	3.709	3.780	3.691
THN3	1022	3.638	3.695	4.230	4.322	4.352
THN4	922	4.258	4.332	4.852	4.972	4.954
THN5	822	5.042	4.141	5.595	5.753	6.182
THN6	722	6.055	6.188	6.478	6.690	7.402
THN7	622	7.379	7.567	7.520	7.804	9.218
THN8	522	9.112	9.404	8.719	9.103	11.457
THN9	422	11.238	11.753	10.033	10.547	14.759
THN10	322	13.476	14.278	11.433	11.995	18.703
THN11	222	15.687	16.716	13.778	14.593	24.299
THK1	1222	5.620	5.806	6.403	6.687	6.933
THK2	1122	6.421	6.654	7.215	7.572	7.771
THK3	1022	7.397	7.687	8.166	8.622	9.117
THK4	922	8.616	8.994	9.283	9.870	10.990
THK5	822	10.132	10.623	10.591	11.354	13.160
THK6	722	12.068	12.730	12.109	13.110	15.177
THK7	622	14.537	15.438	13.844	15.164	18.388
THK8	522	17.591	18.884	15.761	17.501	22.749
THK9	422	20.775	22.804	17.738	20.013	31.886
THK10	322	23.799	26.826	20.370	22.834	40.853
THK11	222	26.767	30.949	23.609	27.043	53.595

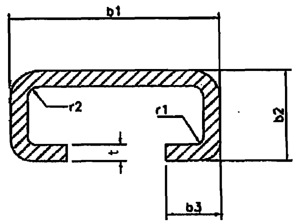

Figure 1
Geometry of Lipped Channel Sections.

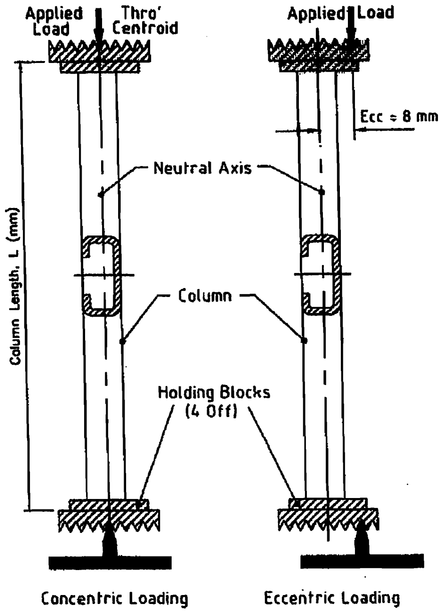

Figure 2:
Column Test Configurations.

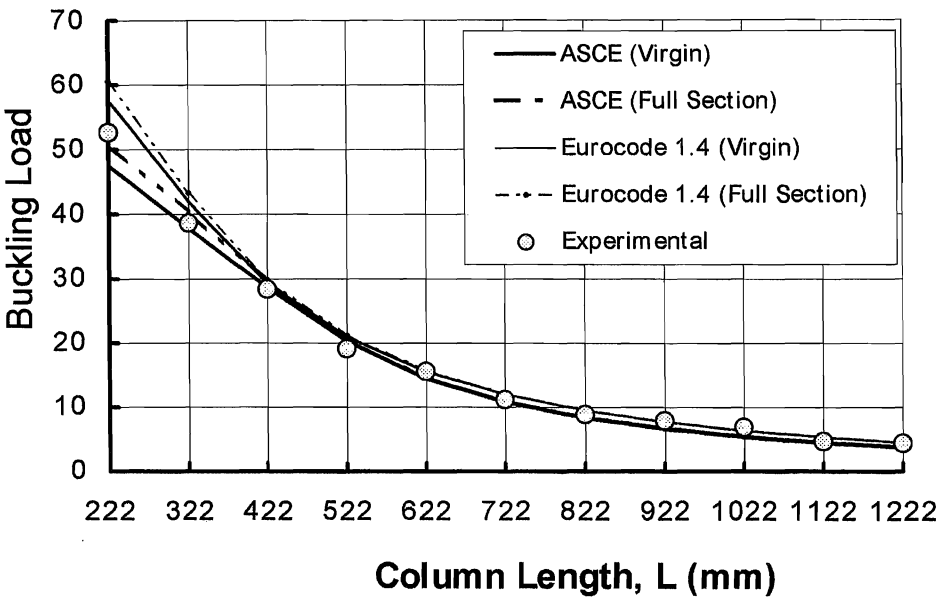

Figure 3: Buckling Load v. Column Length – Concentric Loading: THN Specimens.

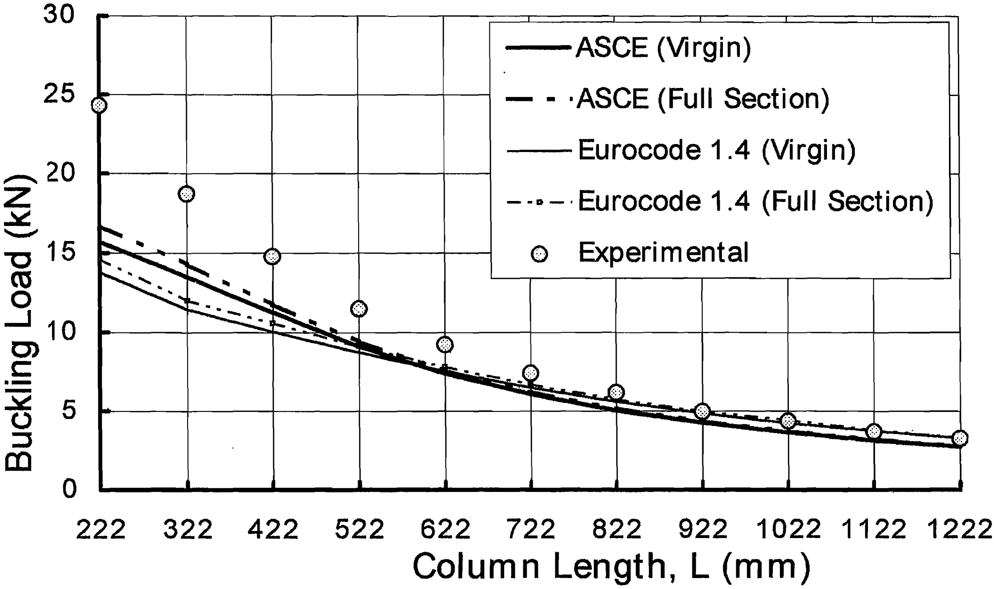

Figure 4: Buckling Load v. Column Length – Eccentric Loading: THN Specimens

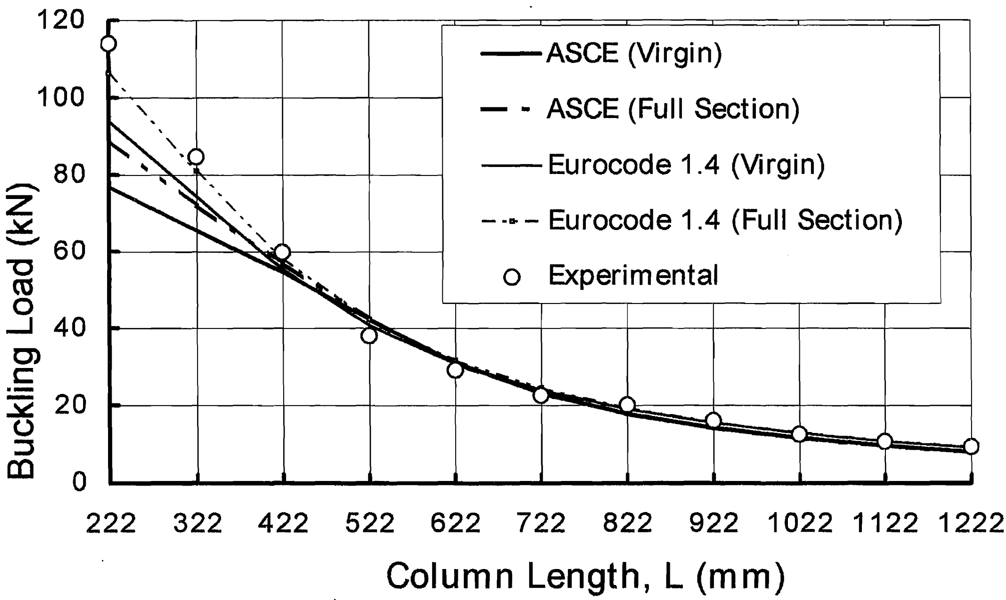

Figure 5: Buckling Load v. Column Length – Concentric Loading: THK Specimens.

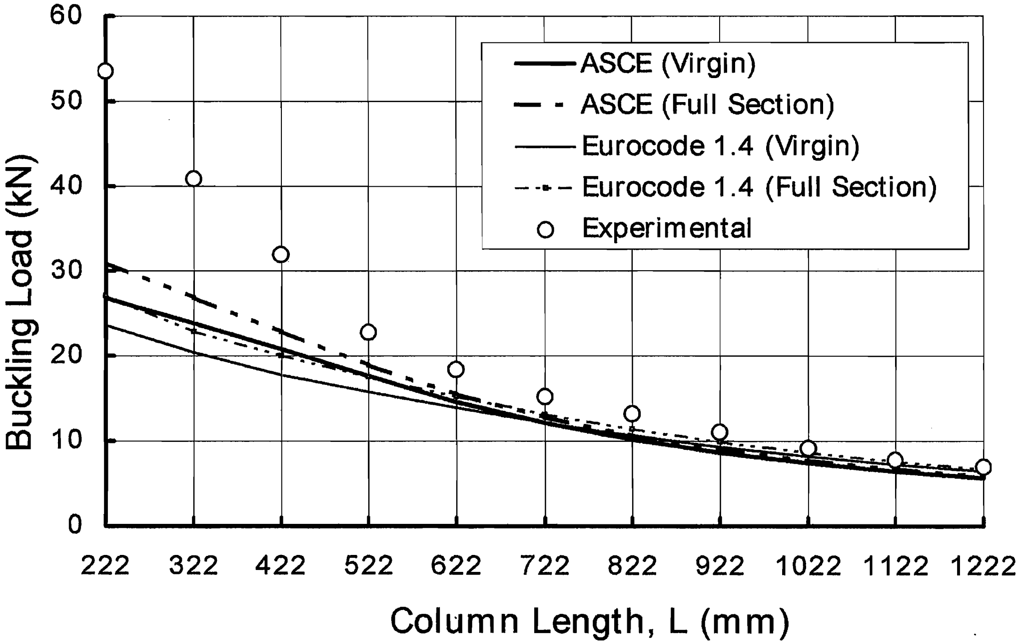

Figure 6: Buckling Load v. Column Length – Eccentric Loading: THK Specimens.