TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING

Vol 48 No 1, March 2006, Pages 8–13, Paper 584

The lateral torsional buckling strength of hot-rolled 3CR12 beams

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3CR12 is a corrosion-resisting steel containing approximately 12 % Cr. It was developed in the early 1980s in South Africa and is available in Europe, specified as DIN 1,4003.

Experimental results of full-scale beam tests on the lateral torsional buckling behaviour of recently developed 3CR12 hot-rolled structural sections are presented. Singly and doubly-symmetric hot-rolled sections were investigated. The experimental work was duplicated for 300WA carbon steel sections to use as a direct comparison.

The experimental results are compared with theoretically calculated values of the South African code of practice (SANS-10162-1:2005) and the European code of practice (Eurocode 3). The recommended resistance factors are used. Conclusions and recommendations of the possible inclusion into the current code of practices are given.

INTRODUCTION

Mittal Steel South Africa has recently started to produce an extensive range of hot-rolled structural sections in 3CR12 under license of Columbus Stainless. This is a world first. It has subsequently become necessary to evaluate the structural behaviour of these sections, as the material properties of 3CR12 are different from those of their carbon steel equivalents. More specifically, the effect of the non-linear material behaviour on the structural behaviour needs to be investigated. The aim of the study is to investigate these 3CR12 hot-rolled sections as flexural members.

It is necessary to be familiar with the unique material properties of stainless steel prior to designing structural members, owing to the more gradual yielding behaviour. The mechanical properties differ in tension and compression, and the proportional limit can be substantially lower than the yield stress (Van den Berg 1996).

Eurocode 3 (1991) currently used in some European countries is applicable to hot-rolled and welded carbon steel sections as well as austenitic and duplex stainless steel sections. There is currently no US-design standard for hot-rolled or fabricated stainless steel members. The AS/NZS (used in Australia and New Zealand) specifications outline minimum requirements when using cold formed stainless steel.

The SANS-10162-1:2005 code of practice is currently used in South Africa for structural steel design. In this investigation a direct comparison is made between 3CR12 hot-rolled sections and similar 300WA sections. Full-scale beam tests under constant moment were conducted for different sections and slenderness ratios. From the information gathered a conclusion was made regarding the difference between 3CR12 and 300WA sections as flexural members, and the possible direct application of the code of practice to 3CR12 hot-rolled sections.

PREVIOUS WORK CONDUCTED ON 3CR12 HOT-ROLLED SECTIONS

Van Wyk (Van Wyk and Van den Berg 1990) investigated the lateral torsional buckling strength of stainless steel sections. The sections were fabricated from cold formed plate. The extent of the investigation included beams fabricated from Type 304, 430 and 3CR12 corrosion resisting steel. It was concluded that the tangent modulus approach predicts the buckling moment resistance of the sections under investigation sufficiently well.

Table 1 Mechanical properties from stub column compression tests

	IPEAA 100x55				127×64×15				152×76×18			
	3CR12		300WA		3CR12		300WA		3CR12		300WA	
	Average	COV (%)	Average	COV (%)	Average	COV (%)	Average	COV (%)	Average	COV (%)	Average	COV (%)
Eo (GPa)	203,0	7,7	210,7	2,2	207,0	1,9	210,3	3,7	209,0	4,1	202,0	10,5
σy (MPa)	380,0	0,4	371,3	0,7	315,7	4,3	342,3	3,3	327,5	0,2	323,0	1,8
σp (MPa)	249,5	3,7	342,0	4,4	230,7	4,2	278,7	7,9	252,5	1,8	277,5	3,3
$\sigma p/\sigma y$	0,66	–	0,92	–	0,73	–	0,81	–	0,77	–	0,86	–

Keywords: flexural buckling, lateral torsional buckling, 3CR12 beams, moment resistance, hot-rolled beams

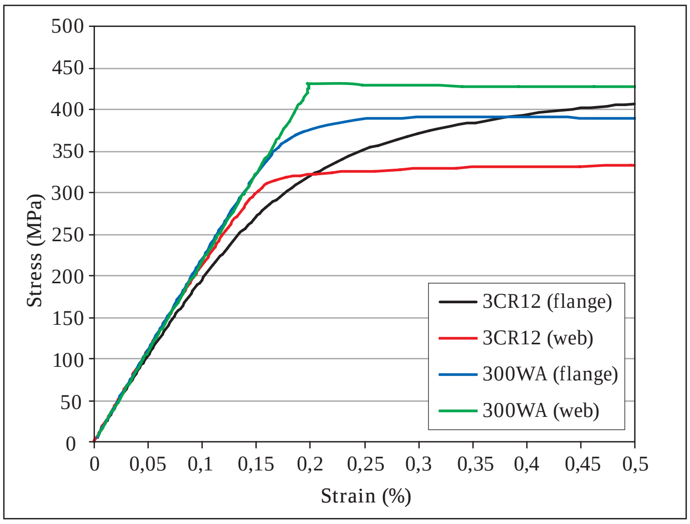

Figure 1** **Representative stress strain curves for 3CR12 and 300WA IPE$_{AA}$ 100×55 sections

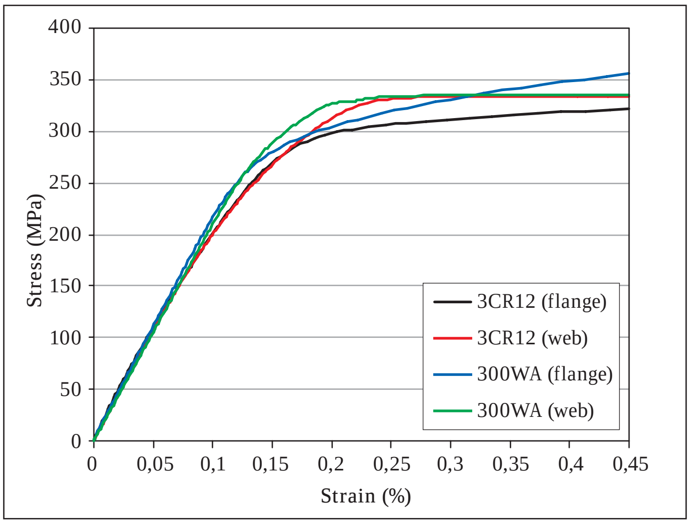

Figure 2** **Representative stress strain curves for 3CR12 and 300WA 127×64×15 channel

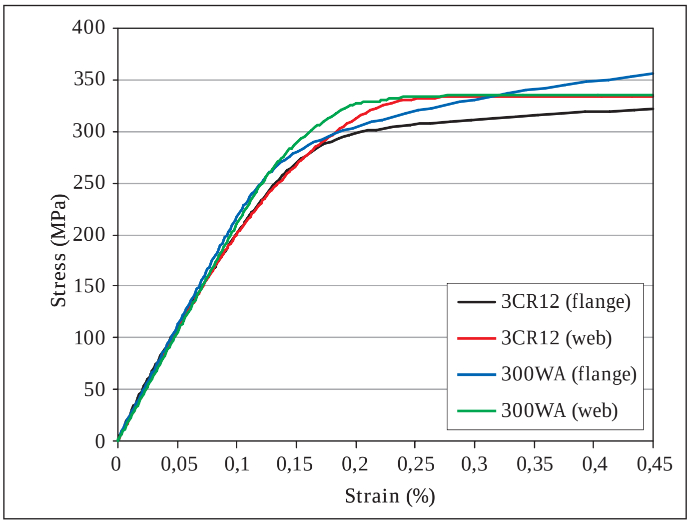

Figure 3** **Representative stress strain curves for 3CR12 and 300WA 152×76×18 channel

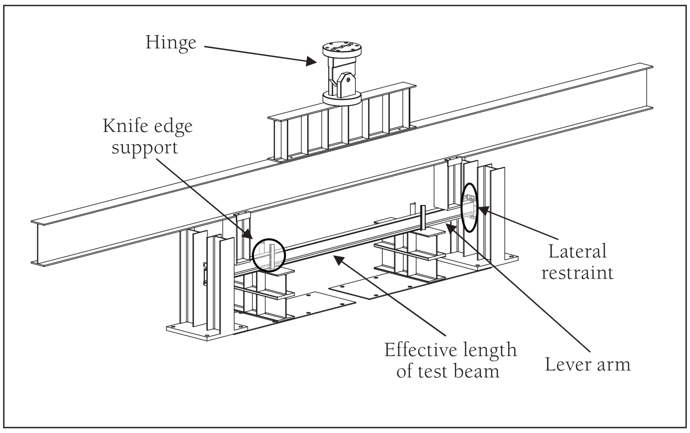

Figure 4** **Experimental set-up

Bredenkamp (1996) found that the buckling strength of 3CR12 built-up I-section columns is best predicted by using the tangent modulus approach. Stub column tests were used to determine the average mechanical properties and were found to be more representative than test specimens machined from the plate used to make up the sections. Stub column tests include the effect of residual stresses present in the section.

The buckling behaviour of hot-rolled 3CR12 columns was investigated by Bosch (Bosch & Van den Berg 1995). His experimental work was conducted on specially rolled equal leg angle sections (70×70×8). The magnitude and distribution of residual stresses were experimentally measured and found to be smaller when compared to equivalent carbon steel sections. The results indicated that the Euler buckling curve used in conjunction with the tangent modulus approach could conservatively predict the buckling strength of 3CR12 columns.

The elastic and inelastic lateral torsional buckling strength of hot-rolled 3CR12 sections were investigated by Barnard (Bredenkamp, Barnard *et al* 1996). The sections used in this investigation (203×133×25 I-sections and 100×50×11 channel) were specially heat-treated. The yielding characteristics varied from sharp yielding to gradual yielding depending on the degree of heat treatment. It was concluded that the SANS-10162-1:2005 design specification can be used to estimate the critical buckling moments for the fully annealed beams under investigation.

SANS: Limit-states design code for hot-rolled steelwork

SANS 10162-1:2005 code of practice for the design of structural steel work is based on the Canadian code. It defines the moment of resistance for three zones of slenderness and applies to doubly-symmetric beams and channel sections. This design specification is applicable to weldable structural steel complying with the SABS 1431. The code takes into consideration the presence of residual stresses.

The elastic critical bending moment (Mcr) is the upper limit of the buckling resistance (ie the lowest load value at which the beam can maintain a bent position). Geometric imperfections and inelastic behaviour caused by imperfections, as well as eccentricity of loading, will decrease the actual magnitude of the buckling moment.

The elastic buckling moment provides a value of the moment that only approximates the buckling moment of very slender beams. In beams of intermediate length, the actual value of the bending moment at which failure due to lateral torsional instability occurs, will be influenced by initial imperfections, eccentricity of loading and the fact that the section is subjected to internal stresses (residual stresses) prior to any external load being applied.

The elastic buckling moment is adjusted to provide a transition between the fully plastic bending moment (which can only be achieved at very low values of lateral slenderness) and the elastic buckling curve (which applies only to very slender beams).

Eurocode 3 Design of steel structures Part 1.1 (General rules and rules for buildings)

This design code covers the structural design of hot-rolled and welded carbon steel sections as well as cold-formed, austenitic and duplex stainless steel sections.

The standard end conditions referred to in the code are (Mahachi 2001):

- Ends are restrained against lateral movement
- Ends are restrained against rotation about the longitudinal axis
- Ends are free to rotate in plan

Table 2 Maximum bending moment of IPE_{AA} 100×55

3CR12								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
50	0,14	12,6	11,8	12,7	12,4	3,7 %	8,6	7,9
100	0,46	10,0	10,8	11,3	10,7	6,3 %	8,6	7,1
200	1,22	7,4	6,4	8,0	7,3	11,1 %	6,5	5,2
300	1,97	6,8	6,0	6,2	6,4	6,6 %	4,4	3,8
300WA								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
51	0,14	10,4	10,2	10,1	10,2	1,6 %	8,6	7,9
102	0,46	9,3	9,7	9,5	9,5	2,6 %	8,6	7,1
203	1,21	8,9	7,9	8,2	8,3	5,8 %	6,5	5,2
305	1,95	6,0	5,7	6,0	5,9	2,7 %	4,4	3,8

Table 3 Maximum bending moment of 127×64×15 channel

3CR12								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
56	0,14	24,5	23,6	24,0	24,0	1,9 %	20,5	21,8
112	0,39	22,7	23,4	21,6	22,6	4,1 %	20,5	20,1
224	0,88	18,8	21,1	19,8	19,9	5,7 %	18,1	16,4
335	1,36	16,2	19,2	18,6	18,0	8,7 %	15,2	13,0
300WA								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
51	0,13	30,6	30,8	29,5	30,3	2,3 %	20,5	21,8
101	0,36	28,7	28,8	29,1	29,2	1,7 %	20,5	20,1
202	0,83	28,1	28,1	25,5	27,2	5,4 %	18,1	16,4
303	1,28	20,8	20,5	19,2	20,2	4,1 %	15,2	13,0

Table 4 Maximum bending moment of 152×76×18 channel

3CR12								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
49	0,14	45,1	45,5	46,5	45,7	1,6 %	30,4	31,5
98	0,41	42,7	42,4	42,6	42,5	0,2 %	29,6	27,7
196	0,97	34,7	35,2	32,3	34,0	4,6 %	22,9	19,8
255	1,29	26,8	26,7	27,8	27,1	2,2 %	18,7	16,2
300WA								
L/r_y	M_p/M_{cr}	T1 (kNm)	T2 (kNm)	T3 (kNm)	Average (kNm)	Coefficient of variation	SANS (2005)	Eurocode 3
50	0,14	40,5	40,6	40,3	40,5	0,4 %	30,4	31,5
100	0,41	40,7	40,6	39,6	40,3	1,5 %	29,6	27,7
200	0,98	35,7	35,3	34,8	35,3	1,3 %	22,9	19,8
260	1,31	30,8	29,8	32,0	30,9	3,5 %	18,7	16,2

The design buckling resistance moment of a laterally unrestrained beam is predicted with the use of a single equation throughout the entire range of possible behaviour. The buckling resistance moment is:

$$M_{b.Rd} = X_{LT}\beta_W W_{pl.y} F_y / Y_{M1} \qquad (1)$$

Where:

β_w = 1 for class 1 and 2 sections (classes are similarly defined as in the SANS-10162-1:2005 code of practice), and

β_w = (Elastic section modulus)/(Plastic section modulus) for primary bending axis (for class 3 sections)

X_{LT} = Reduction factor for lateral torsional buckling. This term is a function of the critical buckling moment, the geometry of the section, as well as the yield stress

$W_{pl.y}$ = Plastic section modulus for axis about primary bending

F_y = Yield stress

Y_{M1} = Partial material factor for member buckling (Van den Berg 1996) usually equal to 1,1

MECHANICAL PROPERTIES

In order to determine the mechanical properties of 3CR12 corrosion resisting steel and 300WA structural steel, test specimens were cut from the longitudinal direction of the sections under investigation. It was assumed that the mechanical properties of the beams for a particular section are similar, as the steel was sourced from the same batch and heat in all cases.

Three different sections were investigated: two channel sections (127×76×15 and 152×76×18) and one IPE (100×55). Six specimens (three to be used for tension tests and three for compression tests) were cut from the flanges and webs (SANS 1431:2003). The specimens were machined and tested in accordance with SABS ISO 6892 (South African National Standard 2003). Testing was conducted on a 5500 Universal Instron machine. Strain was measured by fixing two strain gauges on either side of the specimens, in a half bridge configuration.

The overall mechanical properties of the sections in compression were determined by stub column tests. For short columns the buckling strength is independent of the section under investigation, but determined by the material properties (Dowling *et al* 1992). The mechanical properties obtained from stub column compression tests, include the effect of residual stresses present in hot-rolled sections, and can be used when predicting the flexural resistance of the sections under investigation (Galambos 1998). Two strain gauges were fixed to both the flanges and webs in a quarter bridge configuration for each of the sections tested.

Results of stub column tests

The mechanical properties determined from stub column tests are listed in table 1. Representative stress-strain curves of compression specimen tests conducted are presented in figures 1 to 3.

EXPERIMENTAL PROGRAMME

The experimental set-up utilised for full-scale testing is presented in figure 4. The beams were simply supported on rollers and a constant bending moment was applied between the knife edge supports. The lever arm ends were restrained against lateral movement and rotation. This implies a boundary condition (at the ends of the effective length) somewhere between partially free to rotate and fully fixed. A practically

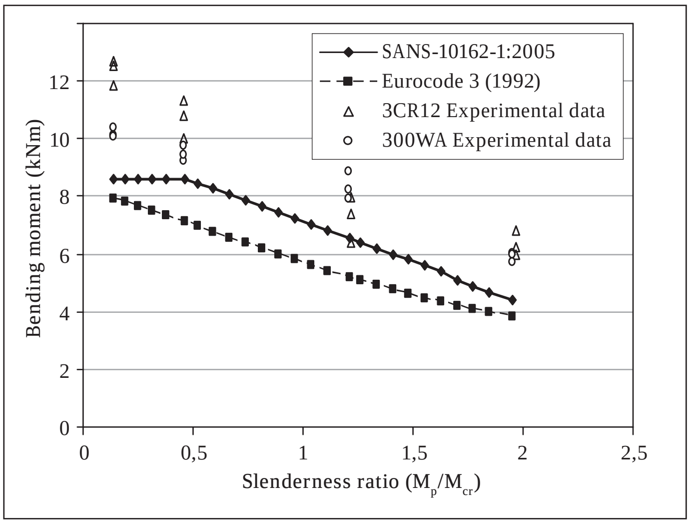

***Figure 5** Critical moment resistance as a function of slenderness ratio for IPE$_{AA}$ (100×55)*

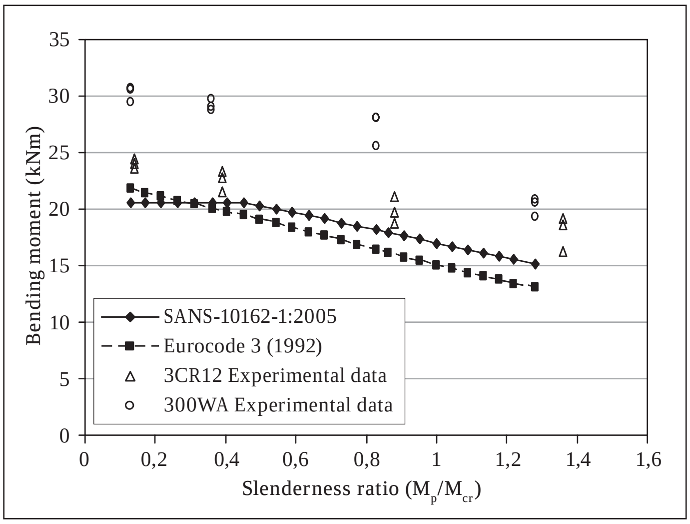

***Figure 6** Critical moment resistance as a function of slenderness ratio for 127×64×15 channel*

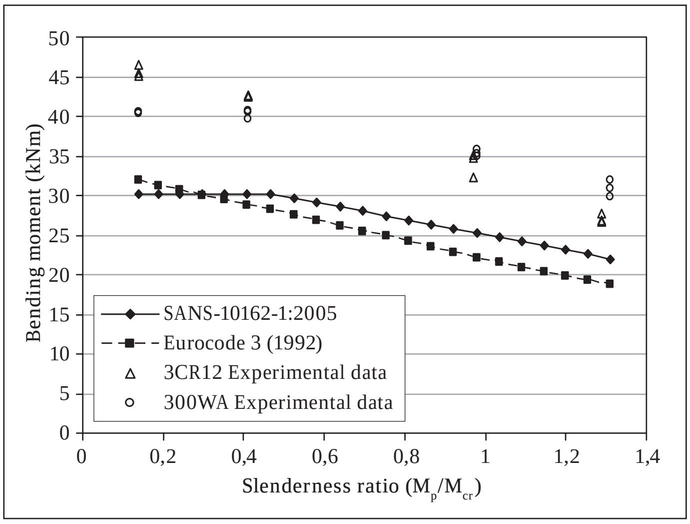

***Figure 7** Critical moment resistance as a function of slenderness ratio for 152×76×18 channel*

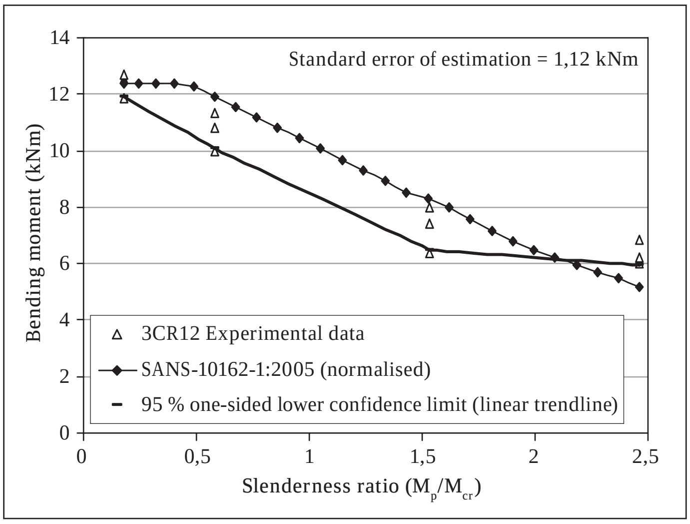

***Figure 8** Critical moment resistance as a function of slenderness ratio for IPE$_{AA}$ (100×55) 3CR12 (normalised)*

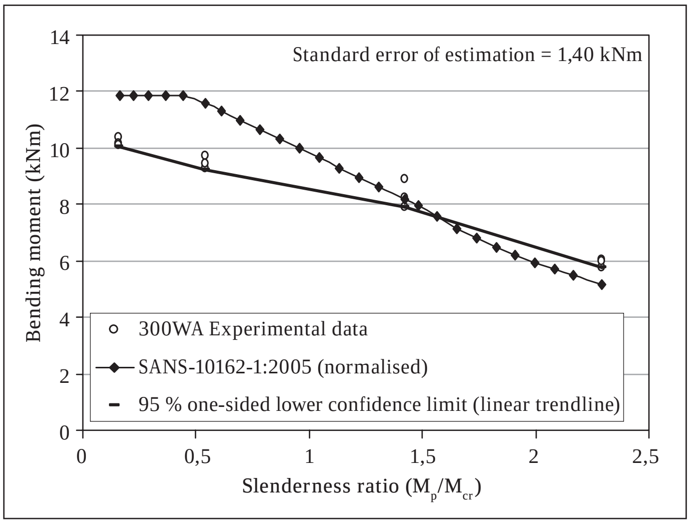

***Figure 9** Critical moment resistance as a function of slenderness ratio for IPE$_{AA}$ (100×55) 300WA (normalised)*

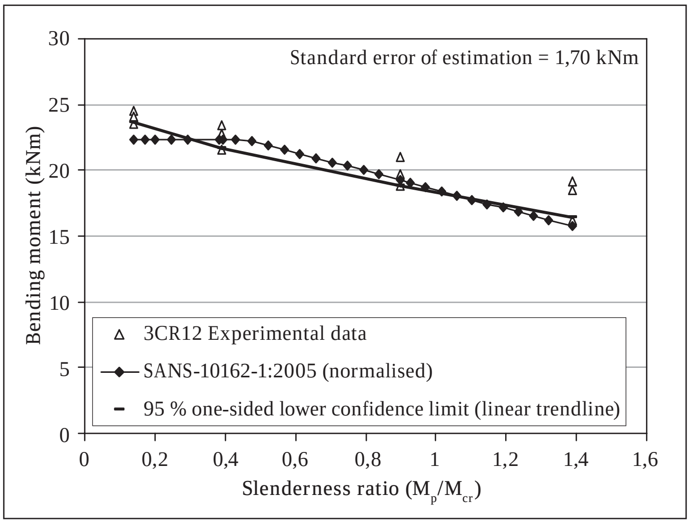

***Figure 10** Critical moment resistance as a function of slenderness ratio for 3CR12 (127×64×15) channel (normalised)*

fixed condition was thus assumed, which implies an effective length factor of 0,7 according to the SANS-10162-1:2005 and the UK national applications document (1992) for the EC3 (Mahachi 2001).

The load was applied to the test beam using a hydraulic Instron actuator at a displacement rate of 2 mm/min for the shorter beams and 3 mm/min for the larger slenderness ratios. Tests were conducted at four different slenderness ratios ranging from 50 to approximately 300.

A total of three tests per section per slenderness ratio were done. This was duplicated for 300WA carbon steel. In all 72 tests were conducted.

The following was measured:

- The maximum bending moment the test beam was capable of resisting
- The vertical deflection of the beam in the middle

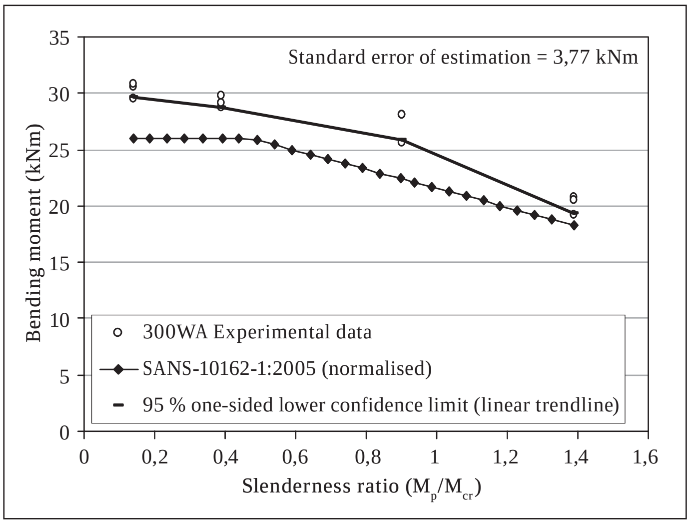

Figure 11 Critical moment resistance as a function of slenderness ratio for 300WA (127×64×15) channel (normalized)

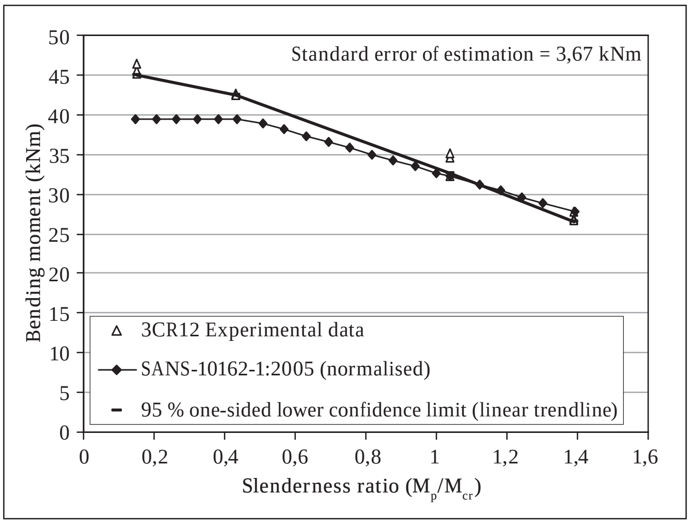

Figure 12 Critical moment resistance as a function of slenderness ratio for 3CR12 (152×76×18) channel (normalised)

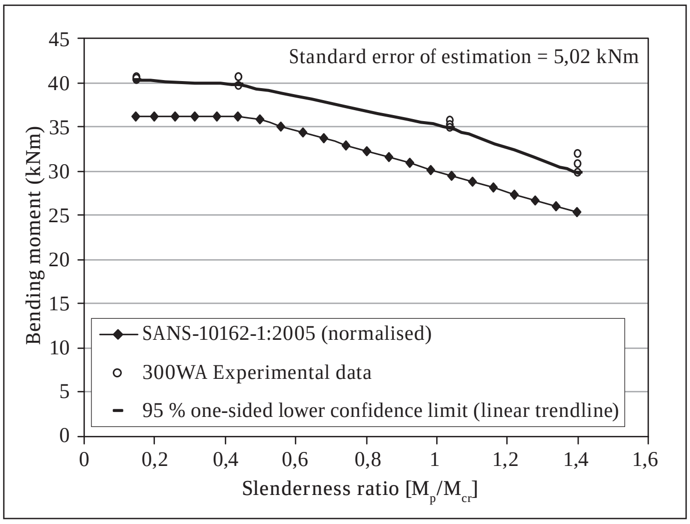

Figure 13 Critical moment resistance as a function of slenderness ratio for 300WA (152×76×18) channel (normalised)

- The initial out-of-straightness

Experimental results

The results of the full-scale beam tests are presented in tables 2 to 4. The experimental data is compared with the code values (using the prescribed material properties as well as section geometric properties) in figures 5 to 7. In figures 8 to 13 the normalised code values are compared with the experimental data obtained. The normalised code values in this case refer to code values obtained by using actual material properties measured and actual section geometric properties. Only the SANS-10162-1:2005 code of practice values were normalised. The resistance factor, ϕ, as used in the SANS-10162-1:2005 code of practice was set to unity.

CONCLUSION

The material tests conducted on the different sections for both 3CR12 and 300WA all displayed yield stresses in excess of 300 MPa. Furthermore, for both materials, it was concluded that all the sections tested complied with clause 5,1,4 of SANS-10162-1:2005 for special structural steels implying that:

- The yield stresses were less than 700 MPa
- The ratio of the ultimate tensile strength to yield strength exceeded 1,2
- The % elongation was more than 15 %

It was also evident that the 3CR12 sections are more gradual yielding than their carbon steel equivalents. This is best illustrated in the lower proportional limit/yield stress ratio as displayed by 3CR12. Typically this ratio varied from 0,66 to 0,77 for 3CR12 and 0,81 to 0,92 for 300WA.

The average maximum moment resistance values obtained from the full-scale beam testing for both materials were in all cases higher than the values predicted by the SANS-10162-1:2005 code of practice (figures 5–7).

The application of the SANS-10162-1:2005 code of practice with actual material data and section properties (normalised) indicated that in most cases the code curves gave a good representation of the actual beam behaviour (figures 8–13). The standard error of estimation was calculated, for the different sections, to evaluate the accuracy with which the normalised SANS-10162-1:2005 code of practice predicts actual beam behaviour. The standard error of estimation increased for the heavier sections and was larger for the 300WA than the 3CR12 sections in all cases.

For short and intermediate slenderness ratios the normalised SANS code of practice values exceeded the experimental results obtained for both the 3CR12 and 300WA 100×55 IPE sections. This over-estimation could be a result of the extraordinarily high yield strengths (370 and 380 MPa) displayed by both these materials for this section. The only other region of concern was with the 127×64×15 3CR12 channel section in the intermediate region where some of the experimental values were over-predicted by the code. This is a direct consequence of the more pronounced gradual yielding behaviour of 3CR12.

When comparing the normalised code predicted values with the experimental data obtained, it indicates that the code more conservatively predicts the buckling resistance of the two 300WA channel sections than the two 3CR12 channel sections. Ignoring the IPE sections the averaged under prediction of the normalised code (when compared to the experimental data) is approximately 13,3 % for the 300WA and 6,3 % for the 3CR12 channel sections.

In conclusion it is difficult to say whether the SANS-10162-1:2005 can be safely used for design purposes for the hot-rolled 3CR12 sections when subjected to bending based on the available experimental data. In all cases, except one, the allowable code values for the moment resistances were lower than the values obtained experimentally. This result may be misleading when one realises that the yield stresses for all the sections tested were above 300 MPa. The effect of the more pronounced gradual yielding behaviour of 3CR12 sections with yield strengths of exactly 300 MPa probably needs to be investigated more fully before any concrete statement can be made. This could be investigated numerically but should also be backed by more experimental work.

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