SDSS'Rio 2010 STABILITY AND DUCTILITY OF STEEL STRUCTURES
E. Batista, P. Vellasco, L. de Lima (Eds.)
Rio de Janeiro, Brazil, September 8 - 10, 2010

PLASTIC DESIGN OF STAINLESS STEEL STRUCTURES

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Keywords: Stainless Steel Structures, Continuous Beams, Plastic Design, Continuous Strength Method.

Abstract. *Despite the high material ductility of structural stainless steels and the existence of a Class 1 limit in the European structural stainless steel design code EN 1993-1-4 [1], plastic design is not permitted for stainless steel structures, which leads to uneconomic design. The present paper investigates the applicability of inelastic design procedures to indeterminate stainless steel structures. Five three-point bending tests and ten two-span continuous beam tests on stainless steel square and rectangular hollow sections are reported herein. Analysis of the results reveals that current design provisions are overly conservative and significant moment redistribution and hence material savings can be achieved if inelastic design procedures are followed at both cross-sectional level and system level.*

1 INTRODUCTION

The need for metallic structures to resist high loads that have a small probability of occurrence in an economic way necessitates the exploitation of the inelastic range of the material's stress-strain curve, provided that they possess sufficient ductility. Modern structural design guidance specifies the extent to which the exploitation of the material's inelastic range is allowed, following the cross-section classification procedure. The European structural design codes for stainless steel EN 1993-1-4 [1] and carbon steel EN 1993-1-1 [2] specify four behavioural classes of cross-sections according to their susceptibility to local buckling. Indeterminate structures employing carbon steel cross-sections classified as Class 1 may be plastically designed. Despite the high material ductility of structural stainless steels [3] and the existence of a Class 1 limit in [1], plastic design is not permitted for stainless steel structures, which leads to uneconomic design.

In this paper the applicability of inelastic design procedures to stainless steel indeterminate structures is investigated. Five three-point bending tests and ten two-span continuous beam tests on stainless steel SHS and RHS are reported. The experimental response of both the simply supported beams and the continuous beams is then compared with the predictions of EN 1993-1-4 [1]. Analysis of the results reveals that current design provisions are overly conservative, since they do not account for material strain-hardening and the significant moment redistribution (in the case of the continuous beams) taking place before collapse occurs. Hence material savings can be achieved if inelastic design procedures are followed at both cross-section level and system level. To this end, the continuous strength method (CSM), outlined in [4]-[6], which allows for the actual material response at cross-sectional level, is adapted to stainless steel indeterminate structures, resulting in more favourable strength predictions.

2 EXPERIMENTAL INVESTIGATION

An experimental investigation into the structural response of stainless steel simple and continuous beams has been carried out in the Structures Laboratory at Imperial College London. The employed cross-sections were SHS and RHS in grade EN 1.4301/1.4307 stainless steel with nominal sizes of 50×50×3, 60×60×3, 100×100×3 and 60×40×3. The specimens were extracted from the same lengths as the ones utilised in the experimental study reported in [7]. The tensile coupon test data reported in [7] are utilised herein, as no further material coupon tests were conducted. The obtained tensile flat material properties are shown in Table 1, where E_0 is the Young's modulus, $\sigma_{0.2}$ and $\sigma_{1.0}$ are the proof stresses at 0.2% and 1% offset strains, respectively, and n and $n'_{0.2,1.0}$ are strain hardening exponents, utilised in the two stage Ramberg-Osgood model [8]-[10]. The 0.2% proof stress $\sigma_{0.2}$, obtained from tensile flat coupons, is utilized to obtain the elastic and plastic moment resistances (M_{el} and M_{pl} respectively).

Table 1: Tensile flat material properties.

Cross-section	E (N/mm^2)	$\sigma_{0.2}$ (N/mm^2)	$\sigma_{1.0}$ (N/mm^2)	σ_u (N/mm^2)	n	$n_{0.2,1.0}$
SHS 50×50×3	198000	552	608	798	5.50	2.90
SHS 60×60×3	197730	483	546	745	5.25	2.90
SHS 100×100×3	201300	419	470	725	5.25	2.25
RHS 60×40×3	191690	538	592	753	5.00	3.50

Five three-point bending tests were initially performed, to provide fundamental flexural performance data, which were utilised to assess the suitability of current design provisions codified in EN 1993-1-4 (2006). Subsequently ten two-span continuous beam tests (five-point bending) were conducted, which enabled the study of stainless steel indeterminate structures and an assessment of the current codified provisions. Performing both simply supported and continuous beam tests on the same cross-sections enables the assessment of the effect of moment redistribution on ultimate capacity.

2.1 Simply supported beam tests

Five simply supported beam tests have been conducted in the three-point bending configuration. One test was conducted for each of the three SHS employed, whilst two tests were conducted for the RHS 60×40×3 specimen, one about the major axis and one about the minor axis. All beams had a total length of 1200 mm and were simply supported between rollers, which allowed axial displacement of the beams' ends. The rollers were placed 50 mm inward from each beam end. Wooden blocks were placed within the tubes at the loading point to prevent web crippling. The applied crosshead movement rate was 3 mm/min.

Prior to testing, measurements of the geometry of the specimens were taken, which are summarised in Table 2, where the experimentally obtained ultimate moment M_u and the M_u/M_{el} and the M_u/M_{pl} ratios are also included. In Table 2, B and D are the outside width and depth of the cross-section respectively, t is the mean section thickness and r_i is the internal corner radius. A typical failure mode, exhibiting local buckling of the compression flange and the upper part of the web, is shown in Figure 1.

Table 2: Measured dimensions and test results from 3-point bending tests.

Specimen	Axis of bending	B (mm)	D (mm)	t (mm)	r_i (mm)	M_u (kNm)	M_u/M_{el}	M_u/M_{pl}
SHS 50×50×3	Major	50.18	50.24	2.76	1.53	7.00	1.68	1.41
SHS 60×60×3	Major	60.37	60.63	2.79	3.50	8.74	1.62	1.36
SHS 100×100×3	Major	99.85	99.93	2.78	2.13	18.77	1.35	1.16
RHS 60×40×3-MA	Major	40.00	60.11	2.75	1.88	7.99	1.84	1.49
RHS 60×40×3-MI	Minor	60.10	39.95	2.75	1.88	5.69	1.66	1.41

Figure 1: Failure mode of the RHS 60×40×3-MA specimen.

2.2 Continuous beam tests

Ten continuous beam tests were conducted on the same section sizes employed for the simply supported beam tests; two tests were conducted for each cross-section. As before, the RHS 60×40×3 was tested about both its major and minor axes. All beams had a total length of 2400 mm and were resting on three roller supports; the end rollers allowed free axial displacements, while the central roller was fixed against axial displacement. The clear span distance between the roller supports was 1100 mm and a further 100 mm were provided at each specimen end. The measured geometric properties are shown in Table 3, where the symbols are as previously defined.

Table 3: Measured dimensions of continuous beam specimens.

Specimen	Axis of bending	Configuration	B (mm)	D (mm)	t (mm)	r_i (mm)
SHS 50×50×3-1	Major	1/2 span	50.22	50.26	2.76	1.38
SHS 50×50×3-2	Major	1/3 span	50.28	50.23	2.76	1.69
SHS 60×60×3-1	Major	1/2 span	60.38	60.68	2.79	3.50
SHS 60×60×3-2	Major	1/2 span	60.36	60.66	2.79	3.50
SHS 100×100×3-1	Major	1/2 span	99.94	99.79	2.78	2.13
SHS 100×100×3-2	Major	1/2 span	99.87	99.85	2.78	2.13
RHS 60×40×3-MA-1	Major	1/2 span	40.05	60.14	2.75	1.88
RHS 60×40×3-MA-2	Major	1/2 span	39.90	60.12	2.75	1.88
RHS 60×40×3-MI-1	Minor	1/2 span	60.10	39.90	2.75	1.88
RHS 60×40×3-MI-2	Minor	1/3 span	60.15	39.90	2.75	1.88

All tests were displacement-controlled with a loading rate of 3mm/min in terms of vertical crosshead movement. Two symmetrical loading configurations were employed to vary the required rotation capacity and moment redistribution before collapse. In the first configuration, denoted '1/2 span' in Table 3, the loads were applied at midspan, whilst in the second configuration, 'denoted 1/3 span', the loads were applied at a distance equal to 366.7 mm (1/3 of the clear span length) from the central support. The 1/3 span configuration is shown in Figure 2, where the employed instrumentation is also depicted. Wooden blocks were inserted at the supports and at the loading points of each specimen and the loads and reactions were applied through a steel block of thickness 15 mm and width 30 mm, to prevent local bearing failure.

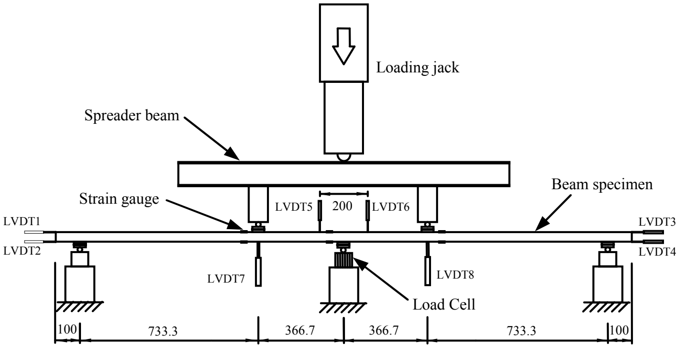

Figure 2: Test configuration '1/3 span' - loads applied at 366.7 mm from central support.

The employed instrumentation consisted of a load cell at the central support, eight LVDTs and six strain gauges, as shown in Figure 3. The load cell was utilised to measure the reaction force at the central support, which is necessary to determine the stress condition of each specimen, due to their static indeterminacy. The strain gauges were affixed at the mid-width of the top and bottom flanges at a distance of 60 mm from each loading point and from the central support point. Their readings verified that no net axial load occurred in the specimens and hence the end rollers did not provide any axial restraint. Six LVDTs were employed in pairs at the ends of the specimens and the central support, as shown in Figure 2, to measure the end rotations and the rotation of the plastic hinge at the central support, whilst two additional LVDTs were employed at the loading points to measure the vertical displacement. The applied load and crosshead movement were also recorded. All readings were taken at 2 second intervals.

The key experimental results are summarised in Table 4, including the ultimate load F_u and the plastic rotation at ultimate load normalised by the corresponding elastic rotation at ultimate load, $\theta_{pl,max}/\theta_{el,max}$. The load corresponding to the formation of the first plastic hinge at the central support, denoted F_{h1}, and the theoretical collapse load F_{coll} are also included. The load F_{h1} was determined based on elastic calculations, whereas F_{coll} was determined by classical plastic analysis procedures, assuming rigid-plastic material (and moment-rotation) response. All specimens failed by developing three distinct plastic hinges, one at the central support and one at each loading point. A typical failure mode for the 1/2 span arrangement is displayed in Figure 3.

Figure 3: Failure mode of SHS 50×50×3-1 - configuration: 1/2 span.

Table 4: Summary of test results from continuous beam tests.

Specimen	Configuration	F_u (kN)	F_{h1} (kN)	F_{coll} (kN)	$\theta_{pl,max}/\theta_{el,max}$
SHS 50×50×3-1	1/2 span	80.24	48.3	54.35	0.95
SHS 50×50×3-2	1/3 span	98.87	48.8	67.67	1.35
SHS 60×60×3-1	1/2 span	97.08	62.2	70.00	0.70
SHS 60×60×3-2	1/2 span	92.47	62.2	69.94	0.79
SHS 100×100×3-1	1/2 span	173.86	156.3	175.83	0.45
SHS 100×100×3-2	1/2 span	172.21	156.3	175.89	0.20
RHS 60×40×3-MA-1	1/2 span	92.99	52.0	58.54	1.10
RHS 60×40×3-MA-2	1/2 span	91.92	51.9	58.37	1.10
RHS 60×40×3-MI-1	1/2 span	63.94	39.0	43.84	1.00
RHS 60×40×3-MI-2	1/3 span	77.57	39.5	54.84	1.70

3 ANALYSIS OF TEST RESULTS AND DESIGN RECOMMENDATIONS

In this section, the reported test data are analysed and discussed. Various design methods are outlined and their accuracy is assessed on the basis of the test data. These include the design provisions specified in EN 1993-1-4 [1], the continuous strength method [4]-[6] and conventional plastic design, assuming rigid-plastic material behaviour. For the simply supported beams, discrepancies between the actual resistance and code predictions are due to the effect of material nonlinearity (i.e. strain-hardening) at cross-sectional level, whilst for the continuous beams (indeterminate structures), nonlinearity affects both individual cross-sections, due to material strain-hardening, and the whole structure, due to statical indeterminacy and the corresponding moment redistribution. A method for plastic design of steel structures, which takes into account strain-hardening, was recently proposed [11] and its applicability to stainless steel indeterminate structures is assessed herein.

3.1 European codified design predictions

No distinct difference in the treatment of Class 1 and Class 2 sections exists in EN 1993-1-4 [1], since plastic design of stainless steel indeterminate structures is not currently allowed, despite the existence of a Class 1 slenderness limit. On average, EN 1993-1-4 [1] underestimates the capacity of the three-point bending specimens by 33% with a coefficient of variation (COV) of 8%. Improved results in terms of consistency are obtained when the calculation is based on the revised slenderness limits and effective width formulae, proposed in [6], as shown in Table 5. The continuous beams are treated similarly to the simply supported ones. Hence failure is assumed to occur when the most heavily stressed cross-section reaches its codified resistance, as determined through cross-section classification. The codified resistance is compared to the actual capacity in Table 6, where the predictions based on the revised slenderness limits are also included. Measured material properties and geometries have been used throughout the comparisons.

Table 5: Codified and proposed classification and effective width formulae for simply supported beams.

Specimen	EN 1993-1-4 [1]		Revised slenderness limits [6]	
	Class	M_{pred}/M_u	Class	M_{pred}/M_u
SHS 50×50×3	1	0.71	1	0.71
SHS 60×60×3	1	0.73	1	0.73
SHS 100×100×3	4	0.65	4	0.68
RHS 60×40×3-MA	1	0.67	1	0.67
RHS 60×40×3-MI	3	0.60	1	0.71
MEAN		0.67		0.70
COV		0.08		0.04

Table 6: Codified and proposed classification and effective width formulae for continuous beams.

Specimen	EN 1993-1-4 [1]		Revised slenderness limits [6]	
	Class	F_{pred}/F_u	Class	F_{pred}/F_u
SHS 50×50×3-1	1	0.60	1	0.60
SHS 50×50×3-2	1	0.49	1	0.49
SHS 60×60×3-1	1	0.64	1	0.64
SHS 60×60×3-2	1	0.67	1	0.67
SHS 100×100×3-1	4	0.68	4	0.71
SHS 100×100×3-2	4	0.68	4	0.72
RHS 60×40×3-MA-1	1	0.56	1	0.56
RHS 60×40×3-MA-2	1	0.56	1	0.56
RHS 60×40×3-MI-1	3	0.52	1	0.61
RHS 60×40×3-MI-2	3	0.43	1	0.51
MEAN		0.58		0.61
COV		0.15		0.13

3.2 Continuous strength method

The continuous strength method (CSM) explicitly accounts for material strain-hardening at cross-sectional level [4]-[6]. Hence, more favourable ultimate capacity predictions can be achieved for both simply supported and continuous beams if the cross-section failure is based on the CSM rather than on cross-section classification, as shown in Table 7. As expected, the ultimate capacity of the simply supported beams is very well-predicted and a low COV is observed. For the continuous beams, the CSM gives more favourable strength predictions compared to the classification procedure, but failure to account for moment redistribution results in excessive conservatism. Moreover, a relatively large COV is observed, due to the dependency of the effect of moment redistribution on the cross-section slenderness.

Table 7: Assessment of the CSM for simply supported and continuous beams.

Specimen	F_{pred}/F_u	
	Simply supported beams	Continuous beams
SHS 50×50×3-1	0.90	0.68
SHS 50×50×3-2	-	0.56
SHS 60×60×3-1	0.95	0.73
SHS 60×60×3-2	-	0.77
SHS 100×100×3-1	0.91	0.89
SHS 100×100×3-2	-	0.90
RHS 60×40×3-MA-1	0.87	0.64
RHS 60×40×3-MA-2	-	0.64
RHS 60×40×3-MI-1	0.87	0.67
RHS 60×40×3-MI-2	-	0.56
MEAN	0.90	0.71
COV	0.04	0.17

3.3 Conventional plastic analysis

Allowing for the effects of moment redistribution is the key feature of plastic analysis. Despite the deviation of stainless steel's material response from the assumed bilinear elastic, perfectly-plastic model, application of plastic design to stainless steel indeterminate structures is attempted herein. The theoretical collapse load F_{coll} has been calculated for all continuous beam specimens and is given in Table 4. In Table 8, the classification procedure codified in EN 1993-1-4 [1] and that proposed in [6] are once again assessed; in this case the capacity of the specimens with Class 1 cross-sections is calculated by means of plastic design, the resistance of the Class 3 beams is calculated using elastic design and for Class 4 beams, elastic design and effective section properties are used. The revised classification approach seems to offer more consistent ultimate capacity predictions than the one codified in EN 1993-1-4 [1]. However the embedded conservatism remains significant.

3.4 Continuous strength method for indeterminate structures

Both the CSM and plastic analysis offer significant improvements in terms both design efficiency compared to the current design approach. However, plastic analysis seems superior to the CSM in terms of consistency of the predictions. This is due to the fact that, when applying the CSM, the effect of moment redistribution has been ignored, thereby reducing the failure of a structural assembly to the failure of a single cross-section.

A method combining the merits of both is desirable, since both strain-hardening at cross-sectional level and moment redistribution affect the structural response of stainless steel indeterminate structures. Gardner and Wang [11] recently proposed a modification to the plastic analysis procedure currently applied to carbon steel structures. The proposed method, called the CSM for indeterminate structures, allows for moment redistribution in a similar fashion to traditional plastic analysis and for full exploitation of material strain-hardening at the location of the first plastic hinge; strain-hardening at subsequent hinges is partly accounted for.

Table 8: Assessment of codified and proposed classification for continuous beams allowing for plastic design.

Specimen	EN 1993-1-4 [1]		Revised slenderness limits [6]	
	Class	F_{pred}/F_u	Class	F_{pred}/F_u
SHS 50×50×3-1	1	0.68	1	0.68
SHS 50×50×3-2	1	0.68	1	0.68
SHS 60×60×3-1	1	0.72	1	0.72
SHS 60×60×3-2	1	0.76	1	0.76
SHS 100×100×3-1	4	0.68	4	0.71
SHS 100×100×3-2	4	0.68	4	0.72
RHS 60×40×3-MA-1	1	0.63	1	0.63
RHS 60×40×3-MA-2	1	0.63	1	0.63
RHS 60×40×3-MI-1	3	0.52	1	0.69
RHS 60×40×3-MI-2	3	0.43	1	0.71
MEAN		0.64		0.69
COV		0.15		0.06

The novelty of the method lies in departing from the traditional rigid-plastic material response and assuming that the ultimate moment capacity of the first plastic hinge can be fully exploited. In essence, the method utilises the upper bound theorem of limit analysis and relies on the determination of a suitable collapse mechanism. The moment capacity at the location of the plastic hinges is calculated by means of the CSM; for the first plastic hinge the full deformation capacity is exploited, whilst for subsequent plastic hinges, the deformation capacity is a fraction of the deformation capacity at the first hinge, proportional to the plastic rotation ratio as determined from kinematics.

Table 9: Assessment of the CSM for indeterminate structures.

Specimen	CSM for indeterminate structures	
	Class	F_{pred}/F_u
SHS 50×50×3-1	1	0.85
SHS 50×50×3-2	1	0.86
SHS 60×60×3-1	1	0.92
SHS 60×60×3-2	1	0.96
SHS 100×100×3-1	4	0.89
SHS 100×100×3-2	4	0.90
RHS 60×40×3-MA-1	1	0.80
RHS 60×40×3-MA-2	1	0.80
RHS 60×40×3-MI-1	1	0.84
RHS 60×40×3-MI-2	1	0.86
MEAN		0.87
COV		0.06

The accuracy of the CSM for indeterminate structures is assessed in Table 9, where all cross-sections classified as Class 1 according to the revised slenderness limits proposed in [6] have been treated with this method. The SHS 100×100×3 specimens, which have a slender (Class 4) cross-section, have been treated with the conventional CSM; hence the effect of moment redistribution has not been considered for these sections. Overall, significant enhancement in design efficiency and good agreement with the test results is observed as evidenced by the low COV of 0.06. Further research into the topic is underway to determine the slenderness range within which the proposed method can be safely applied.

4 CONCLUSIONS

An experimental study comprising five three-point bending tests and ten two-span continuous beam tests (five-point bending) has been conducted and the conservatism embedded in the provisions for stainless steel indeterminate structures codified in EN 1993-1-4 [1] has been highlighted. The application of conventional plastic analysis to stainless steel indeterminate structures and the accuracy of the CSM have been investigated. It was concluded that both material strain-hardening at cross-sectional level (at the location of the plastic hinges) and moment redistribution occurring in indeterminate structures, comprising sections with sufficient deformation capacity, are significant and should therefore be accounted for in design. A recently proposed adaptation of the CSM for carbon steel indeterminate structures [11] has been further investigated and applied to stainless steel indeterminate structures, yielding excellent results for stocky cross-sections. Hence CSM for indeterminate structures emerges as a promising design approach for stainless steel continuous beams.

REFERENCES

[1] EN 1993-1-4. Eurocode 3: Design of steel structures - Part 1.4: General rules – Supplementary rules for stainless steel. CEN, 2006.

[2] EN 1993-1-1. Eurocode 3: Design of steel structures - Part 1.1: General rules – General rules and rules for buildings. CEN, 2005.

[3] Gardner, L. “The use of stainless steel in structures”. Progress in Structural Engineering and Materials, 7 (2), 45-55, 2005.

[4] Gardner, L. and Ashraf, M. “Structural design for non-linear metallic materials”. Engineering Structures, 28 (6), 926-934, 2006.

[5] Ashraf, M., Gardner, L. and Nethercot, D. A. “Structural stainless steel design: Resistance based on deformation capacity”. Journal of Structural Engineering, ASCE, 134 (3), 402-411, 2008.

[6] Gardner, L. and Theofanous, M. “Discrete and continuous treatment of local buckling in stainless steel elements”. Journal of Constructional Steel Research, 64 (11), 1207-1216, 2008.

[7] Nip, K.H., Gardner, L. and Elghazouli, A.Y. “Cyclic testing and numerical modelling of carbon steel and stainless steel tubular bracing members”. Engineering Structures, 32 (2), 424-441, 2010.

[8] Mirambell, E. and Real, E. “On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation”. Journal of Constructional Steel Research, 54 (1), 109-133, 2000.

[9] Rasmussen, K.J.R. “Full-range stress-strain curves for stainless steel alloys”. Journal of Constructional Steel Research, 59 (1), 47-61, 2003.

[10] Gardner, L. and Nethercot, D.A. “Experiments on stainless steel hollow sections - Part 1: Material and cross-sectional behaviour”. Journal of Constructional Steel Research, 60 (9), 1291-1318, 2004.

[11] Gardner, L. and Wang, F. “Influence of strain hardening on the behaviour and design of steel structures”. International Journal of Structural Stability and Dynamics, (submitted).