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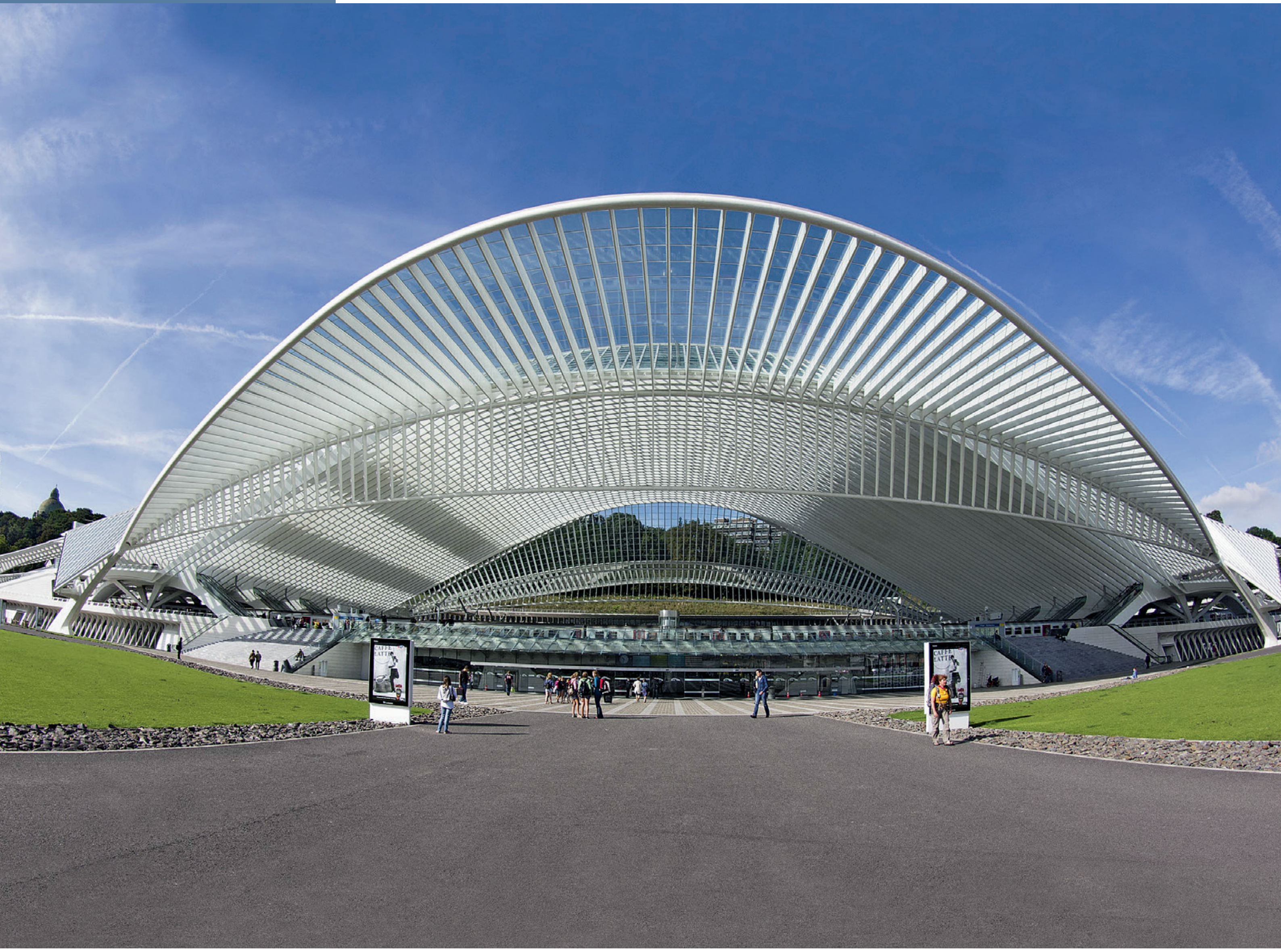

Low-temperature ductility and structural behavior of cold-formed hollow section structrures – progress during the past two decades

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Low-temperature ductility and structural behaviour of cold-formed hollow section structures – progress during the past two decades

Dedicated to Emeritus Professor Dr. Eur.-Ing. *Ram S. Puthli* on the occasion of his 70th birthday

Cold-formed hollow sections are a widely used tubular construction material. The applicability, weldability and reliability of cold-formed rectangular hollow sections are sometimes questioned because of the consequences of cold forming and inhomogeneous cross-sections. One of the main concerns is related to the cold-formed corner areas and possible loss of toughness due to strain ageing in the vicinity of the welds. Conventional hot-rolled C-Mn steels are susceptible to strain ageing, and Eurocode 3 includes restrictions on welding in the cold-formed corner area. Both steelmaking and hot rolling have undergone crucial developments and this has had an impact on cold-formed hollow sections. Thermomechanically rolled fine-grain steels became state of the art at the end of the 1990s. This study confirms that cold-formed EN 10219 hollow sections made of suitable fine-grain steels have a similar Charpy-V toughness on the flat face and in the corner, and that even after ageing the transition temperature T_{40J} in the corner area is at a very low level, typically below –50 °C. The load and deformation capacities of X- and K-joints fulfil the requirements without any noticeable ageing effects. The advances in steelmaking and hot rolling enable the manufacturing of reliable and versatile cold-formed EN 10219 hollow sections for welded structures with good low-temperature ductility even in the cold-formed corner area.

1 Introduction

Tubular materials enable steel structures to be both architecturally and aesthetically impressive and also efficient structures from an engineering point of view. Cold-formed hollow sections, both circular and rectangular, are a widely used tubular construction material. The applicability, weldability and reliability of cold-formed rectangular hollow sections are sometimes questioned because of the consequences of cold forming and inhomogeneous cross-sections. One of the main concerns is related to the cold-formed corner areas that are subsequently heated to temperatures in the range of 100–500 °C; for example, due to their close proximity, the welds are subjected to a loss of toughness due to the phenomenon of strain ageing. This loss of toughness mainly manifests itself in an increase in the ductile-to-brittle transition temperature [1].

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Strain ageing is a well-known characteristic of ferritic steels. Conventional hot-rolled C-Mn steels are susceptible to strain ageing. Thus, welding in rectangular hollow section corners may induce a reduction in the Charpy-V impact toughness adjacent to the welded joints. Ductility is one of the primary features of structural materials and components and one of the underlying principles of Eurocode 3. Consequently, Eurocode 3 part EN 1993-1-8 [2] includes certain restrictions on welding in the cold-formed areas.

Recent studies [3–6] have revealed large scatters in the low-temperature ductility of cold-formed hollow sections from different suppliers. It is well known that there are both good-quality products with excellent Charpy-V toughness, and products with substandard quality too. Until now, information about the fundamental reasons for this scatter has been limited. However, the discovery of cold-formed hollow sections with excellent Charpy-V toughness suggests that manufacturing good quality products is possible, provided the manufacturing of the steel and tube is appropriate.

Materials testing is an important part of the confirmation of structural safety. However, the capacity of a critical joint typically dominates the capacity of the welded structure. The capacity is defined in terms of load-carrying and deformation capacities and depends on the material properties, including the fabrication effects and the joint geometry (dimensions and shape). Therefore, it is always important to check the joint capacities as well when the effects of the fabrication process (cold forming) on the material properties (toughness) are studied.

This paper reviews the data available on the low-temperature toughness of rectangular hollow sections, and highlights the development over the past two decades as well as confirming the structural performance of properly manufactured cold-formed hollow sections.

2 Low-temperature ductility of cold-formed steel

The Charpy-V notch impact energy of conventional structural S355J2 steel is sensitive to cold forming [7], Fig. 1. Cold deformation (degree of cold forming, DCF) up to approx. 15 % substantially reduces the KV_{US} from 140 to 90 J, slightly increases the upper shelf energy minimum temperature T_{US} from ±0 to +20 °C and increases the transition temperature T_{TR} in the order of +80 °C. *Feldmann* et al. [4] evaluated the values in Fig. 1 for KV = 27 J and KV = 40 J, and illustrated the transition temperatures T_{27J} and T_{40J} as a function of cold forming, i.e. effective plastic strain ($DCF = \varepsilon_{eff}$), Fig. 2.

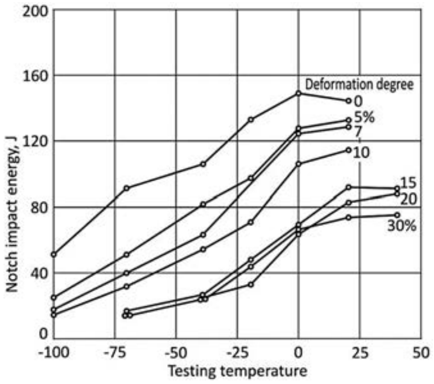


Fig. 1. Change in notch impact energy due to cold-forming of S355J2 steel [7]

As shown in Fig. 2, no significant change in T_{27J} and T_{40J} occurs for S355J2 steels with an increasing degree of cold-forming > 15 %. These results are valid for conventional S355J2 steels. Unfortunately, data for other steels is not available.

In Europe cold-formed hollow sections are specified by the harmonized standard EN 10219-1&2 [8]. Section 8.2.3.2 in EN 10219-1 defines the location of the impact test piece for rectangular hollow sections as follows: "For square or rectangular sections the test pieces shall be taken either longitudinally or transversely, at the discretion of the manufacturer, midway between the corners, from one of the sides not containing the weld", Fig. 3. The specimen taken midway in the flat face incorporates the effects of cold forming at this location.

Feldmann et al. [4] also calculated the DCF in the manufacture of cold-formed rectangular tubes. For common rectangular tube sizes in a thickness range $6 \le T \le 16$ mm, the DCF ranges from 2 to 9 % on the flat face, from 8.7 to 12.5 %, in the corner areas with nominal corner radii and from 11.5 to 16.7 % with minimum allowed corner radii. Thus, on the flat face the degree of deformation and level of T_{27J} and T_{40J} is expected to depend on the actual tube dimension, but in the corner the level of T_{27J} and T_{40J} is expected to be virtually independent of the tube dimension.

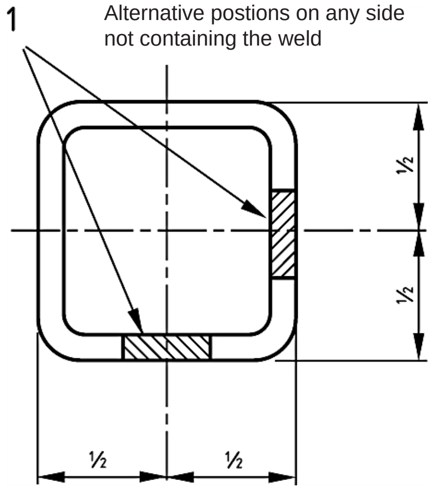


Fig. 3. Location of impact test piece of rectangular hollow sections to EN 10219-1 [8]

Earlier, in 1975, *Soininen* [9] studied the initiation and progress of brittle fractures in low-carbon structural steels. *Soininen* found that welding substantially reduces the upper shelf value KV_{US} from 120 to 80 J, increases the T_{US} minimum temperature from ±0 to +40 °C and increases the transition temperature in the order of +40 °C, Fig. 4. Thus, welding severely reduces even the low-temperature toughness of undeformed grade S355J2 steel.

The aforementioned observations clearly indicate that both cold forming and welding may substantially reduce the low-temperature ductility of conventional S355J2 steels. Furthermore, there is a risk that the Charpy-V testing according to EN 10219-1 with specimens taken from the flat face is not sufficiently representative for the corner areas.

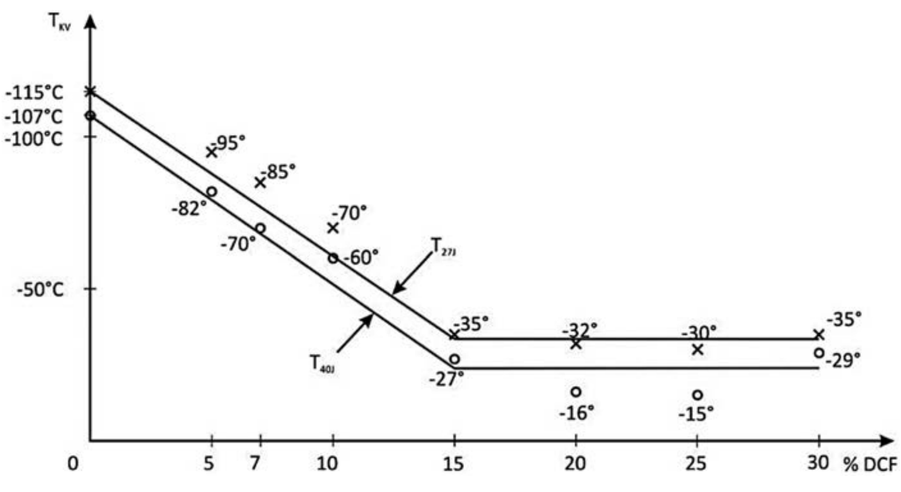


Fig. 2. T_{27J} and T_{40J} as a function of cold forming (DCF) for S355J2 steel [4]

3 Low-temperature toughness of cold-formed rectangular hollow sections

The low-temperature toughness of cold-formed rectangular hollow sections has been studied by *Dagg* et al. in 1989 [10], *Soininen* in 1996 [11], *Kosteski*, *Packer* and *Puthli* in 2003 [3], *Puthli* and *Herion* in 2006 [14], [15] and Ruukki in 2010 [12], 2012 [13] and 2013 [16]. *Feldmann* et al. [4], [6] made a detailed analysis of the results included in [3], [10]–[12]. This paper reviews these studies, with a special focus on the effect of ageing and the steel material on the low-temperature toughness of cold-formed hollow sections.

In 1989 *Dagg* et al. [10] studied the Charpy-V impact toughness of rectangular hollow sections and measured the transition temperature of specimens taken from the flat face and from the corners of cold-formed rectangular hollow sections. The products were made of conventional C-Mn steel with C ≈ 0.15 %, Mn ≈ 0.65 %, S ≈ 0.010 % and Cekv ≈ 0.26. The Charpy-V test specimens were artificially aged at 170 °C for 30 min. *Dagg* et al. found little difference between the toughness–temperature results of Charpy-V test specimens sampled from the flat face versus the corner region of rectangular hollow sections, Fig. 5.

In the mid-1990s *Soininen* [11] carried out an in-depth study of "Fracture behaviour and assessment of design requirements against fracture in welded steel structures made of cold-formed hollow sections". According to *Soininen*, cold deformation causes changes in the impact toughness of steel depending on the steel composition and the amount of cold deformation. Based on literature data from 1970s, *Soininen* concluded that as an estimate, the increase in the impact toughness transition temperature $\Delta T_{TR} \approx 3$ °C/% DCF is normally proposed. This conclusion is in agreement with the diagram prepared by *Feldmann* et al. [4], Fig. 2.

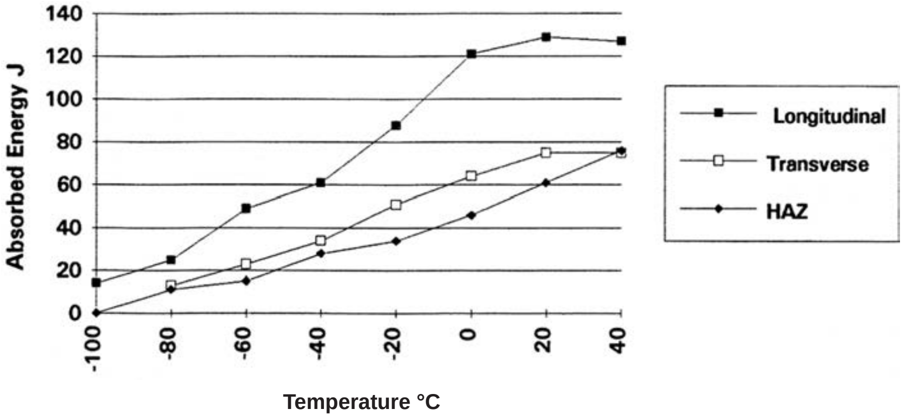


Fig. 4. Charpy-V impact toughness vs. temperature for S355J2 steel and weld HAZ [9]

Soininen also reviewed the most recent literature on strain ageing of cold-formed steels and summarized the influence of cold deformation and strain ageing on the transition temperature shifts of conventional and modern thermomechanically rolled, accelerated cooled, structural steels.

Soininen found that 10 % of cold strain and ageing increases the transition temperature in the range of 40–80 °C for most steels. In addition, *Soininen* also noticed one or two exceptions: in certain accelerated cooled steels the increase is 25–30 °C, and in thermomechanically rolled TMCP steels the increase is 25 °C. These observations indicate that modern fine-grain steels are less prone to strain ageing.

Soininen's research included the fracture toughness of a wide range of grade S355J2H cold-formed rectangular hollow sections according to EN 10219-1&2. The study included 12 individual sizes in the range 50 × 50 × 3 mm to 200 × 200 × 12.5 mm, and covered diameter/thickness ratios from 12 to 42. The study shows that the toughness properties decrease gradually from the feed material to the flat face and then to the corner and, in addition, due to ageing at 250 °C for 30 min.

Soininen's test data for the five largest hollow section sizes are shown in Table 1 and enable the following overall observations:

- The upper shelf energy KV_{US} varies from 180 to 250 J/cm^2 in all locations and conditions.
- The upper shelf temperature T_{US} varies from –30 to +20 °C depending on location and condition.
- The transition temperature T_{27J} on the flat face varies from –68 to –20 °C.
- The transition temperature T_{27J} temperature in the corner varies prior to ageing from –63 to –22 °C, and after ageing from –55 to –18 °C.
- The effect of ageing on the T_{27J} temperature in the corners varies from +4 to +20 °C.
- The change in the transition temperature T_{27J}, flat face vs. corner-aged, varies from ±0 to +25 °C.

The results show a fairly wide scatter. In some cases the change in transition temperature T_{27J} – flat face vs. corner-aged – is quite small, about +5 °C, but sometimes it is more significant, up to +25 °C. Despite rather good toughness on the flat face, the toughness in the corner after ageing may not always fulfil the requirement of 27 J at –20 °C (35 J/cm^2 at –20 °C). The Charpy-V testing according to EN 10219-1 with specimens taken from the flat face is not sufficiently representative of the corner area.

Soininen [11] studied hollow sections supplied by Ruukki according to EN 10219-1&2 during the first half of the 1990s. The products represented a state-of-the-art level at that time. The study revealed the risk of occasionally having a low-temperature toughness in the corner area of the rectangular hollow sections which did not fulfil the requirements after welding. In order to be certain that even the corner areas have the required low-temperature toughness after welding, Ruukki decided on tighter quality requirements in the Charpy-V testing of the structural tubes. Since 1998 Ruukki has supplied grade S355J2H structural tubes according to EN10219-1&2 with a Charpy-V requirement of 35 J/cm^2 at –40 °C.

This decision was a challenge for the supply of feed material, steelmaking and hot rolling. However, the steelmaking and hot rolling were adapted to the needs of tube manufacturing. Ladle refining, micro-alloying, thermomechanical rolling and controlled cooling and coiling were vital in this transition. The introduction of new types of steel, i.e. thermomechanically rolled steels with controlled cooling and coiling, raised several questions concerning the behaviour of welded joints and the influence of HAZ etc. Considerable testing was conducted and over time a number of benefits of the new types of steel were verified.

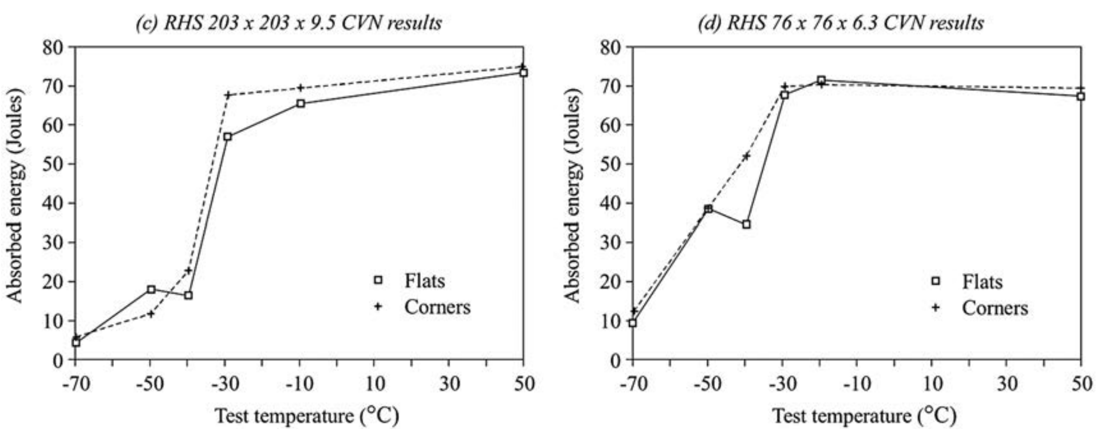


Fig. 5. Charpy-V notch impact toughness of flat face vs. corner region of cold-formed rectangular hollow sections [10]

Hence, a gradual transition to micro-alloyed and thermomechanically rolled steels took place. Since 2002 the entire production of structural tubes has been based on micro-alloyed thermomechanically rolled fine-grain steels.

In 2003 *Kosteski*, *Packer* and *Puthli* accomplished CIDECT project 1B [3], which focused on the low-temperature impact properties of rectangular hollow sections from different sources and demonstrated the diversity of quality while comparing the following:

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

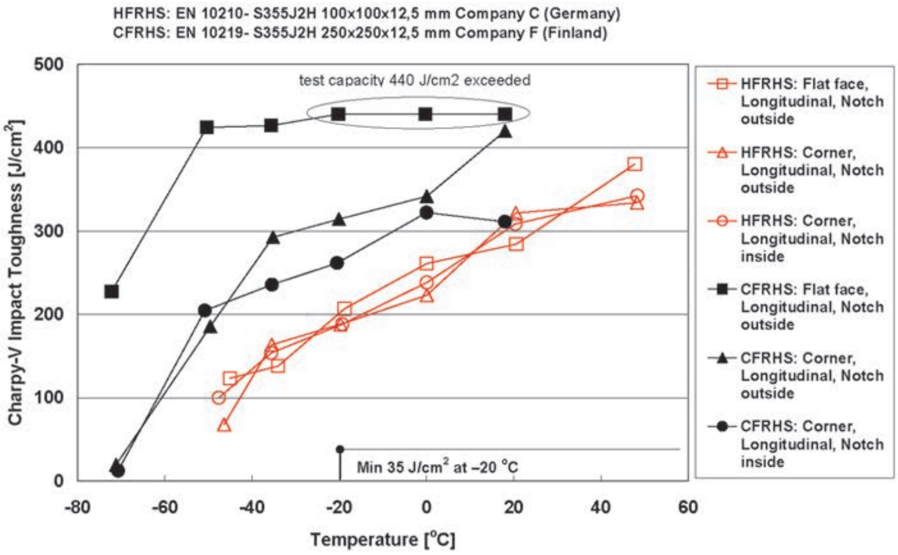


Fig. 6. Low-temperature toughness of grade S355J2H hot-finished EN 10210 vs. a cold-formed EN 10219 rectangular hollow section [3]

The results of *Kosteski*, *Packer* and *Puthli* [3] have also been analysed by *Feldmann* et al. [4, 6] and allow – among other factors – the following observations to be made:

- The upper shelf energy KV_{US} varies from 138 to 425 J/cm² depending on location and supplier.
- The upper shelf temperature T_{US} varies from –50 to +20 °C depending on location and supplier.
- The transition temperature T_{27J} varies from –89 to +3 °C depending on location and supplier.

The materials originated from several sources and were manufactured to various standards. Therefore, the results show a larger amount of scatter than that observed by *Soininen*. Additionally, the location of the notch in the corner area tends to have an effect on the transition temperature T_{27J}. Where the notch is outside, the transition temperature increased from ±0 to +20 °C, and where the notch was inside from ±0 to +40 °C. Contrary to what was believed, this study also revealed that the low-temperature toughness of cold-formed hollow sections can be equally as good as hot-finished hollow sections, Fig. 6. As pointed out elsewhere [13], the manufacturing method, whether hot-finished or cold-formed, is not the fundamental factor dictating low-temperature toughness. The basic reason is related to other factors in steelmaking and tube manufacturing.

In 2005 *Puthli* and *Herion* accomplished the CIDECT project 1A [14], which focused on welding in cold-formed areas of rectangular hollow sections.

The main goals of this research work were:

- To determine the requirements for reliable welding of cold-formed structural hollow section connections on the basis of strain ageing caused by welding.
- To provide recommendations for extending the existing design rules for welding in cold-formed corner areas of rectangular hollow sections.

The investigation focused on the shift in the transition temperature caused by welding (ageing effects) using Charpy-V notch impact specimens on cold-formed hollow sections. For evaluating brittle fractures, the notch was prepared in the zone reheated by welding. Whether this reheating and possible ageing influenced the brittle fracture temperature was also investigated. The transition temperature T_{27J} was determined for the following conditions: flat face, corner area and corner area artificially aged by welding. In order to maintain the variables within reasonable limits, the hollow sections were supplied by just two European manufacturers according to EN 10219 in steel grades S355J2H and S460MLH. The test materials, in the early 2000s, were typical fine-grain steels with C ≤ 0.15 %, S ≤ 0.007 %, CEV ≤ 0.37, Ti- and/or Nb-micro-alloyed and partly also thermomechanically rolled.

The results of *Puthli* and *Herion* [14] were also analysed by *Feldmann* et al. [4], [6] and allow the following observations to be made:

- The upper shelf energy KV_{US} varies from 250 to 445 J/cm² depending on location and condition.
- The upper shelf temperature T_{US} varies from –70 to +20 °C depending on location and condition.
- The transition temperature T_{27J} varies from –90 to –32 °C depending on location and condition.
- In one case ageing slightly reduced the toughness by increasing the T_{27J} with +21 °C from –88 to –67 °C, but despite this reduction the toughness remained on a very good level.
- In three cases ageing improved the toughness by lowering the T_{27J} with –5 to –53 °C; it was assumed that welding in the corner area caused some kind of normalizing effect.

The study by *Puthli* and *Herion* provides evidence that in hollow sections made of fine-grain steels or thermomechanically rolled steels, the low-temperature toughness on the flat face and in the corner is similar, and the effect of ageing remains marginal.

As pointed out in [13], based on the study by *Puthli* and *Herion*, CIDECT prepared a recommendation concerning welding in the cold-formed corner area of rectangular hollow sections. This 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.

In 2010 Ruukki introduced a new standard quality, “Ruukki double grade”, which conforms to EN 10219-1&2 grades S420MH and S355J2H. The feed material for the manufacturing of Ruukki double grade hollow sections is a micro-alloyed thermomechanically rolled low-carbon steel with controlled cooling and coiling. The chemical analysis satisfies the requirements of EN 1993-1-8, EN 1993-1-8:2005/AC for welding in the corners, the carbon equivalent is typically $C_{ekv} \approx 0.30$ and the ASTM grain size is about 13. As reported earlier [13], Ruukki double grade hollow sections exhibit a good level of Charpy-V toughness, both on the flat face and in corner area.

In order to verify the impact of ageing on the Charpy-V toughness of Ruukki double grade rectangular hollow sections, Ruukki undertook internal testing of random production samples in 2013 [16]. The study included three sizes: 200 × 120 × 8 mm, 200 × 120 × 10 mm and 250 × 250 × 12.5 mm. The hollow sections were tested both in ordinary cold-formed conditions and artificially aged at 250 °C for 30 min. The Charpy-V test specimens were taken longitudinally on the flat face as specified in EN 10219-1 and in the centre of the corner. The notch orientation was through the thickness. On the whole, the hollow section dimensions and testing procedure were the same as those used by *Soininen* [11]. The Charpy-V impact toughness transition curves are shown in Figs. 7–9. The characteristic values derived from the diagrams are included in Table 1 and the effect of ageing on the T_{27J} temperature is illustrated in Fig. 10 together with *Soininen*’s results.

The test results of Ruukki double grade, Table 1, allow, among other things, the following observations:

– The upper shelf energy KV_{US} varies from 210 to 300 J/cm^2 in all locations and conditions.
– The upper shelf temperature T_{US} varies from –60 to –20 °C depending on location and condition.
– The transition temperature T_{40J} on the flat face varies from –100 to –70 °C.
– The transition temperature T_{40J} in the corner varies from –100 to –60 °C prior to ageing and from –90 to –50 °C after ageing.

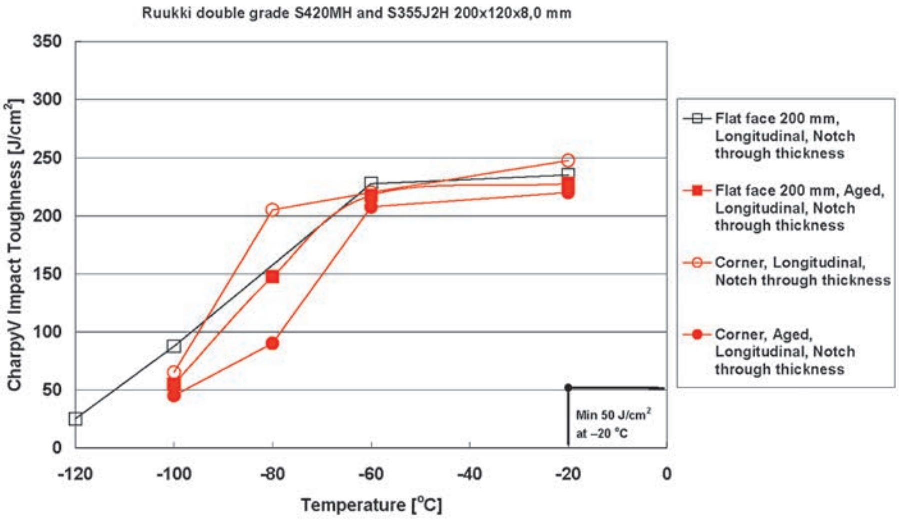


Fig. 7. Charpy-V impact toughness of a cold-formed EN 10219 hollow section, Ruukki double grade S420MH and S355J2H, 200 × 120 × 8.0 mm

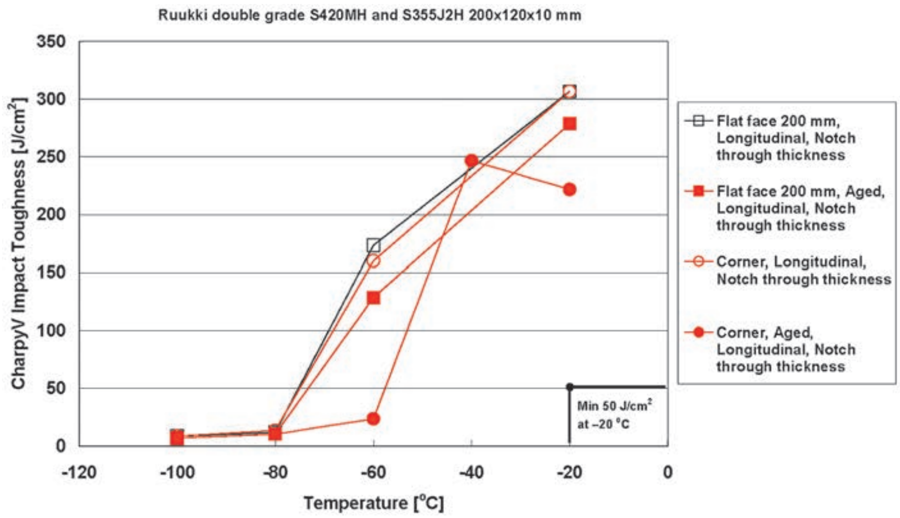


Fig. 8. Charpy-V impact toughness of a cold-formed EN 10219 hollow section, Ruukki double grade S420MH and S355J2H, 200 × 120 × 10 mm

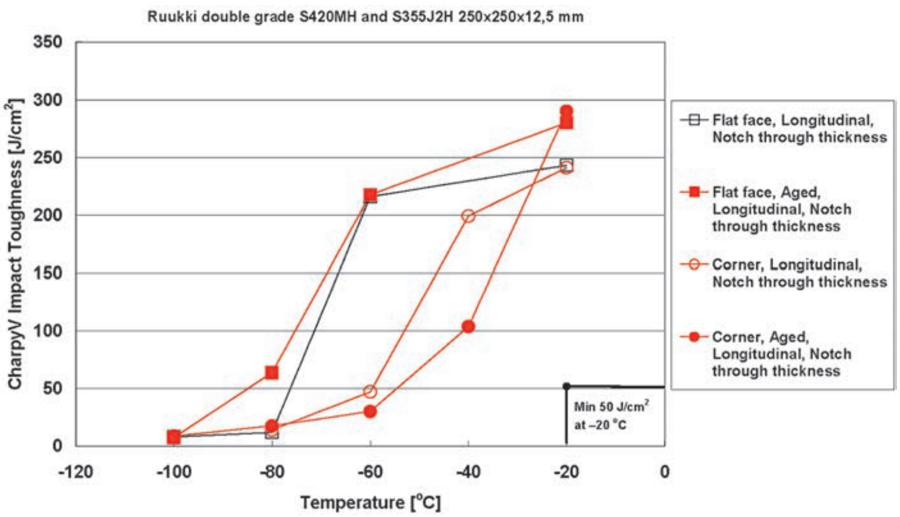


Fig. 9. Charpy-V impact toughness of a cold-formed EN 10219 hollow section, Ruukki double grade S420MH and S355J2H, 250 × 250 × 12.5 mm

– The effect of ageing on the T_{40J} temperature in the corners varies from ±0 to +20 °C.
– The change in the transition temperature T_{40J}, flat face vs. corner-aged, varies from ±0 to +25 °C.

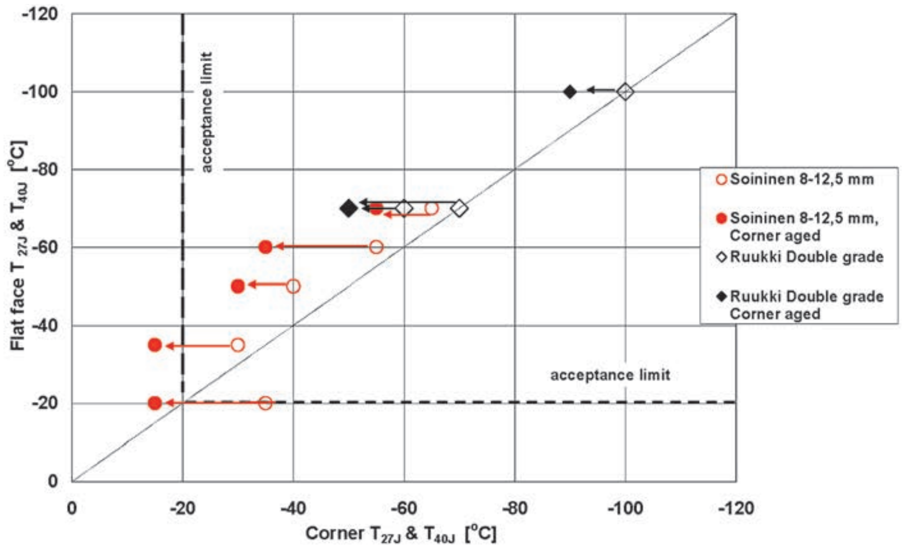


Fig. 10. Effect of ageing on transition temperature of cold-formed EN 10219 hollow sections; T_{27J} for grade S355J2H [11] and T_{40J} for Ruukki double grade S420MH and S355J2H [16]

Feldmann et. al. [4], [6] analysed, on the basis of available data, the transition temperature T_{27J} of the flat face vs. corner. They found a small difference for ordinary steels, but the difference was negligible for micro-alloyed fine-grain steels and thermomechanically rolled steels. The test results of Ruukki double grade are in line with this observation. The flat face vs. corner difference is minor or negligible, see Figs. 7–9 and Table 1. Thus, in this case the Charpy-V testing according to EN 10219-1 with specimens taken from the flat face is fairly representative for the corner areas too.

The impact of ageing on the transition temperature T_{27J}/T_{40J} according to *Soininen* [11] and the measurements with Ruukki double grade [16] are shown in Fig. 10. The impact of ageing for micro-alloyed and thermomechanically rolled fine-grain steel is still readily observable. However, due to the excellent low-temperature properties, even after ageing, the transition temperature T_{40J} in the corner area is very low, below –50 °C. Thus, the effect of ageing does not reduce the toughness to a substandard level.

The studies reviewed above confirm that the cold-formed hollow sections from different suppliers exhibit a large scatter when it comes to low-temperature ductility. There are both good-quality products with excellent Charpy-V toughness, but also products with substandard quality.

During the past two decades, steelmaking, hot rolling and tube manufacturing have made remarkable progress. At present, ladle refining, micro-alloying, thermomechanical rolling and controlled cooling and coiling are at a state-of-the-art level in steelmaking. The observations presented above confirm that state-of-the-art steelmaking and hot rolling enable the manufacture of micro-alloyed and thermomechanically rolled fine-grain steels. These are well suited to manufacturing high-quality cold-formed rectangular hollow sections with good weldability and low-temperature toughness, even in the cold-formed corner area.

4 Structural behaviour of welded hollow section joints made of fine-grain steel

The toughness of the corners and flat sections in the tube itself is an important structural parameter, but in several cases the joints set the capacity limits of the whole structure. Consequently, in terms of structural safety, it is essential to consider the strength of the joints as well. Considering the distribution of the DCF along the perimeter of a cold-formed cross-section, the joints, which cause high local stresses in the corner area of the tube, are the focus of interest. In an X-joint the high stresses occur in the corner of the bracing member, and in the corner of a chord member as illustrated in Fig. 11.

It is especially the stresses in the chord member of the X-joint that are interesting. This is because the stresses that are due to the applied joint load are parallel to the strains caused by

Table 1. Low-temperature characteristics of cold-formed rectangular EN 10219 hollow sections; grade S355J2H [11] and Ruukki double grade S420MH and S355J2H [16]

Reference	Steel grade	Dimension			Flat face			Corner			Corner Aged		
		H	B	T	US_{KV}	T_{US}	T_{27J}/T_{40J}	US_{KV}	T_{US}	T_{27J}/T_{40J}	US_{KV}	T_{US}	T_{27J}/T_{40J}
		[mm]	[mm]	[mm]	[J/cm²]	[°C]	[°C]	[J/cm²]	[°C]	[°C]	[J/cm²]	[°C]	[°C]
Soininen	S355J2H	100	100	8,0	230	0	–50	250	0	–40	250	20	–30
Soininen	S355J2H	100	100	10,0	225	0	–20	250	10	–35	219	10	–15
Soininen	S355J2H	150	150	8,0	188	–10	–70	203	10	–65	172	–30	–55
Soininen	S355J2H	180	180	10,0	200	–10	–60	250	0	–55	200	0	–35
Soininen	S355J2H	200	200	12,5	225	–10	–35	213	0	–30	225	10	–15
Ruukki 2012	S420MH	120	120	8,0	250	–20	–65	250	–20	–55	n.a.	n.a.	n.a.
Ruukki 2012	S420MH	250	250	12,5	260	–20	–55	330	–20	–55	n.a.	n.a.	n.a.
Ruukki 2013	S420MH	200	120	8,0	240	–40	–100	240	–40	–100	210	–60	–90
Ruukki 2013	S420MH	200	120	10,0	300	–20	–70	300	–20	–70	230	–40	–50
Ruukki 2013	S420MH	250	250	12,5	240	–20	–70	240	–20	–60	290	–20	–50

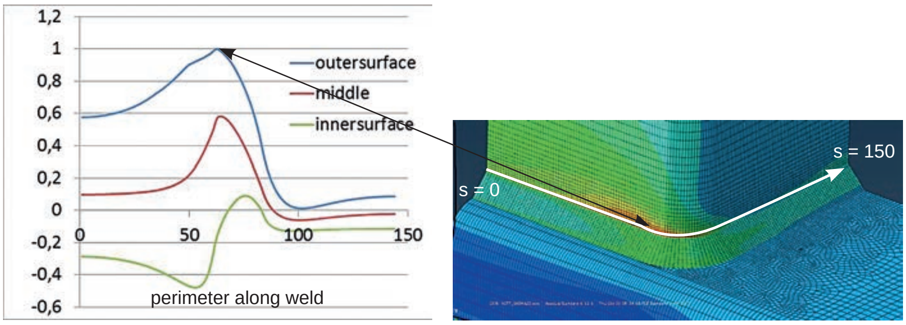


Fig. 11. Relative stress distribution in the corner area of an X-joint

cold forming. In K-joints the gap area is critical, but the highest stresses affect the area with lower DCF and are parallel to the rolling direction. If the tube material is prone to ageing, an X-joint with a relatively high β value is a good choice for investigating this effect. If ageing occurs and consequently reduces the toughness of the material, it should also be noted as being a reduced deformation capacity of the joint. The potential increase in the strength of the joint does not obtain any structural advantage if the deformation capacity is decreased. The tests at low ambient temperature make the potential loss of toughness still more sensitive.

The structural behaviour of the RHS joint has been studied at Lappeenranta University of Technology since the late 1970s and, typically, also at low ambient temperatures. Some of the most important test series and essential results are described briefly below. Although ageing was not the main goal of the research work, the tests were carried out so that the risk of ageing could be noticed if it was activated.

In the 1980s *Niemi* carried out fundamental studies of the capacity of tubular K-joints at low temperatures using typical steels of that period [17]–[19]. These investigations showed that brittle fractures must be considered as a potential failure mode for trusses made of RHS and subjected to high loads at low ambient temperatures. In the 1990s *Soininen* found the mismatching effect in his research work [11]. This mechanism is based on the assumption that the highly cold-formed corners have a higher yield strength than the cross-section next to the corners. Therefore, plastic hinges are placed outside the corners of the chord, which protects the corners from additional plastic deformation. However, some doubts arose as to whether the flat sections also had a high DCF. This occurred in cases where the walls of the cross-section were relatively thick. This was studied in the early 2000s in an RFCS project using X- and K-joints made from the modern fine-grain cold-formed and hot-finished S355 steel grade tubes [15], [20]. The joints were prepared and welded using the GMAW process. The number of passes, and thus heat input, was according to normal workshop practice and hence the potential for ageing was not given any special attention.

The tests were carried out mostly at low temperatures and the results showed good ductility, and no significant differences between the joints made of cold-formed and hot-finished tubes were noticed. Potential ageing can decrease the deformation capacity of the joint and thus the displacements over the joint were measured carefully. The plastic deformations were adequate, which proved that ageing does not play an important role in joint capacity. The load-carrying capacities are plotted in Fig. 12.

The capacities are calculated according Eurocode 3 using real material values and joint geometries. Although most tests were carried out at low ambient temperatures, the results were on the safe side. In addition, the hot-dip galvanized X-joints fulfilled at –40 °C the set deformation requirements (0.005 × chord width for $\beta = 1$ and 0.01 × chord width for $\beta < 1$) and load-carrying capacities as seen in Fig. 12 [21].

Similar X-joint tests were carried out for tubes made of double grade S420MH/S355J2H and S460MH steel tubes [22], [23]. These tests only included the CFRHS tubes and were conducted at room and low temperatures. A typical failure mode and force–displacement curve of an X-joint can be seen in Fig. 13. Although the failure mode presented is brittle, it is a secondary failure mode and occurs after large plastic deformation in the joint, as illustrated in Fig. 13 (right). The load-carrying capacities are shown in Fig. 14 [22], [23]

Despite the high yield strength, ageing seems to play no significant role in joint capacities. The calculated values are based on current EC3 rules using measured joint geometries and material properties, but without applying penalty factors required for steel grades over 350 MPa (0.9 for steel grade up to S460 and 0.8 above S460). Fig. 15 shows the results of K-joints made of steel grade S555. A detailed description of the preparation of test specimens and the test setup is available in [20].

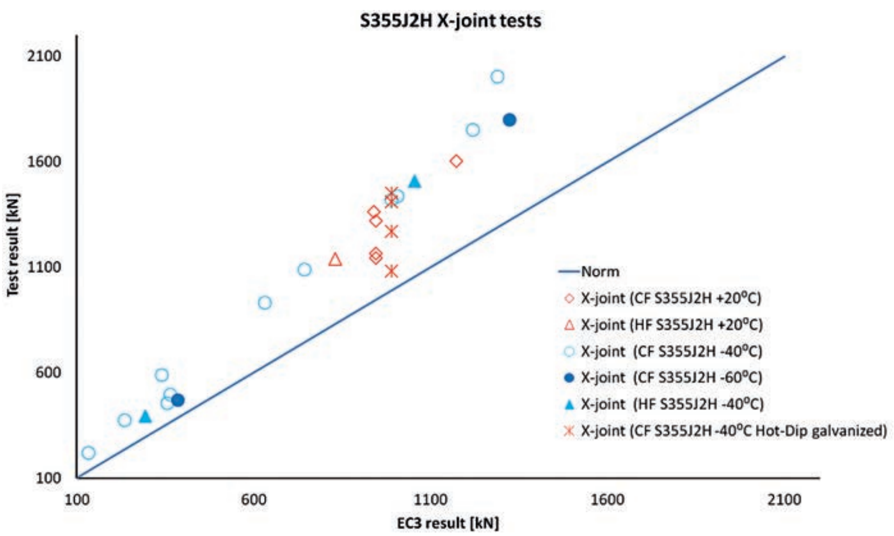
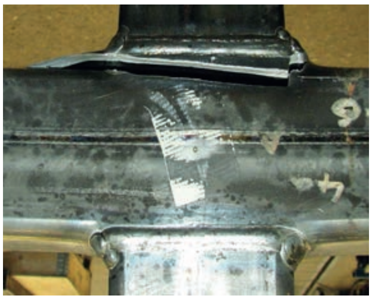


Fig. 12. Results for X-joints made of S355J2H cold-formed and hot-finished tubes, and also including some hot-dip galvanized joints [20], [21]



Brace and Chord 120 × 120 × 6 S420MH

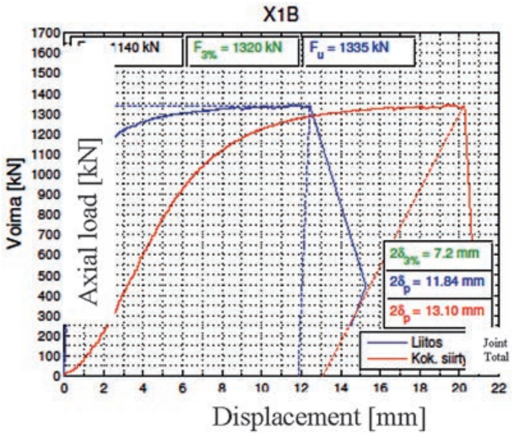


Fig. 13. Brittle secondary failure occurring after large plastic deformation of X-joint at –40 °C [23]

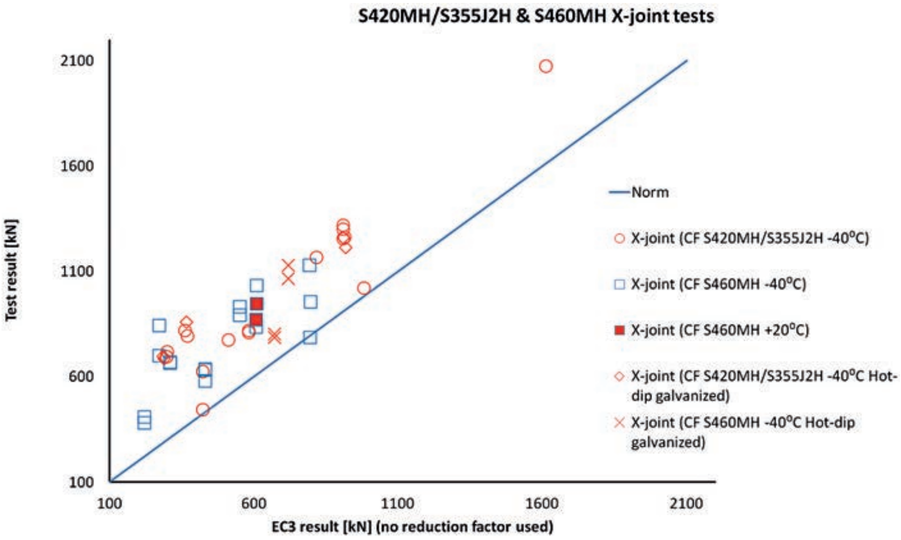


Fig. 14. Results for X-joints made of high-strength cold-formed tubes, and also including some hot-dip galvanized X-joints [22, 23]

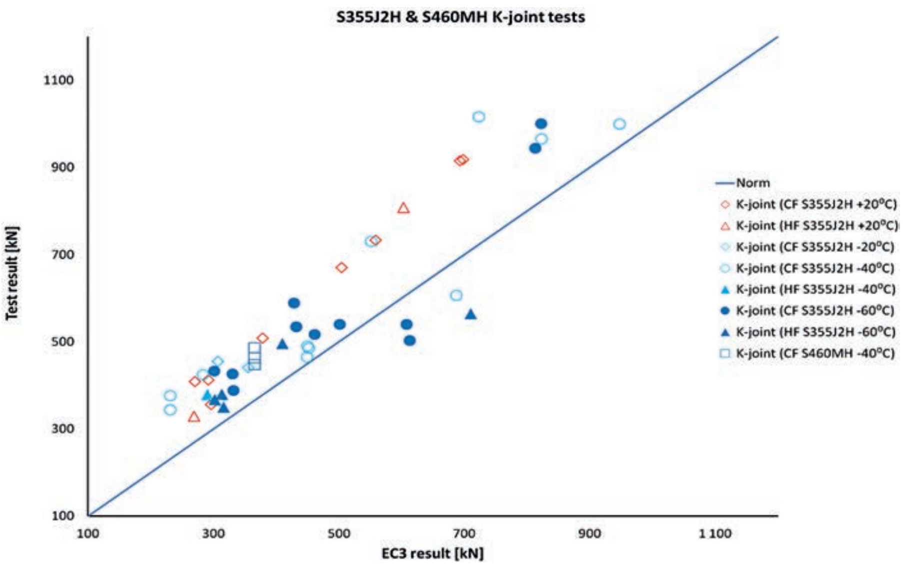


Fig. 15. Results for K-joints in steel grades S355J2H and S460MH [20]

As can be seen in Fig. 15, the required load-carrying capacities were not reached in the four K-tests. These joints were fabricated from cold-formed or hot-finished tubes and were tested at –60 °C. The main reason for the low load-carrying capacity in the test was the lack of deformation capacity due to a narrower gap than that permitted in the current design recommendations. All the other joints fulfilled the required joint capacities, proving that ageing had no particular effect on the K-joints.

5 Conclusions

Over the past two decades the low-temperature toughness and structural performance of cold-formed rectangular hollow sections have been the subject of a number of critical, high-quality investigations. Parallel to these investigations, both steelmaking and hot rolling have undergone crucial developments, which have also had an impact on cold-formed hollow sections.

Conventional C/Mn steels represented the state-of-the-art level in the early 1990s; thermomechanically rolled fine-grain steels became the state-of-the-art level at the end of the 1990s. To meet the more stringent Charpy-V requirement of 35 J/cm^2 at –40 °C, Ruukki gradually changed the feed material for grade S355J2H hollow sections to fine-grain steels. Since 2002 the whole production has been based on thermomechanically rolled fine-grain steels. In 2010 Ruukki introduced a new standard quality, "Ruukki double grade", which conforms to EN 10219-1&2 grades S420MH and S355J2H. Most of the studies referred to in this paper included cold-formed hollow sections supplied by Ruukki. Thus, the developments in feed material are also reflected in these investigations.

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

– Cold forming and welding reduces the low-temperature ductility of cold-formed EN 10219 grade S355J2H hollow sections made of conventional steels. Despite satisfactory toughness on the flat face, the Charpy-V toughness in the corner after welding may not always fulfil the requirement of 27 J at –20 °C.
– Cold-formed EN 10219 hollow sections made of suitable fine-grain steels have similar Charpy-V toughness on the flat face and in the corner. The effect of ageing is still observable, but due to the excellent low-temperature properties, even after ageing, the transition temper-

ature T_{40J} in the corner area is at a very low level, typically below –50 °C. Thus, ageing does not reduce the toughness to a substandard level.
– The load and deformation capacities of X- and K-joints made of cold-formed EN 10219 hollow sections made of suitable fine-grain steels fulfil the requirements without noticeable ageing effects, which is a very important result for practical applications.

Advances in steelmaking and hot rolling enable the manufacture of reliable and versatile cold-formed EN 10219 hollow sections for welded structures with good low-temperature ductility, even in the cold-formed corner area.

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