J. Wardenier

HOLLOW SECTIONS IN STRUCTURAL APPLICATIONS

CIDECT

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J. Wardenier

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PREFACE

Professor Jaap Wardenier has had an enormous impact on the design methods for tubular steel structures in the late 20th. century. The Rectangular Hollow Section is veritably his progeny and it has grown up to be a respectable member of the steel society under his tutelage. Indeed, his output has been so prolific that all subsequent researchers on Rectangular Hollow Sections might well be deemed but footnotes to Wardenier.

Professor Wardenier is universally renowned for his leadership role in international unity efforts to standardize hollow section design rules, particularly while Chair of the International Institute of Welding (IIW) Subcommission XV-E on Tubular Structures, from 1981 to 1991. Similarly, his constant support of CIDECT activities over three decades, whether serving as a Member or Chair of Working Groups, and Member or Chair of the Technical Commission, has been a vital component of its success.

In the 1980s and 1990s a number of technical books and guides for design with hollow sections have been produced, beginning of course with his own landmark treatise, *"Hollow Section Joints"*, in 1982. These books and guides were almost totally directed at the practicing engineer and the complexity of the formulations is perplexing to the novice. So, it is quite fitting that - having scaled to the top of the research mountain - Professor Wardenier can see the big picture so well that he can now paint a smaller version for the newcomer to the field, the student. This book hence fits this role admirably and this "text for students" is a much-needed contribution to the literature on tubular steel structures. The content and presentation is generally oriented to "graduate level" structural engineering students, or those in about Year 5 of their university studies. In addition to being invaluable for a specialist course on "Tubular Steel Structures", parts of the book would be excellent for more introductory-level courses on steel behaviour and design. Aside from succinctly telling the important principles for the behaviour of tubular structures, the book is nicely presented with numerous colour illustrations. The material included is an international consensus of knowledge on the topic at the turn of the Millenium: as such it is an ideal reference book too for all structural design engineers, as well as being a "student text".

Professor Jeffrey A. Packer
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Mr. Noel F. Yeomans
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March 2002.

Acknowledgement

This book serves as a background for students in Structural and Civil Engineering.
Since the available hours for teaching Steel Structures and particularly Tubular Structures vary from country to country, this book has been written in a modular form. To cover the needs in the various countries, a committee was established to review the material. Although the material is mainly based on the Eurocodes, the setup makes it easy to change the lectures and relate them to other (national) codes.

I wish to thank the review committee for their constructive comments during the preparation of this book. In particular I would like to thank my colleagues Prof. Packer, Prof. Puthli and Mr. Yeomans for their very detailed checks and suggestions. I am very grateful that Prof. Packer was willing to check the language in detail.

Appreciation is further extended to the authors of the various CIDECT Design Guides and to CIDECT itself for making parts of these design guides or background information for this book available.

Grateful acknowledgement is made to the contributions of Delft University of Technology in particular for the typing by Mrs van der Wouden and the excellent preparation of the figures and the layout by Dr. Liu.

Last but not least appreciation is extended to Mr. C. H. van Eldik of Bouwen met Staal for the finishing touch of the layout.

Finally, I wish to thank CIDECT for the initiative and sponsoring of this book and the production of a CD-ROM.

Delft, March, 2002
J. Wardenier

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1. INTRODUCTION

Design is an interactive process between the functional and architectural requirements and the strength and fabrication aspects. In a good design, all these aspects have to be considered in a balanced way. Due to the special features of hollow sections and their connections it is even here of more importance than for steel structures of open sections. The designer should therefore be aware of the various aspects of hollow sections.

Many examples in nature show the excellent properties of the tubular shape with regard to loading in compression, torsion and bending in all directions, see Figs. 1.1 and 1.2. These excellent properties are combined with an attractive shape for architectural applications (Figs. 1.3 and 1.4). Furthermore, the closed shape without sharp corners reduces the area to be protected and extends the corrosion protection life (Fig. 1.5).

Another aspect which is especially favourable for circular hollow sections is the lower drag coefficients if exposed to wind or water forces. The internal void can be used in various ways, e.g. to increase the bearing resistance by filling with concrete or to provide fire protection. In addition, the heating or ventilation system sometimes makes use of the hollow section columns.

Although the manufacturing costs of hollow sections are higher than for other sections, leading to higher unit material cost, economical applications are achieved in many fields. The application field covers all areas, e.g. architectural, civil, offshore, mechanical, chemical, aeronautical, transport, agriculture and other special fields. Although this book will be mainly focused on the background to design and application, in a good design not only does the strength have to be considered, but also many other aspects, such as material selection, fabrication including welding and inspection, protection, erection, in service inspection and maintenance.

One of the constraints initially hampering the application of hollow sections was the design of the joints. However, nowadays design recommendations exist for all basic types of joints, and further research evidence is available for many special types of joints.

Based on the research programmes carried out, CIDECT (Comité International pour le Développement et l'Etude de la Construction Tubulaire) has published design guides [1 to 8] for use by designers in practice. Since these design guides are all together too voluminous for education purposes and do not provide the theoretical background, it was decided to write this special book as a background for students in structural and civil engineering.

1.1 HISTORY AND DEVELOPMENTS

The excellent properties of the tubular shape have been recognised for a long time; i.e. from ancient time nice examples are known. An outstanding example of bridge design is the Firth of Forth Bridge in Scotland (1890) with a free span of 521 m, shown in Fig. 1.6. This bridge has been built up from tubular members made of rolled plates which have been riveted together, because other fabrication methods were at that time not available for these sizes.

In that century the first production methods for seamless and welded circular hollow sections were developed. In 1886, the Mannesmann brothers developed the skew roll piercing process (Schrägwalzverfahren), shown in Fig. 1.7, which made it possible to roll short thick walled tubulars.

This process, in combination with the Pilger Process (Pilgerschrittverfahren, Fig. 1.8), developed some years later, made it possible to manufacture longer thinner walled seamless hollow sections.

In the first part of the previous century, the Englishman Whitehouse developed the fire welding of circular hollow sections. However, the production of welded circular hollow sections became more important after the development of the continuous weld process in 1930 by the American Fretz Moon (Fig. 1.9). Especially after the Second World War, welding processes have been perfected, which made it possible for hollow sections to be easily welded together.

The end cutting required for fitting two circular hollow sections together was simplified considerably by the development by Müller of a special end preparation machine (Fig. 1.10).

For manufacturers who did not have such end cutting machines, the end preparation of circular hollow sections remained a handicap.

A possibility to avoid the connection problems was the

use of prefabricated connectors, e.g. in 1937 Mengeringhausen developed the Mero system. This system made it possible to fabricate large space structures in an industrialized way (Fig. 1.11).
In 1952 the rectangular hollow section was developed by Stewarts and Lloyds (now Corus Tubes). This section, with nearly the same properties as the circular hollow section, enables the connections to be made by straight end cuttings.

In the fifties, the problems of manufacturing, end preparation and welding were solved and from this point of view the way to a successful story was open. The remaining problem was the determination of the strength of unstiffened joints.

The first preliminary design recommendations for truss connections between circular hollow sections were given by Jamm [45] in 1951. This study was followed by several investigations in Japan [46,47], the USA [48,49,50] and Europe [30,32,33,35,38,39,40,42,44]. The research on connections between rectangular hollow sections started in Europe in the sixties, followed by many other experimental and theoretical investigations. Many of these were sponsored by CIDECT. Besides these investigations on the static behaviour, in the last 25 years much research was carried out on the fatigue behaviour and other aspects, such as concrete filling of hollow sections, fire resistance, corrosion resistance and behaviour under wind loading.

1.2 DESIGNATION

The preferred designations for structural applications are:

- structural hollow sections (SHS)
- circular hollow sections (CHS)
- rectangular hollow sections (RHS)

In Canada and the USA it is common to speak about Hollow Structural Sections (HSS) instead of (SHS).

1.3 MANUFACTURING OF HOLLOW SECTIONS

As mentioned, hollow sections can be produced seamless or welded. Seamless hollow sections are made in two phases, i.e. the first phase consists of piercing an ingot and the second one consists of the elongation of this hollow bloom into a finished circular hollow section. After this process, the tube can go through a sizing mill to give it the required diameter. Besides the Mannesmann process, other processes are used, most of them based on the same principle [31,32].

Nowadays, welded hollow sections with a longitudinal weld are mainly made with electrical resistance welding processes or with an induction welding process, shown in Fig. 1.12. A strip or plate is shaped by rollers into a cylindrical shape and welded longitudinally. The edges are heated e.g. by electrical resistance. The rollers push the edges together, resulting in a pressure weld. The outer part of the weld is trimmed immediately after welding.

Rectangular hollow sections are made by deforming circular hollow sections through forming rollers, as shown in Fig. 1.13. This can be done hot or cold and seamless or longitudinally welded circular hollow sections can be used.
It is common practice to use longitudinally welded hollow sections. For the very thick sections, seamless sections may be used.

Square or rectangular hollow sections are sometimes made by using channel sections, which are welded together or by shaping a single strip to the required shape and closing it by a single weld, preferably in the middle of a face.

Large circular hollow sections are also made by rolling plates through a so-called U-O press process shown in Fig. 1.14. After forming the plates to the required shape, the longitudinal weld is made by a submerged arc welding process.

Another process for large tubulars is to use a continuous wide strip, which is fed into a forming machine at an angle to form a spirally formed circular, see Fig. 1.15. The edges of the strip are welded together by a submerged arc welding process resulting in a so-called spirally welded tube.

More detailed information about the manufacturing processes and the limitations in sizes can be obtained from [31,32].

Fig. 1.1 Reeds in the wind

Fig. 1.2 Bamboo

Fig. 1.3 Pavilion in Seville

Fig. 1.4 Movable Bridge, Delft

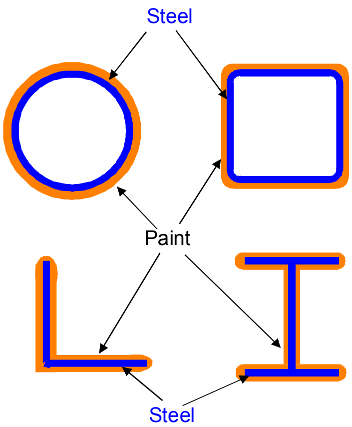


Fig. 1.5 Paint surface for hollow sections vs open sections

Fig. 1.6 Firth of Forth bridge

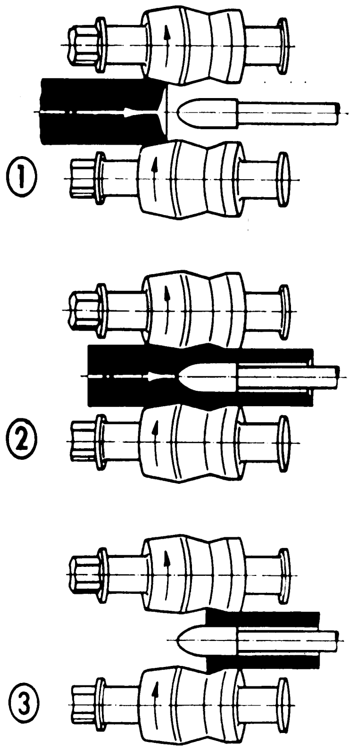


Fig. 1.7 Skew roll piercing process (Schrägwalzverfahren)

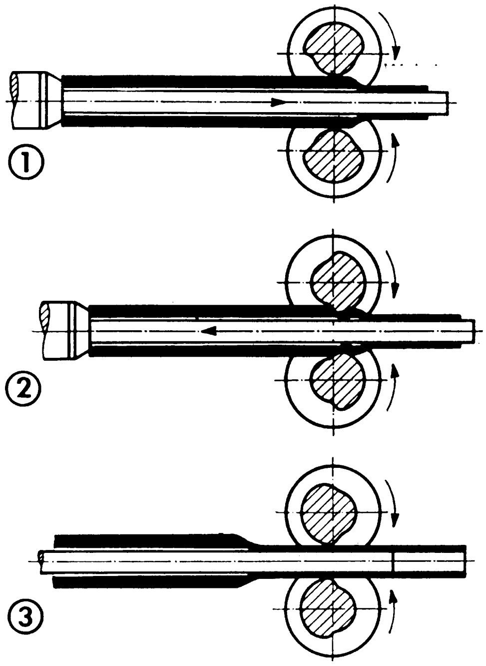


Fig. 1.8 Pilger Process (Pilgerschritt)

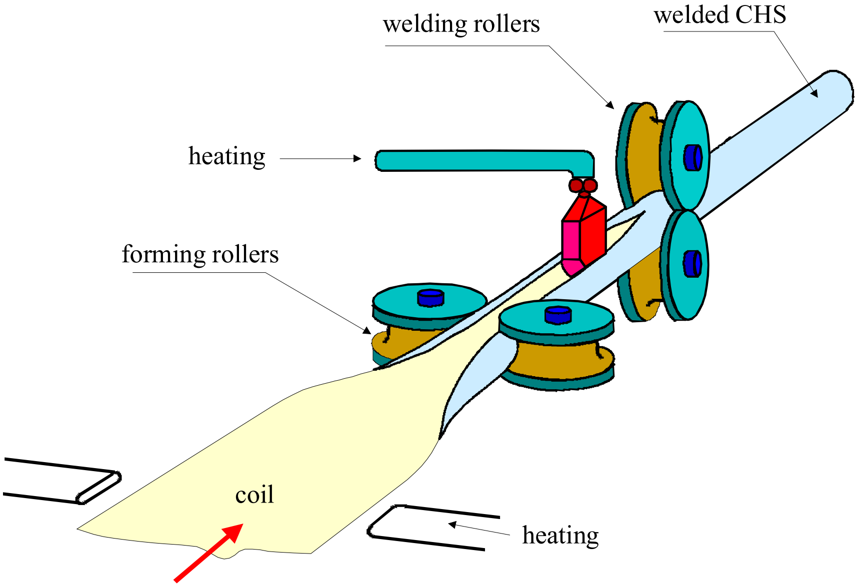


Fig. 1.9 Fretz Moon process

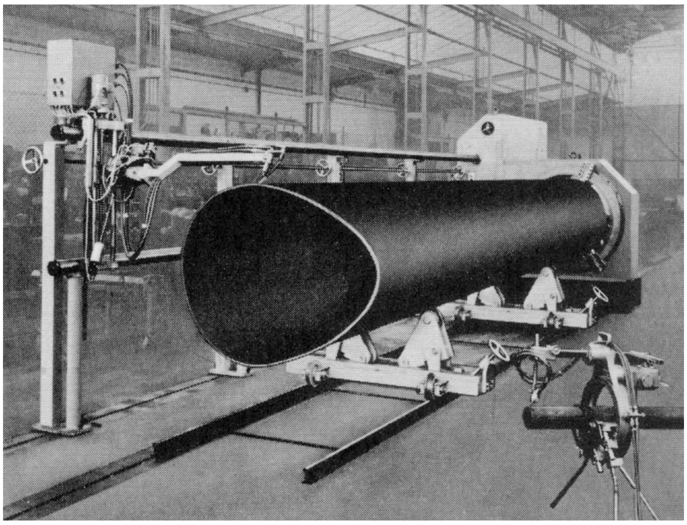


Fig. 1.10 End cutting machine

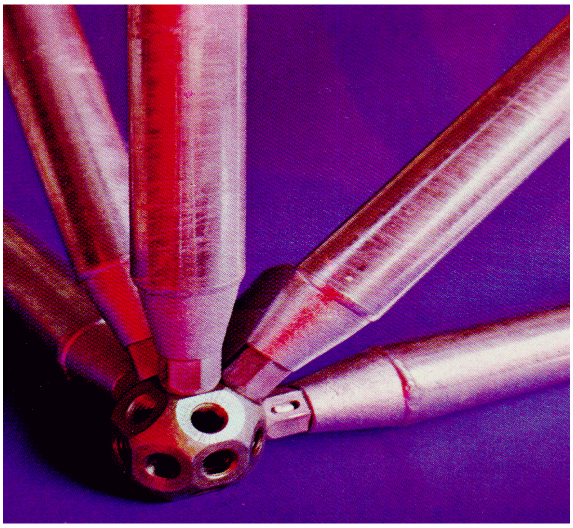


Fig. 1.11 Mero connector

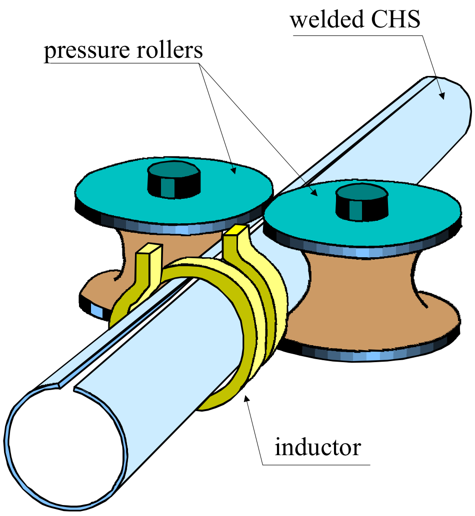


Fig. 1.12 Induction welding process

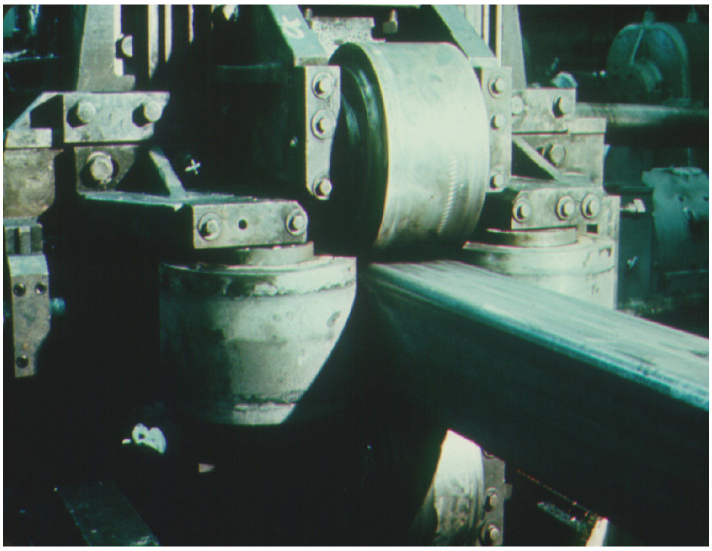


Fig. 1.13 Manufacturing of rectangular hollow sections

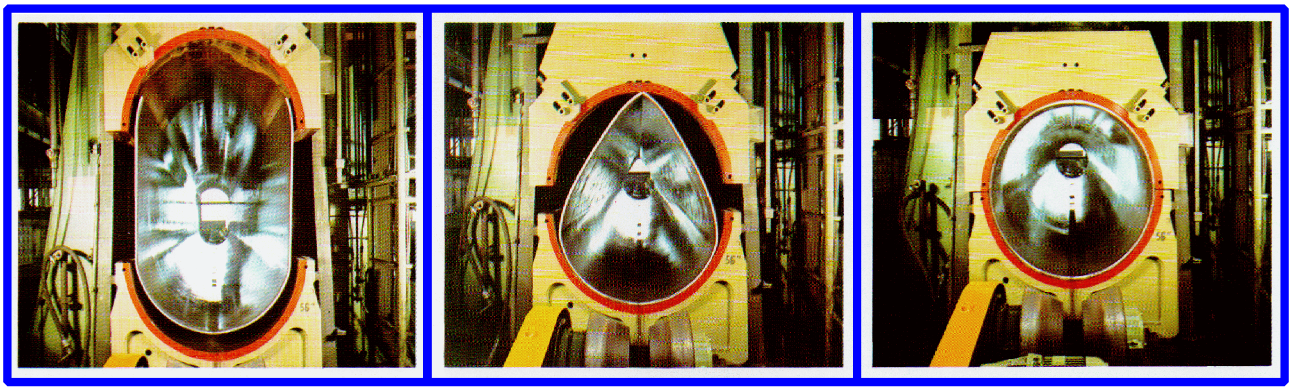


Fig. 1.14 Forming of large CHS

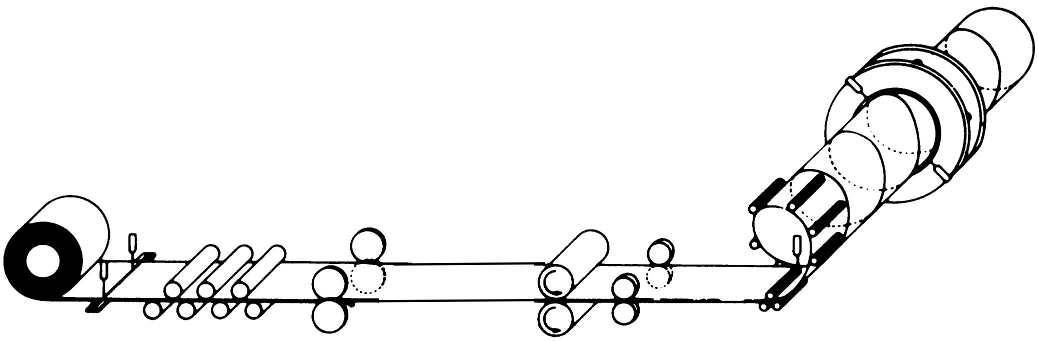


Fig. 1.15 Spirally welded CHS

2. PROPERTIES OF HOLLOW SECTIONS

2.1 MECHANICAL PROPERTIES

Hollow sections are made of similar steel as used for other steel sections, thus in principle there is no difference, and the mechanical properties are given in standards [26 to 29].
Tables 2.1a and 2.2a show, as an example, the mechanical properties according to the European standard EN 10210-1 for hot finished structural hollow sections of non-alloy and fine grain structural steels. The cold formed sections are given in EN 10219-1: Cold formed welded structural hollow sections of non-alloy and fine grain structural steels (see tables 2.1b and 2.2b). As shown, the requirements of EN 10210-1 and EN 10219-1 are almost identical.

Hollow sections can also be produced in special steels, e.g. high strength steel with yield strengths up to 690 N/mm^2 or higher, weathering steels and steel with improved or special chemical compositions, etc.

Generally, the design of members is based on yield, since the deformation under loads becomes excessive. In statically indeterminate structures, yielding of members or yielding at particular locations provides redistribution of loads. In this case, sufficient deformation capacity or rotation capacity is required. E.g. a tensile member made of ductile steel can be brittle if a particular cross section is weakened, e.g. by holes in such a way that this cross section fails before the whole member yields. It is therefore required that yielding occurs first. This shows that the yield to ultimate tensile strength ratio is also important, especially for structures with very non uniform stress distributions, which is a situation that occurs in tubular joints. Some codes, such as Eurocode 3 [12], require the following condition for the specified minimum values:

$$\frac{f_u}{f_y} \geq 1.2 \qquad (2.1)$$

This is only one aspect for ductility. In the case of impact loading, the steel and members should also behave in a ductile manner. That is why a requirement based on the standard Charpy test is also given in tables 2.1.a and 2.2.a.

Nowadays, more refined characterisation methods also exist to characterise the ductility of cracked bodies, e.g. the CTOD (Crack Tip Opening Displacement) method. These characterisation methods are generally used for pressure vessels, transport line pipes and offshore applications, which are beyond the scope of this book.

Another characterisation is sometimes required for thick walled sections which are loaded in the thickness direction. In this case, the strength and ductility in the thickness direction should be sufficient to avoid cracking, called lamellar tearing, see Fig. 2.1.
This type of cracking is caused by non metallic manganese-sulphide inclusions. Thus, if the sulphur content is very low or the sulphur is joined with other elements such as calcium (Ca), such a failure can be avoided.
Indirectly this is obtained by requiring a certain reduction of area R_{AZ} in the tensile test. For example, R_{AZ} = 35 means that in the tensile test the cross sectional area at failure has been reduced by 35% compared to the original cross sectional area.

In most structural steel specifications the yield strength, ultimate tensile strength, elongation and in some specifications also the Charpy V values are specified. Design standards or specifications give further limitations for the f_u/f_y ratio, whereas depending on the application more restrictive requirements may be given related to CTOD values or the properties in the thickness direction (Z quality).
Another aspect is the effect of cold forming on the mechanical properties of the parent steel. In the case of cold forming of hollow sections, the yield strength and to a lesser extent the ultimate tensile strength are increased, especially in the corners, as shown in Fig. 2.2. Further, the yield to ultimate tensile ratio is increased and the elongation somewhat decreased.
If the specifications specify the properties based on the finished product, these properties have been already taken into account. However, some specifications specify the material properties of the parent material. In this case, the increased yield strength can be taken into account for design.

The method for the determination of the increased yield strength given in Eurocode 3 is based on the work of Lind and Schroff [51]. Here it is assumed that the product of the cold formed area times the increase of yield strength is nearly constant. Thus, a small corner radius produces a small cold formed area with a large cold forming effect and consequently a large increase

in yield strength, and a large corner radius does just the opposite. Based on research work [51] it can be assumed that in every corner of 90° the yield strength f_{yb} is increased over a length of 7t to the ultimate tensile strength of the parent material. The total increase over the section $4(7t)t(f_u-f_y)$ can be averaged over the section, resulting in an average yield strength f_{ya}, as shown in table 2.3 and Fig. 2.2.
In those cases where the RHS sections are made from a CHS section a considerable increase in yield strength of the flat sides may also occur.
If the yield stress of the finished product is used this increase is automatically included.

It is noted that the cold formed sections should satisfy the requirements for minimum inside corner radius to guarantee sufficient ductility, see table 2.4 for fully aluminium killed steel.

2.2 STRUCTURAL HOLLOW SECTION DIMENSIONS AND DIMENSIONAL TOLERANCES

The dimensions and sectional properties of structural hollow sections have been standardised in ISO standards ISO 657-14 [20] and ISO 4019 [21] for hot formed and cold formed structural hollow sections respectively.

Various national standards are available which may contain these and other sizes. In Europe the two applicable standards are EN 10210-2 'Hot finished structural hollow sections of non-alloy and fine grain structural steels - tolerances, dimensions and sectional properties' and EN 10219-2 'Cold formed welded structural hollow sections of non-alloy and fine grain structural steels - tolerances, dimensions and sectional properties'.

The majority of manufacturers of structural hollow sections do not produce all the sizes shown in these standards. It should also be noted that other sizes, not included in these standards, may be produced by some manufacturers.

The tolerances on dimensions and shape are given in ISO 657-14 and ISO 4019 for circular and rectangular (including square) sections respectively. Again, various national standards are also applicable and these may or may not contain the same tolerances.

In Europe the tolerances are contained within EN 10210-2 and EN 10219-2 respectively for hot finished and cold formed sections, see Tables 2.5a and 2.5b. The majority of the tolerances given in EN 10219-2 are the same as those in EN 10210-2. Where differences do occur, these are indicated in table 2.5b.

Due to additional mass and length tolerances, considerable variations may occur between the various national standards [52].

Although circular, square and rectangular hollow sections are the generally-used shapes; other shapes are sometimes available. For example, some tube manufacturers deliver the shapes given in Table 2.6. However, these shapes are not dealt with further in this book.

2.3 GEOMETRICAL PROPERTIES

2.3.1 Tension

The design capacity $N_{t,Rd}$ of a member under a tensile loading depends on the cross-sectional area and the design yield strength, and is independent of the sectional shape. In principle, there is no advantage or disadvantage in using hollow sections from the point of view of the amount of material required. The design capacity is given by:

$$N_{t,Rd} = \frac{A \cdot f_y}{\gamma_M} \tag{2.2}$$

where
γ_M is the partial safety factor.

If the cross section is weakened by bolt holes, the net cross section should also be checked in a similar way as for other sections, e.g. acc. to [12]:

$$N_{t,Rd} = \frac{A_{net} \cdot f_u}{\gamma_M} \cdot 0.9 \tag{2.3}$$

The factor 0.9 may vary from country to country depending on the partial factor γ_M used. Where ductile behaviour is required (e.g. under seismic loading), the plastic resistance shall be less than the ultimate resistance at the net section of fastener holes, i.e.:

$0.9\, A_{net} \cdot f_u > A \cdot f_y$

2.3.2 Compression

For centrally loaded members in compression, the critical buckling load depends on the slenderness λ and the section shape.

The slenderness λ is given by the ratio of the buckling length ℓ and the radius of gyration r.

$$\lambda = \frac{\ell}{r} \qquad (2.4)$$

The radius of gyration of a hollow section (in relation to the member mass) is generally much higher than that for the weak axis of an open section. For a given length, this difference results in a lower slenderness for hollow sections and thus a lower mass when compared with open sections.

The buckling behaviour is influenced by initial eccentricities, straightness and geometrical tolerances as well as residual stresses, nonhomogeneity of the steel and the stress-strain relationship.

Based on an extensive investigation by the European Convention for Constructional Steelwork and CIDECT, "European buckling curves" (Fig. 2.3 and table 2.7) have been established for various steel sections including hollow sections. They are incorporated in Eurocode 3.

The reduction factor χ shown in Fig. 2.3 is the ratio of the design buckling capacity to the axial plastic capacity.

$$\chi = \frac{N_{b,Rd}}{N_{pl,Rd}} = \frac{f_{b,Rd}}{f_{yd}} \qquad (2.5)$$

where

$$f_{b,Rd} = \frac{N_{b,Rd}}{A} \text{ (the design buckling strength)} \qquad (2.6)$$

$$f_{yd} = \frac{f_y}{\gamma_M} \qquad (2.7)$$

The non-dimensional slenderness $\bar{\lambda}$ is determined by

$$\bar{\lambda} = \frac{\lambda}{\lambda_E} \qquad (2.8)$$

where $\lambda_E = \pi \sqrt{\frac{E}{f_y}}$ (Euler slenderness) (2.9)

The buckling curves for the hollow sections are classified according to table 2.7.

Most open sections fall under curves "b" and "c". Consequently, for the case of buckling, the use of hot-formed hollow sections generally provides a considerable saving in material.

Fig. 2.4 shows for a buckling length of 3 m a comparison between the required mass of open and hollow sections for a given load.

It shows that in those cases in which loads are small, leading to relatively slender sections, hollow sections provide a great advantage (considerably lower use of material). However, if loads are higher, resulting in low slendernesses, the advantage (in %) will be lower.

The overall buckling behaviour of hollow sections improves with increasing diameter or width to wall thickness ratio. However, this improvement is limited by local buckling. To prevent local buckling, d/t or b/t limits are given e.g. in Eurocode 3, see table 2.8.

In the case of thin walled sections, interaction between global and local buckling should be considered.

In addition to the improved buckling behaviour due to the high radius of gyration and the enhanced design buckling curve, hollow sections can offer other advantages in lattice girders. Due to the torsional and bending stiffness of the members in combination with joint stiffness, the effective buckling length of compression members in lattice girders with K-gap joints can be reduced (Fig. 2.5). Eurocode 3 recommends an effective buckling length for hollow section brace members in welded lattice girders equal to or less than 0.75ℓ, see [2,12], in which ℓ represents the system length. Other codes, e.g. API [15] give a buckling length of 0.8ℓ.

For lattice girders with overlap joints no test results are available and for the time being the buckling length is assumed to be the system length. For chords 0.9 times the system length for in-plane buckling or 0.9 times the length between the supports is taken as the buckling length.

Laterally unsupported chords of lattice girders (see Fig.

2.6) have a reduced buckling length due to the improved torsional and bending stiffness of the tubular members [53,54]. These factors make the use of hollow sections in girders even more favourable.

2.3.3 Bending

In general, I and H sections are more economical under bending about the major axis (I_{max} larger than for hollow sections). Only in those cases in which the design stress in open sections is largely reduced by lateral buckling do hollow sections offer an advantage.

It can be shown by calculations that lateral instability is not critical for circular hollow sections and for rectangular hollow sections with b/h >0.25 (with bending about the strong axis), which are normally used.

It is apparent that hollow sections are especially favourable compared to other sections if bending about both axes is present.

Hollow sections used for elements subjected to bending can be more economically calculated using plastic design. However, then the sections have to satisfy more restricted conditions to avoid premature local buckling. Like other steel sections loaded in bending, different moment-rotation behaviours can be observed.

Fig. 2.7 shows various moment-rotation diagrams for a member loaded by bending moments.

The moment-rotation curve "1" shows a moment exceeding the plastic moment and a considerable rotation capacity. Moment-rotation curve "2" shows a moment exceeding the plastic moment capacity; but after the maximum, the moment drops immediately, so that little moment-rotation capacity exists. Moment-rotation curve "3" represents a capacity lower than the plastic moment capacity, which, however, exceeds the elastic yield moment capacity. In the moment-rotation curve "4" the capacity is even lower than the elastic yield moment capacity. The effect of the moment-rotation behaviour is reflected in the classification of cross sections as shown in table 2.8. The cross section classification is given in limits for the diameter or width to thickness ratio, i.e. d/t, b/t or h/t.

The limits are based on experiments and given as:

$$\frac{d}{t} \leq c \cdot \frac{235}{f_y} \qquad \text{for CHS} \qquad (2.10)$$

$$\frac{b}{t} \leq c \cdot \sqrt{\frac{235}{f_y}} \qquad \text{for RHS} \qquad (2.11)$$

with f_y in N/mm^2 and c depending on the section class, the cross section and the loading.

The cross section classes 1 and 2 can develop the plastic moment capacity up to the given b/t or d/t limits with bi-linear stress blocks, whereas the moment capacity of the cross section classes 3 and 4 is based on an elastic stress distribution (see Fig. 2.8). The difference between the cross section classes 1 and 2 is reflected in the rotation capacity. After reaching the plastic moment capacity, the cross section class 1 can keep this capacity after further rotation, whereas the capacity of the cross section class 2 drops after reaching this capacity. As a consequence, the moment distribution in the structure or structural component should be determined in an elastic way for structures made of sections with cross section classes 2, 3 or 4. For structures made of sections with cross sections in class 1, a plastic moment distribution can be adopted, but an elastic moment distribution is still permissible (and in some countries more common).

Detailed information about the cross sectional classification is given in [2].
Recent research by Wilkinson and Hancock [56] has shown that especially the limits for the web slenderness have to be reduced considerably and that the limits of Eurocode 3 for the h/t ratio are unsafe.

For a beam fully clamped at both ends and subjected to a uniformly distributed loading q, it means that after reaching the plastic moment capacity at the ends, the beam can be loaded until a further plastic hinge occurs at mid span (see Fig. 2.9).

For the class 4 cross section the maximum stress is determined by local buckling and the stress in the outer fibre is lower than the yield strength f_y. Alternatively, an effective cross sectional area based on the yield strength may be determined.

In the absence of shear forces or if the shear forces do not exceed 50% of the shear capacity $V_{p\ell,Rd}$, the effect of shear may be neglected and the bending moment capacity about one axis is given by:

$$M_{c,Rd} = \frac{W_{p\ell} \cdot f_y}{\gamma_M} \quad \text{for cross section classes 1 or 2} \qquad (2.12)$$

$$M_{c,Rd} = \frac{W_{e\ell} \cdot f_y}{\gamma_M} \quad \text{for cross section class 3} \qquad (2.13)$$

$$M_{c,Rd} = \frac{W_{eff} \cdot f_y}{\gamma_M} \quad \text{for cross section class 4} \qquad (2.14)$$

When the shear force exceeds 50% of the shear capacity, combined loading has to be considered, see e.g. Eurocode 3.

2.3.4 Shear

The elastic shear stress can be determined with simple mechanics by:

$$\tau = \frac{V_{sd} \cdot S}{2 \cdot I \cdot t} \leq \frac{f_y}{\sqrt{3}} \qquad (2.\ 15)$$

Fig. 2.10 shows the elastic stress distribution. The design capacity based on plastic design can be easily determined based on the Huber-Hencky-Von Mises criterion by assuming the shear yield strength in those parts active for shear.

$$V_{p\ell,Rd} = A_v \cdot \frac{f_y}{\sqrt{3}} \cdot \frac{1}{\gamma_M} \qquad (2.16)$$

with $A_v = A \cdot \frac{h}{b+h}$ for rectangular sections

(or just 2 h · t) with V in the direction of h.

$A_v = \frac{2}{\pi} \cdot A$ for circular sections

2.3.5 Torsion

Hollow sections, especially CHS, have the most effective cross-section for resisting torsional moments, because the material is uniformly distributed about the polar axis. A comparison of open and hollow sections of nearly identical mass in table 2.9 shows that the torsional constant of hollow sections is about 200 times that of open sections.

The design capacity is given by:

$$M_{t,Rd} = W_t \cdot \frac{f_y}{\sqrt{3}} \qquad (2.17)$$

Circular hollow sections:

$$I_t \approx \frac{\pi}{4} (d-t)^3 \cdot t \qquad (2.18)$$

$$\text{with } W_t = \frac{2I_t}{d-t} \cong \frac{\pi}{2} (d-t) \cdot t \qquad (2.19)$$

Rectangular hollow sections [57]:

$$I_t = \frac{t^3 \cdot \ell_A}{3} + \frac{4 A_m^2 \cdot t}{\ell_A} \qquad (2.20)$$

with:

$$\ell_A = 2(h_m + b_m) - 2 r_m (4 - \pi) \qquad (2.21)$$

$$A_m = b_m \cdot h_m - r_m^2 (4 - \pi) \qquad (2.22)$$

$$\text{with } W_t = \frac{I_t}{t + 2 \frac{A_m}{\ell_a}} \qquad (2.20^a)$$

For thin walled rectangular hollow sections eq. 2.20^a can be approximated by:

$$W_t = 2 h_m \cdot b_m \cdot t \qquad (2.23)$$

The first term in eq. 2.20 is generally only used for open sections however, research [57] has shown that the given formula fits the test results best.

2.3.6 Internal pressure

The circular hollow section is most suitable to resist an internal pressure p.
The design capacity per unit length, shown in Fig. 2.11, is given by:

$$p = f_y \cdot \frac{2t}{d-2t} \cdot \frac{1}{\gamma_M} \quad (2.24)$$

For transport pipelines, the γ_M value may be considerably larger than for other cases, depending on the hazard of the product, the effect of failure on the environment and the inspectability. The design capacities for RHS sections subjected to internal pressure are much more complicated; reference can be made to [58].

2.3.7 Combined loadings

Various combinations of loadings are possible, e.g. tension, compression,bending, shear and torsion.

Depending on the cross sectional classification, various interaction formulae have to be applied. Reference can be made to the relevant codes, e.g. Eurocode 3. It is too extensive to deal with all these formulae in this lecture book, however, the interaction of the various loads in the cross section can be based on the Huber-Hencky-Von Mises stress criterion [60].

For the member checks other interaction formulae apply, see e.g. [12, 60].

2.4 DRAG COEFFICIENTS

Hollow sections, especially circular hollow sections, have a striking advantage for use in structures exposed to fluid currents, i.e. air or water.

The drag coefficients are much lower than those of open sections with sharp edges (see Fig. 2.12 and table 2.10) [31, 33, 61].

2.5 CORROSION PROTECTION

Structures made of hollow sections offer advantages with regard to corrosion protection. Hollow sections have rounded corners (Fig. 2.13) which result in a better protection than sections with sharp corners. This is especially true for the joints in circular hollow sections where there is a smooth transition from one section to another. This better protection increases the protection period of coatings against corrosion.

Structures designed in hollow sections have a 20 to 50% smaller surface to be protected than comparable structures made using open sections. Many investigations [62] have been carried out to assess the likelihood of internal corrosion. These investigations, carried out in various countries, show that internal corrosion does not occur in sealed hollow sections.

Even in hollow sections which are not perfectly sealed, internal corrosion is limited. If there is concern about condensation in an imperfectly sealed hollow section, a drainage hole can be made at a point where water can drain by gravity.

2.6 USE OF INTERNAL VOID

The internal void in hollow sections can be used in various ways, e.g. to increase the compressive resistance by filling with concrete, or to provide fire protection. In addition, the heating or ventilation system is sometimes incorporated into hollow section columns. The possibilities of using the internal space are briefly described below.

2.6.1 Concrete filling

If the commonly-available wall thicknesses are not sufficient to meet the required load bearing resistance, the hollow section can be filled with concrete. For example, it may be preferable in buildings to have the same external dimensions for the columns on every floor. At the top floor, the smallest wall thickness can be chosen, and the wall thickness can be increased with increasing load for lower floors. If the hollow section with the largest available wall thickness is not sufficient for the ground floor, the hollow section can be filled with concrete to increase the load bearing resistance.

A very important reason for using concrete-filled hollow sections is that the columns can be relatively slender. Design rules are given in e.g. Eurocode 4 [13].

Concrete filling of hollow sections contributes not only to an increase in load bearing resistance, but it also improves the fire resistance duration. The extensive test projects carried out by CIDECT and ECSC have shown that reinforced concrete-filled hollow section columns without any external fire protection like plaster, vermiculite panels or intumescent paint, can attain a fire life of even 2 hours depending on the cross-section ratio of the steel and concrete, reinforcement percentage of the concrete and the applied load, see Fig. 2.14 [4].

2.6.2 Fire protection by water circulation

One of the modern methods for fire protection of buildings is to use water-filled hollow section columns.

The columns are interconnected with a water storage tank. Under fire conditions, the water circulates by convection, keeping the steel temperature below the critical value of 450°C. This system has economical advantages when applied to buildings with more than about 8 storeys. If the water flow is adequate, the resulting fire resistance time is virtually unlimited.

In order to prevent freezing, potassium carbonate (K_2CO_3) is added to the water. Potassium nitrate is used as an inhibitor against corrosion.

2.6.3 Heating and ventilation

The inner voids of hollow sections are sometimes used for air and water circulation for heating and ventilation of buildings. Many examples in offices and schools show the excellent combination of the strength function of hollow section columns with the integration of the heating or ventilation system. This system offers maximization of floor area through elimination of heat exchangers, a uniform provision of warmth and a combined protection against fire.

2.6.4 Other possibilities

Sometimes hollow section chords of lattice girder bridges are used for conveying fluids (pipe bridge).
Sometimes in buildings the rain water downpipes go through the hollow section columns (Fig. 2.15) or in other cases electrical wiring is located in the columns. The internal space can also be used for prestressing a hollow section.

2.7 AESTHETICS

A rational use of hollow sections leads in general to structures which are cleaner and more spacious. Hollow sections can provide slender aesthetic columns, with variable section properties but flush external dimensions. Due to their torsional rigidity, hollow sections have specific advantages in folded structures, V-type girders, etc..

Lattice construction, which is often made of hollow sections directly connected to one another without any stiffener or gusset plate, is often preferred by architects for structures with visible steel elements. However, it is difficult to express aesthetic features in economic comparisons. Sometimes hollow sections are used only because of aesthetic appeal, whilst at other times appearance is less important, see e.g. Fig. 2.16a and Fig. 2.16b.

Table 2.1a EN 10210-1 hot finished structural hollow sections non-alloy steel properties

Steel designation	Minimum yield strength N/mm^2			Minimum tensile strength N/mm^2		Min. elong.% on gauge $L_o = 5.65 \sqrt{S_o}$ $t \leq 40$ mm*		Charpy Impact strength (10x10 mm)	
	$t \leq 16$ mm	$16 < t \leq 40$ mm	$40 < t \leq 65$ mm	t<3mm	$3 \leq t \leq 65$ mm	Long.	Trans.	Temp. °C	J
S235JRH	235	225	215	360-510	340-470	26	24	20	27
S275J0H S275J2H	275	265	255	430-580	410-560	22	20	0 -20	27 27
S355J0H S355J2H	355	345	335	510-680	490-630	22	20	0 -20	27 27

* for thicknesses above 40 mm, these values are reduced

Table 2.1b EN 10219-1 cold formed welded structural hollow sections non-alloy steel - steel property different from EN 10210-1

Steel designation	Min. longitudinal elongation, % all thicknesses, t_{max} = 40 mm
S235JRH	24
S275J0H S275J2H	20
S355J0H S355J2H	20

Table 2.2a EN 10210-1 hot finished structural hollow sections - fine grain steel properties

Steel designation	Minimum yield strength N/mm^2			Minimum tensile strength N/mm^2	Min. elong.% on gauge $L_o = 5.65 \sqrt{S_o}$ $t \leq 65$ mm*		Charpy Impact strength (10x10 mm)	
	$t \leq 16$ mm	$16 < t \leq 40$ mm	$40 < t \leq 65$ mm	$t \leq 65$mm	Long.	Trans.	Temp. °C	J
S275NH S275NLH	275	265	255	370-540	24	22	-20 -50	40 27
S355NH S355NLH	355	345	335	470-630	22	20	-20 -50	40 27

Table 2.2b EN 10219-1 cold formed welded structural hollow section fine grain steel - steel property different from EN 10210-1

Steel designation	Feed stock condition* M	
	Min. Tensile strength	Min. longitudinal elongation
S275MH S275MLH	360 - 510	24
S355MH S355MLH	450 - 610	22
S460MH S460MLH	530 - 720	17

M: refers to thermal mechanical rolled steels.

** : Min. Elong. % on gauge* $L_o = 5.65\sqrt{S_o}$

For sections ≤ 60 x 60 mm and equivalent round and rectangular sections, the minimum

Table 2.3 Increase in yield strength due to cold-forming of RHS sections [12]

Average yield strength:

The average yield strength f_{ya} may be determined from full size section tests or as follows:

$$f_{ya} = f_{yb} + (k \cdot n \cdot t^2/A) \cdot (f_u - f_{yb})$$

where

f_{yb}, f_u = specified tensile yield strength and ultimate tensile strength of the basic material (N/mm^2)

t = material thickness (mm)

A = gross cross-sectional area (mm^2)

k = coefficient depending on the type of forming (k = 7 for cold forming)

n = number of 90° bends in the section with an internal radius < 5 t (fractions of 90° bends should be counted as fractions of n)

f_{ya} should not exceed f_u or 1.2 f_{yb}

The increase in yield strength due to cold working should not be utilised for members which are annealed* or subject to heating over a long length with a high heat input after forming, which may produce softening.

Basic material:

Basic material is the flat hot rolled sheet material out of which sections are made by cold mechanical forming.

* Stress relief annealing at more than 580 °C or for over one hour may lead to deterioration of the mechanical properties, thus hot dip galvanizing at about 460 °C gives no reduction of the increased stresses.

Table 2.4 Minimum inner corner radii of full aluminium (≥0.02%) killed cold finished RHS [12]

Steel grade		Wall thickness t (mm)	minimum r/t (r = inside corner radius)
Acc. to EN 10219 [29]	Previous designation		
S 235, S 355, S 275	Fe 360, Fe 430, Fe 510	24 12 10 6	3.0 2.0 1.5 1.0

Table 2.5a EN 10210-2 hot finished structural hollow sections - tolerances

Section type		Square/rectangular	Circular
Outside dimension		the greater of ± 0.5 mm and ± 1% but not more than 10 mm	
Thickness	Welded	-10%	
	Seamless	-10% and -12.5% at max. 25% cross section	
Mass	Welded	± 6% on individual lengths	
	Seamless	-6%; +8%	
Straightness		0.2% of the total length	
Length (exact)		+10 mm, -0 mm, but only for exact lengths of 2000 to 6000 mm	
Out of roundness			2% for d/t ≤ 100
Squareness of sides		90°, ± 1°	-
Corner radii	Outside	3.0 t max.	
Concavity/convexity		± 1% of the side	-
Twist		2 mm + 0.5 mm/m	-

Table 2.5b EN 10219-2 cold formed welded structural hollow sections - tolerance variations from EN 10210-2

Section type		Square/rectangular	Circular	
Outside dimension		b < 100 mm: the greater of ± 0.5mm and ± 1% 100 mm ≤ h, b ≤ 200 mm: ± 0.8%, b > 200 mm: ± 0.6%	± 1%, min. ± 0.5 mm max. ± 10 mm	
Concavity/convexity		max. 0.8% with min. of 0.5 mm	-	
Outside corner radii		t ≤ 6 mm 1.6 to 2.4t 6 mm < t ≤ 10 mm 2.0 to 3.0t t > 10 mm 2.4 to 3.6t	-	
Thickness	Welded	t ≤ 5 mm: ± 10% t > 5 mm: ± 0.5 mm	For d ≤ 406.4 mm, t ≤ 5 mm: ± 10% t > 5 mm: ± 0.5mm	For d > 406.4 mm, ± 10%, max. 2 mm
Mass		± 6%	± 6%	
Straightness		0.15% of the total length	0.20% of the total length	

Table 2.6 Special shapes available

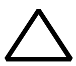
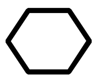
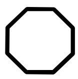
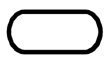
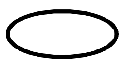
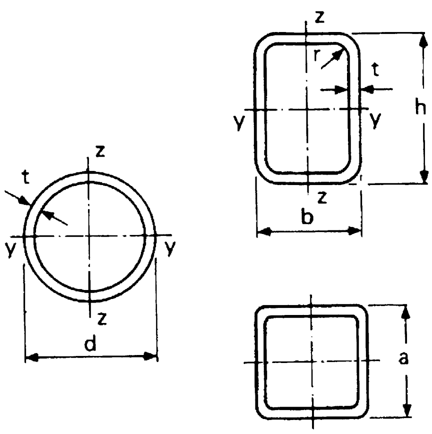
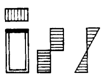
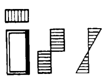
	triangular	hexagonal	octagonal	flat - oval	elliptical	half-elliptical
shape						

Table 2.7 European buckling curves according to manufacturing processes

Cross section	Manufacturing process	Buckling curves
	Hot finished $f_y \geq 420$ N/mm^2	a_o
	Hot finished	a
	Cold formed (f_{yb}* used)	b
	Cold formed (f_{ya}** used)	c

* f_{yb} = yield strength of the basic material
** f_{ya} = yield strength of the material after cold forming

Table 2.8 b/t, h/t and d/t limits for the cross section classes 1, 2 and 3 (for r_0 = 1.5t)

			class	1				2				3			
cross section	load type	considered element	f_y(N/mm^2)	235	275	355	460	235	275	355	460	235	275	355	460
RHS	compression*	compression		45	41.6	36.6	32.2	45	41.6	36.6	32.2	45	41.6	36.6	32.2
RHS	bending	compression		36	33.3	29.3	25.7	41	37.9	33.4	29.3	45	41.6	36.6	32.2
RHS	bending 1)	bending		1)	1)	1)	1)	1)	1)	1)	1)	1)	1)	1)	1)
CHS	compression and/or bending			50	42.7	33.1	25.5	70.0	59.8	46.3	35.8	90.0	76.9	59.6	46

* There is no difference between b/t and h/t limits for the classes 1, 2 and 3, when the whole cross section is only under compression.
* Class 3 limits appear when whole section is in compression.
1) Recent research [56] has shown that the Eurocode limits for the web slenderness should be reduced considerably, e.g. for class 1 to : $\frac{(h-2t-2r_i)}{t} \leq 70 - \frac{5(b-2t-2r_i)}{6t}$

Table 2.9 Torsional strength of various sections

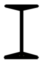
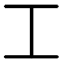
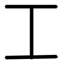
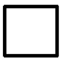
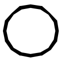
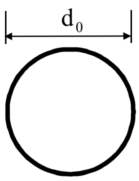
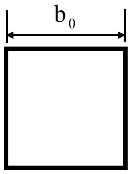
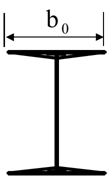
Section		Mass (kg/m)	Torsion constant I_t (10^4 mm^4)
	UPN 200	25.3	11.9
	INP 200	26.2	13.5
	HEB 120	26.7	13.8
	HEA 140	24.7	8.1
	140x140x6	24.9	1475
	168.3x6	24.0	2017

Table 2.10 Drag coefficients for I-profiles and hollow sections depending on Reynold's number

Section	Drag coefficient
	0.5 - 1.2
	0.6 - 2.0
	2.0

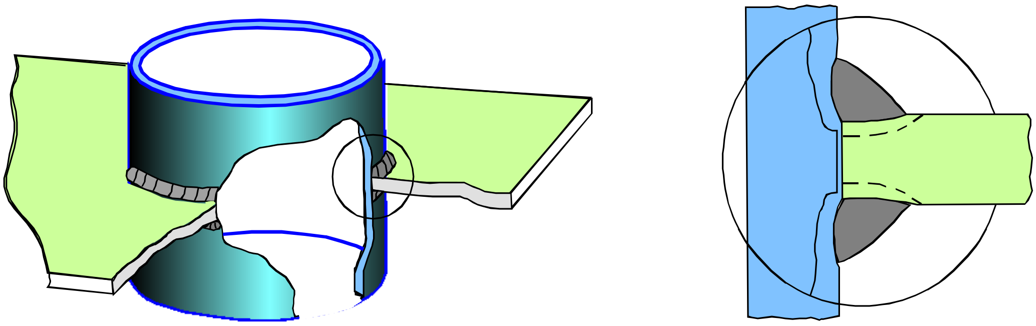


Fig. 2.1 Lamellar tearing

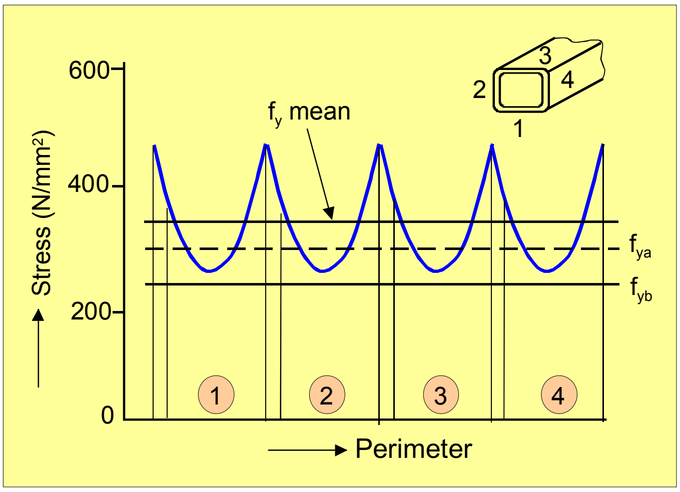


Fig. 2.2 Influence of cold forming on the yield strength for a square hollow section of 100x100x4 mm

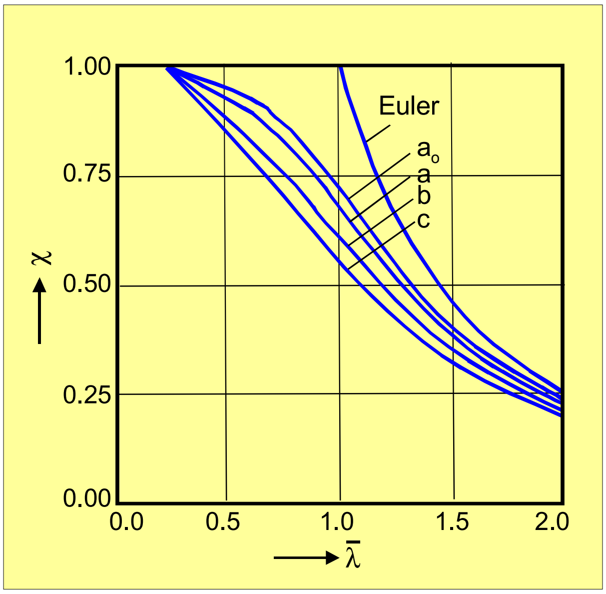


Fig. 2.3 European buckling curves

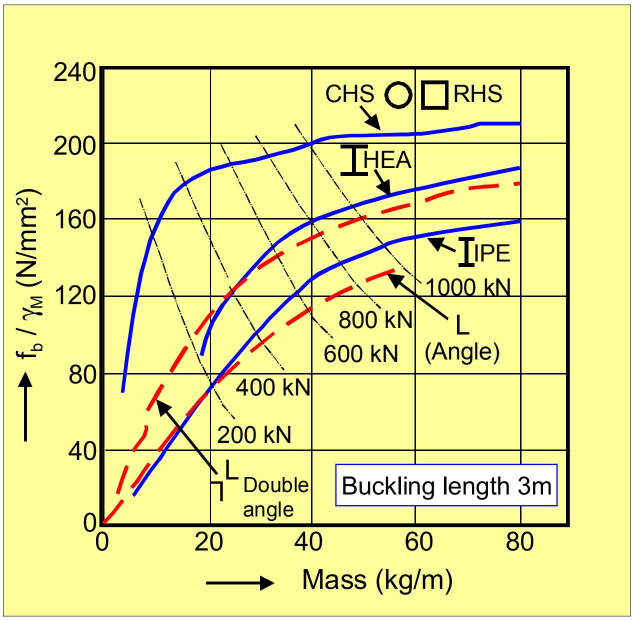


Fig. 2.4 Comparison of the masses of hollow and open sections under compression in relation to the loading

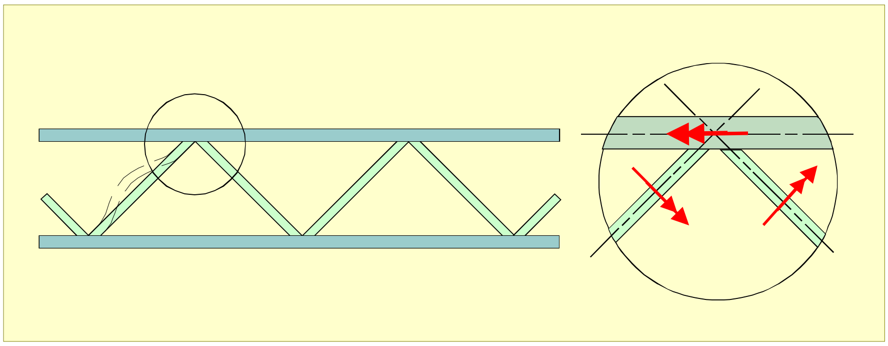


Fig. 2.5 Restraints for the buckling of a brace member

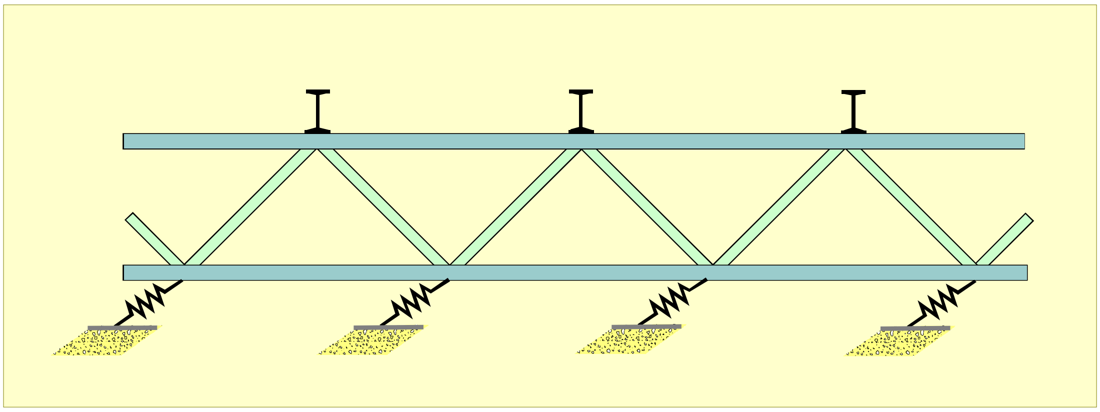


Fig. 2.6 Bottom chord laterally spring supported by the stiffness of the members, joints and purlins

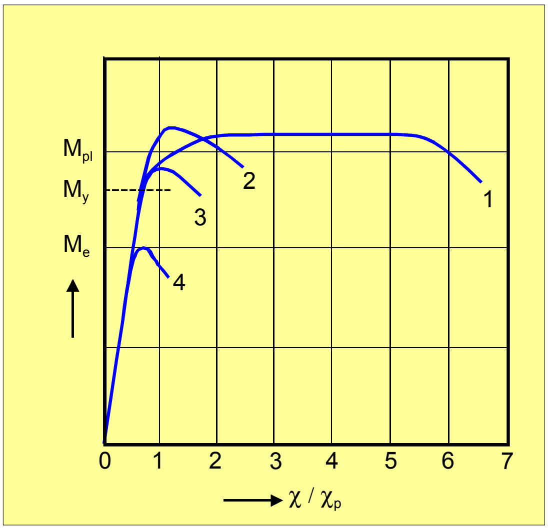


Fig. 2.7 Moment-rotation curves

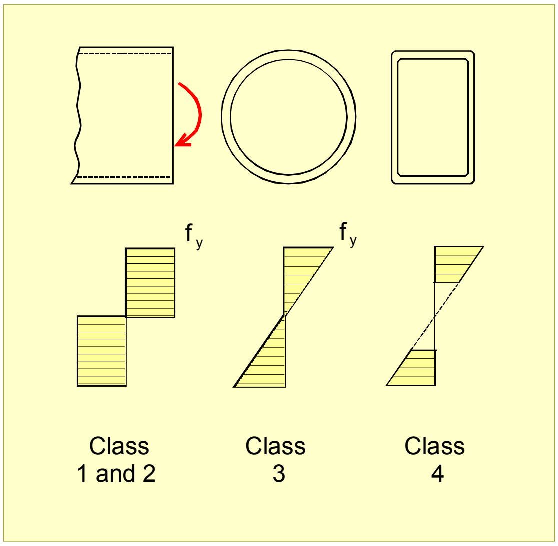


Fig. 2.8 Stress distribution for bending

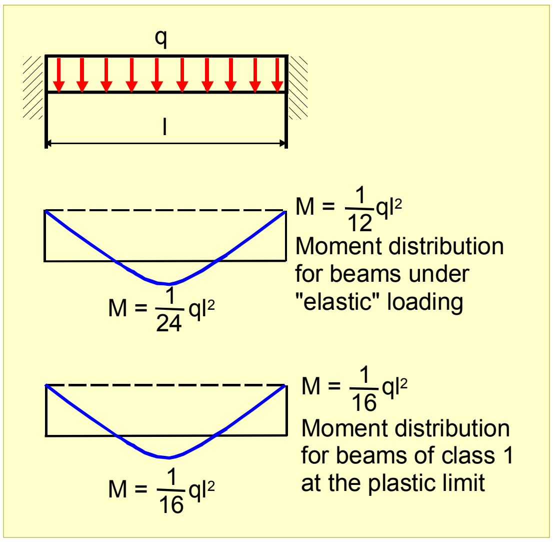


Fig. 2.9 Moment distribution in relation to cross section classification

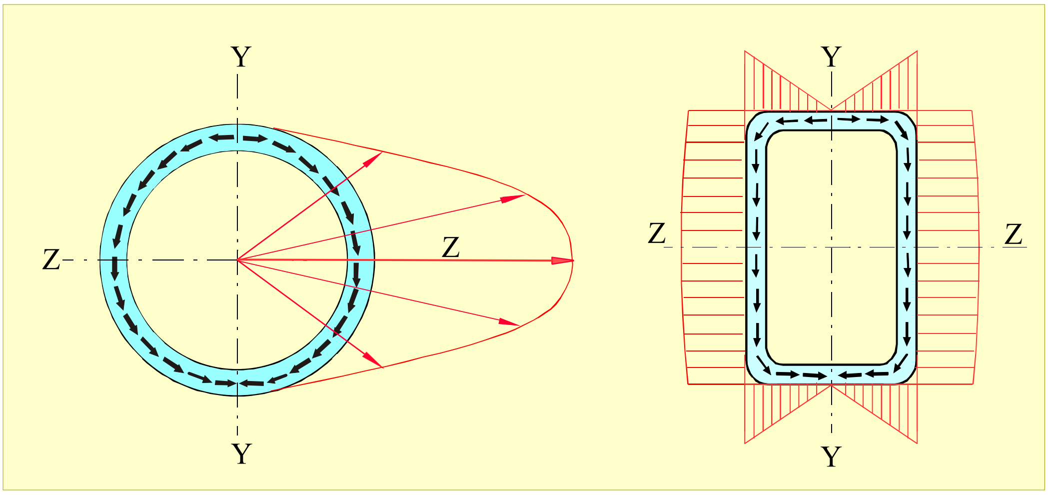


Fig. 2.10 Elastic shear stress distribution

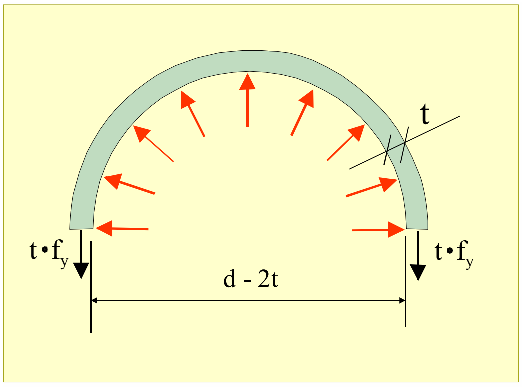


Fig. 2.11 Internal pressure

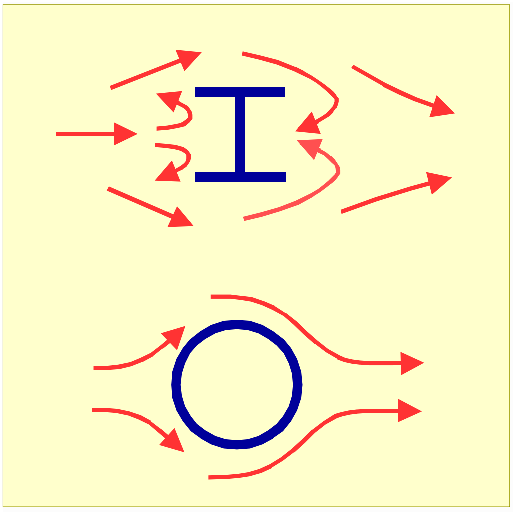


Fig. 2.12 Wind flow for open and circular hollow sections

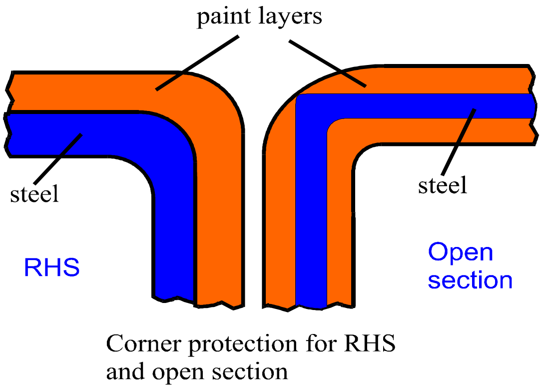


Fig. 2.13 Painted corners of RHS vs. Open sections

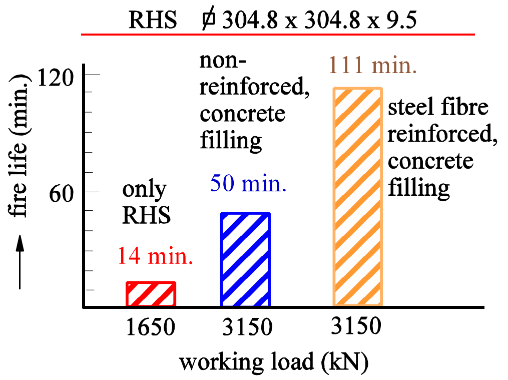


Fig. 2.14 Fire resistance of concrete-filled hollow sections

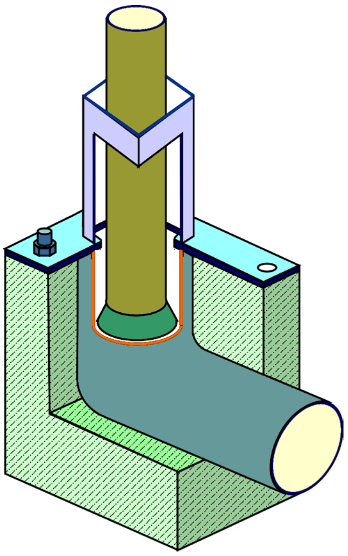


Fig. 2.15 Rain water down pipe through a hollow section column

Fig. 2.16a Aesthetically appealing tubular structures

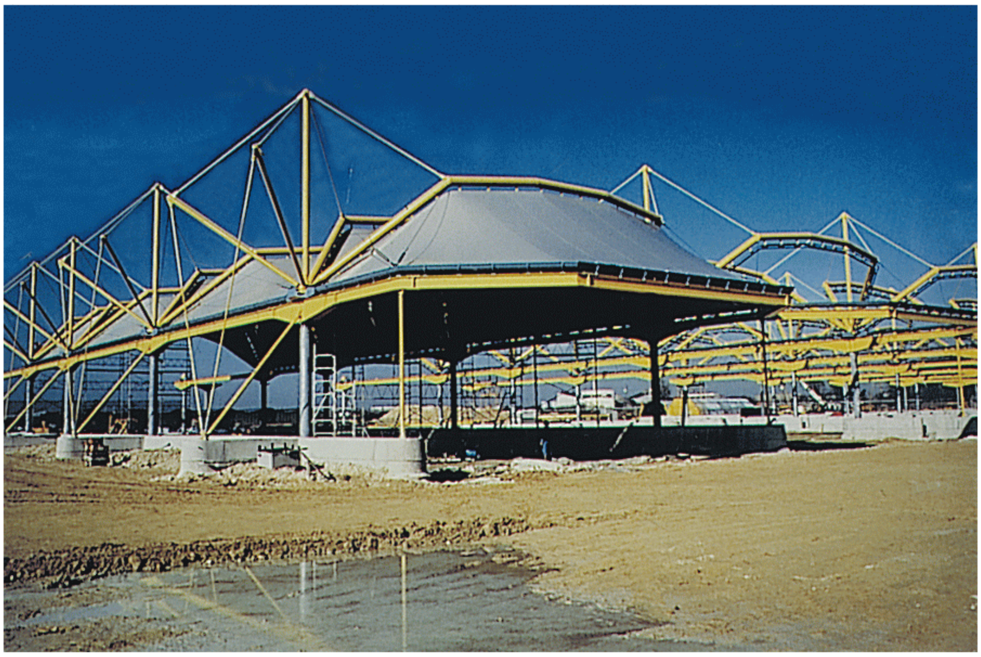


Fig. 2.16b Aesthetically appealing tubular structures