WIDTH-TO-THICKNESS RATIOS FOR CLASSIFICATION OF TUBULAR SECTIONS

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ABSTRACT

This paper compares the three classification systems of steel sections in various design codes such as Eurocode 3, BS5950, AS4100 and AISC-LRFD. The maximum width-to-thickness ratios for each class are summarized. The ratios are found comparable except for the much higher ratios given in AISC-LRFD for RHS web bending and CHS compression. The effect of concrete-filling and large deformation cyclic loading on the maximum width-to-thickness ratio is investigated. It seems that the concrete-filling increases the ratios by about 50%. The large-deformation cyclic loading reduces the ratios by about 50%. Future research work is identified to expand Eurocode 3 such as the smooth transition of moment capacity between class 2 and class 3, the interaction of web buckling and flange buckling for RHS in bending, the maximum width-to-thickness ratio for class 3 CHS in bending, the expressions of maximum width-to-thickness ratio for high strength steel tubes. Other future research may include the benefit of concrete-filling for CHS and the maximum width-to-thickness ratios for concrete-filled tubes under large deformation cyclic loading.

1 INTRODUCTION

Three classification systems of steel sections exist in various design codes. Eurocode 3 [1] classifies sections as Class 1, 2, 3 or 4. BS5950 Part 1 [2] classifies sections as plastic, compact, semi-compact and slender. AS4100 [3] and AISC-LRFD [4] classify sections as compact, non-compact and slender. Which category a section belongs to depends on its cross-section geometry and certain limits on such geometry specified in the design code.

The concept of plate element slenderness (λ_e) is used in AS4100 whereas the concept of width-to-thickness ratio or diameter-to-thickness ratio is used in Eurocode 3, BS5950 Part 1 and the AISC-LRFD specification. The relationship between the plate element slenderness and the width or diameter-to-thickness ratio can be generally expressed as:

$$\lambda_e = \left(\frac{\text{width}}{\text{thickness}}\right)\cdot\sqrt{\frac{f_y}{250}} \quad \text{for RHS} \qquad (1)$$

$$\lambda_e = \left(\frac{\text{diameter}}{\text{thickness}}\right)\cdot\left(\frac{f_y}{250}\right) \quad \text{for CHS} \qquad (2)$$

The plate element slenderness takes account of the yield stress so that a higher yield stress produces a plate element slenderness which is higher and can be compared with a fixed value. By comparison, Eurocode 3, BS5950 and the AISC Specification compare the actual width/thickness ratio with a limit which varies inversely as the square root of the yield stress for RHS or yield stress for CHS. A parameter called ε is defined in Eurocode 3 for this purpose:

$$\varepsilon = \sqrt{\frac{235}{f_y}} \qquad (3)$$

Clear width is used in AS4100 whereas the flat width is used in Eurocode 3, BS5950 and the AISC specification. They are defined in Figure 1.

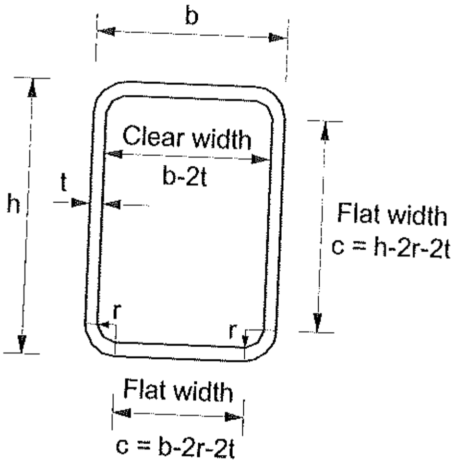

Fig.1 Geometry of an RHS

Limiting values on λ_e or width-to-thickness ratios are specified in different standards based on research all over the world [5,6,7]. In order to show a clear comparison among standards, the symbols and definitions in Eurocode 3 are adopted in this paper as the basis.

This paper compares the three classification systems of steel sections in various design codes such as Eurocode 3, BS5950, AS4100 and AISC-LRFD. It compares the maximum width-to-thickness ratios and comments on the differences. The limits are also influenced by concrete-filling of the section and accumulated damage due to large deformation cyclic loading. In general the concrete-filling increases the limiting ratio whereas the cyclic loading decreases the limiting ratio. The limits specified in Eurocode 3 for empty tubes under static load is compared with three types of limits namely limits for concrete-filled tubes under static loading, limits for empty tubes under cyclic loading and those for concrete-filled tubes under cyclic loading. Future research work is identified to expand the scope of Eurocode 3.

2 CLASFICATION SYSTEMS

The criteria used to determine section classes are summarized in Table 1 where M_{max} is the maximum moment capacity, M_p is the plastic moment capacity, M_y is the yield moment capacity, c is the flat width (see Figure 1), t is the wall thickness and d is the outer diameter of a CHS, R is the rotational capacity and R_{req} is the required rotational capacity. Subscripts 1, 2 and 3 are used for Eurocode 3 and BS5950 to define the limiting values corresponding to the three values specified in those codes. Subscripts p and y are used for AS4100 and AISC-LRFD specification, which corresponds to the plastic slenderness limit and yield slenderness limit. It can be seen that Eurocode 3 and BS5950 have very similar system whereas AS4100 and AISC are similar although the limiting values are slightly different as shown later in the paper. The moment capacity versus width-to-thickness ratio relationship for the purpose of design is schematically shown in Figure 2. It seems that the compact section in AS4100 and in AISC corresponds to the Class 1 section in Eurocode 3 and the plastic section in BS5950. The non-compact section in AS4100 and AISC corresponds to the Class 2 and Class 3 sections in Eurocode 3 or to the Compact and Semi-compact sections in BS5950. The slender section in AS4100 and in AISC corresponds to the Class 4 section in Eurocode 3 and the slender section in BS5950.

It is interesting to observe that there is sudden drop (point B to point C in Figure 2) in moment capacity between Class 2 and Class 3 in Eurocode 3 whereas there is a linear transition (point A to point D in Figure 2) between compact section and slender section in AS4100 and AISC. Research is needed to derive a smooth transition between point B and point D in Figure 2.

Table 1: Criteria for Classification Systems

Criteria	Class in EC3	Class in BS5950	Width-to-thickness ratio in EC3 and BS5950	Class in AS4100 and AISC-LRFD	Width-to-thickness ratio in AS4100 and AISC-LRFD
$M_{max} > M_p$ and $R \geq R_{req}$	1	Plastic	$(c/t) \leq (c/t)_1$ or $(d/t) \leq (d/t)_1$	Compact	$(c/t) \leq (c/t)_p$ or $(d/t) \leq (d/t)_p$
$M_{max} > M_p$ and $R < R_{req}$	2	Compact	$(c/t)_1 < (c/t) \leq (c/t)_2$ or $(d/t)_1 < (d/t) \leq (d/t)_2$	Non-compact	$(c/t)_p < (c/t) \leq (c/t)_y$ or $(d/t)_p < (d/t) \leq (d/t)_y$
$M_y \leq M_{max} \leq M_p$	3	Semi-compact	$(c/t)_2 \leq (c/t) \leq (c/t)_3$ or $(d/t)_2 < (d/t) \leq (d/t)_3$		
$M_{max} < M_y$	4	Slender	$(c/t) > (c/t)_3$ or $(d/t) > (d/t)_3$	Slender	$(c/t) > (c/t)_y$ or $(d/t) > (d/t)_y$

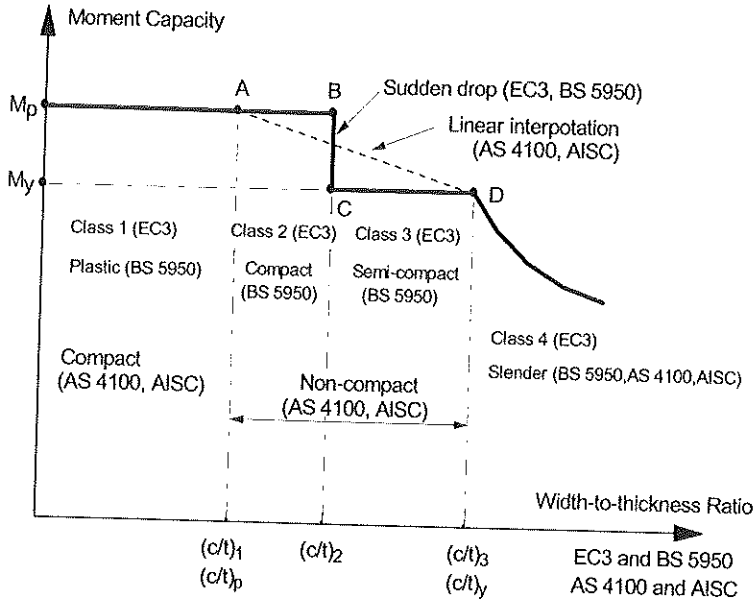

Fig.2 Classification Systems

3 MAXIMUM WIDTH-TO-THICKNESS RATIOS FOR BENDING

The maximum width-to-thickness ratios for bending (RHS flange) are summarized in Table 2. The limiting values in BS5950, AS4100 and AISC are converted to the same format as those in Eurocode 3 for easy comparison. Similar comparisons are given in Table 3 for bending (RHS web) and in Table 4 for bending (CHS).

For bending (RHS flange) all the limits are similar in the four standards listed in Table 2. For bending (RHS web) all the limits are comparable except that AISC gives much higher values. Recent research [8] has shown some interaction between RHS flange buckling and RHS web buckling, which resulted lower limiting values for RHS. For CHS bending $(d/t)_3$ in Eurocode 3 is considerably smaller than those given by other codes.

It is also interesting to note that limiting values for cold-formed RHS are sometimes lower than those for hot-rolled RHS.

Table 2: Maximum width-to-thickness ratios for bending (RHS flange)

Width-to-thickness ratio	Eurocode 3	BS5950	AS4100	AISC-LRFD
$(c/t)_1$ or $(c/t)_p$	33ε	30ε for hot-rolled 28ε for cold-formed	30ε - 2r/t	28ε
$(c/t)_2$	38ε	35ε for hot-rolled 30ε for cold-formed	N/A	N/A
$(c/t)_3$ or $(c/t)_y$	42ε	43ε for hot-rolled 38ε for cold-formed	46ε - 2r/t for hot-rolled 41ε - 2r/t for cold-formed	42ε

Table 3: Maximum width-to-thickness ratios for bending (RHS web)

Width-to-thickness ratio	Eurocode 3	BS5950	AS4100	AISC-LRFD
$(c/t)_1$ or $(c/t)_p$	72ε	69ε for hot-rolled 61ε for cold-formed	85ε - 2r/t	112ε
$(c/t)_2$	83ε	87ε for hot-rolled 76ε for cold-formed	N/A	N/A
$(c/t)_3$ or $(c/t)_y$	124ε	130ε for hot-rolled 114ε for cold-formed	119ε - 2r/t	170ε

Table 4: Maximum width-to-thickness ratios for bending (CHS)

Width-to-thickness ratio	Eurocode 3	BS5950	AS4100	AISC-LRFD
$(d/t)_1$ or $(d/t)_p$	$50\varepsilon^2$	$47\varepsilon^2$	$53\varepsilon^2$	$63\varepsilon^2$
$(d/t)_2$	$70\varepsilon^2$	$59\varepsilon^2$	N/A	N/A
$(d/t)_3$ or $(d/t)_y$	$90\varepsilon^2$	$164\varepsilon^2$	$128\varepsilon^2$	$277\varepsilon^2$

4 MAXIMUM WIDTH-TO-THICKNESS RATIOS FOR COMPRESSION

The maximum width-to-thickness ratios for compression (both RHS and CHS) are summarized in Table 5. For RHS the limiting values of $(c/t)_3$ or $(c/t)_y$ for compression is the same as those for bending (RHS flange) given in Table 2. However for CHS the limiting values of $(d/t)_3$ or $(d/t)_y$ for bending given in Table 4 are much higher than those for compression listed in Table 5 except for Eurocode 3 where same limiting values are adopted.

Table 5: Maximum width-to-thickness ratios for compression

Width-to-thickness ratio	Eurocode 3	BS5950	AS4100	AISC-LRFD
$(c/t)_3$ or $(c/t)_y$	42ε	43ε for hot-rolled 38ε for cold-formed	46ε - 2r/t for hot-rolled 41ε - 2r/t for cold-formed	42ε
$(d/t)_3$ or $(d/t)_y$	$90\varepsilon^2$	$94\varepsilon^2$	$87\varepsilon^2$	$98\varepsilon^2$

5 EFFECT OF CONCRETE-FILLING AND LARGE DEFORMATION CYCLIC LOADING

It is well known that in general the concrete-filling increases the limiting width-to-thickness ratio whereas the large-deformation cyclic loading decreases the limiting ratio [9]. The limits specified in Eurocode 3 for empty tubes under static load are compared with three types of limits in this section, namely limits for concrete-filled tubes under static loading, limits for empty tubes under cyclic loading and those for concrete-filled tubes under cyclic loading. The effect of concrete-filling on the maximum width-to-thickness ratios under static loading can be demonstrated by the comparison shown in Table 6. The increase in the limiting values ranges from 20% to 80%. However, it seems that the same limiting values are used in Eurocode 4 [10] for concrete-filled CHS in compression as those for empty CHS.

The effect of large-deformation cyclic loading on the maximum width-to-thickness ratios for empty tubes can be illustrated by the comparison shown in Table 7. The limiting ratios are about 50% to 80% of those under static loading. The loading scheme and ductility requirement play an important role in determining the maximum width-to-thickness ratios under cyclic loading. As shown in Table 8 the combination of concrete-filling and large deformation cyclic loading has a mixed effect on the maximum width-to-thickness ratios.

Table 6: Effect of concrete-filling on the maximum width-to-thickness ratios under static loading

Case	RHS bending	CHS bending	RHS compression	CHS compression
Ratios	$\frac{(\frac{c}{t})_{1,filled,static}}{(\frac{c}{t})_{1,EC3}}$	$\frac{(\frac{d}{t})_{1,filled,static}}{(\frac{d}{t})_{1,EC3}}$	$\frac{(\frac{c}{t})_{3,filled,static}}{(\frac{c}{t})_{3,EC3}}$	$\frac{(\frac{d}{t})_{3,filled,static}}{(\frac{d}{t})_{3,EC3}}$
Values [Reference]	≈1.6 [9,10]	1.8 [9,10]	≈1.2 [9,10]	1.0 [9,10]
			≈1.5 [13] ≈1.7 [11]	≈1.7 [11]
		≈1.5 [12]	≈1.2 to 1.5 [14]	
			≈1.2 to 1.7 [15]	

Table 7: Effect of large deformation cyclic loading on the maximum width-to-thickness ratios for empty tubes

Case	RHS bending	CHS bending	RHS compression	CHS compression
Ratios	$\frac{(\frac{c}{t})_{1,cyclic}}{(\frac{c}{t})_{1,EC3}}$	$\frac{(\frac{d}{t})_{1,cyclic}}{(\frac{d}{t})_{1,EC3}}$	$\frac{(\frac{c}{t})_{3,cyclic}}{(\frac{c}{t})_{3,EC3}}$	$\frac{(\frac{d}{t})_{3,cyclic}}{(\frac{d}{t})_{3,EC3}}$
Values [Reference]	≈ 0.6 to 0.8 (test data in [16] with R_{req} of 7 to 9 specified in [17])	≈ 0.72 [18]	≈ 0.46 [17]	≈ 0.42 [17]
				≈ 0.6 [19]
				≈ 0.6 to 0.8 [20]

Table 8: Effect of concrete-filling and large deformation cyclic loading on the maximum width-to-thickness ratios

Case	RHS bending	CHS bending	RHS compression	CHS compression
Ratios	$\frac{(\frac{c}{t})_{1,filled,cyclic}}{(\frac{c}{t})_{1,EC3}}$	$\frac{(\frac{d}{t})_{1,filled,cyclic}}{(\frac{d}{t})_{1,EC3}}$	$\frac{(\frac{c}{t})_{3,filled,cyclic}}{(\frac{c}{t})_{3,EC3}}$	$\frac{(\frac{d}{t})_{3,filled,cyclic}}{(\frac{d}{t})_{3,EC3}}$
Values Reference]	≈ 0.7 to 1.5 [21]	≈ 1.6 [21] ≈ 0.7 to 1.0 [22, 23]	≈ 1.0 [17] ≈ 0.6 to1.2 [21]	≈ 0.9 [21]

6 EXPRESSION FOR HIGH STRENGTH TUBES

For CHS the maximum width-to-thickness ratios in Eurocode 3 are $(d/t)_1 = 50\varepsilon^2$ for plastic design and $(d/t)_3 = 90\varepsilon^2$ for local buckling design. The term ε^2 is the ratio of $(235/f_y)$ that is a function of the yield stress f_y. Recent research [24, 25] showed that this expression of maximum width-to-thickness ratio may not be applicable for CHS with very high yield stress (e.g. up to 1,350 MPa). For example, when f_y is 1,350 MPa, $(d/t)_1$ becomes 8.7 and $(d/t)_3$ becomes 16 that are very small. This is partly because very large yield stress was used in the calculation according to the definition of ε^2 and partly because very low residual stress exists in the section [24]. There are two possible approaches for design of high strength CHS. One is to use a higher constant rather than 50 and 90 while keeping the same format for defining the maximum width-to-thickness ratios. The other is to keep the current constant 50 and 90 while deriving a new expression of ε^2 rather than $(f_y/250)$ to take into account the influence of yield stress. There seems a clear knowledge gap between the yield stresses of 450 up to 1,350 MPa where more research is needed.

7 SUMMARY

This paper has compared the three classification systems of steel sections in Eurocode 3, BS5950, AS4100 and AISC-LRFD. The maximum width-to-thickness ratios for tubular sections in each class have been summarized. For CHS bending $(d/t)_3$ in Eurocode 3 is considerably smaller than those given by other codes. The increase in the limiting values due to concrete-filling ranges from 20% to 70%. The limiting ratios for cyclic loading are about 60% to 80% of those under static loading. The combination of concrete-filling and large deformation cyclic loading has a mixed effect on the maximum width-to-thickness ratios. Future research may include the smooth transition of moment capacity between class 2 and class 3, the interaction of web buckling and flange buckling for RHS in bending, the limiting ratio for class 3 CHS in bending, the expressions of maximum width-to-thickness ratio for high strength steel tubes, benefit of concrete-filling for CHS and combined effect of concrete-filling and cyclic loading on the maximum width-to-thickness ratios.

ACKNOWLEDGMENT

Thanks are given to Prof. G.J. Hancock, A/Prof. R.H Grzebieta, Dr. M. Elchalakani and Dr. H. Jiao for their collaboration in determining the limiting ratios for cold-formed tubes.

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KEYWORDS

Steel tubes, width-to-thickness ratio, classification of steel sections, concrete-filling, cyclic loading, high strength steel