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Lateral Torsional Buckling Strength of Doubly Symmetric Stainless Steel Beams

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SYNOPSIS

The findings of an investigation into the lateral buckling strength of cold–formed doubly symmetric stainless steel beams are reported in this study. The purpose of this study was to obtain the necessary information on the lateral buckling strength of doubly symmetric stainless steel beams in order to update the relevant sections of the stainless steel design specifications[1,2,3].

For this study cold–formed stainless steel Type 304, 430 and Type 3CR12 corrosion resisting steel I–beams were chosen. The I–beams were manufactured by spotwelding two cold–formed channels back to back. The lengths of the beams varied between 300 mm and 1600 mm. The beams were simply supported but lateral movement of the beams at supports was prevented by a specially manufactured device. A single point load was applied at midspan. Because it is very difficult to allow freedom for lateral movement of the beam at midspan by using a machine, a special mechanism was developed to apply the load at midspan by means of weights.

It was concluded in this investigation that the tangent modulus approach adopted in the proposed design specifications for stainless steels[2,3] compared well with the experimental results.

GENERAL REMARKS

Very little information is available on the lateral buckling strength of cold–formed stainless steel doubly symmetric beams. The 1968 edition of the Stainless Steel Cold–Formed Structural Design Manual[4] was based on the accumulated experience in the design of cold–formed carbon and low alloy steel structural members[5] and work done by Johnson[6]. The findings of the additional research work conducted by Wang[9] and Errera[7,8], who investigated the performance of structural members cold–formed from cold–rolled austenitic stainless steels and the study by Errera et al[9] on the strength of bolted and welded connections in stainless steels, were incorporated in the 1974 edition of the AISI design specification for stainless steels.[3]

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The stainless steel design specification lacks a considerable amount of design provisions in comparison with the design specification for carbon and low alloy steels.[10] Due to the difference in mechanical behaviour of the stainless steels compared to the carbon and low alloy steels, research on the behaviour of cold–formed stainless steel beams subject to lateral buckling is necessary.

STAINLESS STEELS UNDER CONSIDERATION

The stainless steels under consideration in this study are limited to annealed AISI Type 304 and 430 as well as a modified Type 409 steel, designated 3CR12, a corrosion resisting steel, manufactured by the specialty steel producing company, Middelburg Steel and Alloys. Type 304 and 430 stainless steels are well known types of steel. Type 3CR12 steel has recently been developed as a weldable 12% chromium containing corrosion resisting steel and has not been as widely documented as Type 304 and 430 steels.

In a study by Thomas[11] on the abrasion–corrosion resistance of Type 3CR12 steel, it was concluded that in gold mine waters, waters in coal washing plants, the brackish waters in platinum, phosphate and asbestos mining operations, the corrosion resistance of Type 3CR12 steel is such that the corrosion portion of abrasion–corrosion wear had been largely overcome. That in turn should restrict abrasion to some extent and lead to longer life. Corrosion resisting steels such as Type 3CR12 steel may prove to be cost–effective materials of construction in applications where corrosion is an important consideration.

MECHANICAL PROPERTIES

The mechanical properties of stainless steels Type 304, 430 and Type 3CR12 steel were determined from uniaxial tensile and compression specimens taken from cold–rolled sheet in the longitudinal direction (the direction parallel to the rolling direction) and the transverse direction (the direction perpendicular to the rolling direction).

The tension and compression tests were conducted generally in accordance with the proceedings outlined by the ASTM Standard A370–77.[12] All specimens were tested using an Instron 1195 Universal Testing Machine. Average strain was measured by two strain gauges mounted on either side of the specimen in a full bridge configuration with temperature compensation. Compression test specimens were mounted in a specially manufactured test fixture which prevents buckling of the specimen about the minor axis.

The mechanical properties of stainless steels Type 304, 430 and Type 3CR12 steel are given in Table 1. The mechanical properties for longitudinal compression are subsequently used to calculate the theoretical lateral buckling load of the beams. The stress–strain curves in Figures 1 to 3 were drawn by using the analytical equation, Equation 1 attributed to Ramberg and Osgood.[13]

$$\epsilon = \frac{F}{E_0} + 0{,}002\left(\frac{F}{F_y}\right)^n \qquad (1)$$

where

$$n = \frac{\log \frac{\epsilon_y}{\epsilon_p}}{\log \frac{F_y}{F_p}} \tag{2}$$

where

E_0 = initial elastic modulus
ϵ = strain
ϵ_y = yield strength offset strain
ϵ_p = proportional limit offset strain
F = stress
F_y = yield strength
F_p = proportional limit
n = constant

The reasons to use the two offset strength values and offset strain values in Equation 2 are described in detail by van den Berg[14] and van der Merwe[15]. Johnson[6] and Wang[7] used different values.

The tangent modulus, E_t, which is defined as the slope of the stress–strain curve at each value of stress, is obtained from the inverse of the first derivative with respect to stress of Equation 1. Equation 3 gives the tangent modulus as a function of stress and is displayed in Figures 4 to 6 for each of the steels under consideration.

$$E_t = \frac{F_y . E_0}{F_y + 0{,}002nE_0(\frac{F}{F_y})^{n-1}} \tag{3}$$

LATERAL TORSIONAL BUCKLING STRENGTH OF BEAMS

PREPARATION OF MEMBERS

The I–beams that were tested were made up from two cold–formed channels spot welded back to back by the electric spot welding method. The dimensions of the channels were 15 mm wide and 50 mm deep, giving an I–beam 30 mm wide and 50 mm deep. The thickness of the material was 1,2 mm and the radius of bends were 2,0 mm. The dimensions of the I–beams were chosen such that no local buckling would occur within the experimental limits.

EXPERIMENTAL PROCEDURE

The I–beams were placed on two simply supported supports. Rotation in the direction of the axis of the beam as well as rotation perpendicular to the axis of the beam in a horizontal plane was allowed by means of a 25 mm ball at the supports. Vertical rotation perpendicular to the axis of the beam was prevented by means of a specially manufactured end fixture. At midspan a point load was applied to the beam by means of a specially manufactured fixture as shown in Figure 7. Figure 8 shows a photograph of the method used to apply loads at midspan. Loads were applied to this fixture at midspan manually. This procedure was followed because it is very difficult to apply a load automatically by means of a machine where lateral movement of the test specimen is not restricted. This method to apply the load at midspan proved to be satisfactory.

ANALYTICAL MODEL

Apart from yielding, laterally unbraced beams may fail in lateral torsional buckling. Because the beams were designed such that local buckling would not occur within the experimental limits, the interaction between local buckling and lateral torsional buckling falls beyond the scope of this study.

The critical buckling stress of a singly symmetric I–section beam can be determined by Equation 4.[16]

$$F_{cr} = \frac{C_b \pi^2 E_o I_{yc}}{L^2 Z} \sqrt{1 + \frac{4GJL^2}{\pi^2 I_{yy} E_o d^2}} \qquad (4)$$

where

F_{cr} = critical lateral torsional buckling stress
E_o = initial elastic modulus
E_t = tangent modulus
G = shear modulus
G_t = tangent shear modulus
L = effective length of the beam
d = depth of the beam
I_{yy} = moment of inertia about weak y–axis of the beam
I_{yc} = moment of inertia of compression flange
J = polar moment of inertia
C_b = bending coefficient
Z = section modulus

The inelastic behaviour of stainless steel beams is accommodated in Equation 4 by replacing the initial elastic modulus and shear modulus by the tangent modulus and the tangent shear modulus.[2] The ratio of the tangent shear modulus to the shear modulus is taken in the same proportion as the ratio of the tangent modulus to the initial elastic modulus. The assumption that the ratios of the two moduli remains constant is in accordance with the assumption made by Bleich[17] and is given in Equation 5.

$$G_t = G.\frac{E_t}{E_o} = \frac{E_t}{2(1+\nu)} \qquad (5)$$

where

ν = Poisson's ratio

In the proposed cold–formed stainless steel design specification[2] the second term of Equation 4 is neglected because it is much less than the first term. For design purposes this assumption will simplify calculations without a significant loss of accuracy and will give conservative design values. For the purposes of this study to compare the theoretical design moments with experimental failure moments Equation 5 will be used to determine the theoretical critical lateral torsional buckling stress for singly symmetric I–beams.

In the carbon steel design specification[10] the SSRC[18] concept suggested by the Structural Stability Research Council is used to evaluate the critical lateral torsional buckling strength in the inelastic stress range. This effect is expressed in Equation 6.

$$F_{cr} = F_y\left(1 - \frac{F_y}{4F_e}\right) \qquad (6)$$

where

F_e = elastic critical lateral torsional buckling stress.

RESULTS

The experimental results of the tests on the lateral torsional buckling strength of singly symmetric I–section beams are given in Table 2. A comparison is made between the experimental lateral torsional buckling moments and the two theoretical lateral torsional buckling moments using the tangent modulus concept of the new proposed stainless steel design specification[2,3] and the SSRC concept.[10,18]

In Figures 9, 10 and 11 the experimental results are compared with the two concepts discussed above. The elastic lateral torsional buckling curve is also shown in these figures.

DISCUSSION OF RESULTS

From Table 2 and Figures 8, 9 and 10 it can be concluded that the SSRC approach to evaluate the lateral torsional buckling strength of carbon and low alloy steel beams can not be used for stainless steels. The tangent modulus approach adopted in the proposed design specification for cold–formed stainless steel members[2,3] give satisfactory results.

ACKNOWLEDGEMENTS

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TABLE 1. MECHANICAL PROPERTIES OF STAINLESS STEEL

	SENSE AND DIRECTION OF STRESS			
MECHANICAL PROPERTY	LT	TT	LC	TC
Initial Elastic Modulus				
304	206,4	203,3	205,0	205,9
430	198,6	220,2	208,3	231,9
3CR12	197,7	232,5	202,6	232,9
Yield strength F_y(MPa)				
304	284,8	282,0	266,5	288,3
430	322,9	348,4	351,1	387,7
3CR12	282,2	334,8	303,6	332,2
Proportional limit F_p(MPa)				
304	170,0	195,9	144,2	196,0
430	262,6	304,2	217,7	348,2
3CR12	202,6	273,0	208,2	271,5
Ultimate Strength				
304	758	740	–	–
430	496	528	–	–
3CR12	460	502	–	–
Ratio of F_p/F_y				
304	0,60	0,69	0,54	0,68
430	0,81	0,87	0,80	0,90
3CR12	0,72	0,81	0,69	0,82
Ratio of F_u/F_y				
304	2,66	2,62	–	–
430	1,54	1,52	–	–
3CR12	1,63	1,50	–	–
Elongation				
304	58,1	62,8	–	–
430	28,4	26,8	–	–
3CR12	29,7	28,8	–	–

TABLE 2. COMPARISON OF THEORETICAL AND EXPERIMENTAL BEAM STRENGTH

Steel Type	Length (mm)	M_e kN.m	M_t kN.m	M_s kN.m	M_e/M_t	M_s/M_s
304	300	0,72	0,54	0,58	1,32	1,24
304	400	0,60	0,47	0,55	1,26	1,07
304	600	0,44	0,38	0,50	1,15	0,88
304	800	0,31	0,33	0,44	0,96	0,72
304	1000	0,26	0,28	0,37	0,91	0,69
304	1200	0,21	0,24	0,30	0,86	0,71
304	1400	0,21	0,21	0,24	0,99	0,87
304	1600	0,20	0,19	0,20	1,05	0,97
430	300	0,72	0,70	0,75	1,03	0,96
430	400	0,66	0,62	0,71	1,07	0,93
430	600	0,56	0,52	0,62	1,08	0,90
430	800	0,42	0,43	0,51	0,98	0,83
430	1000	0,37	0,36	0,39	1,05	0,95
430	1200	0,32	0,29	0,30	1,11	1,07
430	1400	0,31	0,24	0,24	1,29	1,27
430	1600	0,24	0,20	0,21	1,19	1,19
3CR12	300	0,72	0,60	0,65	1,19	1,10
3CR12	400	0,63	0,55	0,62	1,14	1,01
3CR12	600	0,42	0,48	0,55	0,88	0,76
3CR12	800	0,39	0,41	0,47	0,95	0,83
3CR12	1000	0,35	0,35	0,38	1,01	0,93
3CR12	1200	0,32	0,29	0,29	1,10	1,07
3CR12	1400	0,30	0,24	0,24	1,26	1,25
3CR12	1600	0,24	0,20	0,20	1,22	1,22
Mean					1,09	0,98
Coefficient of Variation					0,12	0,18

M_e = experimental buckling moment

M_t = theoretical buckling moment using the tangent modulus concept

M_s = theoretical buckling moment using the SSRC concept

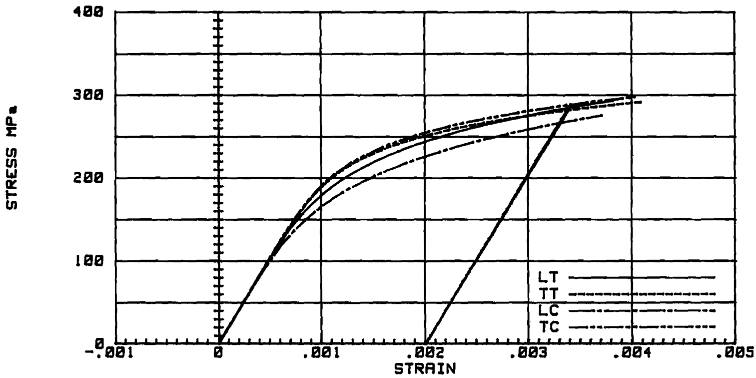

FIGURE 1 ANALYTICAL STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 304

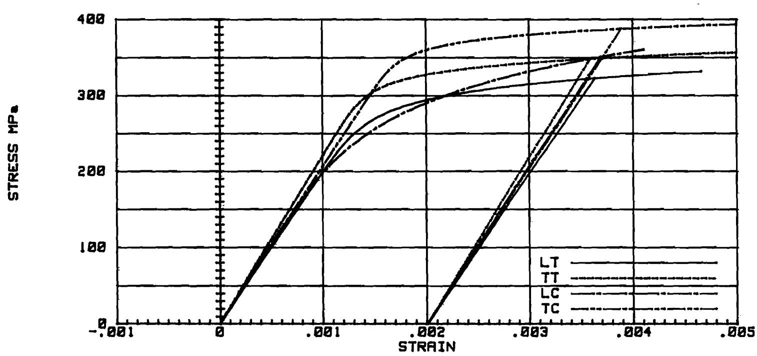

FIGURE 2 ANALYTICAL STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 430

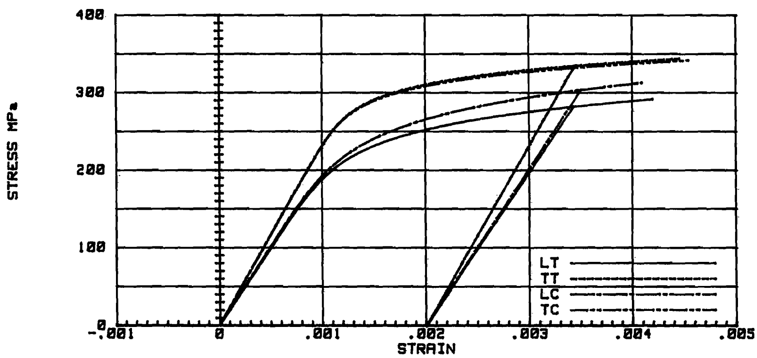

FIGURE 3 ANALYTICAL STRESS-STRAIN CURVES FOR TYPE 3CR12 CORROSION RESISTING STEEL

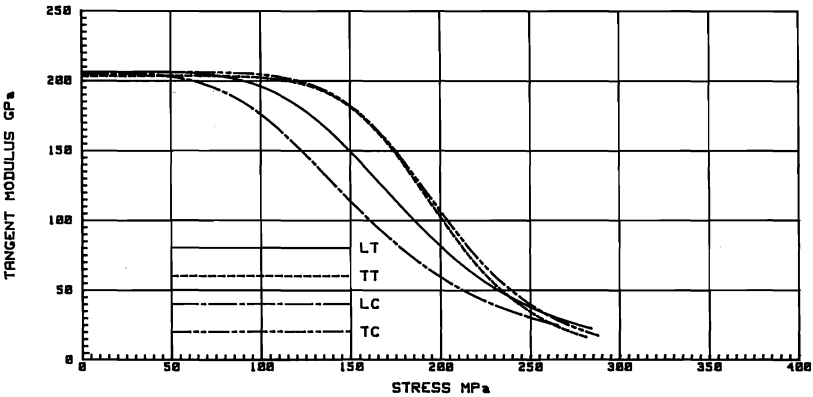

FIGURE 4 ANALYTICAL TANGENT MODULI FOR STAINLESS STEEL TYPE 304

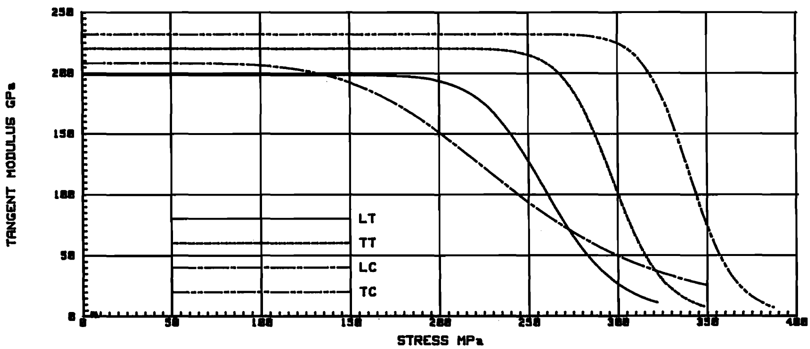

FIGURE 5 ANALYTICAL TANGENT MODULI FOR STAINLESS STEEL TYPE 430

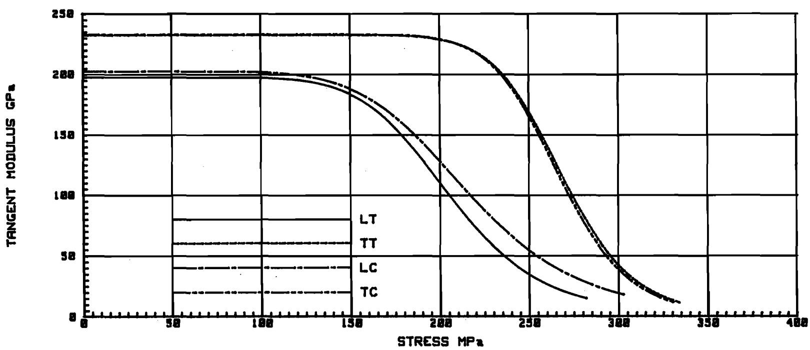

FIGURE 6 ANALYTICAL TANGENT MODULI FOR TYPE 3CR12 STEEL

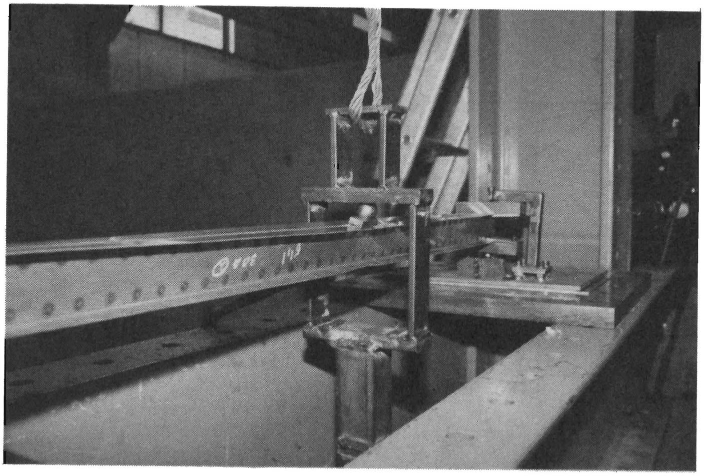

FIGURE 7. LAYOUT OF BEAM

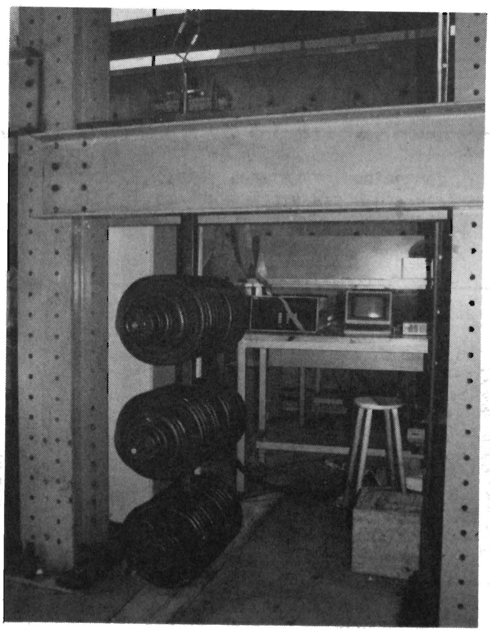

FIGURE 8. METHOD TO APPLY LOADS

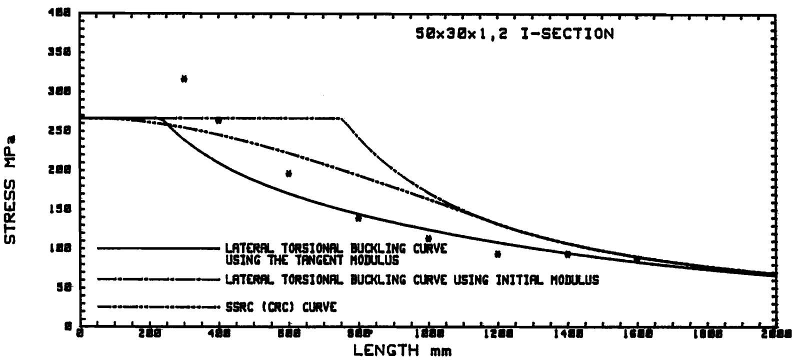

FIGURE 9 COMPARISON OF LATERAL TORSIONAL BUCKLING STRENGTHS FOR STAINLESS STEEL TYPE 304

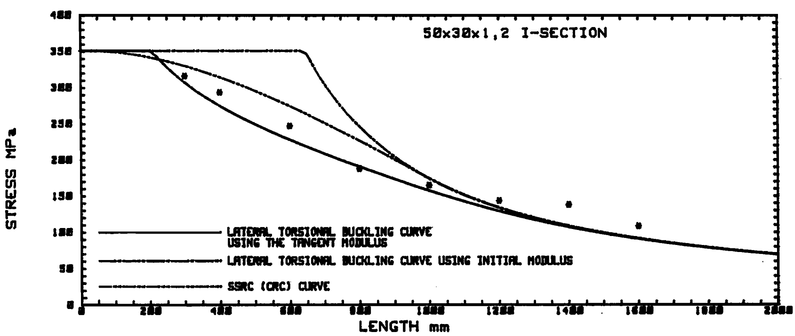

FIGURE 10 COMPARISON OF LATERAL TORSIONAL BUCKLING STRENGTHS FOR STAINLESS STEEL TYPE 430

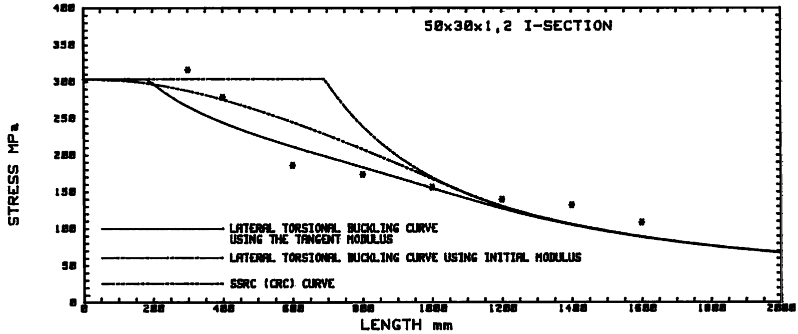

FIGURE 11 COMPARISON OF LATERAL TORSIONAL BUCKLING STRENGTHS FOR TYPE 3CR12 CORROSION RESISTING STEEL