



Cold-formed high-strength tubes for structural applications

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Cold-formed hollow sections are the dominant tubular construction material. The applicability of cold-formed tubes is sometimes questioned because of doubts about low-temperature ductility, deformation capacity of welded joints, suitability for welding in the cold-formed corner, poor fatigue behaviour of the corner or suitability for hot-dip galvanizing. It is also claimed that by choosing hot-finished tubes, such risks can be automatically avoided. This study confirms that appropriate tube manufacturing yields cold-formed EN 10219 tubes in grades S355J2H to S460MH with a performance equal to or better than hot-finished tubes. Properly made cold-formed high-strength tubes are available for fabricating efficient lightweight structures and can be safely used even at low temperatures without the aforementioned doubts.

- Reduction in environmental impact and life cycle cost

Over the course of the last 30 years we have experienced a continuous transition towards higher-strength structural tubes, see Fig. 2 [4]. During the 1980s grade S275 dominated. In the 1990s grade S355 gradually took over and has been dominant since

1 Introduction

Many examples in nature show the excellent properties of the tubular shape with regard to loading in compression, torsion and bending in all directions. Furthermore, the closed shape reduces the area to be protected and extends the corrosion protection life. These excellent properties are combined with an attractive shape for architectural applications [1]. Tubular materials enable steel structures that are both architecturally and aesthetically impressive and also efficient structures from an engineering point of view [2]. Increased strength opens up the chance to reduce wall thicknesses and the weight of the structure, see Fig. 1 [3].

Reduced wall thickness and less weight usually bring benefits:

- Easier processing
- Lower transportation costs or increased payloads
- Possibility of realizing structures that are not feasible with lower-strength steels

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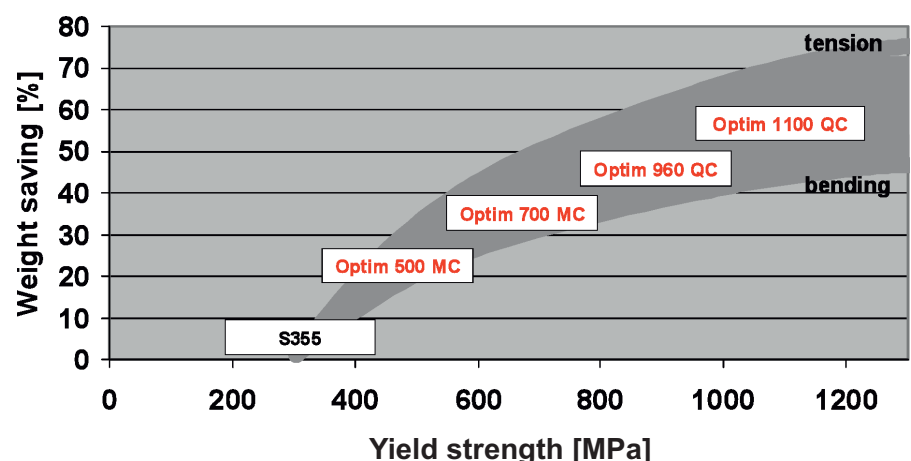


Fig. 1. Weight-saving potential of steel for tension and bending [3]

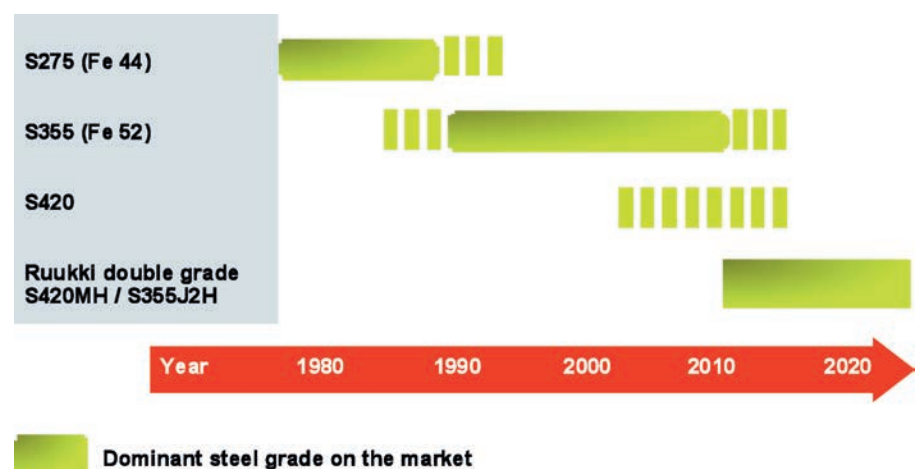


Fig. 2. Evolution of structural tube strengths [4]

then. Right now we are again witnessing a transition and grade S420MH is anticipated to take over as the standard material. This evolution is not incidental. It is due to progress in steel-making, tube manufacturing, workshop fabrication, welding technology and design.

2 Structural tubes

From a global perspective we are dealing with a diversity of quality. According to *Packer and Chiew* [5], structural tubes for steel construction are manufactured in diverse locations around the world, to a variety of standards, by either a hot-finishing or seamless process or, more commonly, by cold-forming. The implications of using material produced to a particular standard in various statically loaded or dynamically loaded applications are often not fully appreciated. Problems regarding surface finish, corner cracking and hot-dip galvanizing have been encountered in North America and Asia with certain cold-formed square and rectangular hollow sections. Due to these observations these products are now subject to constraints for seismic applications. This has also led to a fundamental re-appraisal of the cold-formed manufacturing specification in North America.

In Europe we have harmonized standards for two main types of product:

- EN 10210-1&2 – Hot-finished structural hollow sections of non-alloy and fine-grain steels
- EN 10219-1&2 – Cold-formed welded structural hollow sections of non-alloy and fine-grain steels

The manufacturing methods for these products are different. Consequently, the dimensions, tolerances and cross-sectional properties are slightly different, too.

“Hot-finished” stands for a manufacturing method where the final forming process of the tube is carried out hot, with final deformation > 700 °C, or where the tube is cold-formed and then subsequently full body heat-treated at a temperature > 550 °C. Normalized and normalized rolled tubes are regarded as hot-finished provided the tubes are processed or heat-treated in the normalizing temperature range.

“Cold-formed” stands for a manufacturing method where the main forming process of the tube is carried out at ambient temperature and the product is supplied without additional heat treatment (except the weld seam may be heat-treated). Cold-formed hollow sections are the dominant tubular construction material (by a rough estimate 80–90 % of the volume). Economical and environmental constraints favour cost competitiveness and higher strength. The cold-forming route is naturally economical and can mostly adapt to higher strength, too.

The applicability of cold-formed tubes is sometimes questioned or limited due to doubts about:

- Low-temperature ductility
- Deformation capacity of welded joints
- Suitability for welding in the cold-formed corner
- Poor fatigue behaviour
- Suitability for hot-dip galvanizing

It is also claimed that choosing hot-finished tubes means it is possible to avoid the above risks because these products have inherently better grain structure and superior mechanical properties compared with their cold-formed counterparts [5]. In other words, there are claims that cold-formed tubes do not offer an acceptable level of structural safety and reliability.

The manufacture of high-quality cold-formed tube comprises three crucial steps:

1. Integrated steelmaking – ladle refining – slab casting
 - appropriate chemistry of the steel
2. Hot rolling – controlled cooling and coiling
 - appropriate microstructure and mechanical characteristics of the flat steel
3. Tube manufacturing – cold forming – welding – (weld normalizing)
 - shaping
 - appropriate dimensions and structural properties and suitability for shop fabrication, downstream processing and structural use

Thus, the quality of tube is not pure serendipity. It is a result of the adequate processing of the steel and manufacturing of the tube.

The aim of this paper is to highlight:

- The fundamental reasons for the doubts listed above regarding cold-formed tubes.
- The importance of the proper manufacturing of structural hollow sections.
- The reliability and performance of appropriate cold-formed structural hollow sections.

3 Low-temperature ductility

Kosteski et al. [6] carried out a comprehensive study of the low-temperature impact properties of rectangular hollow sections from different sources and demonstrated the diversity of quality while comparing:

1. Products from various manufacturers: North America, South America, Japan and Europe
2. Product properties in various parts of the cross-section
3. Product properties in various orientations in the cross-section

Some of the observations from *Kosteski et al.* [6] are shown in Fig. 3.

Comparison with European standards EN 10210 and EN 10219 enables the following conclusions:

- Hot-finished hollow section (d) is quite uniform and conforms to EN 10210 grade S355J2H in all locations over the cross-section.
- Cold-formed hollow section (c) is quite heterogeneous and does not conform to EN 10219 grade S355J2H in any location over the cross-section.
- Stress-relieved hollow section (g) is extremely heterogeneous but conforms to EN 10219 grade S355J2H in all locations over the cross-section.
- Cold-formed product (h) is rather uniform and conforms to EN 10219 grade S355J2H in all locations over the cross-section.

The study of *Kosteski et al.* [6] enables important conclusions:

1. The products available on the market are rather diverse.
2. The product properties do not correlate with the method of manufacture.
3. Grade S355J2H rectangular hollow sections with impact properties conforming to EN 10210 or

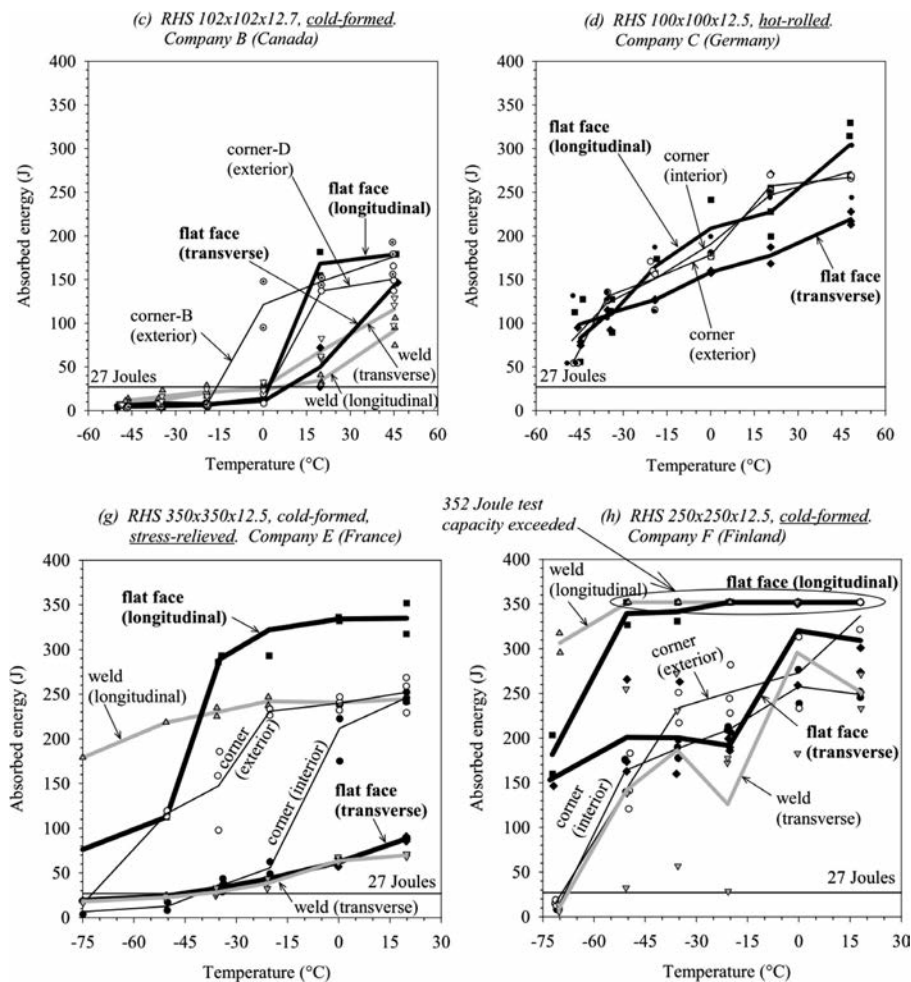


Fig. 3. Charpy-V impact properties of hollow sections from various manufacturers [6]

EN 10219 in any location and in any orientation are technically possible and available on the European market.

Ruukki's current standard quality "Ruukki double grade S420MH/S355J2H" conforms to EN 10219-1&2 grades S420MH and S355J2H and fulfils the corresponding Charpy-V requirements both on the flat face and in corner area as well, see Figs. 4 to 6.

The manufacturing method, hot-finished or cold-formed, is not the fundamental factor that dictates the low-temperature toughness. The basic reason is related to other factors in steelmaking and tube manufacturing. Hence, the quality of the product very much depends on the supplier. Properly manufactured grade S355J2H and grade S420MH rectangular hollow sections with impact properties conforming to EN 10219 in any location of the cross-section and in any orientation are technically possible and available on the European market.

4 Welding in the cold-formed corner area

Rectangular hollow sections are well suited to the manufacture of welded

structures. For historical reasons, there are concerns regarding the possible strain ageing caused by welding and hence the reduction in impact toughness of rectangular hollow section corners. Consequently, Eurocode 3 includes restrictions on welding in the corner area [7].

EN 1993-1-8 section 4.14 "Welding in cold-formed zones", states the following [7]:

- "Welding may be carried out within a length $5t$ either side of a cold-formed zone provided that one of the following conditions is fulfilled:
- the cold-formed zones are normalized after cold-forming but before welding
 - the r/t -ratio satisfy the relevant value obtained from Table 4.2. in EN 1993-1-8"

The requirements for the corner profile of EN 10219 hollow sections [8] are given in Table 2.

A comparison of Tables 1 and 2 illustrates that rectangular hollow sections according to EN 10219 do not automatically satisfy the requirements of EN 1993-1-8 for welding in the cold-formed corners.

Verification of reliable welding in cold-formed corners of rectangular hollow sections was the subject of a detailed study by *Puthli* and *Herion* [9], [10]. Their study focused on cold-formed rectangular hollow sections produced by selected European manufacturers to European standard EN 10219 and included the influence of:

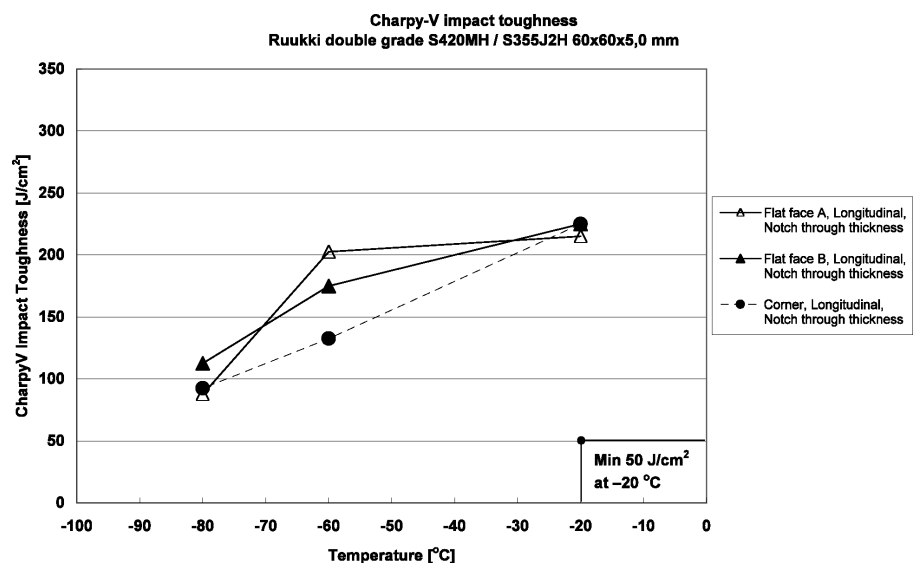


Fig. 4. Charpy-V impact toughness of cold-formed hollow section, EN 10219 – Ruukki double grade S420MH/S355J2H – $60 \times 60 \times 5$ mm

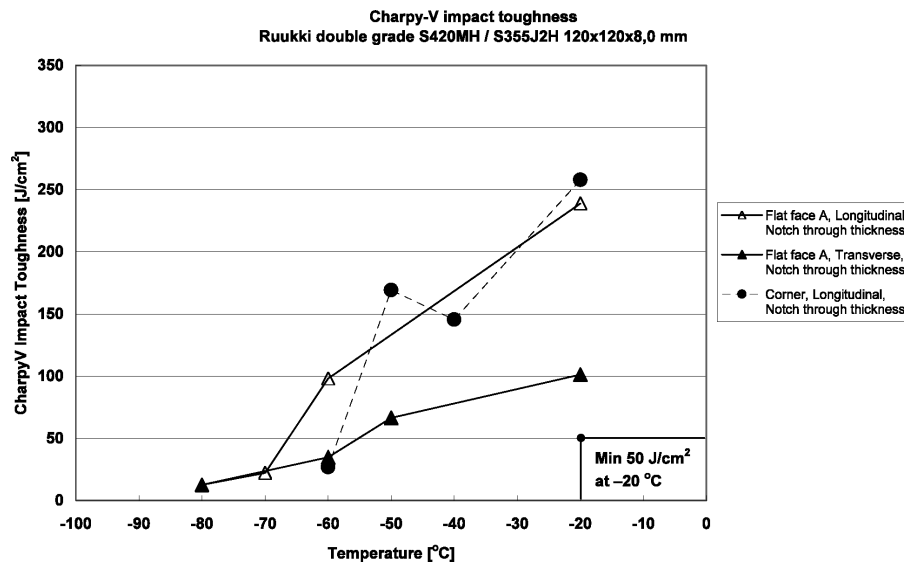


Fig. 5. Charpy-V impact toughness of cold-formed hollow section, EN 10219 – Ruukki double grade S420MH/S355J2H – 120 × 120 × 8 mm

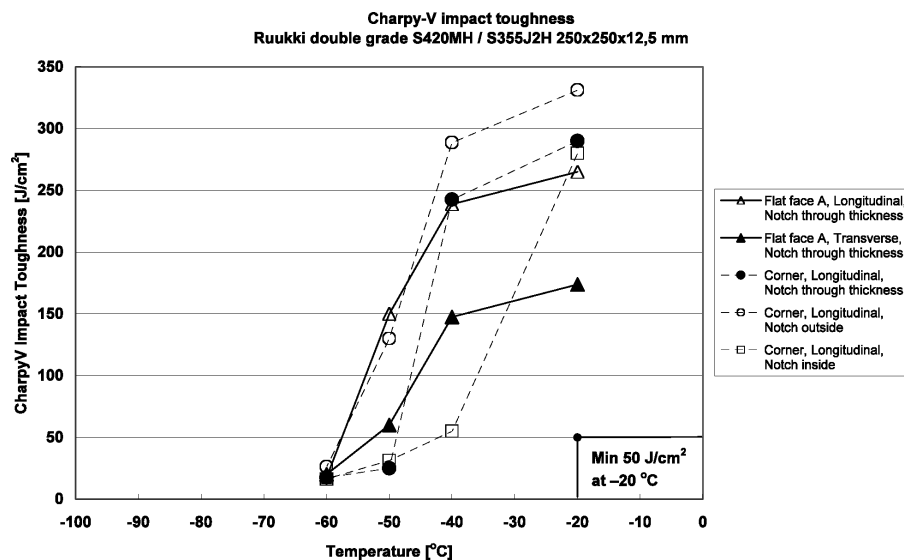


Fig. 6. Charpy-V impact toughness of cold formed hollow section, EN 10219 – Ruukki double grade S420MH/S355J2H – 250 × 250 × 12.5 mm

Table 2. Tolerances on external corner profiles, EN 10219-2 Table 3 [8]

Thickness T [mm]	External corner profile C ₁ , C ₂ or R*
T ≤ 6	1.6 T to 2.4 T
6 < T ≤ 10	2.0 T to 3.0 T
10 < T	2.4 T to 3.6 T

* The sides need not be tangential to the corner arcs.

- chemical composition
- corner radius
- welding parameters
- steel grades
- service temperature

The characterization and testing of the tubular cross-sections was very detailed. Welding in the corner was tested to clarify the influence of welding on the Charpy-V impact toughness in the corner area. The testing included base material from the flat face, cold-formed corner as supplied and the corner as welded. The position of the notch in the welded corner specimen is shown in Fig. 7.

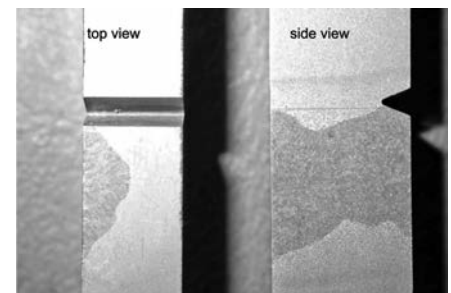
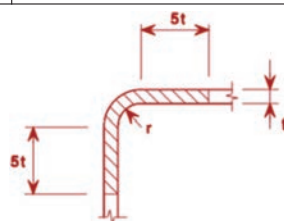


Fig. 7. Position of the notch crossing the HAZ in the middle of the Charpy-V specimen, Fig. 4-1 [9]

Table 1. Conditions for welding cold-formed zones and adjacent material, EN 1993-1-8 Table 4.2 [7]

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



Some observations from *Puthli* and *Herion* [9] are shown in Fig. 8. Apparently, cold-forming and ageing by welding has an insignificant effect on Charpy-V impact toughness in these cases.

CIDECT has prepared a recommendation based on the study by *Puthli* and *Herion* [9], [10]:

“In respect of welding in cold formed areas of hollow sections made of S275J2H, S355J2H and S460MLH subjected to fatigue load following recommendation can be given:

1. According to EN 1993-1-8:2003 welding in the cold formed zones of cold formed hollow sections according to EN 10219 is permitted, if the requirements given in

clause 4.14 in EN 1993-1-8:2003 are fulfilled.

2. If the requirements for r/t given in Table 4.2 of EN 1993-1-8:2004 are not fulfilled, the welding in the cold-formed zones is permitted, provided that
 - The minimum requirements for the external corner profile of EN 10219-2 are fulfilled
 - The maximum nominal wall-thickness is not exceeding 12.5 mm
 - Aluminium killed steels with the quality Grades J2H, K2H, MH, MLH, NH or NLH are used and that the following maximum values are kept:
 $C \leq 0.18 \%$, $P \leq 0.020 \%$ and $S \leq 0.012 \%$ ”

The CIDECT recommendation is now included in the July 2009 corrigendum to EN 1993-1-8, EN 1993-1-8:2005/AC, Eurocode 3: Design of steel structures – Part 1-8: Design of joints, corrigendum July 2009 [11].

EN 10219 hollow sections satisfying the EN 1993-1-8 criteria for welding in the cold-formed corner are available on the European market. These materials can be welded without concerns regarding the possible reduction in impact toughness of hollow section corners. Ruukki's EN 10219 cold-formed hollow sections in grades J2H, K2H, MH and MLH have now fulfilled the current EN 1993-1-8 requirements for welding in the cold-formed zones for more than a decade.

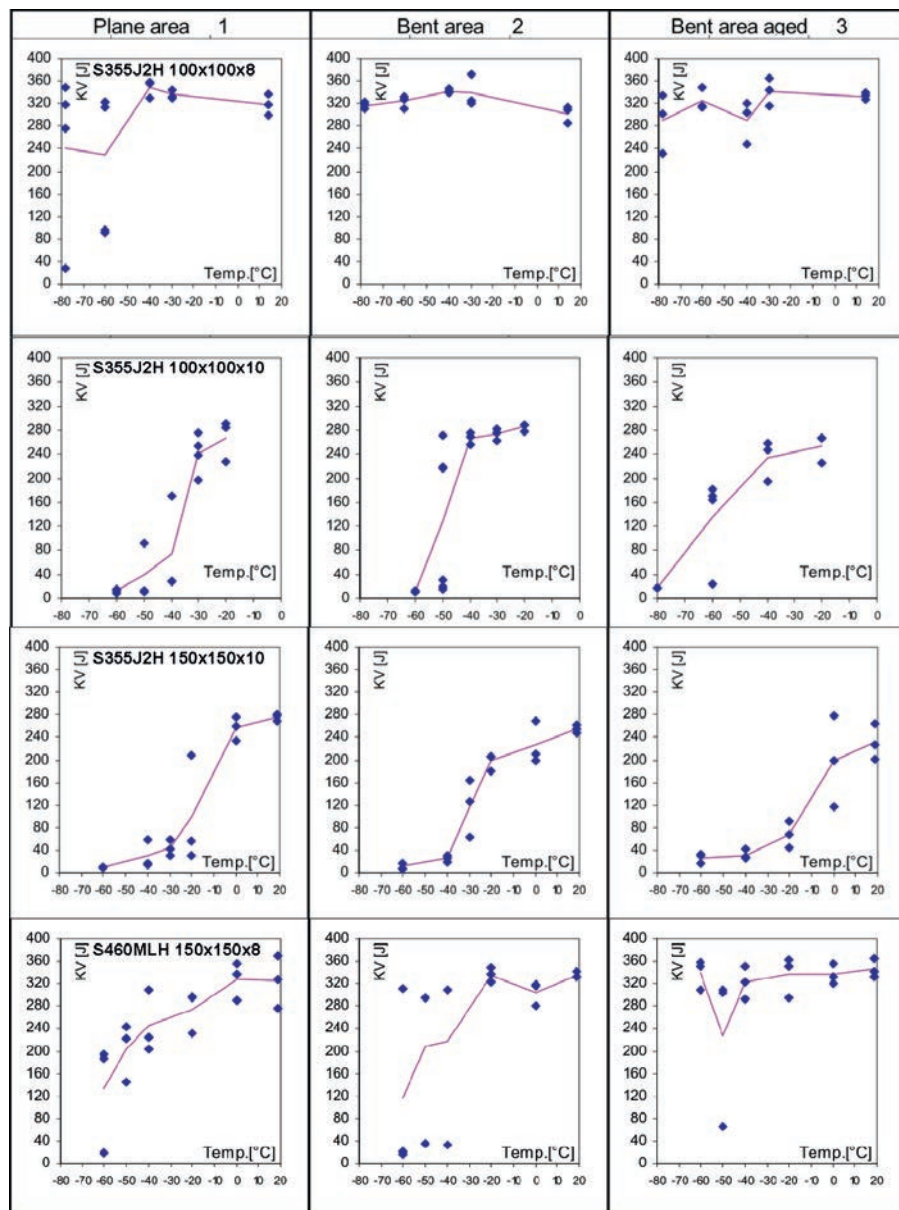


Fig. 8. Charpy-V impact toughness of EN 10219 rectangular hollow sections from selected European manufacturers, *Puthli* and *Herion* [9]

5 Fatigue behaviour of the corners

The applicability of cold-formed tubes is sometimes questioned or limited because of doubts regarding poor fatigue behaviour of the cold-formed corner areas. It is also claimed that by choosing hot-finished tubes, the aforementioned problems are automatically avoided. *Bäckström* et al. [12] and *Kokkonen* and *Björk* [13] have studied the fatigue strength of rectangular hollow section corners.

Bäckström et al. [12] studied rectangular hollow section corners by using Ruukki's cold-formed products conforming to EN 10219 grade S355J2H and good quality European hot-finished products conforming to EN 10210 grade S355J2H. The results are summarized in Fig. 9.

The fatigue strength of cold-formed test series CF-A seems to be clearly higher than the fatigue strength of hot-finished series HF-A and the fatigue strength of cold-formed and considerably corroded series CF-B. The fatigue strength of series HF-A and CF-B is about the same. According to *Bäckström* et al. [12], the smaller corner radius and the initial cracks of hot-finished sections caused by the manufacturing process seem to decrease the fatigue strength significantly at longer lives and at lower levels. Corrosion pits on the inside corner surface of corroded cold-formed hollow sections seem to have the same effect.

Kokkonen and *Björk* [13] studied fatigue strength of hollow section cor-

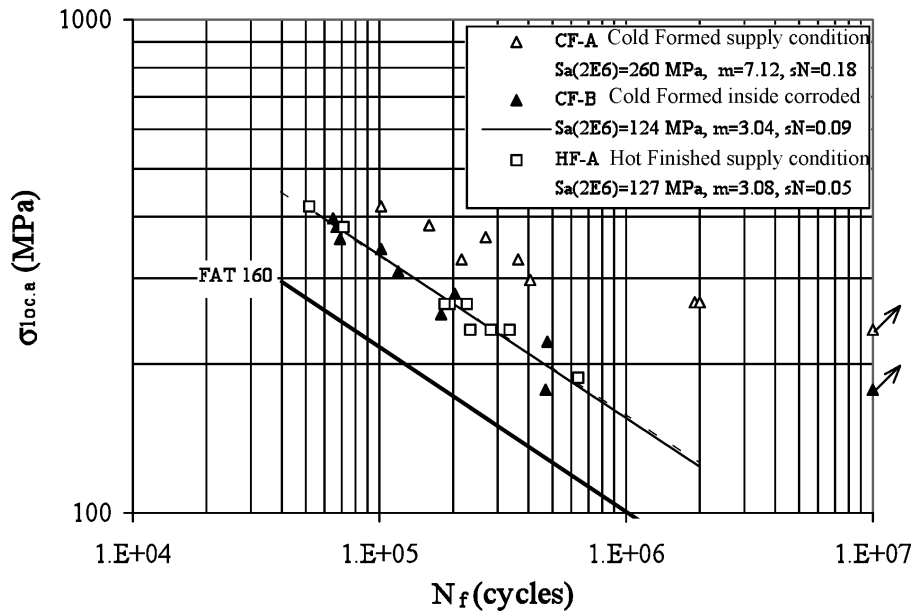


Fig. 9. Fatigue strength of grade S355J2H rectangular hollow section corners as a function of nominal normal stress amplitude, Bäckström et al. [12]

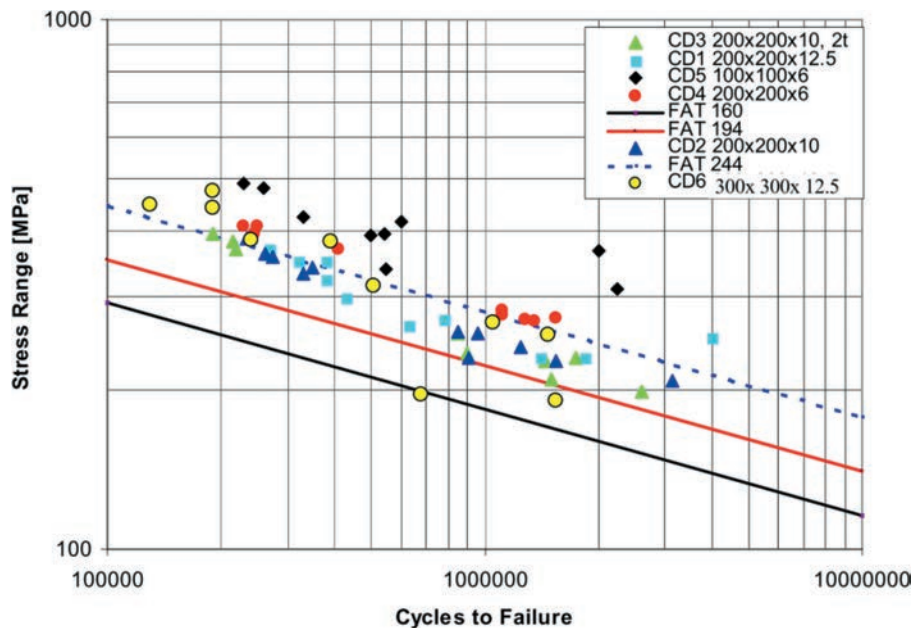


Fig. 10. Fatigue strength of hollow section corners according to Kokkonen and Björk [13]; mean and characteristic lines for material S355 tests and a design value FAT 160 MPa are shown; note: specimen CD3 external corner radius 2t; specimen CD6 in grade S460MH

ners by using Ruukki's EN 10219 hollow sections in grades S355J2H and S460MH, see Fig. 10.

The conclusions of Kokkonen and Björk [13] include the following:

- “Transverse fatigue strength of cold-formed rectangular hollow section corners fulfil the requirements (FAT 160) obtained in Eurocode 3 and CIDECT design guides
- Fatigue class could be increased by avoiding the dents due to rolling scale in the corner”

The studies [12], [13] referred to above confirm that the method of manufacturing hollow sections, hot-finished or cold-formed, is not the prime factor dictating the fatigue strength of the material. The fundamental reasons are related to geometrical factors and soundness of the surface. EN 10219 provides a good basis for high-performance hollow sections. Properly manufactured cold-formed rectangular hollow sections with fatigue strength equal to or better than hot-finished EN 10210 hollow sections

are technically possible and available on the European market.

6 Hot-dip galvanizing

Hot-dip galvanizing is one of the prime corrosion protection methods for tubular structures. Corner cracking sometimes occurs while hot-dip galvanizing square and rectangular tubes. According to Packer and Chiew [5], the appearance of corner cracks in cold-formed rectangular hollow sections has been discussed since 1993. In the last decade the incidence has increased in North America and Asia, particularly during hot-dip galvanizing. Complete structures made of galvanized rectangular hollow sections have even been condemned due to cracking, e.g. sign bridges. In Europe this phenomenon is deemed to be a “rare but important issue” [5].

The problem with corner cracking has been generally attributed to liquid metal embrittlement (LME) in association with very high residual stresses in the cold-formed rectangular hollow section corners. Interaction of three conditions determines the occurrence of LME [14]:

- Critical level of internal stress, e.g. residual stress due to cold working and welding
- Susceptible material, e.g. non-aluminium killed steel, high yield-to-tensile ratio, pre-existing microcracks as a result of forming or adverse chemical composition
- Liquid metal, especially with the presence of impurities or additives

According to the study of Poag and Zervoudis [15], the predominant factor affecting cracking upon galvanizing was the rectangular hollow sec-



Fig. 11. Example of extreme corner cracking in a rectangular hollow section during hot-dip galvanizing [5]

tion itself. In the worst case, corner cracking can completely damage the structure, see Fig. 11. But even more dangerous is hidden invisible cracking, which may reduce the strength of the structure.

Ruukki has undertaken internal studies with both cold-formed and hot-finished rectangular hollow sections in order to verify the influence of hot-dip galvanizing and susceptibility to LME and corner cracking. The verification was done using Ruukki's own cold-formed products conforming to EN 10219 grades S355J2H, S420MH and S500MH and good quality European hot-finished products conforming to EN 10210 grade S355J2H.

The influence of hot-dip galvanizing on the tensile test is shown in Figs. 12 and 13. Hot-dip galvanizing has a minor influence on the strength of the material up to grade S500MH. The influence is similar regardless of manufacturing method, hot-finishing or cold-forming.

Susceptibility to LME and corner cracking was verified by using a “corner opening test”, i.e. a “three-point bending test” at controlled temperatures from +20 to –60 °C. The test is performed by flattening out the corner and measuring the force–displacement curve. The test setup is shown in Fig. 14.

Fig. 15 illustrates an example of a hollow section susceptible to LME and corner cracking. The material is ductile prior to hot-dip galvanizing in the as-supplied condition even at an extremely low temperature of –60 °C. But hot-dip galvanizing triggers the LME, and corner cracking starts to appear even at room temperature, see Fig. 15.

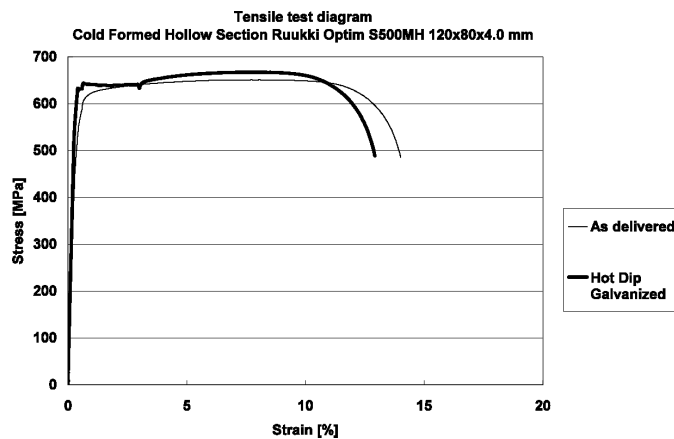


Fig. 13. Influence of hot-dip galvanizing on the tensile strength of hollow sections; Ruukki's cold-formed hollow section, EN 10219 – Optim S500MH – 90 × 80 × 4 mm

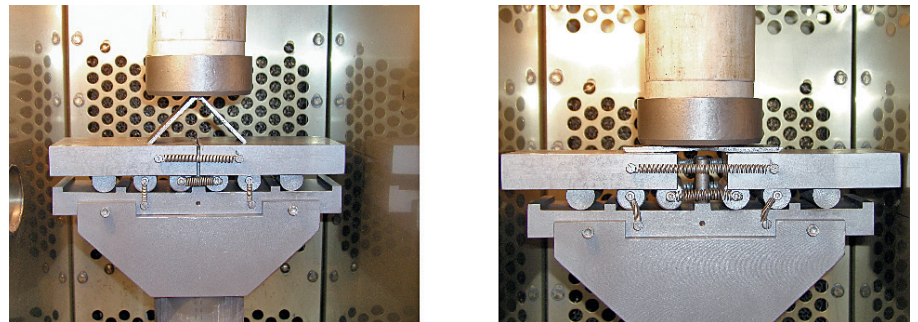


Fig. 14. Test setup for “corner opening test”; left: “initial position”, right: “final position”

The test results shown in Figs. 16 and 17 confirm that properly manufactured hot-finished and cold-formed hollow sections behave similarly and are not susceptible to LME. The test results in Fig. 18 confirm that properly manufactured cold-formed hollow sections without susceptibility to LME and corner cracking up to grade S500MH are available on the market.

The influence of hot-dip galvanizing on welded structures has been

verified by testing hollow section X-joints made of “Ruukki double grade S420MH/S355J2H”, which conforms to grades S420MH and S355J2H. The tests were carried out at Lappeenranta University of technology at a temperature of –40 °C [16]. Two examples are shown in Fig. 19. In the as-supplied condition, the deformation capacity of the X-joints exceeds the minimum requirement by factors of 9.8 (Fig. 19, left) and 2.4 (Fig. 19, right). Hot-dip galvanizing has a mi-

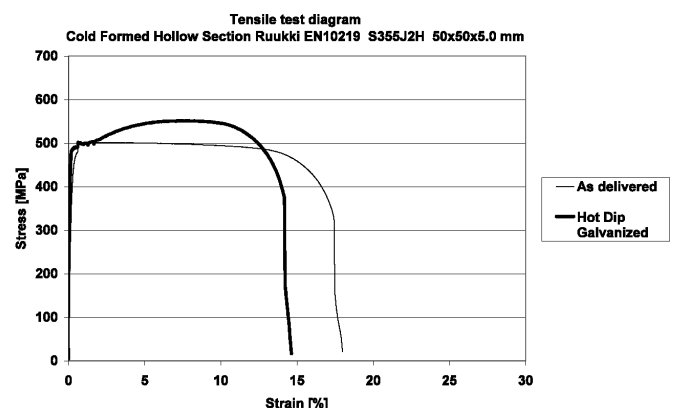
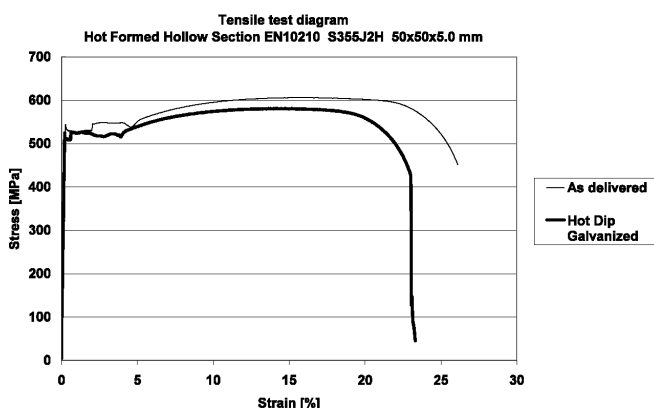


Fig. 12. Influence of hot-dip galvanizing on the tensile strength of hollow sections; left: European hot-finished hollow section, EN 10210 – S355J2H – 50 × 50 × 5 mm; right: Ruukki's cold-formed hollow section, EN 10219 – S355J2H – 50 × 50 × 5 mm

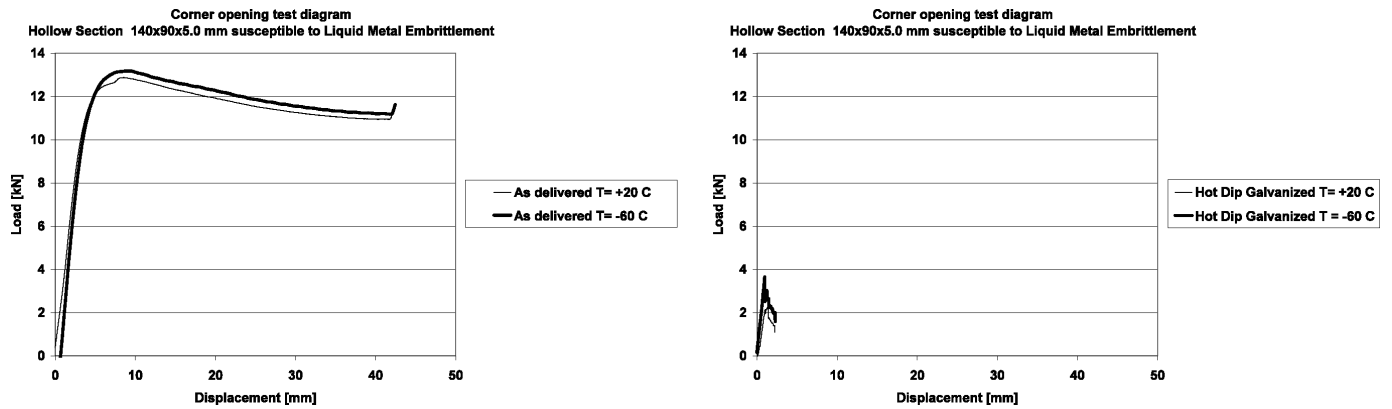


Fig. 15. Corner opening diagram for hollow section susceptible to LME; left: prior to hot-dip galvanizing, right: hot-dip galvanized

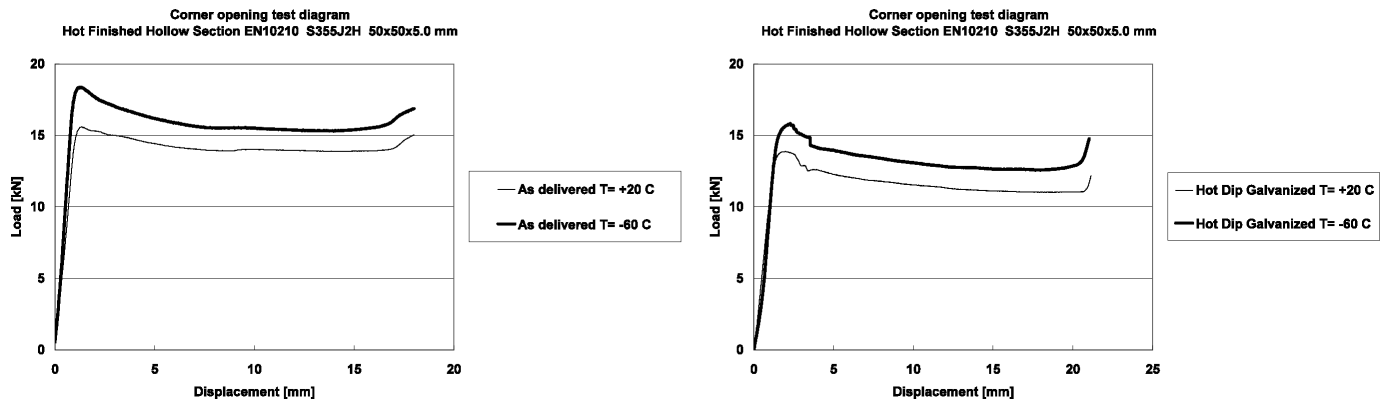


Fig. 16. Corner opening diagram for European hot-finished hollow section, EN 10210 – S355J2H – 50 × 50 × 5 mm; left: prior to hot-dip galvanizing, right: hot-dip galvanized

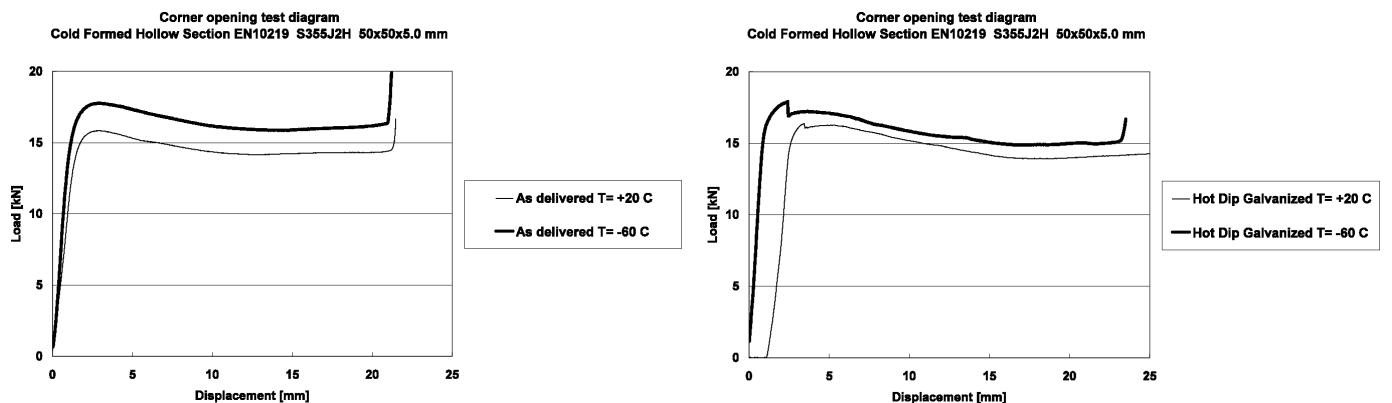


Fig. 17. Corner opening diagram for Ruukki's cold-formed hollow section, EN 10219 – S355J2H – 50 × 50 × 5 mm; left: prior to hot-dip galvanizing, right: hot-dip galvanized

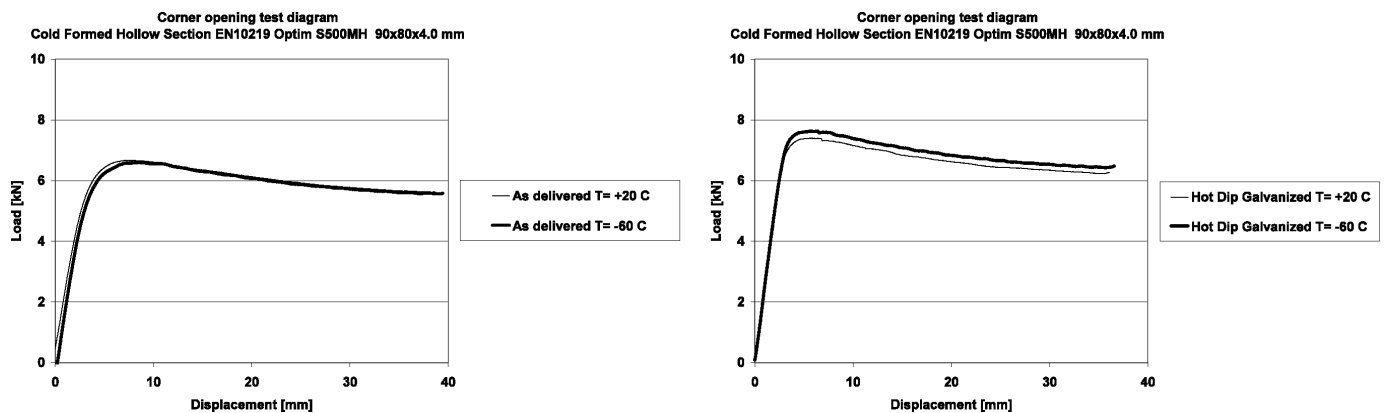


Fig. 18. Corner opening diagram for Ruukki's cold-formed hollow section, EN 10219 – Optim S500MH – 90 × 80 × 4 mm; left: prior to hot-dip galvanizing, right: hot-dip galvanized

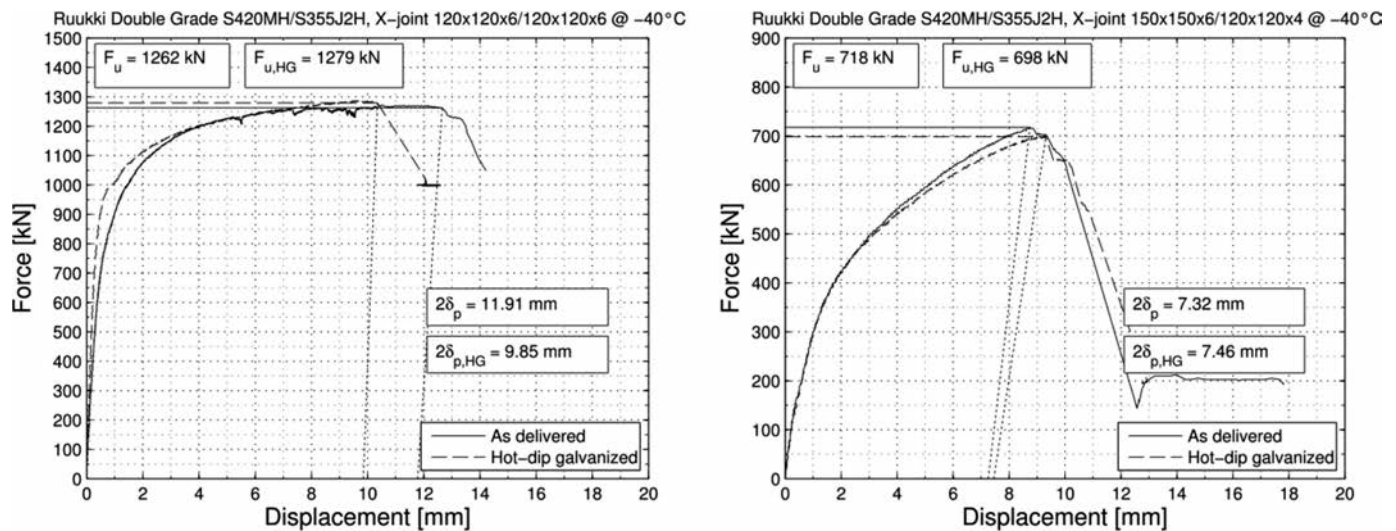


Fig. 19. Influence of hot-dip galvanizing on the force-displacement diagram of a hollow section X-joint at a temperature of -40°C ; left: $120 \times 120 \times 6/120 \times 120 \times 6 \text{ mm}$, right: $150 \times 150 \times 6/120 \times 120 \times 4 \text{ mm}$; material: EN 10219 – Ruukki double grade S420MH/S355J2H

nor influence on the strength and deformation capacity of the X-joint.

The observations above confirm that properly made cold-formed hollow sections do not have a tendency to LME and corner cracking and hot-dip galvanizing essentially does not alter the strength or ductility of the hollow sections. Welded structures made of properly manufactured cold-formed EN 10219 hollow sections can be safely protected against corrosion by hot-dip galvanizing.

7 Conclusions

Tubular materials enable the construction of steel structures that are both architecturally and aesthetically impressive and also efficient structures from the engineering point of view. Increased strength opens up the chance to reduce wall thicknesses and the weight of the structure. Cold-formed hollow sections are the dominant tubular construction material. Economical and environmental constraints favour cost competitiveness and higher strength. The cold-forming route is naturally economical and can mostly adapt to higher strength, too. The applicability of cold-formed tubes is sometimes questioned or limited due to doubts regarding the quality of the products.

The observations presented in this paper allow the following conclusions to be drawn:

- Hollow sections from different sources exhibit diversity of quality

and thus also a wide scatter in their structural performance.

- The manufacturing method, hot-finished or cold-formed, is not the fundamental factor dictating the properties of hollow sections. The basic reason is related to other factors in steelmaking and tube manufacturing. Hence, the quality of the product very much depends on the supplier.
- The quality of hollow sections results from adequate processing of steel and tube.
- High-quality cold-formed EN 10219 hollow sections in grades S355J2H to S460MH with a performance equal to or better than hot-finished tubes
 - are technically possible and available on the European market,
 - satisfy the requirements for low-temperature ductility, deformation capacity of welded joints and welding in the corner,
 - exhibit good fatigue behaviour, and
 - are suitable for hot-dip galvanizing.

High-quality cold-formed EN 10219 hollow sections constitute a safe, reliable and versatile high-performance structural material for environmentally sound and competitive solutions.

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