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MANUFACTURING SPECIFICATIONS FOR HOLLOW SECTIONS IN 2010

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***Abstract**. The minimum mechanical and geometric property requirements, stipulated in contemporary manufacturing specifications for cold-formed and hot-finished structural hollow sections internationally, are reviewed and compared. Many of the key criteria are shown to have implications for the structural performance under static, impact and seismic loading conditions, as well as under hot-dip galvanizing. Considerable effort is currently being expended by an industry task force in North America to produce a new manufacturing standard for higher performance cold-formed hollow structural sections, to address current limitations of the product. Features of this resulting draft standard (termed ASTM A1xxx herein) are presented in the tables.*

1 CONTEMPORARY MANUFACTURING SPECIFICATIONS

The proportion of Hollow Structural Sections (HSS) within the structural steel market continues to grow, particularly within North America. Roughly 3 million tons of cold-formed HSS were produced in North America in 2008, compared to approximately 5.6 million tons of hot-formed steel I-sections (or "W-shapes") [1]. Beyond Europe, the most popular HSS material is that made to ASTM A500 [2], yet this product stills bears a warning regarding application to dynamically loaded structures. Despite this, the use of HSS to ASTM A500 is ubiquitous and the limitations of this structural section – and indeed many other hollow sections – are not well-appreciated. In the following, some of the key geometric and mechanical properties of prominent internationally-produced hollow sections are reviewed. Concern over the performance of hollow sections manufactured to some specifications has even caused certain jurisdictions (e.g. Singapore) to disapprove product produced to particular standards [3]. The outside dimensions of hollow sections are well-controlled with tight tolerances, so these are not discussed below.

1.1 ASTM A500 [2]

This is a cold-formed, electric-resistance-welded (ERW) product, currently restricted to perimeters of 1630 mm or less and wall thicknesses up to 16 mm, noted for its very liberal geometric production tolerances. A tolerance of -10% is permitted on wall thickness, with no tolerance on mass, weight or cross-sectional area (see table 1), resulting in tubes being produced routinely undersize. The American Institute of Steel Construction Specification [4] accounts for this practice by designating a "design wall thickness" of 0.93 times the nominal wall thickness for structural design in the U.S., whereas the Canadian Institute of Steel Construction [5] stipulates a "design wall thickness" of 0.90 times the nominal wall thickness for structural design in Canada. All section properties for each country are then calculated based on the respective design thickness. ASTM A500 tubing is also in use in many other countries worldwide without such design guidance, which – considering the much-diminished engineering properties relative to the expected values – may result in unsafe design situations.

Further confusion arises with minimum mechanical properties, since Grades B and C have different guaranteed yield strengths for circular hollow sections (CHS) and rectangular hollow sections (RHS), as indicated in table 1. Manufacturers in North America now commonly dual-certify their ASTM A500 product to both Grades B and C, producing to the higher grade and working to a “one product fits all” approach [6]. This makes it difficult to apply such material to seismic applications since the stipulated R_y value (to account for member expected over-strength) becomes very unreliable. Recognizing this problem, the latest Canadian steel structures standard [7] has stipulated that the product R_yF_y be taken as not less than 460 MPa (N/mm^2) for all HSS. The ASTM A500 standard has no provision for a Charpy V-notch toughness rating (table 1), further limiting its applicability to many dynamic loading situations. A large number of Charpy V-notch tests on A500 square HSS have, in fact, confirmed the inherent very low notch toughness level of this material, even in the longitudinal (or rolling) direction [8].

1.2 CAN/CSA G40.20-04/G40.21-04 [9]

This is another production specification for structural tubing in North America, governing part of the overall stock made in Canada. Although it is a cold-formed, ERW product and similar to ASTM A500, it has improved features that include (see table 1): (i) a single Grade 350W; (ii) strict geometric tolerances on thickness and mass/area, which result in hollow sections that are made to nominal cross-sectional properties and hence have a “design wall thickness” equal to the nominal wall thickness; (iii) the ability to specify a Charpy V-notch toughness requirement, by stipulating Grade 350WT and one of five toughness categories. The latter range from Category 1 of 27 Joules at 0^o C, to Category 4 of 27 Joules at -45^o C, and even a Category 5 “to be specified by purchaser”. CAN/CSA G40.20/G40.21 is unique amongst cold-formed HSS production standards in that the cold-formed end product (Class C) can be heat-treated to form an alternative Class H product, by heating to 450^o C or higher followed by cooling in air [9]. This reduces the residual stresses in the cross-section and justifies the use of a column resistance curve for compression member design that is higher than that for Class C [7].

1.3 ASTM A501 [10]

This is an American specification for the manufacture of hot-formed HSS, but these products are not manufactured in the U.S. This specification was recently revived to facilitate the importation of hot-finished hollow sections from Europe, manufactured in accordance with EN10210 [11], [12]. Although it has no wall thickness tolerance there is a very tight mass/area tolerance, ensuring that sections are made to nominal cross-section properties (table 1). The higher-strength Grade B also automatically has a reasonable energy absorption capacity, for wall thicknesses greater than 8 mm (table 1).

1.4 ASTM A53 [13]

This is actually a pipe production specification, intended for mechanical and pressure applications. The product needs to satisfy a hydrostatic test and is only produced in circular shapes, but Grade B – produced by an ERW process – is used for structural purposes in many parts of the U.S. by adopting a “design wall thickness” of 0.93 times the nominal wall thickness, as for ASTM A500 [4]. Despite a low F_y/F_u ratio, which is favourable for seismic design, this material possesses a particularly low yield strength and – like ASTM A500 – is subject to slack geometric tolerances and does not have any notch toughness provision (table 1).

1.5 API 5L [14]

This specification for steel pipe, for pipeline transportation systems, covers a multitude of tube grades and sizes of which some are used for structural applications. PSL2 pipe is a common structural choice and Grade X52 is probably the most common choice for structural purposes. With a tight mass tolerance, a toughness requirement (table 1) and a diameter range from 10.3 to 2134 mm, this high-quality pipe material addresses a frequent need for either large diameter or thick-walled hollow sections. Other special features of PSL2 pipe are an upper bound on the yield strength (e.g., for X52 the minimum and maximum yield strengths are 360 and 530 MPa, respectively), and a maximum yield-to-tensile stress ratio of 0.93 in the as-delivered pipe (for D > 323.9 mm).

Table 1: Manufacturing standards for HSS and Pipe with minimum specified mechanical properties of common grades and influential dimensional tolerances on individual sections.

HSS or Pipe Specification		Grade	F_y (MPa)	F_u (MPa)	Toughness[b] (Joules @ °C)	Wall thickness Tolerance	Mass or Area tolerance
ASTM A500	CHS	B	290	400	–	-10%	–
		C	315	425			
	RHS	B	315	400			
		C	345	425			
ASTM A53		B	240	415	–	-12.5%	-10%
ASTM A501		B	345	483	27J @ -18°C for t>8mm	–	-3.5%
CSA-G40.20/G40.21		350W	350	450	5 Categories: 27J @ 0, -20, -30, -45°C, or as specified	-5%	-3.5%
API 5L		PSL 2 X52N	360	460	27J @ 0°C for D≤762mm	–10% for 5<t<15 -0.5mm, t<5	–3.5% for regular plain-end
EN10210		S355J2H	355 for t≤16 345 for 16<t≤40	470 for 3<t≤100	27J @ -20°C	–10% (more liberal for seamless)	-6%
EN10219		S355J2H	355 for t≤16 345 for 16<t≤40	470 for 3<t≤40	27J @ -20°C	–10%, t≤5 -0.5mm, t>5 for D≤406.4	-6%
AS/NZS 1163		C350L0	350	430	27J @ 0°C	–10% for D≤406.4	-4%
		C450L0	450	500			
SANS 657-1		355WA[c]	355[c]	450	On request	–9% for 3≤t≤4[d] –7.5% for 4<t≤5[d] –6.5% for 5<t≤6[d] –6.0% for t>6[d]	-10%
JIS G3475	CHS	STKN 490B	325 for t ≤40	490	27J @ 0°C for D≥400 if CHS, and t>12		
JIS-Approved	RHS	BCP325	325 for t<12 335 for 12≤t≤40				
ASTM A1xxx (For perimeters ≥ 317.5mm)		–	345	450	27J @ -18°C	-5%	–

Notes: a: Dimensions (of D, t and Perimeter) in mm.; b: Charpy V-notch impact test value for full-size (10 x 10 mm) longitudinal coupons; c: SANS 657-1 355 MPa yield strength grade launched in February 2010; d: After Amendment No.2 to SANS 657-1:2005.

1.6 EN10210 [11], [12]

EN10210 is the current European specification for hot-finished (or "hot-formed") structural hollow sections, which are manufactured primarily in the U.K., Germany, France and Brazil. This material is fine-grained, has very low residual stresses, is available in a wide range of sizes and thicknesses, and the most common grade is S355J2H. Sections to this specification are typically made by cold-forming, using an ERW process, then re-heated to normalizing temperature and finished to final shape. The hot-finishing method produces smaller outside corner radii on square and rectangular hollow sections than with cold-formed RHS. These characteristics, and the properties shown in table 1, probably place this specification at the forefront of HSS manufacturing standards internationally. One concern arises, however, over the governing thickness tolerance of -6% (assuming constant HSS thickness), which has no "design thickness" compensation like for ASTM A500 [2]. Under-sizing of a hollow section (relative to expected or nominal size) can have a serious negative effect on the member capacity, member deflection and even connection strength, where the latter is proportional to t^{α} with $1 \leq \alpha \leq 2$ [15]. Very thick tubes to this specification – with low D/t, as used in bridges – are likely to be manufactured by the "seamless" process. This is apt to leave an unsmooth surface finish, which may raise concerns with the client.

1.7 EN10219 [16], [17]

EN10219 is the current European specification for cold-formed structural hollow sections, made primarily by the ERW process. The influential mechanical and geometric properties are very similar to EN10210 [11], [12], as indicated in table 1, except the wall thickness/mass tolerances result in a governing thickness tolerance of -6% (assuming constant HSS thickness) only up to 8.33 mm thickness; above that thickness the permissible under-sizing is less than 6% due to the -0.5mm tolerance controlling.

1.8 AS/NZS 1163 [18]

The latest Australasian standard for cold-formed ERW hollow sections has two popular grades, C350 and C450 (table 1), the potential for a Charpy V-notch toughness rating (sub-grading of L0 at 0^{o} C), and wall thickness/mass tolerances that are second only to CSA [9]. For Grade C450 there is a ductility concern, since the nominal F_y/F_u ratio of 0.9 is very high and it is accompanied by minimum elongations at failure of only 12% for CHS and 10% for RHS (for $t \leq 15$ mm). However, this standard is unique in that, while all HSS manufacturing standards require mechanical properties to be demonstrated just after production, AS/NZS 1163 also requires artificial "strain ageing" of the test pieces prior to tensile or impact testing. Ageing is achieved by heating to 150^{o} – 200^{o} C for at least 15 minutes, which raises the yield stress and decreases the ductility, thus somewhat ameliorating the above ductility characteristics.

1.9 SABS/SANS 657–1 [19]

The latest version of this South African standard, with Amendments 1 and 2 (2009), brings production tolerances close to EN10219-2 [17] except the wall thickness/mass tolerances for $t \leq 6$ mm are even more liberal (-9%t for $3.0 \leq t \leq 4.0$ mm; -7.5%t for $4.0 < t \leq 5.0$ mm; -6.5%t for $5.0 < t \leq 6.0$ mm). The sole grade for structural hollow sections (yield strength of 300 MPa) was relatively low, but a higher grade of 355 MPa has now been launched in February 2010. Whereas most cold-formed HSS manufacturing standards specify that the mechanical properties be determined from the finished product, this standard permits the properties to be determined from either the parent metal *or* the finished product. The former is typically chosen, giving South African hollow sections an inherent over-strength.

1.10 JIS G3475 [20]

Japan has a complex set of standards and approval bodies but steel CHS for building construction generally fall under the purview of the Japanese Industrial Standards. For structural members in which plastic deformation may occur – a common criterion for Japanese seismic design – Grades STKN490B and STKN400B have minimum yield strengths of 325 MPa and 235 MPa, respectively. Cold-formed square hollow sections (termed BCR and BCP materials, depending on the manufacturing process) are a very popular choice for building columns in Japan but standards for such are not established by JIS; instead, they are approved as structural members by the Ministry of Land, Infrastructure and Transport of Japan. For wall thicknesses of 12 mm and greater, both the circular and square hollow section standards provide an upper limit on the actual yield stress, an upper limit of 0.80 on the yield-to-tensile strength ratio in the as-delivered material (key for plastic deformation capacity), and a Charpy energy absorption rating. Table 1 gives further specification details for these materials.

2 CORNER CRACKING IN COLD-FORMED RHS

Cracking in the corners of cold-formed, square and rectangular hollow sections (RHS) has been reported and discussed for some time [21]. In the last decade the incidence has increased in North America and Asia, particularly during hot-dip galvanizing, where the problem has been generally attributed to Liquid Metal Embrittlement (LME) in association with very high residual stresses in the cold-formed RHS corners. Although this phenomenon is deemed a "rare but important issue" in Europe [22], the plethora of reports and studies published post-2000 substantiates this widespread problem (e.g. [23]). Complete structures made of galvanized RHS have even been condemned due to cracking, such as sign bridges in British Columbia, Canada, in 2006.

The occurrence of RHS corner cracking during hot-dip galvanizing seems to have become more prevalent since tin and bismuth were added to the zinc bath mixture by the dominant supplier, Teck Cominco, with the launch of a new coating system *BritePlus*™ that "enhances coating quality while producing a bright spangled appearance". Teck Cominco was blamed for causing this change in the ability to galvanize, but the interaction of three conditions determines the occurrence of LME [24]:

- A critical level of internal material stress (e.g. very high levels of residual stress due to severe cold working and welding) – see Section 2.1 below.
- A susceptible material (e.g. non-aluminium killed coil, high yield-to-ultimate stress ratio, pre-existing microcracks in the metal as a result of forming, adverse chemical composition) – see Section 2.2.
- Liquid metal, especially with the presence of impurities or additives.

Teck Cominco duly undertook some experimental research [25] into the galvanizing of contemporary RHS (127 x 76 x 9.5 mm), concluding that the dominant factor affecting cracking upon galvanizing was the RHS itself. Galvanizing bath chemistry did have a lesser effect, but only on already-susceptible RHS. The use of pre-galvanizing stress-relieving was also shown to be effective in retarding the incidence of cracking. However, experience in Canada has shown that corner cracking can still occur with CSA Class H RHS [9], which is stress-relieved to 450°C (Section 1.2). The ASTM document catering to LME on galvanizing [26] advises that … "for heavy cold deformation exemplified by cold rolling … subcritical annealing temperatures from 650 to 705°C should be employed". HSS manufacturers are aware of this potential cracking, but there is no definitive guidance on this issue from structural steel associations.

2.1 RHS production method

Corner cracking can be avoided by using hot-finished (or "hot-formed" and seamless) RHS, as these products have inherently better grain structure and superior mechanical properties compared to their cold-formed counterparts, but hot-finished RHS is either unavailable in much of the world or prohibitively expensive. With cold-formed RHS the tightness of the corner radii is critical. Kinstler [23] pointed out that … "the amount of cold work, as measured by the bending radius, is the most important single factor to consider when there is concern for brittle-type failure of steel galvanized after cold working".

In Europe, both the production standard EN10219 [17] and the structural steel design code Eurocode 3 contain requirements for corner radii of cold-formed RHS. Table 2 shows a composite of these recommendations which have been adopted by IIW [27] and are also now part of a draft international standard (ISO 14346). The IIW [27] data in table 2 are recommended outside corner radii for welding in the zones of cold-forming without heat treatment, but the recommendations apply equally to galvanizing as both represent criteria affected by the extreme corner residual stresses induced by cold-forming. The European codes logically specify minimum outside corner radii to avoid problems with welding or cracking in the corners, but table 2 shows that the current North American standards specify just maximum outside corner radii, due to an emphasis on achieving a reliably large "flat width" dimension. North American RHS section properties are calculated based on a standard outside corner radius of 2.0 times the "design wall thickness" and an inside corner radius equal to the "design wall thickness", for all wall thicknesses. As can be seen by the IIW [27] corner requirements, producing to an outside corner radius of around 2t – for thicker-walled sections – is inviting corner cracking problems, unless there is careful control of the steel chemistry.

Table 2: Manufacturing ranges for outside corner radii of cold-formed RHS.

Specification	RHS thickness, t (mm)	Outside or External Corner radius (r_o)	
		for fully Al-killed steel ($Al \geq 0.02\%$)	for fully Al-killed steel *and* $C \leq 0.18\%$, $P \leq 0.02\%$ and $S \leq 0.012\%$
IIW [27] based on EC3 & EN 10219-2	$2.5 \leq t \leq 6$	$\geq 2.0t$	$\geq 1.6t$
	$6 < t \leq 10$	$\geq 2.5t$	$\geq 2.0t$
	$10 < t \leq 12$	$\geq 3.0t$	$\geq 2.4t$ (up to t =12.5)
	$12 < t \leq 24$	$\geq 4.0t$	–
ASTM A500	All t	$\leq 3.0t$	
CSA-G40.20/G40.21	$t \leq 3$	≤ 6 mm	
	$3 < t \leq 4$	≤ 8 mm	
	$4 < t \leq 5$	≤ 15 mm	
	$5 < t \leq 6$	≤ 18 mm	
	$6 < t \leq 8$	$\leq$ 21 to 24 mm	
	$8 < t \leq 10$	$\leq$ 27 to 30 mm	
	$10 < t \leq 13$	$\leq$ 36 to 39 mm	
	$t > 13$	$\leq 3.0t$	
AS/NZS 1163	All t, up to 50 x 50 mm	1.5t to 3.0t	
	All t, larger than 50 x 50	1.8t to 3.0t	
SANS 657-1	$t \leq 6$	1.5t to 2.5t	
	$6 < t \leq 10$	2.0t to 3.0t	
	$t > 10$	2.4t to 3.6t	
ASTM A1xxx (For perimeters ≥ 317.5mm)	$t \leq 10$	1.6t to 3.0t	
	$t > 10$	2.4t to 3.6t	

Both the Australasian [18] and the South African [19] HSS production standards specify minimum corner radii (table 2), the former permitting a very small corner radii for thick-walled sections since the tolerance range is independent of thickness, but the latter is almost identical to EN 10219-2 [17]. Most standards acknowledge that the RHS sides need not be tangential to the corner arcs (i.e. the RHS corner sweeps out an angle less than 90^o). In such cases the outside corner radius requirement becomes an "external corner profile" requirement, with the latter applying to r_o, c_1 or c_2, where c_1 and c_2 are dimensions measured from the RHS outside of one flat wall to the end of the "flat" on the adjacent wall.

Tolerances for local surface imperfections (such as gouges or grooves) are usually provided in HSS standards, typically as a percentage of the wall thickness, with permissible repair procedures. However, micro-cracks in the corners of RHS – pre-existing in the coil material or produced during cold-forming of the RHS – are another issue that is not covered by HSS manufacturing specifications. The presence of micro-cracks in the corners may have a dramatic influence if the RHS is subsequently hot-dip galvanized.

2.2 Chemical composition of steel

Although all modern steels used for HSS are presumed to be fully-killed, the chemistry of the input material is vital to ensuring a quality product with the expected mechanical properties. The permitted amounts (by weight) of key chemical ingredients, by cast or heat analysis, for popular grades of prominent HSS specifications show many similarities, but the current ASTM specifications are notable for containing little prescription, particularly with regard to silicon (discussed below). The chemical compositions do not provide a sufficient recipe for achieving the desired mechanical properties in many cases, as a low carbon, micro-alloyed input steel is needed for “higher performance” HSS.

3 SUITABILITY OF COLD-FORMED RHS FOR GALVANIZING

This topic is generally avoided altogether in HSS manufacturing specifications, or blanket statements are given such as in EN10219 … “the products shall be suitable for hot dip galvanizing” [16]. Both the South African [19] and Australasian [18] standards discuss suitability for hot-dip galvanizing, if galvanizing is required by the purchaser, and AS/NZS even goes as far as recommending that a sample be hot-dip galvanized to determine its actual performance for a given bath and tube characteristics. The problem with such a purchaser-driven approach is that most HSS produced internationally is sold to stock-holders, so the end user or fabricator does not usually interact with the manufacturer at the time of production. The ASTM document catering to LME on galvanizing [26] states that … “a cold bending radius of three times the section thickness … will ordinarily ensure satisfactory properties in the final product”. However, this cautious advice is a blanket provision, regardless of metallurgical content.

With hot-dip galvanizing, the piece is normally dipped in molten zinc at a temperature that can vary from 440 to 465^{o}C. The zinc temperature and immersion time do influence the thickness of the zinc coating obtained, but the most critical factor is the steel chemical composition and in particular the silicon content. The American Galvanizing Association recommends the following for good coatings:

- C < 0.25%; P < 0.04% and Mn < 1.35%
- Si < 0.04% *or* 0.15% < Si < 0.22%.

The Silicon range above specifically avoids 0.04% < Si < 0.15%, a zone of high reactivity termed the “Sandelin effect”. The Australasian HSS standard [18] also notes that caution should be exercised for 0.04% < Si ≤ 0.14%. Fully Al-killed steels are now commonplace so Si levels can now be easily manipulated, with low silicon content also helping to avoid corner cracking. A further qualification sometimes added to the silicon level is for (Si + 2.5P) ≤ 0.07 to 0.09 (the latter being cited in AS/NZS 1163 for use with low Si levels), but this does result in relatively thin zinc coatings, of around 80 μm.

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