UNIFIED SLENDERNESS LIMITS FOR STRUCTURAL STEEL CIRCULAR HOLLOW SECTIONS

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Abstract. Circular hollow sections (CHS) are widely used in a range of structural engineering applications. The sections may be hot-finished or cold-formed from a variety of metallic materials with a range of yield strengths. The design of these sections is covered by all major design codes, yet there are significant differences in the treatment of local buckling, as considered through cross-section classification. Cross-section classification criteria relate to rotation capacity and strength requirements (attainment of the plastic or elastic moment in bending and the yield load in compression), while the relative performance of structural CHS is governed by susceptibility to local buckling and is influenced by cross-section slenderness, material stiffness and yield strength, forming process (affecting geometry, material homogeneity and residual stresses), material strain hardening characteristics and ovalization. Furthermore, the classification criteria and reliability requirements vary among the different structural design codes. This paper presents a review of 153 test results on CHS in bending, covering structural steel, aluminium, stainless steel and very high strength steel. Based on the available test data, current codified provisions in the European, North American and Australian Standards are reassessed, and following reliability analyses new unified slenderness limits are proposed for structural steel CHS.

Key words: circular hollow sections, reliability analysis, section classification, slenderness limits, tubular construction.

1. INTRODUCTION

Circular hollow sections (CHS) have been manufactured and used since the early 1800s for structural members such as columns, beams, tension members and trusses [1]. They are thin-walled structural elements, and therefore a primary consideration in their design is local buckling. Current design codes adopt the concept of cross-section classification for the treatment of local buckling in thin-walled tubular members, but there is significant variability between the slenderness limits employed to separate the individual classes.

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EN 1993-1-1 (2005) [2] and BS 5950 (2000) [3] for structural steelwork, together with EN 1993-1-4 (2006) [4] for stainless steel and EN 1999-1-1 (2007) [5] for aluminium, define four behavioural classes of cross-section, based upon their susceptibility to local buckling. Class 1 cross-sections, called plastic sections in BS 5950, are capable of reaching and maintaining their full plastic moment M_{pl} in bending by forming plastic hinges with sufficient rotation capacity for plastic design. Class 2 cross-sections, referred to as compact sections in BS 5950, are also capable of reaching their full plastic moment in bending but have a lower deformation capacity. In Class 3 cross-sections, called semi-compact sections in BS 5950, local buckling prevents attainment of the full plastic moment and the bending moment resistance is limited to the yield moment M_{el}. Class 4 cross-sections, commonly referred to as slender sections, exhibit local buckling before the yield stress is reached. The moment-rotation characteristics of the four behavioural classes are illustrated in Fig. 1. AISC 360 (2005) [6] and AS 4100 (1998) [7] effectively define three classes of cross-section: Class 1 cross-sections are referred to as compact, there is no equivalent to Class 2 sections, Class 3 sections are termed non-compact, while Class 4 cross-sections are referred to as slender sections. The Class 3 limit also separates cross-sections that are fully effective in compression, where the section capacity is taken as the yield load, from those that fail by local buckling prior to the attainment of the yield load. For both compression and bending the cross-section level resistance is determined based on an effective cross-section defined by the CHS diameter-to-thickness (D/t) ratio.

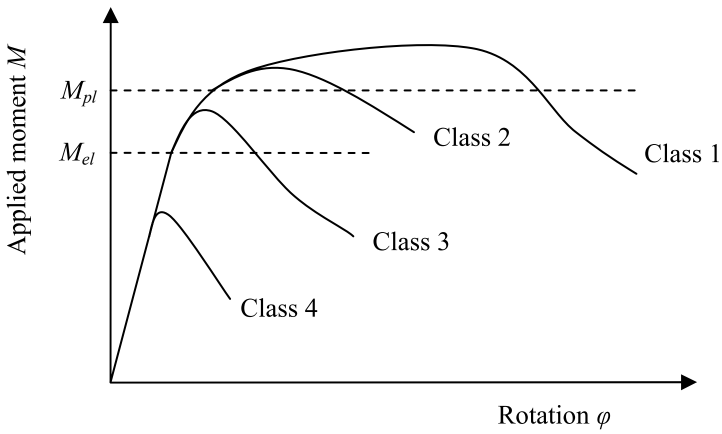

Fig. 1 – Four behavioural classes of cross-sections.

In this paper, the factors influencing local buckling and the structural response of circular hollow sections are discussed; test data on structural steel, stainless steel and aluminium tubes are collated and analysed; and slenderness limits prescribed in a series of international design standards, which exhibit significant variability, are evaluated. This study focuses on structural hollow sections rather than cylindrical shells with very high diameter-to-thickness ratios. Finally unified slenderness limits for structural steel CHS are proposed following reliability analyses.

2. FACTORS AFFECTING LOCAL BUCKLING AND STRUCTURAL RESPONSE OF CHS

Local buckling occurs in thin-walled sections when the applied compressive stress exceeds a critical value, and is characterised by local ripples in the cross-section wall. Local buckling and the structural response of CHS are influenced by a number of factors, which are discussed in this section.

The elastic buckling stress of a cylindrical shell in the axis-symmetric mode (σ_{cr}) is given by Eq. 1:

$$\sigma_{cr} = \frac{2E}{\sqrt{3(1-\nu^2)}}\left(\frac{t}{D}\right), \tag{1}$$

where E is the Young's modulus, ν is Poisson's ratio and D/t is the diameter-to-thickness ratio of the section and the geometric parameter that controls local buckling. The susceptibility to elastic buckling in preference to yielding depends on the yield strength of the material f_y, and this therefore also appears in slenderness parameters, such as those adopted in design codes. With higher yield strengths, the slenderness of the section effectively increases; i.e. the section is more susceptible to local buckling prior to yielding. Previous studies have however shown that the slenderness limits derived for normal strength steel tubes become conservative when applied to very high strength steel [8]. This is linked to the presence and influence of initial geometric imperfections and residual stresses. Residual stresses are typically induced in structural components through plastic deformation and differential cooling during manufacture. Their influence on structural members is to cause premature yielding and loss of stiffness, often leading to a reduction in load carrying capacity. In high strength steel sections, residual stresses are a smaller fraction of the yield strength and therefore their detrimental effect is reduced compared with normal strength steel [9].

Initial geometric imperfections can also have a significant influence on the strength of thin-walled sections [10] by amplifying buckling deformations and hence expediting the initiation of yield. The effect of imperfections is less detrimental to the response of high strength structural components. A modified imperfection factor for columns which reduces with increased yield strength has been proposed to reflect this behaviour [9]; this issue has also been highlighted in the context of local buckling [11].

Local buckling and the structural response of CHS are also influenced by the stress-strain behaviour of the constituent material, which is largely controlled by its chemical composition and physical properties, but is also affected by the section forming process. Generally, there are two different types of stress-strain curves – yield point and round house. Hot-finished sections typically have a yield point stress-strain curve, where stress is linearly proportional to strain up to the yield point, after which a yield plateau and strain hardening may be observed. A round house stress-strain curve deviates from linearity at low stresses and displays a gradually yielding behaviour and no sharply defined yield point. Stainless steel and aluminium exhibit this type of behaviour as the basic material response; cold-formed steel sections also display a rounded stress-strain curve. This is due to the Bauschinger effect, whereby residual stresses resulting from plastic deformations induced during production cause deviation of the stress-strain response from linearity upon load reversal. Resistance to local buckling depends on the stiffness of the material, and hence local buckling is promoted by any loss of stiffness due to yielding or nonlinearity. Gradual loss of stiffness as opposed to a sharp yield point is usually regarded as being beneficial in terms of structural performance [12, 13], with a greater degree of strain hardening enabling higher compressive and moment capacities in stocky sections of low D/t ratios. Research is currently being undertaken to utilise strain hardening for enhanced section capacity in low D/t ratio circular hollow sections.

A further factor to be considered in the response of CHS in bending is ovalization. This refers to the gradual flattening of a tube under bending resulting from the inclined nature of the forces in the tube wall that arise in the deformed configuration [14, 15]. The material and geometric properties of structural metallic tubes preclude failure by ovalization wholly in the elastic range, with yielding or local buckling being the key factors limiting structural resistance. However, ovalization may contribute to failure since hoop stresses are induced in the wall of the tube that will influence the onset of plasticity, and there is a reduction in local curvature of the most heavily compressed region of the tube, which facilitates the onset of local buckling.

3. EXISTING SLENDERNESS PARAMETERS AND LIMITS

Slenderness parameters for CHS in all structural design codes include the geometric diameter-to-thickness ratio D/t and the material yield strength f_y. However there is a range of slenderness values, due to the yield strength being normalized by different values in the codes, which are summarized in Table 1 along with the treatment of Class 4 (slender) sections.

Table 1

CHS slenderness parameters adopted in different structural design codes

Design code	Cross-section slenderness parameter	Guidance on effective properties for Class 4 (slender) cross-sections	
		Compression	Bending
EN 1993-1-1 (2005) Structural steel	$\frac{D}{t}\frac{f_y}{235}$	–[1]	–[1]
BS 5950 (2000) Structural steel	$\frac{D}{t}\frac{f_y}{275}$	Clause 3.6.6	Clause 3.5.6.4
AISC 360 (2005) Structural steel	$\frac{D}{t}\frac{f_y}{E}$	Section E7	Section F8
AS 4100 (1998) Structural steel	$\frac{D}{t}\frac{f_y}{250}$	Section 6.2	Section 5.2
EN 1993-1-4 (2006) Stainless steel	$\frac{D}{t}\frac{f_y}{235}\frac{210\,000}{E}$	–[1]	–[1]
EN 1999-1-1 (2007) Aluminium	$\frac{D}{t}\frac{f_y}{250}$	Clause 6.1.5	Clause 6.1.5

Note: [1] No effective section properties are provided but designer is directed to EN 1993-1-6 (2007) [16] for shells.

In order to make a direct comparison between the various design codes, the slenderness limits have been converted to a common basis, using the slenderness parameter adopted for stainless steel in EN 1993-1-4. This is appropriate since the EN 1993-1-4 slenderness parameter includes the Young's modulus E and the material yield strength, which can therefore reflect the different material behaviours. Aluminium in particular has a significantly lower Young's modulus than both structural steel and stainless steel. The values adopted for the material Young's modulus are: 210 000 N/mm^2 for structural steel, 200 000 N/mm^2 for stainless steel and 70 000 N/mm^2 for aluminium. The modified slenderness limits are presented in Table 2.

From Table 2, it can be observed that the Class 3 slenderness limits in compression are fairly consistent between the structural steel and stainless steel design codes, but a more relaxed limit is applied to aluminium. The Class 1 and 2 slenderness limits in bending are also fairly consistent across the range of design codes and materials. However, the Class 3 slenderness limits in bending show significant variation. It should be noted that EN 1993-1-1 and EN 1999-1-1 adopt the same Class 3 slenderness limit for both compression and bending, 90.0 and 171.6 respectively.

Table 2

Summary of CHS slenderness limits in different structural design codes

Material	Structural steel				Stainless steel	Aluminium
Design code	EN 1993-1-1	BS 5950	AISC 360	AS 4100	EN 1993-1-4	EN 1999-1-1
Class 1 limit in bending	50.0	46.8	62.6	53.2	50.0	42.9
Class 2 limit in bending	70.0	58.5	-	-	70.0	90.8
Class 3 limit in bending	90.0	163.8	277.0	127.7	280.0	171.6
Class 3 limit in compression	90.0	93.6	98.3	87.2	90.0	171.6

The Class 3 limit is of particular practical significance because it represents the borderline between fully effective and slender sections, with the latter requiring additional calculation effort for designers. There are two principal reasons for the variation in this slenderness limit between the different design codes. The first relates to the pool of available structural performance data, noting that classification limits are often sensitive to the slenderness range of test data upon which they are based [17]. The Class 3 limit for CHS in bending in EN 1993-1-1 was derived on the basis of tests on stocky sections [18]; whereas the same limit in AISC 360, which is significantly more relaxed, was based on a far wider range of slenderness values [19–22]. The second reason relates to the different regional practices in terms of structural reliability. The partial safety factors adopted in the different design codes are summarised in Table 3.

Table 3

Partial safety factors for cross-section resistance adopted in different design codes

Material	Structural steel				Stainless steel	Aluminium
Code	EN 1993-1-1	BS 5950	AISC 360	AS 4100	EN 1993-1-4	EN 1999-1-1
Partial safety factor	1.00	1.00	0.90[1]	0.90[1]	1.10	1.10

Note: [1] Partial factor appears in the numerator, while others appear in the denominator; 1/0.9=1.11.

Reliability of the design provisions for cross-section resistance depends upon both the adopted slenderness limit and the partial safety factor. The target reliability index and material over-strength are also influential, as are any possible regional differences in manufacturing standards and tolerances. EN 1993-1-1 employs a partial safety factor of unity, while AISC 360 and AS 4100 adopt a value of 1.11

(0.9 in the numerator). The EN 1993-1-1 limits would therefore be expected to be stricter, since the limit itself has to effectively compensate for the disparity in safety factors. Reliability analyses have been performed and unified slenderness limits are proposed for structural steel CHS in the following section.

4. EVALUATION OF TEST DATA AND PROPOSED SLENDERNESS LIMITS

A total of 153 test results on circular hollow section beams of different materials and configurations under bending have been collated in this study. The following tests were undertaken: 52 tests on hot-finished structural steel sections [15, 18, 20, 21], 33 tests on cold-formed structural steel sections [21, 23–25], 21 tests on fabricated structural steel sections [19, 22, 26], 12 tests on very high strength structural steel sections [27], 20 tests on stainless steel sections [28, 29] and 15 tests on aluminium sections [30]. The tests were conducted in three different configurations: 25 in pure bending, 119 in four-point bending and 9 in three-point bending. The cross-section slenderness of the beams varied from 20.4 to 294.5 (using the EN 1993-1-4 measure of slenderness from Table 1). A graph of the ultimate test moment normalised by the elastic moment capacity plotted against the cross-section slenderness is shown in Fig. 2. The Class 3 slenderness limits in bending from the design codes are also shown. The collated test results display the anticipated trend of decreasing normalised moment capacity with increasing slenderness, though there is significant scatter in the data, which is believed to relate to the factors discussed previously. The superior performance of the very high strength structural steel sections is particularly evident.

In order to obtain a unified slenderness limit achieving a consistent level of safety and incorporating the uncertainty in the test results and the variability of the basic variables (material and geometric properties) in the design expression, a reliability analysis in accordance with EN 1990 (2002) [31] was performed, as outlined in [32]. The analysis was performed on the 106 tests on hot-finished, cold-formed and fabricated structural steel sections. Since no formula for deriving effective section properties for Class 4 CHS is provided in EN 1993-1-1, a modified expression based on the BS 5950 provisions was adopted in calculating the design moment capacity for these sections, as given by Eq. 2:

$$W_{eff} = W_{el}\frac{90}{D/t}\cdot\frac{235}{f_y}, \tag{2}$$

where W_{eff} and W_{el} are the effective and elastic section moduli, respectively.

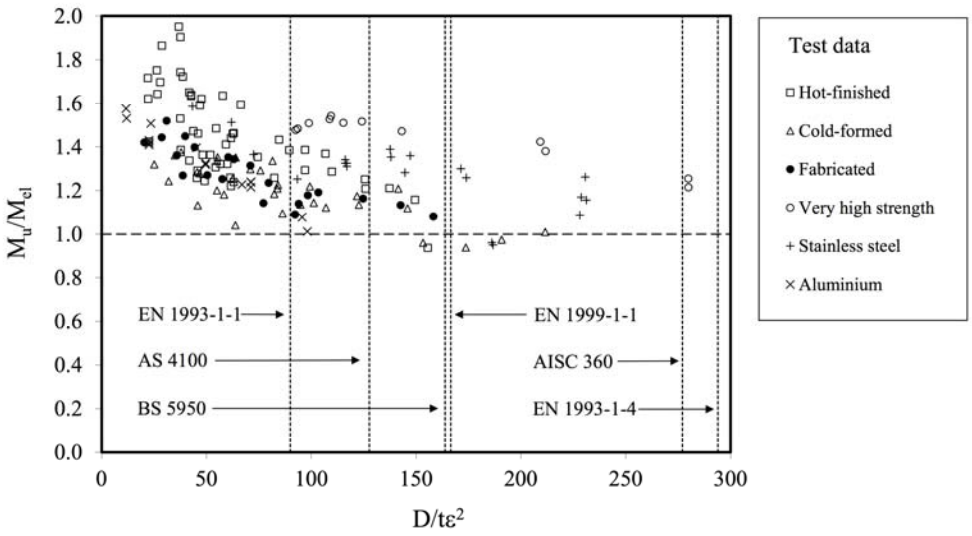

Fig. 2 – Normalised test moment capacity versus cross-section slenderness, with Class 3 slenderness limits from codes.

The parameters assumed in the statistical analyses were based on previous findings on the mechanical properties of structural steel: the ratio of mean to nominal yield strengths (i.e. the material over-strength) was taken as 1.16 and the coefficients of variation of yield strength and geometric properties were taken as 0.05 and 0.02 respectively [33, 34]. These values originate from industrial data obtained from European steel producers. The results of the analysis and a summary of the key statistical parameters are presented in Table 4. The following symbols are used: $k_{d,n}$ = design (ultimate limit states) fractile factor for n tests, where n is the population of test data under consideration; b = average ratio of experimental to model resistance based on a least squares fit to the test data; V_δ = coefficient of variation of the tests relative to the resistance model; V_r = combined coefficient of variation incorporating both model and basic variable uncertainties; and γ_{M0}' = factor by which the mean curve should be reduced to provide a reliable design curve.

Table 4

Summary of statistical analysis parameters for EN 1990

n	$k_{d,n}$	b	V_δ	V_r	γ_{M0}'
106	3.18	1.10	0.131	0.142	1.24

A least squares regression fit to the test data set is plotted in Fig. 3, which is then scaled down by the required safety factor of 1.24 obtained from the reliability analysis to produce the design curve. The unified Class 3 slenderness limit (where the design curve passes through M_u/M_{el} = 1.0) for steel sections was found to be

100 with partial factor of 1.00 adopted in EN 1993-1-1 and 135 for the AISC 360 and AS 4100 partial factor of 0.9 (in the numerator), with the latter design curve being scaled down by a factor of 1.12 (=1.24×0.9) from the mean.

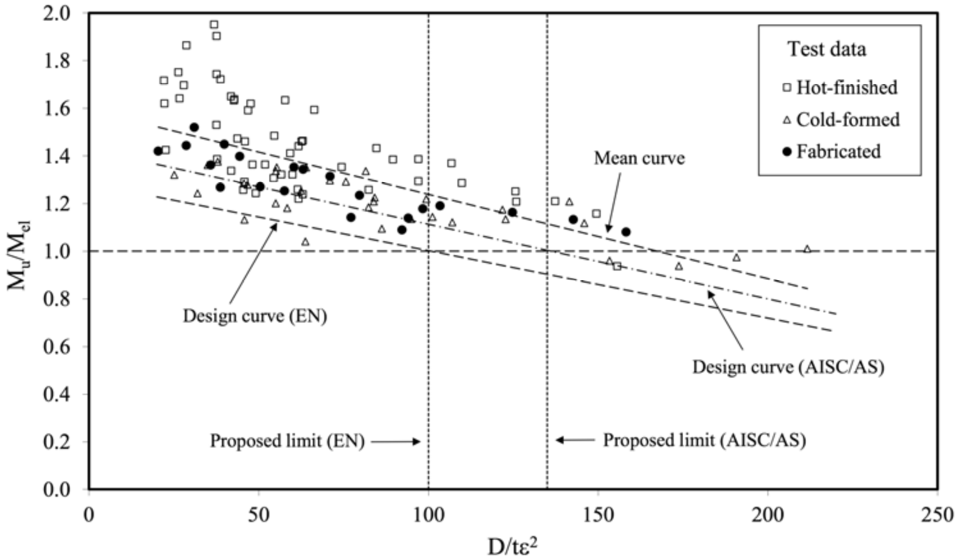

Fig. 3 – Normalised test moment capacity versus cross-section slenderness, with statistical analysis.

5. CONCLUSIONS

The factors affecting local buckling in CHS and the treatment of this instability in various structural design codes have been discussed. A large disparity in the Class 3 slenderness limits in bending was observed between the different design codes. Towards the establishment of unified slenderness limits, the results of 153 bending tests on CHS were examined, and reliability analyses were performed in accordance with EN 1990. Revised structural steel Class 3 slenderness limits of 100 for EN 1993-1-1 and 135 for AISC 360 and AS 4100 were proposed. These slenderness limits provide a unified treatment across the design codes since the more relaxed slenderness limit proposed for AISC 360 and AS 4100 is offset by the inclusion of the partial safety factor of 1.11 (0.9 in the numerator) adopted in these codes. Further investigation is underway in this area, and into utilising strain hardening for enhanced section capacity in low *D*/*t* ratio circular hollow sections.

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