



Coeur Défense atrium, Paris, France  
Architect: J.P. Viguier



Florida Exhibit, Festival of Speed 2005, Goodwood, Sussex, England  
Architect: Gerry Judah ; Engineer: NRM Bobrowski

## ELLIPTICAL HOLLOW SECTIONS THREE-PART SERIES PART ONE: PROPERTIES AND APPLICATIONS

Jeffrey A. Packer

**E**lliptical Hollow Sections are the newest members of the family of manufactured steel tubes. Being different, these tubes just look modern and they offer additional scope for visual expression.

Elliptical Hollow Sections (EHS) began initially with Circular Hollow Sections (CHS) and then expanded to include Square and Rectangular Hollow Sections (SHS and RHS, respectively). EHS have been produced in Europe since 1994. The use of this product has steadily grown, with architects employing EHS in many structures utilizing Architecturally Exposed Structural Steel (AESS). The principal application of EHS initially was as structural supporting members for glass roofs and glass façades, such as the Coeur Défense atrium. In this building the EHS strong axis for bending is oriented towards the imposed load. If viewed through a glazed wall a minimal member width is then seen.

### THE PRODUCT

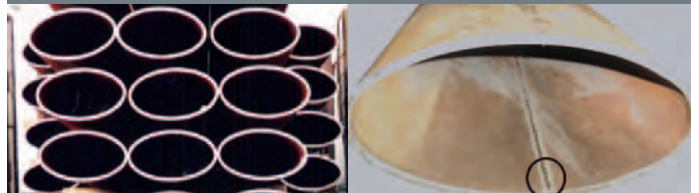
All EHS are produced, with major-to-minor axis dimensions of 2:1, as hot finished hollow structurals. They are produced as continuously welded sections, joined by high frequency induction welding and finished to final shape at extremely high (normalizing) temperatures, with the outside weld bead removed but the inside weld bead typically left in place. Due to the hot finishing process EHS have a fine grain structure, uniform mechanical properties, excellent weldability, negligible residual stress, are suitable for hot-dip galvanizing and are applicable for dynamic loading situations. As a mark of their acceptance into the community of hollow sections, the most recent European production standard for hot finished structural hollow sections includes EHS in the scope.

### APPLICATIONS

Architects have found novelty in using EHS for columns in Europe – and also in Canada too. The Legends Centre in Oshawa Ontario, as well as the Electronic Arts stair in Vancouver, have both won CISC Steel Design Awards. Another project specifying EHS at the moment is the CANMET Materials Testing Laboratory at the McMaster Innovation Park in Hamilton, Ontario, designed by Diamond + Schmitt (Architects) and Read Jones Christoffersen

### PROPERTIES

EHS are hot finished hollow structural section produced to EN 10210 (CEN 2006a, 2006b). They are available in the grade S355J2H which has a minimum yield strength of 355 MPa up to 16mm wall thickness (the current limit of availability) and a Charpy impact resistance of 27 Joules at -20° C. Being manufactured only by the hot finishing process, EHS thus meet CAN/CSA-G40.20-04/G40.21-04 Grade 350WT Class H Category 2 (CSA 2004) or ASTM A501 Grade B (ASTM 2007) in North America.



Elliptical Hollow Sections are produced with an aspect ratio of 1 to 2. The weld bead is present on the inside only.

(Structural Engineers). These members will be exposed, skewed columns in the central atrium, with an elliptical-shaped steel stair wrapping around them. EHS have also been used in bridges such as the Society Bridge in Scotland, as an alternative section for enhancing the visual appeal. EHS also appear in novel steel "sculptures" or works-of-art such as the Honda Exhibit at the "Festival of Speed" in England. It is possible to fill EHS with concrete and to even obtain stainless steel oval sections. Concrete-filling results in greater axial load capacity, and greater ductility, compared to empty EHS; a feature that can be employed with EHS columns perhaps, if the upper size range proves insufficient in compression.



Society Bridge, Braemar, Scotland

Their use is new but the novelty is unlikely to wear off as more architects start to specify EHS in Architecturally Exposed Structural Steel applications. This first article is an introduction to the product. The next two articles will deal with Member Design and Connection Design. Stay tuned!

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### PRODUCERS

EHS are produced by Tubeurop in France (which became a part of Arcelor Tubes, which in turn became a part of Grupo Condesa, headquartered in Spain). Their product sizes range from 120 x 60 x 3.2 up to 480 x 240 x 14.2 ([www.condesa.com](http://www.condesa.com)). Other producers in Europe now include Corus Tubes in the U.K. where the product range, marketed as Celsius® 355 Ovals (OHS), is standardized on six tube sizes ranging from 150 x 75 x 4.0 to 500 x 250 x 16 ([www.corusconstruction.com](http://www.corusconstruction.com)). This supplier even has a North American agent (Brad Fletcher: [brad.fletcher@corusgroup.com](mailto:brad.fletcher@corusgroup.com); Tel: 847-592-3712) to handle imports. Another manufacturer in Europe is Ancofer Stahlhandel GmbH ([www.ancofer.de](http://www.ancofer.de)) in Germany, with the same product range as Condesa.

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## ELLIPTICAL SECTIONS THREE-PART SERIES PART TWO: EHS MEMBER DESIGN

Jeffrey A. Packer

In Part One of this series, properties and applications of a new steel section on the market were presented. There is no doubt that many of our readers were excited to see these unique Elliptical Hollow Sections (EHS), perhaps for the first time. With a few Canadian applications already visible – as shown above with the Telus Atrium – architects are likely going to want to use them more often. Engineers will surely share their enthusiasm once they know how they can design them. Where can one find the properties and dimensions of EHS? How does one determine their slenderness? To what extent is their resistance in compression and bending different to Rectangular or Circular Hollow Sections (RHS and CHS)? How does one connect them?

The design of compression and flexural members requires knowledge of the cross-section classification. However, this is not covered by any current code, specification or standard at present. Fortunately, a Table of 46 shapes has been developed at the University of Toronto to provide engineering properties of EHS cross-sections. A sample Table is shown in this article. (The full list is available on the CISC website.) The format is very similar to the familiar Handbook of Steel Construction Tables.

The EHS section classification and member design issue has been pursued intensely by Gardner and colleagues in the U.K. and elsewhere. On the basis of experimental and numerical (finite element (FE)) studies, Gardner and colleagues have classified EHS into Classes 1, 2, 3 and 4 (per Eurocode 3 (CEN 2005)) with limiting wall slenderness ratios for various aspect ratios. Their system for cross-section classification has covered all prime loading cases: axial compression, bending about both principal axes and

combined compression plus bending. The Eurocode 3 class limits for CHS (very similar to those in Canada (CSA 2009)) were shown to be applicable to EHS if the EHS was treated as a CHS with an equivalent diameter of  $D_e$ . Two definitions of  $D_e$  have been used in the literature, which are herein termed  $D_{e, old}$  and  $D_{e, new}$ , defined by:

$$D_{e, old} = 2a (a / b) \text{ for axial compression and minor axis bending} \quad (1)$$

$$D_{e, old} = 1.3a (a / b) \text{ for major axis bending, with aspect ratios of 2:1} \quad (2)$$

$$D_{e, new} = 2a (1 + f [a / b] - 1) \text{ for axial compression,} \quad (3)$$

$$D_{e, new} = 0.8a (a / b) \text{ for major axis bending, with aspect ratios of 2:1} \quad (4)$$

$$\text{with } f = 1 - 2.3 (t / 2a)^{0.6} \quad (5)$$

where  $a$  is half the larger EHS dimension and  $b$  is half the smaller EHS dimension, as illustrated in the schematic. That figure also illustrates the diameter of equivalent CHS ( $D_{e, old}$  and  $D_{e, new}$ ) for axial loading on an EHS with dimensions of  $2a \times 2b$  and of medium wall slenderness ( $2a/t = 35$ ). The equivalent diameters can be seen to be much larger than the major dimension ( $2a$ ) of the EHS. Thus, by taking the less conservative of Gardner's two approaches for axial compression loading, an EHS cross-section could be deemed to be non-slender (not "Class 4") providing (interpreting Table 1 of CSA-S16-09):

$$D_{e, new} / t \leq 23\,000 / F_y \quad \text{or} \quad 2a (1 + f [a / b] - 1) / t \leq 23\,000 / F_y \quad (6)$$

If one, however, looks at the local buckling failure mode of a typical EHS stub column in compression (see laboratory image), it resembles plate buckling more than cylinder (shell) buckling.

Thus, it was deemed that an “equivalent RHS shape” might be a better transformation of the elliptical tube, for the purpose of cross-section classification. Packer and colleagues proposed an equivalent RHS depth ( $D_{e, RHS}$ ) equal to  $2a$ , while the width of the equivalent RHS was determined using the condition of maintaining the same cross-sectional area. This equivalent RHS shape is also shown in the schematic. It was possible to demon-

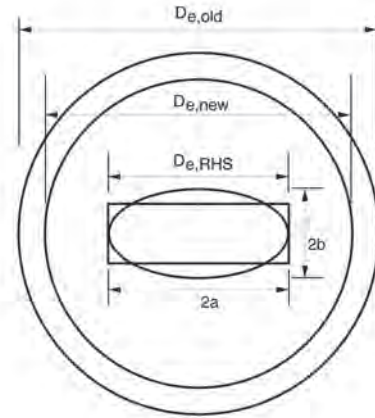


EHS stub column after failure, by inelastic local buckling or “squashing”; this mode of failure resembles plate buckling more than cylinder (shell) buckling.

strate that this “equivalent RHS” approach was a good estimator of whether EHS axially-compressed stub columns fail by yielding (squashing) or elastic local buckling, when compared with test results by Packer and colleagues as well as all others available internationally. In fact, the correlation with test results – using either the Eurocode 3 (CEN 2005) or CSA S16 (CSA 2009) “Class 4” slenderness limit – was better for the “equivalent RHS” approach than for either of the “equivalent CHS” approaches. Thus, elastic local buckling was shown to be avoided if (interpreting Table 1 of CSA-S16-09):

$$(D_{e, RHS} - 4t) / t \leq 670 / \sqrt{F_y} \quad \text{or} \quad (2a - 4t) / t \leq 670 / \sqrt{F_y} \quad (7)$$

The schematic, the laboratory results and the foregoing experimental validation for the axial compression loading case, suggest promise for the “equivalent RHS” method of handling elliptical cross-sections. Interestingly, if one applies the cross-section classification limits of equations (6) and (7) to the 46 shapes



Schematic of equivalent CHS diameters and equivalent RHS depth, for EHS in axial compression (for  $a/b = 2$  and  $2a/t = 35$ )

available, one obtains almost identical consensus: by equation (6) 9 EHS are slender, and by equation (7) 8 EHS are slender, with the slender cross-sections generally occurring in large depth EHS.

The concept of applying the “equivalent RHS” method to define EHS members as Class 1, 2, 3 or 4 in *flexure* has been checked against available experimental data (18 tests by Chan and Gardner). For major axis bending the “equivalent RHS” approach is more accurate than the “equivalent CHS” approach. For minor axis bending (less common) the opposite is true, but the “equivalent RHS” approach is very conservative.

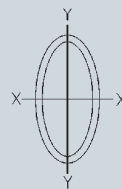
Hence, should engineers be faced with designing such a shape, two alternatives can be considered: the equivalent CHS or the equivalent RHS approach. At present, it appears that an equivalent rectangular shape shows the most promise for sizing a member. But what about connecting an EHS to another EHS? Current state of research will be presented in the next and third article on Elliptical Hollow Sections.

## HOLLOW STRUCTURAL SECTIONS CSA G40.20 Elliptical

### PROPERTIES AND DIMENSIONS

Designation	Wall Thickness	Mass	Dead Load	Area	Axis X-X				Axis Y-Y				Torsion Inertia Constant	Torsion Modulus Constant	Surface Area
					$I_x$	$S_x$	$r_x$	$Z_x$	$I_y$	$S_y$	$r_y$	$Z_y$			
mm x mm x mm	mm	kg/m	kN/m	mm <sup>2</sup>	10 <sup>6</sup> mm <sup>4</sup>	10 <sup>3</sup> mm <sup>3</sup>	mm	10 <sup>3</sup> mm <sup>3</sup>	10 <sup>6</sup> mm <sup>4</sup>	10 <sup>3</sup> mm <sup>3</sup>	mm	10 <sup>3</sup> mm <sup>3</sup>	10 <sup>6</sup> mm <sup>4</sup>	10 <sup>6</sup> mm <sup>3</sup>	m <sup>2</sup> /m
EHS 500x250 x12.5	12.50	112	1.10	14 200	350	1 400	157	1 960	118	943	91.0	1 200	353 000	2 110	1.21
EHS 320x160 x10	10.00	56.7	0.556	7 230	71.8	449	99.7	631	23.9	299	57.5	385	71 900	665	0.776
EHS 250x125 x10	10.00	43.8	0.429	5 580	33.2	265	77.1	376	10.9	174	44.2	228	32 900	385	0.605
EHS 200x100 x8	8.00	28.0	0.275	3 570	13.6	136	61.7	193	4.46	89.3	35.4	117	13 500	197	0.485

Sample Handbook Style Table of EHS Engineering Properties



The full list of References and the complete Table of Engineering Properties for the 46 EHS shapes are available on the CISC website: [www.cisc-icca.ca/publications/advantagesteel/36](http://www.cisc-icca.ca/publications/advantagesteel/36)

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Terril Meyer Bookie

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## ELLIPTICAL SECTIONS THREE-PART SERIES PART THREE: EHS CONNECTION DESIGN

Jeffrey A. Packer

In Part II, we examined member design of elliptical sections. In Part III, the last of the series, we take a closer look at connection design of EHS. As with member design, every attempt is made to simplify and rely on what is familiar. In fact, many conventional limit state failure models can still be applied to EHS connections. For example, research on gusset plate to slotted end EHS welded connections (Figure 1) has shown that the failure modes of circumferential fracture of the tube and tear out (or “block shear”) of the tube – well recognized for slotted end CHS and RHS connections – are still applicable to EHS too, and efficient design recommendations have been advocated.

Directly welded tube-to-tube connections always represent a potential problem in tubular construction, due to the high flexibility of the hollow section walls, and recently some tests on welded EHS-to-EHS connections have been performed. Bortolotti et al. and Pietrapertosa and Jaspart undertook the first laboratory tests, in Belgium, on truss-type N- and X- connections, with EHS branches welded to the wide side of the EHS chord, followed by numerical modelling of the same connections. Choo et al. in Singapore extended the finite element modelling of EHS-to-EHS X-connections by studying branches welded to both the wide and narrow sides of the chord, and with the branch also oriented in both orthogonal directions for each chord orientation.



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A recent study in Canada on EHS connections consisted of branch plates and through plates (both longitudinal and transverse) welded to both the wide and narrow sides of an EHS chord member (Willibald et al.), as shown in Figure 2. In the analysis of these tests, the notion of using “equivalent CHS” or “equivalent RHS” dimensions for transforming elliptical shapes was attempted. The design of CHS and RHS welded connections is now based on over 40 years of international research, so the prospect of repeating this research volume for EHS members is daunting – hence the quest to relate the design of welded EHS-to-EHS

connections to other well-established design procedures for hollow steel sections.

### FUTURE RESEARCH

Interest in EHS behaviour in compression has also now extended to concrete-filled sections (Yang et al.; Zhao and Packer) and even stainless steel oval sections (Theofanous et al.). As might be expected, it has been shown that concrete-filled EHS provide much greater axial load capacity, and greater ductility, compared to empty EHS; a feature that can be employed with EHS columns perhaps, if the upper size range proves insufficient. Research on welded EHS-to-EHS connections is still continuing at the University of Toronto; this is currently focussed on truss-type T- and X-connections (Figure 3) and is being performed by Ms. Tarana Haque. So, architects may soon be venturing into exotic elliptical tube trusses and even bolder AESS statements.

### ACKNOWLEDGEMENTS

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Figure 1: Gusset plate-to-slotted EHS connection under axial tension – slot end open (University of Toronto)

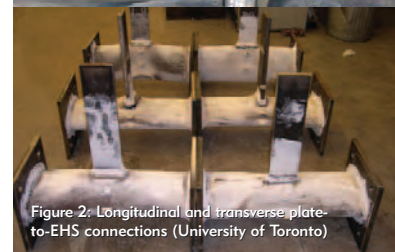


Figure 2: Longitudinal and transverse plate-to-EHS connections (University of Toronto)

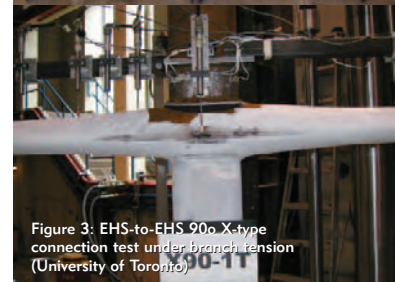


Figure 3: EHS-to-EHS 90° X-type connection test under branch tension (University of Toronto)