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Application of cold formed hollow steel sections

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Professional paper

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According to EN 1993-1-1, the application of hollow steel sections is permitted in the execution of steel structures, regardless of whether they are hot finished according to EN 10210 or cold finished according to EN 10219. Steel designers often have doubts about the use of cold formed hollow sections due to unfavourable effects of cold forming. Such doubts may be due to inconsistencies in EN 1993-1-8 relating to the permissibility of welding in cold formed zones. The main objective of this paper is to present guidelines for the selection of appropriate rectangular hollow sections in the design of steel structures, with justification of the use of cold formed hollow sections.

Key words:
hollow sections, manufacturing, welding, brittle fracture, joints

Stručni rad

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Primjena hladno oblikovanih šupljih čeličnih profila

Prema EN 1993-1-1 primjena šupljih profila dopuštena je u izradi čeličnih konstrukcija neovisno o tome jesu li profili toplo dogotovljeni prema EN 10210 ili hladno oblikovani prema EN 10219. Kod projektanata često postoji dvojba u vezi s primjenom hladno oblikovanih profila uslijed negativnog utjecaja hladnog oblikovanja na njihovo ponašanje. Nedoumicu može izazivati i nedorečenost u normi EN 1993-1-8 koja se odnosi na mogućnost zavarivanja u hladno oblikovanim zonama. Osnovna svrha rada je prikazati smjernice za odabir pravokutnih šupljih profila kod projektiranja čeličnih konstrukcija, a posebno se obrazlaže opravdanost primjene hladno oblikovanih profila.

Ključne riječi:
šuplji profili, proizvodnja, zavarivanje, krti lom, priključci

Fachbericht

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Anwendung kaltgeformter Stahlhohlprofile

Laut EN 1993-1-1 ist die Anwendung von Stahlhohlprofilen in der Ausführung von Stahlkonstruktionen erlaubt, unabhängig davon ob sie laut EN 10210 warmgefertigt oder laut EN 10219 kaltgefertigt wurden. Konstrukteure haben im Entwurf oft Zweifel bezüglich der Anwendung kaltgeformter Hohlprofile aufgrund der negativen Auswirkungen der Kaltfertigung. Zweifelfälle können auch durch Inkonsistenzen der Norm EN 1993-1-8 bezüglich der möglichen Anwendung von Schweißverbindungen in kaltgeformten Zonen bedingt sein. Das grundgelegene Ziel dieser Arbeit ist, Richtlinien für die Auswahl von rechteckigen Hohlprofilen im Entwurf von Stahlkonstruktionen zu präsentieren, und insbesondere die gerechtfertigte Verwendung von kaltgeformten Profilen zu erläutern.

Schlüsselwörter:
Hohlprofile, Herstellung, Schweißen, Sprödbruch, Verbindungen

1. Introduction

According to the long-standing experience of the authors, designers often have doubts about application of hot finished sections according to EN 10210 [1], and cold formed hollow sections according to EN 10219 [2]. The term "Hot-finished" refers to tubes for which the final forming process is carried out in hot environment, with the final deformation occurring at > 700 °C, or where the tube is cold formed and then subsequently heat-treated at the temperature of > 550 °C. Normalized and normalized rolled tubes are also regarded as hot-finished. The term “Cold-formed” denotes a manufacturing method where the tube forming process is carried out at an ambient temperature without subsequent heat treatment, except for the weld seam, which may be heat-treated.
Hot finished hollow sections have a much tighter corner profile as a result of metal flow during the forming process, and they have no residual stress in corners. The cross section has a homogeneous structure and hardness. Cold-formed hollow sections exhibit a high level of cold working in corner regions during the forming process (EN 10210-2:2006, Table 2), and

Figure 1. Hot finished circular hollow section with pitted surface [3]

could be susceptible to corner cracking if manufactured with tight radius corners. To take this into consideration, larger radii are specified in EN 10219-2: 2006 (cf. EN 10219-2, Table 3).
From the aesthetic point of view, the advantage of cold-formed hollow sections lies in their smooth surface. Hot formed sections can be pitted, as shown in Figure 1.
The main objective of the paper is to compare performance of hot finished and cold formed hollow sections, and to provide guidelines for the selection of rectangular hollow sections in the design of steel structures.

2. Welding in cold formed zones

Welding reduces toughness in cold formed zones of hollow sections and increases the risk of cracking. Therefore, according to EN 1993-1-8, Clause 4.14 [4], welding may be carried out within the length of 5t at either side of a cold-formed zone, cf. EN 1993-1-8, Table 4.2 [4], provided that one of the following conditions is fulfilled:

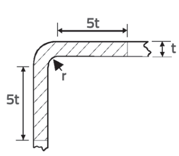
- cold-formed zones are normalized after cold-forming but before welding;
- r/t-ratio satisfies the relevant value obtained from EN 1993-1-8, Table 4.2 [4].

It is specified in EN10219 that all steel must be fully killed (i.e. deoxidised and aluminium treated).
According to corrigendum to EN 1993-1-8 from July 2009 [5], cold formed hollow sections according to EN 10219 that do not satisfy the limits given in Table 4.2 can be assumed to satisfy these limits if:

- they are no more than 12.5 mm in thickness,
- they are aluminium killed with the quality grades J2H, MH, MLH, NH, or NLH, and if they further satisfy C ≤ 0,18 %, P ≤ 0,020 % and S ≤ 0,012 %.

Table 1. Conditions for welding cold-formed zones and adjacent material (EN 1993-1-8, Table 4.2 [4])

Ratio r/t	**Strain due to cold forming** [%]	**Maximum thickness** [mm]		
		Generally		**Fully killed Aluminium-killed steel** [Al ≥ 0,02 %]
		Predominantly static loading	**Where fatigue predominates**	
≥ 25	≤ 2	any	any	any
≥ 10	≤ 5	any	16	any
≥ 3,0	≤ 14	24	12	24
≥ 2,0	≤ 20	12	10	12
≥ 1,5	≤ 25	8	8	10
≥ 1,0	≤ 33	4	4	6



- In other cases welding is only permitted within a distance of 5t from the corners if it can be shown by tests that welding is permitted for that particular application.

Misunderstandings in the interpretation of Clause 4.14 of EN 1993-1-8 refer to formulation that the welding may be carried out within the length of 5t at either side of a cold-formed zone. This could be interpreted that the welding is not allowed in the cold formed corner. However, the figure in Table 4.2, EN 1993-1-8, correctly shows that, if the requirement r/t is satisfied, then the welding of cold formed corners is also allowed. Therefore, Evolution Group on EN 1993-1-8 [6] proposed formulation of the clause 4.14(1) as follows: "In the bent areas and up to distance 5t from these areas (see figure in Table 4.2) welding may be carried out when one of the following conditions is fulfilled:".
Based on the above it can be concluded that the welding of cold formed rectangular hollow sections according to EN 10219, may be carried out on the whole cross section, if the above conditions are met. A cold formed structural member welded on the whole cross section is shown in Figure 2.

Figure 2. Cold formed structural member welded on the whole cross section [3]

3. Avoiding brittle fracture

The evaluation of toughness, i.e. avoidance of brittle fracture of structural elements made of cold formed hollow sections according to EN 10219, is not clearly defined in EN 1993-1-10 [7]. Therefore, the Workgroup European Commission Joint Research Centre (JRC) prepared a document [8] in which the method for the selection of cold-formed hollow sections to avoid brittle fracture has been proposed. This procedure is compliant with EN 1993-1-10 and is proposed as a part of amendments to this standard. The allowed hollow-section thickness depending on the steel grade and reference temperature of up to T_{Ed} -50°C is presented in EN 1993-1-10, Table 2.1. The adjustment $\Delta T\varepsilon_{cf}$ for the level of cold forming ε_{cf} has been added in the new procedure, adapted for cold formed hollow sections (cf. Eq. 1). The Table 2.1. from EN 1993-1-10 was extended for reference temperatures of up to -120 °C.
Based on the new procedure proposed in paper [8], reference temperatures T_{Ed} were calculated in paper [9], as well as lowest air (operating) temperatures for the specific return period T_{md} for structures using cold-formed RHS to EN 10219 according to:

$$\mathbf{T}_{md} = \mathbf{T}_{Ed} - \Delta\mathbf{T}\varepsilon_{cf} \quad (1)$$

The Equation (1) is valid for:

$$\Delta\mathbf{T}_r = \Delta\mathbf{T}_\sigma = \Delta\mathbf{T}_R = \Delta\mathbf{T}_{\dot{\varepsilon}} = 0 \quad (2)$$

Where is:
ΔT_r - the adjustment for radiation loss,
ΔT_σ - the adjustment for stress and yield strength of material, crack imperfections, and member shape and dimensions,
ΔT_R - the safety allowance, if required, to reflect different reliability levels for different applications,
$\Delta T_{\dot{\varepsilon}}$ - s the adjustment for strain rate other than the reference strain rate $\dot{\varepsilon}_0$.

Lowest permissible reference temperatures T_{Ed} and air (operating) temperatures T_{md}, for rectangular hollow sections according to EN 10219 [2], are shown in Table 2.

Table 2. Lowest permissible reference temperatures T_{Ed} and air (operating) temperatures T_{md}, for hollow rectangular sections to EN 10219 [2], adapted from [9]

Square and Rectangular Structural Hollow Sections					
EN 10219 steel grade		Charpy V-notch impact test		Lowest design temperature	
		Test temperature [°C]	Impact energy [J]	T_{Ed} [°C]	T_{md} [°C]
S235	JRH	20	27	-85	-50
S355	J2H	-20	27	-95	-60
	MH	-20	40	-100	-65
	MLH	-50	27	-120	-85
S420	MH	-20	40	-90	-55
	MLH	-50	27	-110	-75
S460	MH	-20	40	-85	-50
	MLH	-50	27	-105	-70

Temperatures T_{Ed} and T_{md} given in Table 2 are calculated for the cold formed section wall thickness of t = 12,5 mm. For lower thicknesses, the values are on the safe side. For the serviceability limit state, design temperature values are calculated for the stress level σ_{Ed} = 0,75 f_y. If the stress level is lower, the values are on the safe side. It was found that the temperature adjustment for cold formed hollow sections depends on the wall thickness [8]. Thus, the temperature shift $\Delta T_{\varepsilon cf}$ is –35 °K for wall thicknesses t ≤ 16 mm and -45 °K for wall thicknesses 16 mm < t ≤ 40 mm. As shown in Table 2, a large range of rectangular hollow sections satisfy requirements for avoiding brittle fracture at very low operating temperatures T_{md} from -50 °C to -85 °C.

4. Resistance of structural members

According to EN 1993-1-1 [10], cold formed and hot finished hollow sections do not differ with regard to the bending and tension resistance. For compression members, the differences are due to magnitude of residual stresses. Hot finished hollow sections have a lower residual stress, and are assigned to a more favourable buckling curve "a" when designing compression members. On the other hand, cold formed hollow sections have a higher residual stress, and are assigned to a less favourable buckling curve "c".
The paper [3] gives a comparison of hot finished and cold formed hollow section members under compression in terms of material consumption and costs. Mechanical characteristics and prices for hollow sections 150 x 150 x 6,3 and 200 x 200 x 10 are used with effective buckling lengths of 3 m, 4 m, 5 m, 8 m, and 10 m. The study has shown that the buckling resistance of hot finished hollow sections, using the buckling curve "a", is by 14 % to 28 % higher when compared to cold formed hollow sections using the buckling curve "c". For that reason, the use of hot finished hollow sections reduces the weight of structures by 14 % to 17 % on an average, but their price is still 5 % to 33 % higher. As to concrete filled hollow-section compression members according to EN 1994-1-1 [11], their buckling resistance is irrespective of the product (hot finished- or cold-formed). The buckling curve "a" is to be chosen for the reinforcement ratio $r_s \le 3$ %, and "b" for the reinforcement ratio 3 % < $r_s \le 6$ %.

5. Resistance of joints in hollow section lattice girders

According to EN 1993-1-8, the resistance of joints in hollow section lattice girders is irrespective of the product (hot finished or cold formed). The recommended values of partial factors are based on probabilistic calibration. For joints in hollow section lattice girders, the recommended value of partial factor is γ_{M5} = 1,0. The recommended value is accepted in almost all countries of the European Union. In Croatian National Annex HRN EN 1993-1-8/NA [14], the adopted value of partial factor is γ_{M5} = 1,35. This value is conservative, which may result in a higher lattice girder weight, and in higher construction costs. This issue is illustrated in the following design example of a joint in a hollow section lattice girder. For the lattice girder 40 m in span, 2,5 m in height, and for the design load of 54 kN in nodes (27 kN in peripheral nodes), the verification was conducted according to EN 1993-1-1 for the upper chord, bottom chord and brace members. The SHS 140x8 was chosen for the upper chord, SHS 140 x 6.3 for the lower chord, and SHS 80x5 for brace members. Steel grade S355 was adopted for all members. The static layout of the lattice girder, with the analysed welded joint, is shown in Figure 3. The design of the joint was conducted out according to Clause 7.5 EN 1993-1-8.

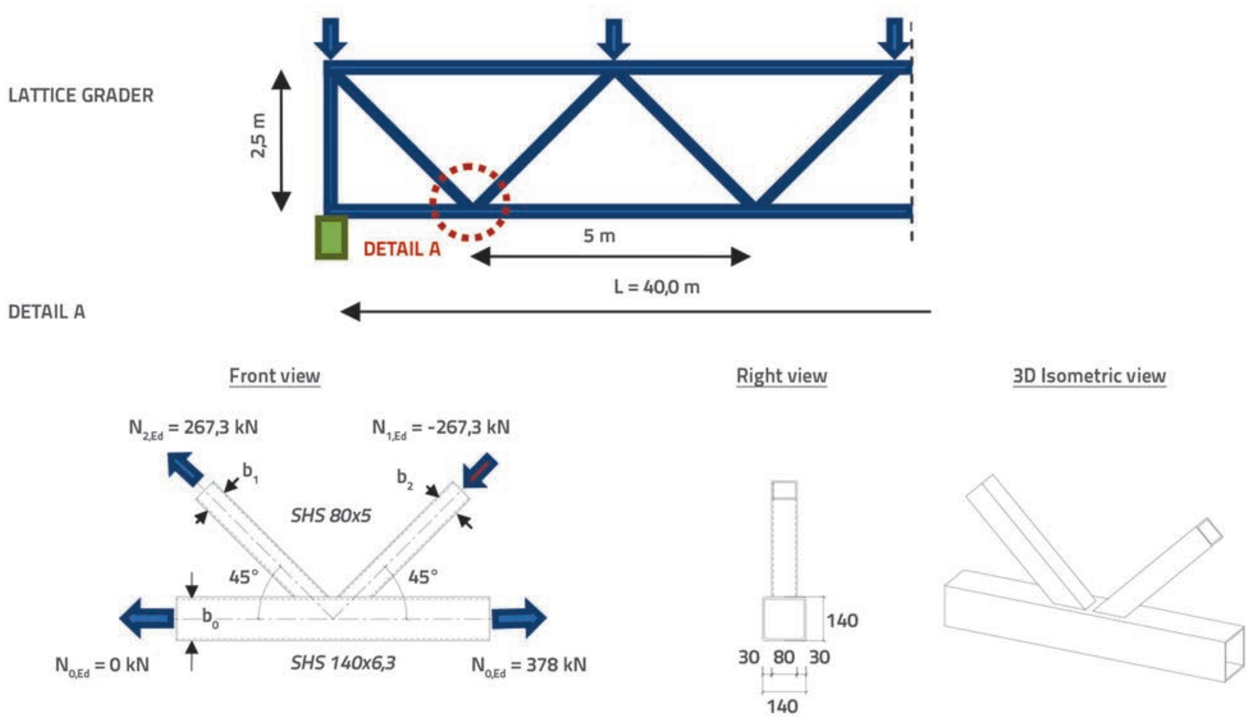


Figure 3. Welded joint in hollow section lattice girders

The following should be verified for the considered joint: chord face failure, chord punching, chord shear, and welds fracture. A requirement of Clause 7.3.1 (4) EN 1993-1-8 for the minimal weld throat thickness for the steel grade S355 is $a_w > 1{,}1t$ (t is the section wall thickness). For the considered joint, the weld throat thickness $a_w = 6$ mm was adopted on the whole perimeter of the brace member cross section.
The weakest component of the joint is the chord face failure according to the following expression (Table 7.10 EN 1993-1-8):

$$N_{1,Rd} = \frac{8{,}9\gamma^{0,5} k_n f_{y0} t_0^2}{\sin\theta_i}\left(\frac{b_1+b_2}{2b_0}\right)/\gamma_{M5} \quad (3)$$

Where:

$\gamma = b_0/(2t_0)$ - ratio of the chord width or diameter b_0 to twice its wall thickness t_0,

$k_n = 1{,}3 - \frac{0{,}4\,n}{\beta} \le 1{,}0$ - coefficient that takes into account stresses in the chord,

β - coefficient that takes into account geometry of connection bars,

$n = \sigma_{0,Ed}/f_{y,0}$ - stress level in the chord.

The joint resistance verification based on the partial factor γ_{M5} = 1,0 is satisfactory with the utilization ratio of 79 %. If the partial factor of γ_{M5} = 1,35, as given in HRN EN 1993-1-8 NA, is used, the joint resistance is not satisfactory with the utilization ratio of 107 %. Therefore, the joint has to be reinforced by overlapping the brace members, using stronger cross sections, or by adding a flange plate. Each reinforcement method increases the cost and can make hollow sections uncompetitive.

8. Seismic performance

Steel frame systems with cold formed hollow section columns are used to resist seismic forces in Japan, which is characterized by high seismic activity. Extensive studies [20] and experience from Japan justify the use of such columns. In the USA, simple frames supported with hollow section brace systems are more often used. Brace members in tension and compression (buckling) contribute to the dissipation of seismic energy. Studies on circular hollow sections [21] show that the section slenderness (d/t) is a factor relevant for ductility, and that the cold formed as well as hot finished hollow sections are suitable for use in seismically active areas.

9. Certification

Proving quality of construction products is one of the most important issues in modern construction industry. The testing and quality certificates are the same for the cold formed and hot finished hollow sections, and are split into two categories. The first category is a "specific test", and the second a "non-specific test". The "specific test" is related to actual products to be supplied, and is presented by a "test certificate". This certificate ensures popper presentation of the product's quality. The "non-specific test" is performed by the manufacturer in accordance with its own procedures and is presented by means of a test report. The results supplied need only be "representative" of the material grade and so are generally not from the products actually supplied, and sometimes not even from material of the same dimensions. Therefore, it does not ensure a correct presentation of the product's quality. Cold formed sections that are suitable for structural applications must be supplied with test certificate to be truly suitable for construction. Lower-price commodity cold formed products intended for general engineering applications are supplied with a test report only. The CE (Conformity European) marking is obligatory for products made of structural steel. Before the product is marked with the CE mark, manufacturers must comply with the conformity assessment procedures according to the CPD (Construction Products Directive). This means that the CE marking for hot finished and for cold-formed rectangular hollow sections should demonstrate compliance with EN 1090 [22, 23] as well as with [1, 2, 4,10]. Therefore, all products correctly specified, manufactured, and supplied with appropriate certification, are suitable for the realization of all types of steel structures.

10. Hot-dip galvanising

Hot-dip galvanizing is often used for corrosion protection of hollow sections. The process of hot-dip galvanizing may cause cracks in the corners of rectangular hollow sections. This problem is attributed to the effect of LME (Liquid Metal Enbrittlement), which is the result of interaction of three conditions [24]:

- A critical level of residual stresses due to cold forming or welding;
- Susceptible material, e.g. non-aluminium killed steel, high yield-to tensile ratio, pre-existing micro cracks as a result of forming, or adverse chemical composition;
- Liquid metal, especially with the presence of impurities or additives.

Tests have shown [25, 26] that the high-quality manufactured hollow steel sections produced according to EN 10219 S355 J2H, S420 MH, S500MH, are not sensitive to LME. Also, welded assemblies made of high-quality manufactured hollow sections produced according to EN 10219 for the listed qualities can be hot-dip galvanized without the risk of LME [26].

11. Conclusion

The application of cold-formed hollow sections produced in accordance with EN 10219 may be questionable or limited due to negative impact of cold forming on their behaviour. Regarding the welding possibility, welding can be carried out on the whole cross section for cold-formed sections meeting the criteria given in Clause 14.4 EN 1993-1-8. As a part of amendments to EN 1993-1-10A, a new method is proposed that allows selection of materials for cold formed hollow sections to avoid brittle fracture.

If corrosion protection is performed by hot dip galvanizing, cold formed hollow sections may be susceptible to cracking due to the effect of LME. Appropriate quality grades of rectangular hollow sections can be hot-dip galvanized without the risk of LME.

With regard to resistance, compression members made of cold formed rectangular hollow sections have a lower buckling resistance compared to hot finished sections. However, considering the lower price of cold formed hollow sections, the selection of larger dimensions of cold formed hollow sections, or greater wall thickness, can still result in a lower price of structures. There are no differences between hot finished and cold formed hollow sections with respect to buckling resistance of hollow sections filled with concrete and fire resistance.

Cold formed hollow sections have better appearance as they have a smooth surface, which is an architectural advantage for structures with visible steel elements. Another advantage of cold formed sections concerns a smaller geometric tolerance of cross section. Therefore, for instance, an automatic welding can be applied for butt welding of cold-formed hollow sections. High-quality automatic welding can not be performed for greater tolerances, and so manual welding must be applied, which can increase execution costs.

It is shown in this paper that cold-formed hollow sections manufactured according to EN 10219, which are correctly specified and supplied with the appropriate certificates, are suitable for all types of steel structures.

REFERENCES

[1] EN 10210 (2006): Hot finished structural hollow sections of non-alloy and fine grain steels – Part 1: Technical delivery conditions; – Part 2: Tolerances, dimensions and sectional properties.

[2] EN 10219 (2006): Cold formed welded structural hollow sections of non-alloy and fine grain steels – Part 1: Technical delivery conditions; – Part 2: Tolerances, dimensions and sectional properties.

[3] Puthli, R., Packer, J. A.: Structural design using cold-formed hollow sections. *Steel Construction*, 6 (2013), No. 2, pp. 150-157.

[4] EN 1993-1-8 (2005): Eurocode 3: Design of steel structures. Part 1-8: Design of joints;

[5] EN 1993-1-8 (2005): Eurocode 3: Design of steel structures. Part 1-8: Design of joints; including Corrigendum dated July 2009.

[6] Ummenhofer, T.: Proposal of Amendments or Corrigenda on EN1993-1-8:2005-05, Evolution Group on EN 1993-1-8, 2013.

[7] EN 1993-1-10 (2010): Eurocode 3: Design of steel structures. Part 1-10: Material toughness and through thickness properties.

[8] Feldmann, M., Eichler, B., Kühn, B., Stranghöner, N., Dahl, W., Langenberg, P., Kouhi, J., Pope, R., Sedlacek, G., Ritakallio, P., Iglesias, G., Puthli, R. S., Packer, J. A., Krampen, J.: *Choice of steel material to avoid brittle fracture for hollow section structures.* Report EUR 25400 EN, European Commission Joint Research Centre Scientific and Policy Report for the evolution of Eurocode *3*, 2012.

[9] Ongelin, P., Valkonen, I.: Structural hollow sections. *EN 1993 Handbook*, Rautaruukki Oyj, Finland 2012.

[10] EN 1993-1-1 (2010): Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings.

[11] EN 1994-1-1 (2010): Eurocode 4: Design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings.

[12] Androić, B., Dujmović, D., Lukačević, I.: *Projektiranje spregnutih konstrukcija prema Eurocode 4, prvo izdanje*, I.A. Projektiranje, Zagreb, 2012.

[13] Dujmović, D., Androić, B., Lukačević, I.: *Primjeri proračuna spregnutih konstrukcija prema Eurocode 4, prvo izdanje*, I.A. Projektiranje, Zagreb, 2014.

[14] HRN EN 1993-1-8 (2008)/NA:2013: Eurokod 3: Projektiranje čeličnih konstrukcija - Dio 1-8: Proračun priključaka - Nacionalni dodatak.

[15] EN 1993-1-9 (2010): Eurocode 3: Design of steel structures. Part 1-9: Fatigue.

[16] Zhao, X. L., Herion, S., Packer, J. A., Puthli, R., Sedlacek, G., Wardenier, J., Weynand, K., van Wingerde, A. M., Yeomans, N.: *Design guide for circular and rectangular hollow section welded joints under fatigue loading, CIDECT Design Guide No. 8.* Köln: TÜV-Verlag 2000.

[17] Bäckström, M. et al.: A new fatigue testing method for the corners of struc- tural hollow Sections. Design and Analysis of Welded High-Strength Steel Structures, Proceedings of Fatigue 2002, 8th International Fatigue Congress, Stockholm, 2–7 June 2002, pp. 277–302.

[18] Twilt, L., Hass, R., Klingsch, W., Edwards, M., Dutta, D.: *Design guide for structural hollow section columns exposed to fire. CIDECT Design Guide No. 4.* Köln: TÜV-Verlag 1994.

[19] EN 1993-1-2 (2010): Eurocode 3: Design of steel structures. Part 1-2: General rules – Structural fire design.

[20] Kurobane, Y., Packer, J. A., Wardenier, J., Yeomans, N.: *Design guide for structural hollow section column connections. CIDECT Design Guide No. 9,* Köln: TÜV-Verlag 2004.

[21] Packer, J. A., Chiew, S. P., Tremblay, R., Martinez-Saucedo, G.: Effect of material properties on hollow section performance. Structures and Buildings, *Proceedings of the Institution of Civil Engineers* 163 (2010), No. SB6, pp. 375–390.

[22] EN 1090-1 (2006): Steel and aluminium structural components. Part 1: General delivery conditions.

[23] EN 1090-2 (2007): Steel and aluminium structural components. Part 2: Technical requirements for steel structures.

[24] Galvanizing structural steelwork –An approach to the management ofliquid metal-assisted cracking. BCSA & GA Publication No. 40/05, 1st Ed.,British Constructional Steelwork Association & Galvanizers Association, London, 2005.

[25] Poag, G., Zervoudis, J.: Influence of various parameters on steel cracking during galvanizing. AGA Tech Forum, Kansas, MO, USA, 2003.

[26] Ritakallio, P. O.: Cold-formed high-strength tubes for structural applications. Steel Construction, 5 (2012), No. 3, pp. 158-167.