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Rational application of hot finished rectangular hollow sections in steel structures

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Abstract. Steel hollow sections are manufactured as both welded and seamless elements. The influence of manufacturing technology causes tubes made from the same carbon-manganese steel to differ significantly in terms of their mechanical properties. The cold-formed welded tubes are produced from a steel strip that is roll formed and welded; both technological processes take place at room temperature. This profile type is characterised by less favourable mechanical properties and by much higher inhomogeneity within the cross-section than the seamless tube. However, due to the lower cost of manufacturing, welded tubes are much more often used in building structures than seamless ones. After thermomechanical treatment, the welded tubes, which are referred to as "hot finished", have almost the same mechanical properties as seamless tubes. However, hot finished sections are more expensive than welded ones; therefore if they are to be applied in the structure in a reasonable way, higher unit cost should translate into an appropriate increase of the load bearing capacity. The aim of the paper is to indicate the application areas of hot finished rectangular hollow sections in which their use is economically justified.

1 Introduction

Steel hollow sections are characterised by very favourable weight distribution in the cross section, resulting in a large ratio of radius of inertia and torsional stiffness to their self-weight. This type of profiles is used in contemporary steel structures not only due to low self-weight but also to a number of other favourable technical and operational features, such as low drag coefficient or smaller painting area.

Despite the fact that designers started using riveted steel tubes for truss bridges as early as in the second half of the 19th century, the application of steel hollow sections in other types of steel bearing structures was initially quite limited because of their high manufacturing costs, relatively poor quality, high labour consumption required for the execution of connections and lack of knowledge concerning the design of direct joints, i.e. tube to tube connections without a gusset plate. Interestingly, progress in this area was not initiated by the building industry but by the machinery and mining industries. The popularisation of steam engines and the beginning of the extraction and transport of oil on an industrial scale caused a strong increase in demand for steel line pipes. This, in turn, led to the need to find a

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technology that would enable relatively cheap mass production of pipes with low self-weight and high strength, allowing for the use of larger pipe diameter and higher operational pressure. The first method of industrial manufacturing of steel pipes was patented in 1825 by James Whitehouse. In this method, welded pipes were produced from steel stripe sections heated in a furnace, forged over a mandrel, then heated again and drawn through the drawing die where the stripe edges were pressure welded. However, the pressure weld had low strength and the method itself was too costly for mass production.

A significant improvement in pipe strength was achieved due to the development of technology for production of hot-rolled seamless steel pipes, which was firstly patented in 1886 by the Mannesmann brothers. This technology was modified and improved by several engineers and inventors: Stiefel, Assel, Diescher, Ehrhardt, and others. As a result of the continuous development of steel manufacturing and joining techniques, operational pressure in oil pipelines increased 60 times over 90 years: from 2 bars in 1910 to 120 bars in 2000 [1] The total length of pipelines transporting oil and gas is currently estimated as 2 000 000 km [2].

Despite the initial failures, the production of welded pipes was continued. The manufacturing technology was developed because the process was, and still is, much less energy-consuming and cheaper than the production of seamless pipes. Improvement of the production methods had two main goals: to increase the strength of the seam and to enhance production efficiency. Welding seam technology was developed in two ways: using electric resistance welding and using electric arc welding.

In the early 1950s, the production of square and rectangular hollow sections began [3]. These sections, as opposed to circular hollow sections, were used mainly as structural elements. Due to the flat cutting line and flat wall surface, they facilitate the execution of welded and bolted joints. In 1962 the CIDECT (Comité International pour le Développementet l'Etude de la Construction Tubulaire), an international association, was founded to promote hollow steel section usage in construction industry by initiating and participating in appropriate research projects. Contemporary European Standard provisions for steel hollow sections are based on the results of CIDECT works.

The manufacturing technology of seamless rectangular hollow sections was also developed. These profiles are characterised by much smaller values of residual stress and higher homogeneity of mechanical properties in the cross section.

The development of manufacturing technology results in the elaboration of the technique for the second hot-rolling of the welded hollow sections. As a result of this additional treatment, welded sections have practically the same parameters as seamless ones. The welded hollow sections after thermomechanical treatment and the seamless hollow sections are both called "hot finished sections". The production of both types of profiles is regulated by the provisions of the PN-EN 10210 Standard [4]. These profiles have better technological properties than profiles that are cold formed at ambient temperature pursuant to PN-EN 10219 [5]. However, they are more expensive, so their application in the structure should be reasonably justified by the designer.

2 Material properties

Hot finished and cold formed hollow sections are made of carbon-manganese non-alloy quality steels, with minimum yield strength R_{eH} in the range of 235 MPa to 355 MPa. Hot finished profiles can also be produced from fine grain steels, normalized or normalized rolled to increase impact energy at low temperatures. The reduction in grain size also increases steel yield strength. The introduction of the following alloy additions: Ni, Cr, Cu, V, Mo, Nb allows it to achieve two additional strength grades (420 MPa and 460 MPa) of fine grain alloy special steels, which are included in PN-EN 1993-1-1 [6]. Hot finished tubes are formed at 830-900°C, which corresponds to the temperatures of the full annealing process, during which steel microstructure changes causing the reduction of its hardness and increase in ductility and toughness.

As far as cold formed profiles are concerned, two types of manufacturing are allowed: normalizing or normalizing rolling and thermomechanical rolling. Both processes provide the same minimum impact energy at low temperatures, required by appropriate Standards [4-5], however thermomechanically rolled steels are characterised by 10-15% lower carbon equivalent values. It should also be noted that stress relieving annealing, sometimes carried out after the cold forming, which is normally conducted at a temperature of 400-450°C does not increases steel toughness [7].

3 Geometrical and technological properties

Geometrical dimensions of square hot finished hollow sections manufactured in compliance with PN-EN 10210-2 [8] vary from 40 to 400 mm for side dimensions and from 2.6 to 20 mm for wall thickness. As far as rectangular hollow sections are concerned, the side dimensions are slightly different: from 50x30 to 500x300 but the range of wall thickness is the same. The side dimensions of the cold formed square hollow sections listed in PN-EN 10219-2 [9] range from 20 to 400 mm with the wall thickness of 2.0 to 16.0 mm, while rectangular hollow sections have side dimensions from 40 x 20 to 400 x 300 with the thickness from 2.0 to 16.0 mm. However, some European manufacturers offer hot finished sections with dimensions that exceed the values given in [8-9]: up to 700x700 mm for the side dimension and the wall thickness up to 40 mm [10].

Despite the same side size and wall thickness for hot finished and cold formed hollow sections, their sectional parameters differ due to the slightly different corner shaping (Fig. 1).

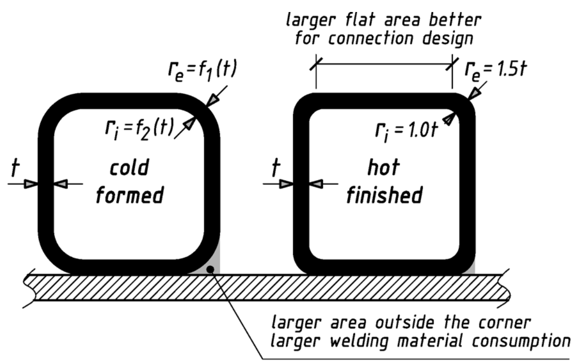

Fig. 1. Comparison of the cross section geometry for cold formed and hot finished hollow sections.

Hot finished profiles have smaller corner radii and the thickness of the corner is not uniform. Their external corner radius r_e is $1.5t$, where t is wall thickness, and the internal corner radius r_i is $1.0t$. Additionally, the surfaces of the corner and the flat part of the wall do not have the same tangent line at the place of their connection. For cold formed hollow sections, the corner radius depends on the wall thickness t and equals: $r_e = 2.0t$ and $r_i = 1.0t$ for $t < 6$ mm, $r_e = 2.5t$ and $r_i = 1.5t$ for 6 mm $< t \leq 10$ mm, $r_e = 3.0t$ and $r_i = 2.0t$ for $t > 10$ mm. Comparing hot finished and cold formed hollow sections with the same side dimension and wall thickness, one can notice that hot finished profiles have slightly larger (by about a few percent) self-weight and more favourable properties of the cross section: its area, moment of inertia, radius of gyration, elastic and plastic section moduli.

As for cold formed sections that were not normalized after cold forming, the value of corner radius significantly affects the technological conditions for weld execution. When the internal corner radius to wall thickness ratio r_i/t is lower than the minimum value provided in Table 4.2 of PN-EN 1993-1-8 [11] then, to avoid brittle cracking, welding is permitted only in zones $5t$ away from the beginning of the flat part of the external surface. Table 1 below compares values of the r_i/t ratio for hot finished and cold formed hollow sections manufactured according to [8-9] with the provisions of [11]. The wall thicknesses for non-normalized cold formed profiles that are not allowed to be welded in the corner zone were indicated. This restriction is especially bothersome for profiles with the smallest wall thickness in the series, due to significant reduction of the permitted welding zone. In extreme cases, welding may even be impossible.

There are no similar welding restrictions that apply to hot finished sections, even if they do not fulfil the conditions given in Table 1, because hot-rolled sections do not have a cold-formed zone and the hot finished products made from cold formed sections are subject to metallurgical conditions equivalent to those for hot-rolled profiles.

Table 1. Nominal and minimum values of r_i/t for rectangular hollow sections.

Wall thickness [mm]	**r_i/t [-] PN-EN 10210-2**	**r_i/t [-] PN-EN 10219-2**	**min. r_i/t [-] PN-EN 1993-1-8**
$t \le 4$	1.0	1.0	1.0
$4 < t \le 6$		1.0	1.5
$6 < t \le 8$		1.5	1.5
$8 < t \le 10$		1.5	2.0
$10 < t \le 12$		2.0	2.0
$12 < t \le 24$		2.0	3.0

According to the amendment to PN-EN 1993-1-8 [11], published in September 2009, welding in the corner zones of cold formed rectangular hollow sections may be allowed for profiles that do not fulfil the requirements given in Table 1, provided that: wall thickness $t \le 12.5$ mm, steel is fully-killed, sub-grades are limited to: J2H, K2H, MH, MLH, NH, NLH, with the content of carbon, phosphorus and sulphur following restrictions: C ≤ 18%, P ≤ 0.020% and S ≤ 0.012%. In most cases, these limits are lower than the qualification requirements for steel grades specified in PN-EN 10219-1 [12] and none of the steel grades fails to fulfil them all. Consequently, welding in the profile corner zone cannot be allowed only on the basis of thickness and steel grade verification – additional analyses of the very restricted requirements for steel chemical composition are necessary.

Larger thickness range of hot finished profiles can be an advantage in case of architecturally exposed steel structures, where the aesthetic aspects require a constant size of the elements and at the same time the economic reasons require the reduction of element self-weight in order to adapt to the variation of the internal forces (Fig. 2). Changes of profile wall thickness are hidden inside the element, which allows to keep its external surface aesthetic and smooth.

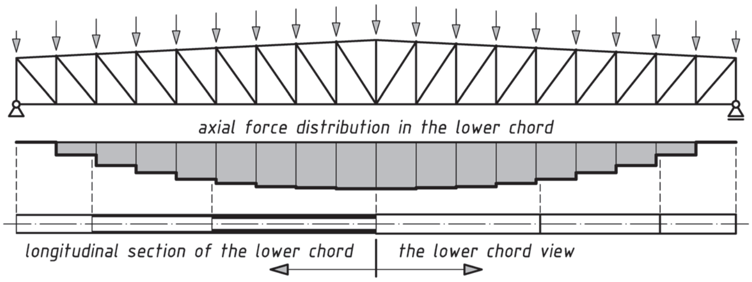

Fig. 2. Realisation of the idea of the cross-section adaptation to axial force distribution.

Larger wall thickness of hot finished hollow sections may also be relevant in the case of steel supporting structures of façades and glass roofs, where increasing of the element optical slenderness has aesthetic and practical (more daylight) advantages. Due to smaller internal corner radii the longitudinal fillet welds require less weld deposit and therefore are cheaper (Fig. 1). At the same time, the lower amount of heat transferred to the base metal reduces the residual welding stresses.

Seamless hot finished hollow sections without longitudinal weld – which is a structural notch – have also higher fatigue strength than cold formed profiles. Pursuant to PN-EN 1993-1-9 [13] hot-rolled sections have the highest detail category $\Delta\sigma_c$ = 160 N/mm^2. Fatigue strength for cold formed hollow sections should be determined using lower detail categories [13]: $\Delta\sigma_c$ = 140 N/mm^2 for the profile wall thickness $t \leq 12.5$ mm and $\Delta\sigma_c$ = 120 N/mm^2 for $t > 12.5$ mm.

The unique properties of hot finished hollow sections allow to design innovative steel structures such as the heavy dynamically loaded crane runway beam shown in Fig. 3 [14].

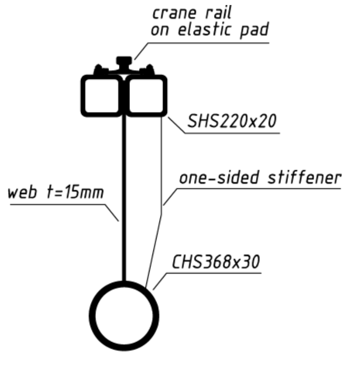

Fig. 3. Innovative crane runway beam with thick-walled hollow section flanges without bracing of lower flange.

4 Residual stresses and their influence on the resistance of axially loaded elements

The manufacturing technologies for hot finished and cold formed hollow sections are completely different, so, consequently, distributions and values of residual stresses also differ significantly. Figure 4 shows the distribution of longitudinal residual stresses on the external surface of the cold formed sections: without (Fig. 4a) and after (Fig. 4b) the hot finishing process [15]. One may notice that heat treatment results in almost two times smaller residual stresses. Apart from that, the differences between the global maximum and minimum residual stresses are also reduced. The maximum values of the stresses, obtained at weld seam axis, are: 414.9 MPa for cold formed and 196.7 MPa for hot finished section. These values correspond to 79.8% and 41.7% of the actual steel yield strength, respectively.

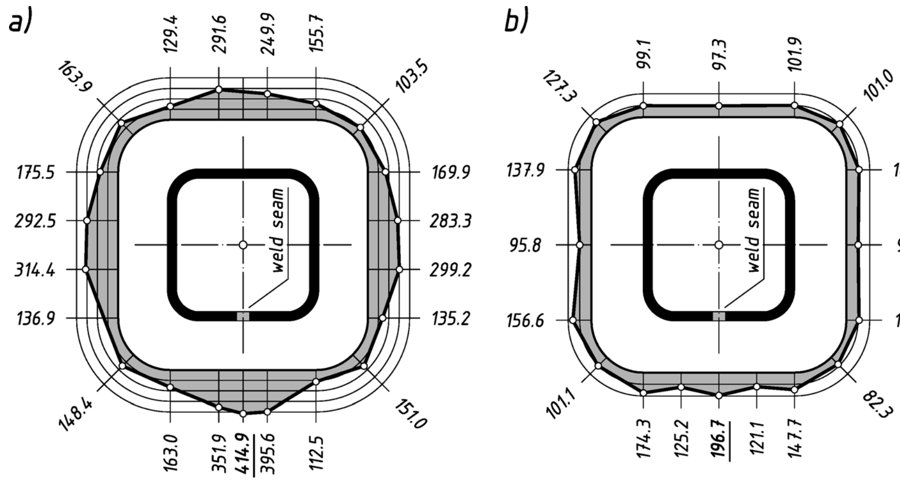

Fig. 4. Residual stresses distribution in [MPa] for: a) cold formed and b) hot finished hollow sections.

Such more favourable distribution of residual stresses results in higher resistance of axially loaded elements made of hot finished hollow sections. The differences between residual stresses distribution in these two types of hollow sections were taken into account in the provisions of PN-EN 1993-1-1 [6]. In the design procedure of axially loaded elements, the cold formed sections are associated with the buckling curve *c* and the imperfection factor α = 0.49, while for hot finished profiles there are two buckling curves: curve a_0 with the imperfection factor α = 0.13 for steel grade S460 and curve *a* with the imperfection factor α = 0.21 for other steel grades. Relative differences between the values of reduction factor (buckling coefficient) for hot finished χ_{HF} and cold formed χ_{CF} hollow sections

$$\delta\chi = (\chi_{HF} - \chi_{CF}) / \chi_{CF} \tag{1}$$

are presented in Fig. 5.

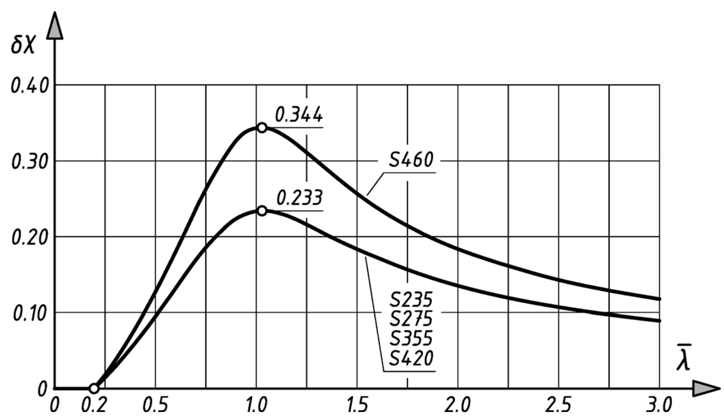

Fig. 5. Relative differences between reduction factor χ for hot finished and cold formed hollow sections.

The lower the value of buckling coefficient χ, the larger the reduction of the design buckling resistance of the compression member.

The largest relative differences in buckling coefficient χ are achieved in the range of medium non-dimensional slenderness. The functions presented in Fig. 5 reach their extremes for non-dimensional slenderness of approximately 1.0. Maximum increment of the buckling coefficient value steel grades S235 to S420 is 23.3% and for steel grade S460 – 34.4%.

5 Summary

Contemporary methods of manufacturing steel rectangular hollow sections enable their production as both hot rolled and cold formed elements. Additional thermomechanical treatment of cold formed profiles causes changes in the microstructure of steel, which becomes more homogeneous. This improves steel toughness and significantly decreases residual stresses. After this process, the metallurgical properties and residual stresses of cold formed sections are practically equivalent to those for hot finished sections. Therefore, they are covered by the same EN 10210 Standard [4]. The increase in the carrying capacity of axially loaded elements, resulting from lower residual stresses and improved mass distribution in cross section for the hot finished sections, can reach up to about 40% and depends on the steel grade. These values cannot, however, fully compensate for the increased unit price of hot finished sections, which depends on market fluctuations, profile size or the tonnage order and may vary in the range from 5% to 54% [16]. However, the decision-making criterion may be the favourable technological properties of hot finished sections, mainly the lack of restrictions for directly (tube to tube) welded connections that exist in the case of cold formed sections with wall thickness t in the ranges: (4.0 mm, 6.0 mm⟩, (8.0 mm, 10.0 mm⟩ and (12.0 mm, 24.0 mm⟩. An additional advantage of hot finished profiles made from cold formed welded tubes is the high quality of external surface finishing, which may be important e.g. in the case of architecturally exposed steel structures of such public buildings as: airport terminals, railway stations, shopping centres, etc.

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