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THE LATERAL TORSIONAL BUCKLING STRENGTH OF COLD-FORMED STAINLESS STEEL BEAMS

by

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ABSTRACT

The findings of an investigation of the lateral torsional buckling strength of cold-formed stainless steel beams are reported in this study. The sections under consideration are cold-formed lipped channel sections spot-welded back to back to form doubly-symmetric lipped I-beams. The beams were fabricated from a modified AISI Type 409 stainless steel, designated Type 3CR12 corrosion resisting steel.

The purpose of this study is to compare the experimental lateral torsional buckling strengths of doubly-symmetric beams to the theoretical predictions proposed by the ASCE Specification for the Design of Cold-Formed Stainless Steel Structural Members[1]. It was concluded in this investigation that an acceptable prediction of beam strength may be obtained through the use of the tangent modulus approach adopted in the ASCE stainless steel design specification[1].

INTRODUCTION

Since very little experimental data were available on the lateral torsional buckling strength of cold-formed stainless steel beams, the current cold-formed stainless steel structural design manual[1] was based on accumulated experience gained in the specification for the design of cold-formed carbon and low alloy steel structural members[2]. Due to the difference in the mechanical behaviour of stainless steels compared to carbon and low alloy steels, research on the behaviour of cold-formed stainless steel beams subjected to lateral torsional buckling is necessary.

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Recent studies undertaken by the Chromium Steels Research Group at the Rand Afrikaans University by Van Wyk, Van den Berg and Van der Merwe[3] (1990) and Bredenkamp, Van den Berg and Van der Merwe[4] (1992), produced some experimental data on this subject.

The findings of an investigation into the lateral torsional buckling strength of cold-formed stainless steel lipped channel sections spot-welded back to back to form doubly-symmetric lipped I-beams are reported in this study.

MECHANICAL PROPERTIES

Test Procedure

Tension and compression test coupons were cut from the cold-rolled sheets used to fabricate the beam specimens. Four coupons were cut from each sheet to obtain a compression and a tension coupon for both the longitudinal direction (the direction parallel to the rolling direction) and the transverse direction (the direction perpendicular to the rolling direction) of the sheets. The coupons are labelled LT, LC, TT and TC, referring to longitudinal tension, longitudinal compression, transverse tension and transverse compression respectively.

Uniaxial tensile and compression tests were carried out on the specimens generally in accordance with the procedures outlined by ASTM A370-77[5]. Average strain was measured by two strain gauges mounted on either side of the coupon in a full bridge configuration. The compression coupons were tested using a bracing jig to prevent buckling of the coupon about the minor axis.

Results of Coupon Tests

Type 3CR12 corrosion resisting steel yields gradually under load. In order to compute the initial modulus, E_0, and subsequently the proportional limit, F_p, defined as the 0,01% offset strength, and the yield strength, F_y, defined as the 0,2% offset strength from experimental data, a computer program has been developed. This program enables the computation of the best fit straight line for the initial part of the stress-strain curve through a process of iterative linear regression. The slope of the best fit straight line is considered to be the initial modulus, E_0.

The mean values of the mechanical properties given in Table 1 were used together with Equation 1, the revised Ramberg-Osgood[6] equation, to produce the analytical stress-strain curves shown in Figure 1.

TABLE 1 Mechanical Properties of the Sheets

Property		LT	TT	LC	TC
Initial Elastic Modulus E_o (GPa)					
	Mean	195,3	232,0	202,3	232,1
	COV	2,04	6,04	2,18	4,97
Yield Strength F_y (MPa)					
	Mean	277,7	315,3	295,4	326,1
	COV	4,64	6,97	5,05	4,53
Proportional Limit F_p (MPa)					
	Mean	211,8	264,6	189,6	245,9
	COV	6,24	5,61	6,58	6,55
Tensile Strength F_u (MPa)					
	Mean	456,5	505,0	-	-
	COV	4,91	4,51	-	-
Elongation (%)					
	Mean	27,4	22,4	-	-
	COV	5,60	2,21	-	-

$$\epsilon = \frac{F}{E_o} + 0{,}002\left(\frac{F}{F_y}\right)^n \quad (1)$$

where

$$n = \frac{\log\left(\frac{\epsilon_y}{\epsilon_p}\right)}{\log\left(\frac{F_y}{F_p}\right)} \quad (2)$$

ε = strain
F = stress
E_o = initial elastic modulus
F_y = yield strength
F_p = proportional limit

ε_y = yield offset strain of 0,2%

ε_p = proportional limit offset strain of 0,01%

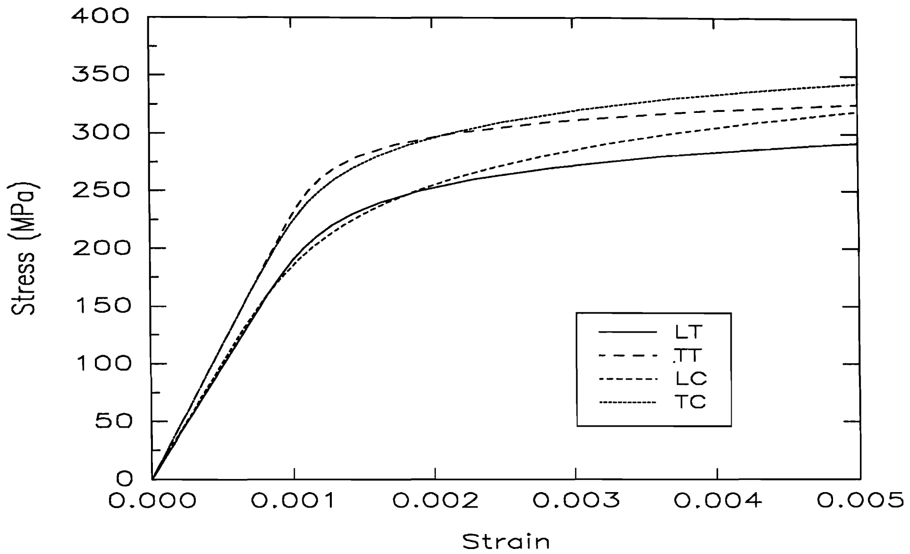

Figure 1. Analytical Stress Strain Curves for Type 3CR12 Steel Sheets

Since the tangent modulus can be used to determine the lateral torsional buckling strength of stainless steel beams, it is necessary to determine the tangent modulus at all levels of stress. The tangent modulus, E_t, is defined as the slope of the tangent to the stress-strain curve at each value of stress. It is determined as the inverse of the first derivative of Equation 1 with respect to stress and can be computed by using Equation 3.

$$E_t = \frac{F_y\,E_o}{F_y + 0{,}002\;n\;E_o\left(\frac{F}{F_y}\right)^{n-1}} \qquad (3)$$

Figure 2 shows the tangent moduli, E_t, as a function of stress as determined by Equation 3 for each of the four stress-strain curves in Figure 1.

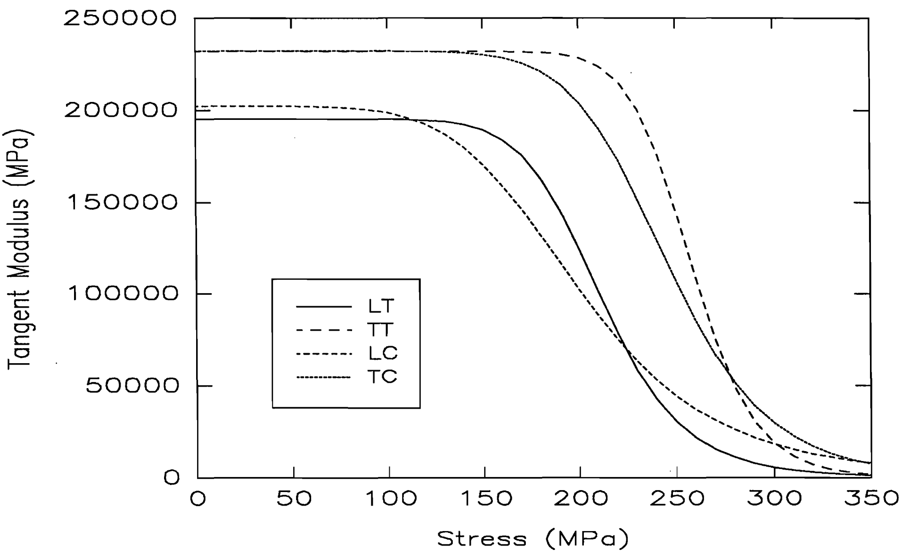

Figure 2. Tangent Moduli for Type 3CR12 Steel Sheets

LATERAL TORSIONAL BUCKLING STRENGTH OF DOUBLY SYMMETRIC BEAMS

Analytical Model

Beams may fail, apart from yielding, also in lateral torsional buckling. For the design of doubly symmetric flexural members subjected to a constant bending moment over the whole section the ASCE stainless steel design specification[1] requires that the nominal flexural strength be calculated as the smaller of either Equation 4 or Equation 5.

$$M_n = S_e F_y \tag{4}$$

where

S_e = elastic section modulus of the effective section

F_y = yield strength of the material in compression

or

$$M_n = S_c \left(\frac{M_c}{S_f}\right) \tag{5}$$

where

S_c = section modulus of the effective section at a stress M_c / S_f
S_f = section modulus of the full unreduced section

The critical moment, M_c, in Equation 5 has a maximum value of M_y and can be calculated by either Equation 6 or Equation 7 for doubly symmetric I-sections bent about the centroidal axis perpendicular to the web.

$$M_c = \pi^2 E_o C_b \left(\frac{d I_{yc}}{L^2}\right)\left(\frac{E_t}{E_o}\right) \tag{6}$$

or

$$M_c = C_b r_o A \sqrt{\sigma_{ey} \sigma_t} \tag{7}$$

In the foregoing.

C_b = bending coefficient depending on the moment gradient
d = depth of section
I_{yc} = moment of inertia of the compression portion of the section about the gravity axis of the entire section parallel to the web, using the full unreduced section
L = unbraced length of member
r_o = polar radius of gyration of the cross section about the shear centre
A = full cross sectional area

$$\sigma_{ey} = \left[\frac{\pi^2 E_o}{K_y L_y / r_y^2}\right]\left(\frac{E_t}{E_o}\right)$$

$$\sigma_t = \left(\frac{1}{A r_o^2}\right)\left(G_o J + \frac{\pi^2 E_o C_w}{(K_t L_t)^2}\right)\left(\frac{E_t}{E_o}\right)$$

$K_y L_y$ = effective length for bending about the y-axis

r_y = radius of gyration of the cross section about the centroidal y-axis
G_o = initial shear modulus
J = St. Venant torsion constant
C_w = torsional warping constant
K_tL_t = effective length for twisting

Effective flange widths and web heights were calculated by using the provisions for uniformly compressed stiffened elements in the ASCE stainless steel design specification[1]. These provisions are similar to the provisions in the AISI cold-formed carbon and low alloy steel design specification[2].

Preparation of Members

Two different lipped I-sections were fabricated. The lipped I-sections were fabricated by cutting the sheets with a guillotine into strips along the longitudinal rolling direction of the sheet. Lipped channels were cold-formed by a press brake process to the desired dimensions and were then spot welded back to back to form the desired lipped I-section. The spot welding was done according to the provisions laid down by Taylor[7]. The mean dimensions of the lipped I-sections are given in Table 2.

TABLE 2 Dimensions of the Lipped I-Sections

Dimensions	Web Height (mm)	Flange Width (mm)	Sheet Thickness (mm)	Radius of Bend (mm)	Lip Length (mm)
64x33	64,3	32,9	1,6	2,0	10,6
96x43	96,5	43,0	1,6	2,0	10,4

The dimensions of the lipped channels were chosen such that no local buckling would occur in the compression flange of the lipped I-section before the full sectional strength was reached. The 64x33 section has a w/t ratio of 16,08 and the 96x43 section a w/t ratio of 22,38. The webs of the sections were chosen to be fully effective throughout.

Experimental Setup and Procedure

The experimental setup was essentially similar to the setup used by Galambos[8] for testing lateral torsional buckling of beams. The beam is simply supported, using a four point loading system to ensure a constant moment between the two middle supports. At the supports the beam is free to rotate in the direction of the axis of the beam but is fixed for lateral rotation as well as warping.

The load was applied to the beam using a hydraulic Instron actuator at a displacement rate of 2 mm/minute. Load readings were taken at five second intervals and loading was stopped once the applied load dropped to approximately 10% below the maximum recorded load.

RESULTS

The experimental results of the tests on the lateral torsional buckling strength of cold-formed lipped I-section beams are given in Table 3. A comparison is made between the experimental lateral torsional buckling moments, M_e, and two theoretical lateral torsional buckling moments, (1) the lateral torsional buckling moment, M_t, using the tangent modulus concept as adopted in the ASCE cold-formed stainless steel design manual[1] and (2) the lateral torsional buckling moment, M_s, using the SSRC approach as adopted in the AISI cold-formed steel design manual[2].

In Figures 3 and 4 the experimental results are compared with the lateral torsional buckling moment curves using the tangent modulus approach as given in the ASCE cold-formed stainless steel design specification[1] as well as the SSRC approach adopted in the AISI cold-formed steel design specification[2].

DISCUSSION OF RESULTS

It is evident from Figure 1 that Type 3CR12 corrosion resisting steel yields gradually under load, thus falling outside the scope of the carbon and low alloy steel design specifications. However, the results of the cold-formed stainless steel I-sections, especially for the 64x33 I-section, show that by using the AISI lateral torsional buckling curve better results are obtained. Comparing the larger section, 69x43 I-section, with the two analytical beam curves five out of the seven experimental beam strengths fell below the carbon steel beam curve (AISI beam curve).

Previous work by Van Wyk et al.[3] who tested the lateral torsional buckling strength of stainless steel beams subjected to a moment gradient and a shear force, found that the tangent modulus approach predicted stainless steel beam strength the best. A similar conclusion was reached by Bredenkamp et al.[4] on tests conducted on lipped channel beams. Therefore, although conservative, the authors suggest that the tangent modulus approach still be used to predict stainless steel beam strength.

TABLE 3 Experimental and Analytical Beam Strengths

Beam Length (mm)	Beam No.	Flange Width (mm)	M_e (kNm)	M_t (kNm)	M_s (kNm)	$\frac{M_e}{M_t}$	$\frac{M_e}{M_s}$
1000	1	33,3	2,735	2,173	2,680	1,258	1,021
1100	2	33,4	2,813	2,094	2,650	1,344	1,061
1500	3	34,1	2,745	1,821	2,369	1,507	1,159
1700	4	32,8	2,633	1,699	2,196	1,550	1,199
1900	5	33,4	2,186	1,578	2,002	1,385	1,092
2100	6	33,1	1,905	1,456	1,786	1,308	1,067
2300	7	32,9	1,613	1,331	1,548	1,212	1,042
2400	8	33,5	1,665	1,267	1,424	1,314	1,170
2800	9	33,0	1,254	1,012	1,046	1,240	1,199
Mean						1,346	1,112
COV						8,65	6,27
900	10	43,2	4,569	4,981	5,520	1,008	0,909
1200	11	43,1	5,019	4,491	5,520	1,017	0,828
1300	12	42,9	4,675	4,353	5,490	1,074	0,852
1500	13	43,4	5,225	4,103	5,277	1,274	0,990
1700	14	44,0	5,156	3,875	5,033	1,331	1,024
2300	15	43,3	4,523	3,249	4,120	1,392	1,098
2600	16	43,7	3,188	2,937	3,560	1,086	0,895
Mean						1,169	0,973
COV						13,61	15,30

CONCLUSIONS

It can be concluded from experimental results of the cold-formed stainless steel doubly symmetric lipped I-beam tests that some agreement is found between the experimental results and the predicted results, although very conservative, when using the tangent modulus approach as specified by the ASCE cold-formed stainless steel specification[1]. However, on account of previous work on lateral torsional buckling of stainless steel beams it is still suggested that the tangent modulus approach be used for predicting beam strength of Type 3CR12 corrosion resisting steel.

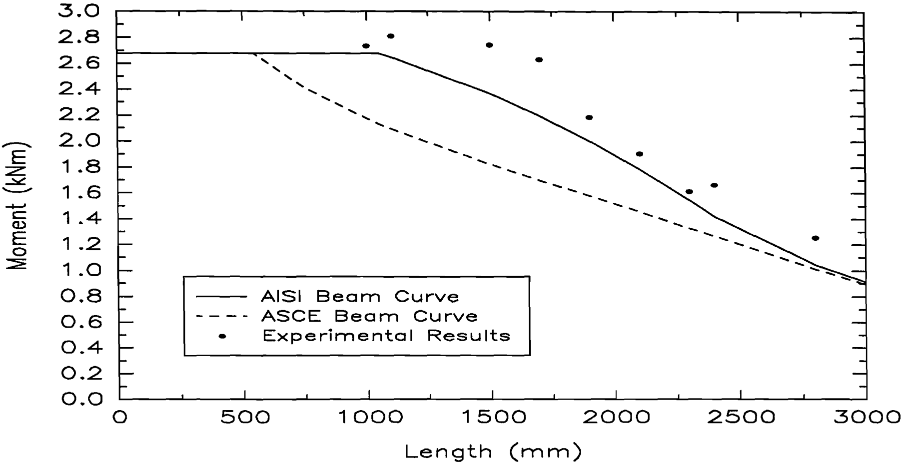

Figure 3. Lateral Torsional Buckling Moment vs Length for 64x33 I-Section

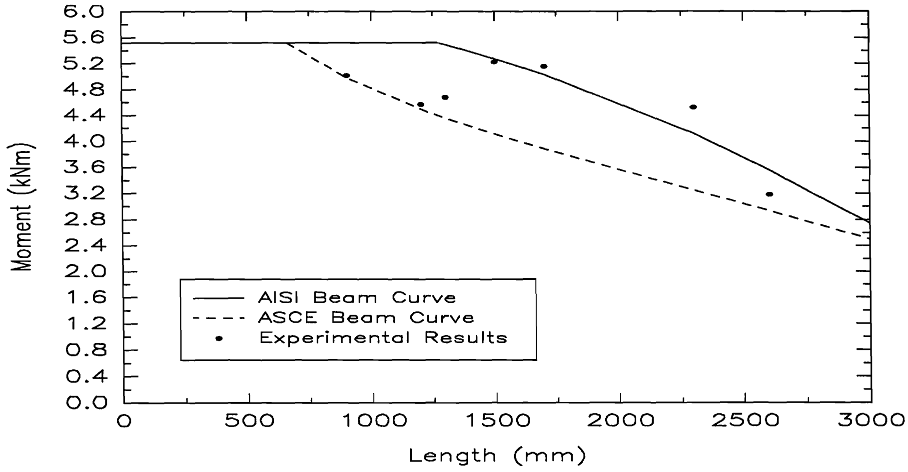

Figure 4. Lateral Torsional Buckling Moment vs Length for 96x43 I-Section

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