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COMPARATIVE STUDY OF RESULTS OBTAINED THROUGH THE AISC 360-10 AND EUROCODE EN 1993 STANDARDS FOR THE ANALYTICAL VERIFICATION OF LONG STEEL CYLINDRICAL MEMBERS WITH SLENDER SECTIONS

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Abstract. *Cylindrical steel columns with slender section are treated differently in hand calculation design for buckling verification in the two most recognized western steel structures codes: AISC 360-10 and Eurocode EN 1993. This paper details the differences between their design philosophy and formulation for a simple case of pure compression, and compares the results obtained for the capacity of several geometry cases. Capacities are adjusted taking into account each code load factors. The geometries analysed vary both on section and member global slenderness in order to identify possible over-conservativeness or verification loopholes on each code. In the conclusion a loophole on the EN 1993 flexural buckling consideration for long slender cylinders with Class 4 section is explained and a revision on the code is suggested.*

1 INTRODUCTION

Cylindrical elements (or Round Hollow Structural Section – Round HSS members) are often selected in the design of steel columns due to their capability to withstand compression in a manner that no weak axis for buckling exists in a given unbraced length. Its gyration radius value is maximized when compared to other structural sections, bringing the most efficient slenderness ratio.

In order to maximise the gyration radii and decrease the member global slenderness, designers of those circular sections will tend to choose large diameters, and keep the area of steel to the minimum necessary, decreasing the section wall thickness. In this situation, both the verification of the cylinder wall loss of stability on compression (henceforth denominated local bucking) and the global buckling of the member on its unbraced length (henceforth denominated global bucking) are required. Those limit states are clearly determined on American code AISC's [1] Table User Note E1.1. It states that the applicable verifications for pipes with slender sections are the limit states of LB (Local Buckling) and global FB (Flexural Buckling).

This paper presents a comparison on the capacities obtained both by the American AISC and the European Eurocode [2] for cylindrical columns with slender cross sections considering both the limit states mentioned above. For simplicity's sake, this article will analyse a pure compression loading upon a long cylinder with simple pinned boundary conditions at both ends and a normal fabrication quality class.

For the analytical calculation (hand calculation) of the capacity of this type of member, the AISC 360-10 [1] and the Eurocode EN 1993-1-1 [2] codes pose different methodologies. Both codes bring prescriptions for Finite Element Analysis of the problem, but it is a standard practice on the industry to perform analytical formulation design due to its practicality for implementation of code-checks on computer programs.

The AISC 360-10 [1] uses an approach based on tests evidence performed by Sherman [3] for the design of pipe members with noncompact sections, bringing a reduction factor (Q) on the global flexural buckling capacity formulation to take into account the possibility of local buckling. The verifications are directed to section E7 (Members with Slender Elements) of the code and the relevant formulation is displayed on Table 1 below.

Table 1. AISC 360-10 Formulation [1].

Symbol	Definition	Formula	AISC 360-10 Equation
λ_r	Limiting slenderness parameter for noncompact element.	$\lambda_r = 0.11\frac{E}{F_y}$	Table B4.1a
	Noncompact element Check	$\mathrm{D}/t > \lambda_r$	
Q	Net reduction factor accounting for all slender compression elements	When: $0.11\frac{E}{F_y} < \frac{D}{t} < 0.45\frac{E}{F_y}$ $Q = Q_a = \frac{0.038E}{F_y(D/t)} + \frac{2}{3}$	(E7-19)
F_e	Elastic buckling stress	$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}$	(E3-4)
F_{cr}	Critical stress	When: $\frac{KL}{r} \leq 4.71\sqrt{\frac{E}{QF_y}}$ $\quad F_{cr} = Q\left[0.658^{\frac{QF_y}{Fe}}\right]F_y$ $\frac{KL}{r} > 4.71\sqrt{\frac{E}{QF_y}}$ $\quad F_{cr} = 0.877F_e$	(E7-2) (E7-3)
P_n	Nominal axial strength	$P_n = F_{cr}A_g$	(E7-1)
$\varphi_c P_n$	Design compressive strength		

Where:

E - Young's modulus of elasticity = 200000 MPa in this analysis

F_y - Specified minimum yield stress = 250 Mpa in this analysis

D - Outside diameter of round HSS

t - Pipe wall thickness

Q_a - Reduction factor for slender stiffened elements

L - Length of member

K - Effective length factor = 1 for Apendix 7 – Table C-A-7.1 – Both ends Rotation free and translation fixed

r - Radius of gyration

A_g - Gross cross-sectional area of member

$\varphi_c = 0.90$ – (LRFD) Resistance factor for compression

On the other hand, EN 1993-1-1 [2] redirects the design of pipe members with slender cross sections (Class 4 sections) to EN 1993-1-6 [4]. This code, for the buckling verification (Limit State LS3), indicates a different formulation for the analytical check, using a stress design methodology and compares key values of compressive and shear membrane stresses to their related design resistance. Those are obtained by formulas derived from linear shell analysis using membrane theory on simple load cases.

According to Rotter [5], the elastic critical meridional buckling stress is derived from the classical linear Donnell-type shell buckling theory applied to medium-length cylinders under uniform axial compression with the addition of a coefficient that covers the special features of short and long cylinders. Rotter [5] also states that the Euler flexural buckling (global buckling) is not covered by those rules. AISC has clear prescriptions to take that effect into account.

Table 2 lists the relevant expressions necessary for this verification and their location on the document:

Table 2. EN 1993-1-6 Formulation [4].

Symbol	Definition	Formula	Eurocode Equation ID
Δw_k	Characteristic imperfection amplitude	$\Delta w_k = \frac{1}{Q}\sqrt{\frac{r_s}{t}} \cdot t$	(D.15)
ω	Dimensionless length parameter	$\omega = \frac{l}{r_s}\sqrt{\frac{r_s}{t}} = \frac{l}{\sqrt{r_s t}}$	(D.1)
	Long Cylinder Verification	$\omega > 0{,}5\frac{r_s}{t}$	(D.7)

C_x	Cx meridional factor	The factor C_x should be found as: $$C_x = C_{x,N}$$ In which $C_{x,N}$ is the greater of: $$C_{x,N} = 1 + \frac{0,2}{C_{xb}}\left[1 - 2\omega\frac{t}{r_s}\right]$$ and $$C_{x,N} = 0,6$$	(D.9) , (D.10)
σx,Rcr	Elastic critical meridional buckling stress	$$\sigma_{x,Rcr} = 0,605EC_x\frac{t}{r_s}$$	(D.2)
Parameters:			
α_x	Meridional elastic imperfection reduction factor	$$\alpha_x = \frac{0,62}{1 + 1,91(\Delta w_k/t)^{1,44}}$$	(D.14)
β	Meridional Plastic range factor	$$\beta = 0,60$$	(D.16)
η	Meridional interaction exponent	$$\eta = 1,0$$	(D.16)
Slenderness Values:			
$\overline{\lambda_x}$	Meridional relative shell slenderness	$$\overline{\lambda_x} = \sqrt{f_{yk}/\sigma_{x,Rcr}}$$	(8.17)
$\overline{\lambda_p}$	Meridional plastic limit relative slenderness	$$\overline{\lambda_p} = \sqrt{\frac{\alpha}{1-\beta}}$$	(8.16)
$\overline{\lambda_0}$	Meridional squash limit slenderness	$$\overline{\lambda_0} = 0,20$$	(D.16)
Buckling verification:			
χ_x	Meridional buckling reduction factors ("x" Subscript for direction clarification)	$\chi_x = 1$ when $\overline{\lambda_x} \le \overline{\lambda_0}$ $\chi_x = 1 - \beta\left(\frac{\overline{\lambda} - \overline{\lambda_0}}{\overline{\lambda_p} - \overline{\lambda_0}}\right)^\eta$ when $\overline{\lambda_0} < \overline{\lambda_x} < \overline{\lambda_p}$ $\chi_x = \frac{\alpha}{\overline{\lambda_x}^2}$ when $\overline{\lambda_p} \le \overline{\lambda_x}$	(8.13), (8.14), (8.15)

$\sigma_{x,Rk}$	Meridional characteristic buckling stresses	$\sigma_{x,Rk} = \chi_x f_{yk}$	(8.12)
$\sigma_{x,Rd}$	Meridional design buckling stress	$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_{M1}$	(8.11)
	Buckling strength verification:	$\sigma_{x,Ed} \leq \sigma_{x,Rd}$	(8.18)
$F_{x,Rd}$	Calculated value of the meridional buckling force set at the maximum resistance condition (Design value)	$F_{x,Rd} = \sigma_{x,Rd} \cdot 2\pi r_s t$	Section (A.2.1)

Where:

$Q = 16$ For fabrication tolerance quality Class C – Table D.2 Eurocode

r_s - Radius of cylinder middle surface (Changed from the EN 1993-1-6 [4] r , in order to avoid the same nomenclature with AISC 360-10 [1] Radius of gyration)

t - Pipe wall thickness

l - length of shell segment (Unbraced lenght)

$C_{xb} = 1$ Parameter for the boundary conditions BC2f (pinned at both ends) - Table D.1 Eurocode

E - Young's modulus of elasticity = 200000 MPa in this analysis

f_{yk} - characteristic yield strength = 250 Mpa in this analysis

$\gamma_{M1} = 1{,}1$ - partial factor for resistance to buckling

2 METHOD

Using the formulation from both codes, the design strength (design resistance on Eurocode`s terminology) for various column typology were calculated. Upon that strength, a load factor (partial factor on Eurocode) was reversely applied in order to obtain the nominal load (characteristic load on Eurocode) that can be safely applied to the member. Those values were then compared.

In order to minimize the inevitable differences that arise from each code consideration on safety margin, the load factor to be applied was found for the simplest load case combination, which is only permanent (rare variation) dead load in a persistent design situation basis.

The partial factor in Eurocode's evaluation is considered as related to an unfavorable value of permanent actions and is taken from EN 1990 [6]. Equation 6.10 from Table A1.2 (B) of this code shows the design value for that action as:

$$\gamma_{G,j,sup} G_{k,j,sup} \tag{1}$$

Where:

$\gamma_{G,j,sup} = 1{,}35$ - Partial factor for permanent action j in calculating upper design values

$G_{k,j,sup}$ Upper characteristic value of permanent action j

So, the characteristic load to be compared was obtained from the Calculated Value of the Meridional Buckling Force (Design Value) using following formula:

$$G_{k,j,sup} = \frac{F_{x,Rd}}{\gamma_{G,j,sup}} = \frac{F_{x,Rd}}{1{,}35} \tag{2}$$

On the other side, AISC 360-10 [1] redirects to ASCE-07 [7] to determine the nominal loads, which states the combination for only dead loads as:

$$1.4(DL + F) \tag{3}$$

Where:

$DL =$ Dead Load (In the code this variable is “D“. Here it was changed to “DL“ to avoid confusion with the outside diameter)
$F =$ Load due to fluids with well-defined pressures and maximum heights (Not considered in this evaluation)

Thus, the AISC 360-10 [1] nominal compressive load to be compared is:

$$D = \varphi_c P_n / 1.4 \tag{4}$$

The typologies analyzed are determined in order to explore different ranges of the diameter-to-thickness ratio and different member global slenderness factor (kl/r). The unbraced column length was defined as 20,0m for all the cases analyzed.

The geometry ranges were set in a way that several values between the bottom (0.11E/Fy) and top limits (0.45E/Fy) for the diameter-to-thickness ratio of slender Round HSS sections prescribed by AISC 360-10 [1] are explored. For the global slenderness factor, three values were chosen: the smallest related to a compact column, the largest related to a column reaching the inelastic buckling limit, and a value approximately on the middle of those.

3 RESULTS

The Nominal Loads obtained are listed and compared on Table 3 (Case 1 – Compact Column), Table 4 (Case 2 – Medium Slenderness) and Table 5 (Case 3 Column with slenderness near the inelastic limit) shown below:

3.1 Case 1 – Compact Column (D = 2000mm; KL/r=28.6)

Table 3. Case 1 – Compact column.

D/t	88	224	360
t (mm)	22.7	8.9	5.6
AISC Nominal Load (kN)	43076	13639	7976
EUROCODE Characteristic Load (kN)	37281	10692	4329
EUROCODE/AISC LOAD LIMIT COMPARISON	**0.87**	**0.78**	**0.54**

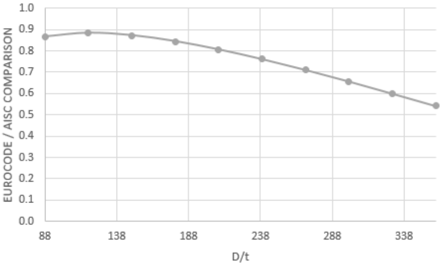

Figure 1. Case 1 – Compact column comparison.

On Table 3 and Figure 1, EN 1993-1-6 [4] presented a more conservative result when compared to AISC 360-10 [1]. Eurocode’s conservativeness increases with the elevation of the diameter-to-thickness ratio. For the limit of section slenderness where the comparison is yet possible, EN 1993-1-6 [4] presents a capacity of only 54% the one prescribed by the AISC 3610-10 [1] code.

3.2 Case 2 – Medium Slenderness Column (D = 1000mm; KL/r=57.2)

Table 4. Case 2 –Medium slenderness.

D/t	88	224	360
t (mm)	11.4	4.4	2.8
AISC Nominal Load (kN)	9440	3076	1811
EUROCODE Characteristic Load (kN)	9320	2673	1080
EUROCODE/AISC LOAD LIMIT COMPARISON	**0.99**	**0.87**	**0.60**

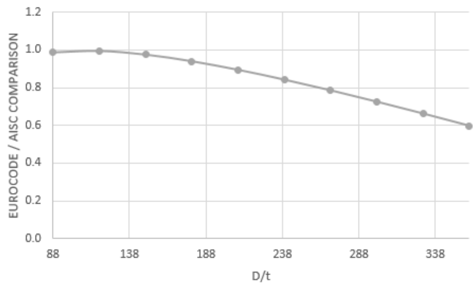

Figure 2. Case 2 – Medium Slenderness

On Table 4 and Figure 2, Eurocode EN 1993-1-6 [4] yet again presented a more conservative result, but closer to the AISC 360-10 [1] than the ones found for the compact column case shown in Table 3 and Figure 1. For cylinders near the bottom limit range of slender sections, the results are practically the same. The difference increases for larger values of diameter-to-thickness ratio and, at the top limit, EN 1993-1-6 [4] presents a result that is 60% of the AISC 360-10 [1].

3.3 Case 3 – Column with slenderness near the inelastic buckling limit (D = 500mm; KL/r=114.4)

Table 5. Case 3 – Column with slenderness near the inelastic limit.

D/t	88	224	360
t (mm)	5.7	2.2	1.4
AISC Nominal Load (kN)	1393	509	308
EUROCODE Characteristic Load (kN)	2330	668	270
EUROCODE/AISC LOAD LIMIT COMPARISON	**1.67**	**1.31**	**0.88**

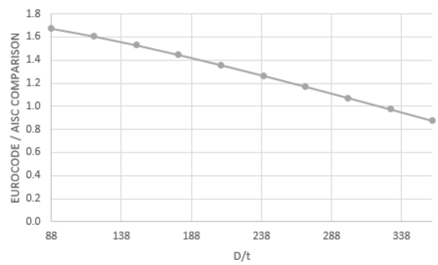

Figure 3. Case 3 – Column with slenderness near the inelastic limit.

On Table 5 and Figure 3, for the lower boundary of diameter-to-thickness ratio, EN 1993-1-6 [4] presents a much higher capacity when compared to the AISC 360-10 [1] (67% more). This difference decreases for larger values of diameter-to-thickness ratio. For those ratio values near the top boundary, EN 1993-1-6 [4] is again more conservative bringing a result of 88% of the one found by AISC 360-10 [1].

4 CONCLUSION

The comparison of the results demonstrates relevant differences on the characteristic capacity prescribed by both codes regarding the geometries analysed.

It was expected that Eurocode would bring more conservative results. In several situations, Rotter [5] mentions this conservativeness on both the formulation and also on the reduction factors used. But, what calls attention is that EN 1993-1-6 [4] states on page 5: "… It should be noted that the stress design rules of this standard may be rather conservative if applied to some geometries and loading conditions for relatively thick-walled shells." But the results demonstrated larger differences between the procedures for **thin**-walled shells.

An even more relevant result is found for Case 3 – Column with slenderness near the inelastic buckling boundary. There, Euler`s global flexural buckling is relevant due to the higher global member slenderness ratio (114.4). In this case, Eurocode presented a much higher capacity for any section other than the very thin-walled top limit (D/t=360). This is due to the fact that EN 1993-1-6 [4] does not cover the global flexural buckling nor its interaction with the local shell buckling on its rules. Neither is there a reference on the code to take this effect into account in analytical verifications.

Rotter [5] states that EN 1993-1-6 [4] rules are sufficiently conservative, due to conservativeness on $C_{x,N}$ and α_x factors, rendering unnecessary to take into account the interaction between global and local buckling. But he also states on page 171 that the **global buckling must be checked separately**, and suggests the use of EN 1993-1-1 [2]. This leads to a situation of problematic interpretation, since no prescription for buckling verification of Class 4 sections exists on EN 1993-1-1 [2].

Therefore, the designer may be lead to a mistake when following only the EN 1993-1-1 [2] and EN 1993-1-6 [4] prescriptions for hand calculation, which can lead to an unsafe design that is acceptable by the code`s rules. A revision on Eurocodes [2] [4], with the indication of specific rules to consider directions for accounting the global flexural buckling of long cylinders with thin walled shells is strongly recommended.

5 REFERENCES

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