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Structural Applications of Ferritic Stainless Steels (SAFSS)

WP 5.3 Design guidance for welded connections in ferritic stainless steels

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1 INTRODUCTION

In order for ferritic stainless steels to be used in structural applications, it is necessary to understand how they perform at joints and connections. This report aims to provide guidance for both welded and tubular connections, in line with the methods given in EN 1993-1-4 (2006) and EN 1993-1-8 (2005).

A study into the weldability of ferritic stainless steel has been completed (Anttila and Heikkinen, 2011) as part of Task 5.2 in the SAFSS project and it was found that ferritics are generally weldable materials although care must be given to the welding procedures used for particular grades. Typically, ferritic stainless steels are welded with austenitic filler as they provide superior toughness properties compared with ferritic filler metals. Although autogenous welding (i.e. without using a filler) is not typically used for stainless steels as it can result in poor corrosion resistance as well as loss of ductility and toughness, it is possible to use this technique for some grades of ferritic stainless steel if necessary.

Mechanical tests on welded samples have been completed as part of the current project (Anttila, 2012). Of the grades included in the study, it was found that ferritic Grades 1.4003, 1.4509 and 1.4621 are the most suitable for autogenous welding as those specimens failed in the base metal. However, according to the test results, the ultimate tensile strength (UTS) of the autogenous welds rarely matched that of the base material. Conversely, when austenitic fillers were used, it was established that the ultimate tensile strength of the weld was higher than that of the base metal. Furthermore, fracture typically occurred in the base metal.

This report covers welded connections (Section 2), welded tubular joints (Section 3) and the fatigue behaviour of welded connections (Section 4). Section 5 summarises the findings and presents some concluding comments, as well as recommendations for future work.

2 WELDED CONNECTIONS

EN 1993-1-8 provides design rules for various types of welded connections including (i) butt welds (ii) fillet welds and (iii) plug welds. Used in conjunction with EN 1993-1-4, these rules can also be applied for stainless steels, including the ferritic grades 1.4003, 1.4016 and 1.4512. However, no structural tests have been carried out on welded connections in ferritic stainless steels.

It is essential that welds are made by suitably qualified welders using correct procedures, including compatible consumables. This is important not only to ensure the strength of the weld and to achieve a defined weld profile but also to maintain corrosion resistance of the weld and surrounding material. Current design guidance for stainless steel in structural applications, e.g. the Euro Inox and SCI *Design Manual for Structural Stainless Steel* (2006), includes a list of suitable welding consumables for different grades as well as the mechanical properties of these consumables. However, although the information provides a useful background, ferritic stainless steels are not included.

There is however information available in international welding codes and handbooks. Section 2.1 provides a state-of-the-art review of the guidelines given for welding ferritic stainless steels.

This is followed by a description of the SAFSS welding test programme and the results obtained. As part of the SAFSS project, a series of mechanical tests on welds have been conducted, as well as a metallographic examination of the welds in order to assess the weldability of ferritic stainless steel. A discussion of the results is presented including the implications of these test results for structural design.

2.1 State-of-the-art: Welding ferritic stainless steels

Several international standards and handbooks provide information and rules for welding ferritic stainless steels.

2.1.1 EN 1011-3 (2000)

The European standard for welding metallic materials (EN 1011-3, 2000) states that ferritic stainless steels can be welded using manual metal arc welding (MMA welding), metal-arc inert gas welding (MIG welding), metal-arc active gas welding (MAG welding), tungsten inert gas welding (TIG welding) and plasma arc welding. Other methods such as electron beam welding and laser welding may be used also, if necessary.

Ferritics are susceptible to grain growth at temperatures above 950 °C, resulting in decreased toughness. Therefore the welding heat input should be kept low, e.g. small weld pool and faster travel speeds. It is advised that austenitic welding consumables are preferred rather than ferritic fillers because of the higher ductility of the austenitic weld metal. Ferritic stainless steel consumables may be selected if having similar thermal expansion, similar surface colour of welds or nickel-free welds are required. Furthermore, TIG-welding can be carried out either with or without filler metal (i.e. autogenous welding).

Importantly, it is recommended that shielding gases are argon-based mixtures which do not contain carbon dioxide, hydrogen and/or nitrogen, in order to minimise the susceptibility to embrittlement.

The welder should be aware of possible consequences of welding ferritic stainless steels such as the possibility of cracking occurring and the susceptibility to corrosion in some cases.

2.1.2 AWS Structural welding code – Stainless steel AWS D1.6 (2007)

AWS D1.6 covers ferritic stainless steels, as stated in Clause 1.2.2, although only limited guidance is provided. They are categorised as ‘nonprequalifed stainless steels’. As in EN 1011-3, it is stated that ferritics are susceptible to embrittlement from grain growth during welding and the following techniques are recommended in order to minimise the effects of this phenomenon:

1. Use of low heat input single-pass welding procedures;
2. Slip welding to avoid build-up in one area;
3. Short time PWHT;
4. Use an austenitic filler rather than a ferritic filler.

That is the extent of the advice given in this standard for welding ferritic stainless steels.

2.1.3 Outokumpu Welding Handbook (2011)

This handbook gives specific advice for welding ferritic stainless steels. For all ferritics, care should be taken as they may be susceptible to grain growth in the HAZ, which results in reduced toughness. Ferritics which have been stabilised with elements such as titanium or niobium are less prone to grain growth and are readily weldable. One method of overcoming some of the effects of grain growth is to use laser welding.

When welding together two parts of the same stainless steel grade, the parent material generally determines the choice of filler material. For ferritic grades, selecting austenitic fillers is advisable to improve the mechanical properties, such as ductility. Table 2.1 shows the fillers that are recommended in the Outokumpu Handbook. Note that grade 1.4621 is not included in this table as it is not produced by Outokumpu.

Table 2.1 **Suitable filler for welding ferritic stainless steels (Outokumpu Stainless Oy, 2010)**

Grade	Welding consumables	
	Covered electrodes ISO 3581 ISO 14172	**Wires** ISO 14343 ISO 18274
1.4003	13 or 19 9L	13 or 19 9L
1.4016	19 9L or 23 12L	19 9L or 23 12L
1.4509	19 9 Nb or 18 8 Mn	19 9 Nb or 18 8 Nb
1.4521	19 12 3L or 23 12 2L	19 12 3L or 23 12 2L

Ferritic stainless steels can be welded to mild steel and other stainless steels provided that an over-alloyed filler, e.g. 23Cr12No or 23Cr12Ni2Mo, is used.

Similar to the publications discussed previously, this handbook notes that ferritic stainless steels are susceptible to hydrogen embrittlement and therefore moist electrodes and shielding gases that contain hydrogen should be avoided.

2.1.4 Summary of the advice available

It is clear from the descriptions given above that there is general agreement between the various publishers regarding the best methods for welding ferritic stainless steels. The main points which are given in each of the publications are summarised below:

- The welding heat input should be kept low as ferritics are susceptible to grain growth at higher temperatures;
- Austenitic welding consumables are preferable to ferritic fillers because of the higher ductility of the austenitic weld metal;
- It is recommended that shielding gases are argon-based mixtures which do not contain carbon dioxide, hydrogen and/or nitrogen, in order to minimise the susceptibility to embrittlement.

Finally, it is advisable to take advice from experts this in field before undertaking welding of ferritics, and ensure that suitably qualified and knowledgeable welders are appointed.

Guidance on welding is also given in the ISSF/ICDA publication *The Ferritic Solution* (2007).

2.2 Welding tests

The SAFSS test programme for welded connections (Task 5.2) included welding tests as well as tension, hardness and corrosion tests. ‘Gleeble’ thermal tests (to investigate heat inputs) and impact toughness tests were also performed. Three categories of weld test were conducted:

- Pulsed gas metal arc-welding (GMAW, MIG/MAG) was carried out for materials with a thickness of 2.0 to 3.5 mm, using two austenitic filler metals (308LSi and 316LSi) and three ferritic filler metals (409LNb, 430LNb and 430Ti). The shielding gas employed was 98%Ar + 2%O_2, with the root gas being pure argon.
- Pulsed gas tungsten arc-welding (GTAW, TIG) was carried out for materials with a thickness of 1.0 to 2.0 mm. These welds were fabricated autogenously, i.e. without a filler metal. Pure argon gases were used for shielding.
- Shielded metal arc-welding i.e. stick welding (SMAW, MMA) was carried out for materials with a thickness of between 3.0 and 6.0 mm. Basic austenitic electrodes (E308L-15) were used in these tests.

The experiments showed that ferritic weld metals can differ substantially depending on (i) the grade, (ii) the welding method and (iii) the filler used. A major limitation for ferritic stainless steels in structural applications, and particularly welded connections, is the perceived lack of toughness. This was confirmed through the impact toughness tests completed in the SAFSS project (Anttila, 2012). As stated in Section 2.1, ferritics are susceptible to grain growth at temperatures above 950 °C which results in decreased toughness. Furthermore, refining by heat treatment (PWHT) is not possible.

However, the grain growth is less pronounced in stabilized ferritic stainless steels. This was confirmed in the test programme where it was found that specimens made from stabilized grades (i.e. 1.4509 and 1.4521 and 1.4621) and which are up to 3 mm in thickness can behave in a ductile manner at room temperature when reasonable heat inputs are used. Of the grades covered in this programme, only grade 1.4003 was found to provide adequate toughness for sections thicker than 3 mm.

In order for ferritics to be usable in structural applications, the results of the welding tests must be interpreted in the context of welded connections and joints. The main objective of this report is to assess the weldability of ferritic stainless steels for structural applications and to provide design guidance where possible. Ideally, welded joints should at least match the properties of the base material in terms of strength, ductility and toughness.

Autogenous welds

It was found that autogenous TIG welds rarely matched the ultimate tensile strength of the base metals. Grades 1.4003, 1.4509 and 1.4621 are most suitable for autogenous welding, even though the ultimate tensile strength may be lower than that of the base metal. Autogenous welds for Grades 1.4016 and 1.4521 typically fractured in the weld metal, which is unfavourable.

Welds with fillers

The results verified that austenitic filler metals are the most suitable for welding ferritic grades. Generally, the ultimate tensile strength of the weld metal is higher than that of the base metal, and fracture typically occurred in the base metal, which is favourable. The test results on samples using ferritic fillers showed that these are only suitable for grades 1.4003 and 1.4016 of the materials examined.

Toughness

As stated before, the toughness properties of ferritic stainless steel welded joints require careful consideration during the structural design process. The test results showed that cold-rolled material displayed better toughness than hot rolled materials. The HAZ (heat affected zone) toughness is reasonable for all Grade 1.4003 materials and for stabilised grades with a thickness of up to 2 to 3 mm.

Grade 1.4016 exhibited poor toughness properties in the autogenous welds and in the HAZ, irrespective of the thickness. This was attributed to the presence of grain boundary martensite. It is however possible to improve the toughness of the joint to some degree by carrying out a post-weld heat treatment (PWHT).

In conclusion, the test results can be summarised as follows:

- austenitic filler metals are the most suitable consumables for structural purposes at ambient temperatures, compared with welds with ferritic fillers and autogenous welds;
- cold-rolled materials have better toughness properties compared with hot-rolled;
- the stabilized grades (1.4509 and 1.4521 and 1.4621) are more suitable for welded connections than the non-stabilised materials;
- most grades covered in this project, with the exception of Grade 1.4003, are only suitable for welding for specimens with a thickness of 3 mm or less.

2.3 Design guidance for welded joints

As stated previously, the strength rules given in EN 1993-1-8 for various types of welded connection can be applied to stainless steels, in conjunction with EN 1993-1-4 for material thicknesses greater than 4 mm and EN1993-1-3 for thinner materials. Given that ferritics have been shown to be only be weldable for materials 3 mm or less (with the exception of grade 1.4003), it is most likely that the strength rules given in EN 1993-1-3 will be most suitable.

It is essential that welds are made using correct procedures, including compatible consumables, with suitably qualified welders. Compatible consumables should be used, such as those described in earlier sections of this report, so that the weld yield strength and ultimate strengths exceed those of the parent material. Intermittent fillet welds and intermittent partial penetration butt welds should be avoided to reduce the possibility of corrosion.

Further design guidance is available in the Euro Inox and SCI *Design Manual for Structural Stainless Steel* (2006).

3 WELDED TUBULAR JOINTS

Trusses and space frames are target structural applications for ferritic stainless steels and, in this context, welded tubular joints are a key concern. This section provides a background description on the types of joints that are likely to be employed and also some discussion and design guidance, where possible. It is worth highlighting from the outset, however, that, to the best of the authors' knowledge no experiments have been carried out on ferritic stainless steel tubular joints to date. Therefore, the level of design guidance that can be offered is limited.

3.1 Types of welded tubular joint

There are six main classifications of joint types – 'T', 'Y', 'X', 'N', 'K' and 'KT' joints'. The most common of these are N and K-joints which can be sub-divided into gap N- or K-joints and overlapping N- or K-joints, depending on whether the bracings gap or overlap. are N- and K- joints. The following design parameters need to be considered for tubular joints:

- Eccentricity;
- Gap;
- Overlap;
- Chord width to thickness ratio;
- Bracing width to chord width ratio; and
- Bracing angle (lower angle is better).

3.2 Failure modes

There are several different failure modes for tubular joints which must be considered in design, as covered in EN 1993-1-8, including:

- Chord face failure;
- Chord side-wall failure;
- Chord shear failure;
- Punching shear failure;
- Local brace failure (effective width); and
- Local buckling.

If the welds are not strong enough, weld failure can also occur.

3.3 Design rules for carbon steel welded joints

Extensive research was performed on welded connections of carbon steel circular hollow sections (CHS) and square hollow sections (SHS) during the 1960s, 1970s, and 1980s. The research was described in detail in Section 6 of Comite´ International pour le Developpement et l'Etude de la Construction Tubulaire (CIDECT) Monograph No. 6 (CIDECT, 1986) and compiled in design guide publications by CIDECT (e.g. Wardenier *et al*. (1991) for CHS's and Packer *et al*. (1992) for RHS's) and books (e.g. Packer and Henderson, 1997). The design guidelines described in these publications were adopted in the International Institute of Welding (IIW) document ''Design Recommendations for Hollow Section Joints—Predominantly Statically Loaded (IIW, 1989) and in Eurocode 3 (EN1993-1-8, 2005). More recently, CIDECT have produced further guidance and discussion (Wardenier, 2001; Wardenier *et al*., 2010), the latter of which is considered to represent the current state-of-the-art for the design of tubular joints; it is expected that the recommendations in this book will be incorporated into the next revision of EN1993-1-8. More information can be found at http://www.cidect.org/.

The most recently published CIDECT book (Wardenier *et al*., 2010) includes provisions for welded joints between circular hollow sections (CHS's) and square hollow sections (SHS's) as well as joints between hollow and open sections. All of the CIDECT design strengths already incorporate joint resistance (or capacity) factors (Φ) and are determined as the product of the nominal strength and an appropriate resistance factor. The Φ factors (as commonly used in North America and Australia) are equivalent to the γ_M factors used in Europe although Φ is a multiplier whereas γ_M is a divider. In general, the value of $1/\gamma_M$ is almost equal to Φ. Hence, Eurocode 3 provides the same design strengths as the CIDECT recommendations when the nominal strength is multiplied by the resistance factor.

3.4 Design rules for stainless steel tubular joints

As stated before, the CIDECT design rules were developed for carbon steel joints and do not cover stainless steel applications. The Australian/New Zealand Standard for stainless steel structures (AS/NZS 4763, 2001) is the only international design standard that currently provides design rules for cold-formed stainless steel tubular joints. The design rules given in this standard are generally adopted directly from the CIDECT recommendations for carbon steel tubular joints (CIDECT, 1986; Wardenier *et al*., 1991; Packer *et al*., 1992), but replace the yield stress with the 0.2% proof stress, as determined from the finished tube rather than the annealed material.

In addition to the Australian/New Zealand design rules, it is anticipated that the next version of the ASCE Specification for the Design of Cold-Formed Stainless Steel Structural Members (8-02), with an unknown publication date, will contain rules for stainless steel joints. These are expected to be identical to those include in the Australian/New Zealand standard.

The CIDECT and Eurocode design rules for carbon steel tubular joints are limited to materials with a yield stress of 355 and 460 MPa, respectively. This is mainly because the rules are based on experimental data which was obtained for joints with yield stresses less than these values. In addition, carbon steel joints with yield stress greater than these values may not have adequate ductility.

Stainless steel has a more rounded stress-strain curve compared with carbon steel and therefore deformations of stainless steel joints typically exceed those of carbon steel joints. It is therefore important to give particular attention to joint deformations when considering stainless steel joints and to whether these are likely to exceed acceptable limits under service loads. On the other hand, Rasmussun and Young (2001) found that lack of ductility is not a concern for austenitic stainless steel structures since austenitic stainless steel generally have high ratios of ultimate tensile strength to tensile proof stress and high values of elongation after fracture. Based on the findings in the SAFSS project, lack of ductility should not be a problem for ferritic stainless steels either.

3.4.1 Tests on stainless steel tubular joints

The CIDECT design rules were adopted in the AS/NZS code following experimental investigations of cold-formed stainless steel tubular joints in Australia by Rasmussen and Young (2001) for SHS X- and K-joints and Rasmussen and Hasham (2001) for circular hollow section (CHS) X- and K-joints. Further tests have since been conducted in Hong Kong by Feng and Young (2008 and 2010) on cold-formed stainless steel SHS and RHS T- and X-joints. Table 3.1 to Table 3.4 shows the parameters that were varied in the various test programmes, thereby highlighting the most salient variables to the joint strength.

Table 3.1 Parameters varied in the test programme of Rasmussen and Young (2001)

Cross-section	Joint-type	Varied parameter
SHS	X-Joint	Brace-to-chord-width ratio
		Direction of loading
	K-Joint	Brace-width-to-chord width ratio
		Angle between the brace and chord members
		Preload applied to the chord

Table 3.2 Parameters varied in the test programme of Rasmussen and Hasham (2001)

Cross-section	Joint-type	Varied parameter
CHS	X-Joint	Brace-to-chord-diameter ratio
		Direction of loading
	K-Joint	Brace-to-chord-diameter ratio
		Angle between the brace and chord members

Table 3.3 Parameters varied in the test programme of Feng and Young (2008)

Cross-section	Joint-type	Varied parameter
SHS and RHS	T- Joint	Brace width to chord width ratio
		Brace thickness to chord thickness ratio
		Chord width to chord thickness ratio

Table 3.4 Parameters varied in the test programme of Feng and Young (2010)

Cross-section	Joint-type	Varied parameter
SHS and RHS	X-Joint	Brace width to chord width ratio
		Brace thickness to chord thickness ratio
		Chord width to chord thickness ratio
		Compressive chord preload

Australian tests

All of the specimens in these programmes were made using manual metal arc welding and used a 3.25 mm type E308L-16 electrode. All welds consisted of a single run. The chord and brace members had a thickness of between 2.85 and 3.4 mm. The study into SHS X- and K-joints (Rasmussen and Young, 2001) verified that these connections can be designed using the CIDECT recommendations (Packer *et al*., 1992) for carbon steel joints by replacing the yield stress with the 0.2% proof stress, as determined from the finished tube. When based on the 0.5% proof stress, the CIDECT strength provisions become optimistic in the presence of high compressive forces (preloads) in the chord. Hence, the CIDECT rules for carbon steel tubular joints have been adopted in the AS/NZS 4763 design standard (2001) for stainless steel tubular joints (using the 0.2% proof strength).

For the CHS X- and K-joints, it was also shown that these can be designed using the CIDECT recommendations for carbon steel joints by replacing the yield stress by either the 0.2 or 0.5% proof stress, as determined from the finished tube rather than the annealed properties (Rasmussen and Hasham, 2001). It is not necessary to check for deformations of the K-joints under service loads although X-joints loaded in compression with small brace-diameter to chord-diameter ratios may experience deflections slightly greater than 1% under service loads. The results of this test programme led to the adoption of the CIDECT design rules for carbon steel joints in the AS/NZS 4763 standard for stainless steel for CHS X- and K-joints (replacing the yield strength with the 0.2% proof strength, as before).

Hong Kong tests

A total of 20 tests on T-joints and a further 10 tests on X-joints were reported by Feng and Young (2008 and 2010, respectively). Both square and rectangular hollow sections of varying dimensions were used. The specimens in these series were welded using shielded metal arc welding. The type of electrode employed depended on the materials being tested with E2209-17 electrodes used for the duplex and high-strength austenitic specimens and E308L-17 electrodes used for the normal strength austenitic stainless steel members. In both test series, three different failure modes were observed: (i) chord face failure (ii) chord side wall failure, and (iii) local buckling failure of brace. These failure modes were correctly depicted by finite element simulations, as described in the publications.

The authors used the test results (Feng and Young, 2008) to conduct an assessment of the adequacy of the CIDECT design rules (Packer *et al*., 1992). The test results showed that the design strengths predicted by the CIDECT rules are generally conservative for both high strength and normal strength cold-formed stainless steel welded tubular T-joints when the 0.1%, 0.2%, 0.5% and 1.0% proof stresses are used in the design calculation. Furthermore, it was shown that the ultimate limit state controls rather than the serviceability limit state for most of the high strength and normal strength stainless steel test specimens.

Further analysis was done using finite element (FE) analysis (Feng and Young, 2011) which agreed with earlier observations that the CIDECT design rules are generally conservative. However, there was one case where the design rules were found to be unconservative and that is for stainless steel tubular T- and X-joints subjected to chord face failure. The design rules were found to be slightly conservative for stainless steel tubular T- and X-joints subjected to combined chord face failure and chord side wall failure, and were also shown to be suitable for specimens which failed by local buckling of brace.

Using these test and numerical results, new design formulae were proposed for cold-formed stainless steel tubular T- and X-joints based on the current CIDECT design rules for carbon steel tubular joints (Feng and Young, 2011). Reduction factors for different failure modes were introduced. The steel yield stress in the CIDECT equations is replaced by the stainless steel 0.2% proof stress in the proposed equations.

3.5 Design rules for ferritic stainless steel joints

All of the tests described in Section 3.4 are for either austenitic or lean duplex stainless steels. At the time of writing, it has not been shown experimentally or numerically if the CIDECT rules are applicable to ferritic stainless steel grades. The Australian/New Zealand Standard for stainless steel structures (AS/NZS 4763, 2001) includes design rules for stainless steel tubular joints (which, as stated before are identical to the CIDECT carbon steel rules except use the 0.2% proof strength instead of the yield strength). This standard covers ferritic stainless steel Grades 1.4003, 1.4016 and 1.4512 (the latter of which is not included in the current project) as well as austenitic and lean duplex grades. However, there is no experimental evidence that the rules have been validated for ferritic stainless steel tubular joints.

The Stainless Steel Hollow Section Handbook (Finish Constructional Steelwork Association (FCSA), 2008) has a chapter on structural hollow section joints wherein it refers to the CIDECT guide for the design of stainless steel tubular joints. Although it does not specify which grades these rules are applicable to, there is no suggestion that ferritic grades are not included.

The key issues to consider for the design of ferritic stainless steel tubular joints are the ductility and toughness properties. In terms of toughness, it was stated in Section 2 of this report that ferritic stainless steels offer limited toughness, particularly for thicker specimens and those that are made from unstabilised grades. However, for thinner sections the toughness properties of the stabilised ferritics should be adequate. This requires numerical and/or experimental validation.

It is unlikely that inadequate ductility should be a concern for ferritic stainless steel joints as, according to the test results obtained from the SAFSS project and presented in Table 3.5, the ratio of ultimate tensile strength (R_m) to tensile proof stress ($R_{p0.2}$) of these grades is relatively high, as is the value of elongation after fracture. On the contrary, it is far more likely that joint deformations are likely to be critical in the design of all stainless steel structures because the loss of stiffness associated with the low proportional stress encourages deformations to develop at loads considerably below ultimate. The CIDECT design guides (e.g. Wardenier *et al*., 1991; Packer *et al*., 1992) propose that joint deformations under service loads should be limited to 1% of the chord width/diameter. The test results discussed in the previous section found that the serviceability limit state corresponding to this limit will not be reached if the CIDECT strength rules are adopted. However, this would need to be verified for ferritic stainless steels through testing before the same assumptions could be made. Further analysis is also necessary to establish if the failure loads and failure modes are appropriate for ferritic stainless steel tubular joints.

Table 3.5 Summary of tensile test results of all studied grades and thicknesses.

Quantity	Average	Std. Deviation	Min	Max
Ratio of measured $R_{p0,2}$ to the minimum value required by the material standard	1.40	0.24	1.12	2.05
R_m / $R_{p0,2}$	1.37	0.10	1.13	1.55
Ramberg-Osgood n-value	14.2	5.1	7.2	27.8
Tensile elongation A80 (%)	28	4.6	16	35

4 FATIGUE BEHAVIOUR OF WELDED JOINTS

4.1 General

Fatigue is a mechanism whereby cracks develop in a structure under fluctuating stress. Cracks are unavoidable, even in smooth surfaces, and are most likely to develop at locations with high stress peaks, such as at welded joints. These discontinuities then grow and propagate under fluctuating stress. The rate of growth depends on (i) the stress range, (ii) the crack size and (iii) any geometrical discontinuities. Final failure generally occurs when the reduced cross section becomes insufficient to carry the load without rupture.

The Eurocode (EN 1993-1-9, 2005) proposes a simplified method of assessing fatigue in carbon steel structures which follows the following steps:

1. determine the fatigue strength curve (S-N curve) for the detail in question;
2. calculate the secondary bending moments in the joint;
3. determine the partial safety factor for fatigue strength; and
4. conduct the fatigue assessment for variable amplitude loading.

This method relies on empirically derived relationships for the material between applied elastic stress ranges and fatigue life, presented as the number of cycles to failure. These curves are known as *S-N* curves. According to EN 1993-1-9 for carbon steel joints, the *S-N* curve is determined depending on the detail type, as described in Tables 8.1 to 8.10 of the code. This code does not make a distinction for material type. These tables cover simple details as well as more complicated details such as hollow section joints. The allowable fatigue stresses are determined from the nominal direct and shear stresses modified by appropriate factors to account for stress concentrations, secondary bending moments, section size, variable amplitude loading and other relevant parameters.

In EN 1993-1-9, the fatigue strength for members with butt welded or fillet welded end-to-end connections, with plates or members with attachments, etc. is given as the stress range corresponding to 2×10^6 cycles. For welded details, the classification is independent of the steel grade. Fatigue design of hollow section joints is, in general, different from that of simple welded connections between plates. This is because in welded joints between hollow sections the stiffness around the intersection is non-uniform, resulting in a geometrical non-uniform stress distribution. Further guidance on this is available in the CIDECT design publication (Wardenier *et al*., 2010).

4.2 Fatigue assessment of ferritic stainless steel welded connections

In common with carbon steel structures, the combination of stress concentrations and defects at welded stainless steel joints leads to these locations being more prone to fatigue failure than other parts of the structure (Euro Inox and SCI, 2006). EN 1993-1-4, includes some ferritic stainless steel grades, and directs users to EN 1993-1-9 for estimating the fatigue strength of stainless steel structures.

However, clause 1.1(4) of EN 1993-1-9 states: *'The assessment methods given in this part are applicable to all grades of structural steels, stainless steels and unprotected weathering steels except where noted otherwise in the detail category tables. This part only applies to materials which conform to the toughness requirements of EN 1993-1-10.'* EN 1993-1-10 gives specific toughness requirements for carbon steel and so is not applicable to ferritic stainless steels. Therefore, it can be deduced that the rules in EN 1993-1-9 for determining fatigue resistance cannot be assumed to apply to ferritic stainless steels.

A literature search on the fatigue performance of the welded ferritic stainless steel grades studied in this project was carried out. From studies at The Welding Institute in the UK into the fatigue behaviour in air for welded joints of 1.4003, it was found that the fatigue strengths for different types of joints (class F, G and W in BS 7608) were very similar to those of typical carbon steels. Manual metal arc welding with an austenitic stainless steel consumable was used in these studies. It is probable that similar performance would be expected for better fatigue details.

To ensure good fatigue performance it is necessary to control the microstructure. There have been examples where a heat sensitized microstructure in grade 1.4003 resulted in localised corrosion at the welds which in turn affected the fatigue performance. Therefore any recommendations on the fatigue performance of ferritic stainless steels assumes that correct welding procedures are employed to maintain the optimum performance.

Studies have also been carried out on the fatigue behaviour of butt welds of the 1.4003 alloy using gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), friction stir welding (FSW) and electron beam welding (EBW). A duplex stainless steel was used as the consumable for GMAW and SMAW and in some cases GTAW. The fatigue behaviour appears to be dependent on the welding method used and the fatigue strength of the joints were either above or below the mean curves (BS 7608) for similar joints of carbon steels, depending on the welding method used.

With regards to information on the other alloys, only fatigue crack growth data for grade 1.4521 is available.

Work on high temperature fatigue performance has been carried out to determine performance for exhaust systems in automotives (Bucher, L., P.-O. Santacreu, et al, 2006 and Bucher, L., P.-O. Santacreu, et al, 2006).

The risk of failure due to fatigue at welded joints or other locations can be brought to an acceptable level by good design together with good fabrication and inspection. This involves judiciously selecting the overall structural configuration and carefully choosing constructional details that are fatigue resistant. The key to fatigue resistant design is a rational consideration of fatigue early in the design process (Euro Inox and SCI, 2006). Early consultations with the fabricators and erectors are recommended to point out areas of the structure which are most sensitive to fatigue cracking, to discuss special precautions and to become aware of fabrication and erection problems. In particular, the use of holes or lifting attachments to ease fabrication or erection should be considered during the fatigue evaluation.

The fatigue performance of a welded joint can be enhanced by the use of weld improvement techniques such as (Davison and Owens, 2012):

- weld geometry improvement (e.g. grinding, etc.),
- residual stress reduction (e.g. peening, etc.).

An extended crack initiation life can be achieved by (i) reduction of the stress concentration of the weld, (ii) removal of crack-like deflects at the weld toe, and (iii) reduction of tensile welding residual stresses or introduction of compressive stresses.

5 CONCLUSIONS

This aim of this report is to summarise information relating to welding of ferritic stainless steel and provide design guidance where possible. The report is broken down into three main parts:

- Section 2 deals with welded connections,
- Section 3 is concerned with welded tubular joints, while
- Section 4 provides advice for dealing with fatigue of welded connections.

In terms of the welded connections, the information acquired through testing in the SAFSS project, in conjunction with information available in the literature, enables reasonable advice to be proposed for the design of ferritic stainless steel welded connections. The main points include:

- The strength rules given in EN 1993-1-8 for various types of welded connection can be applied to stainless steels, in conjunction with EN 1993-1-4 for material thicknesses greater than 4 mm and EN1993-1-3 for thinner materials.
- Austenitic filler metals are the most suitable consumables for structural purposes at ambient temperatures, compared with welds with ferritic fillers and autogenous welds.
- Cold-rolled materials has better toughness properties compared with hot-rolled material.
- The stabilized grades (1.4509 and 1.4521 and 1.4621) are more suitable for welded connections than the non-stabilised materials
- The HAZ (heat affected zone) toughness is reasonable for grade 1.4003 (1 – 6 mm thick) and for stabilised grades with a thickness of up to 2 to 3 mm.
- Most grades covered in this project, with the exception of grade 1.4003, are only suitable for welding for specimens with a thickness of 3 mm or less.
- It is essential that welds are made using correct procedures, including compatible consumables, with suitably qualified welders. Plenty of advice on suitable fillers, types of welding procedures etc. is provided in the report.

In relation to ferritic stainless steel tubular joints, a summary is given of the state-of-the-art for both austenitic and ferritic stainless steel. The various types of tubular joint and the different failure modes which must be considered are discussed as well as the different approaches adopted by international design codes. This discussion is included with a view to providing design guidance for tubular joints using ferritic stainless steel. However, it was found that although one international design standard (the Australian/New Zealand design standard) includes guidance which can be applied to ferritic tubular joints (the same rules as those for austenitic stainless steel), there is no experimental or numerical evidence that these rules are valid for ferritics. Therefore, it is impossible to provide definitive design rules for ferritic steel welded tubular joints until experimental and/or numerical studies have been completed.

The Australian/New Zealand design rules are generally adopted directly from the CIDECT recommendations for carbon steel tubular joints (CIDECT, 1986; Wardenier *et al*., 1991; Packer *et al*., 1992), but replace the yield stress with the 0.2% proof stress, as determined from the finished tube rather than the annealed material. This standard covers ferritic stainless steel Grades 1.4003, 1.4016 and 1.4512 even though there is no experimental evidence that the rules have been validated for ferritic stainless steel tubular joints.

The main issues to consider for the design of ferritic stainless steel tubular joints are the ductility and toughness properties. Both of these were discussed in this report and, so long as the findings presented for welded connections are followed (i.e. in terms of thickness and whether the material grade is stabilised or not), it is unlikely that inadequate ductility or toughness will be an issue. However, this requires numerical and/or experimental validation. As stated before, it is not possible to propose design rules for ferritic steel welded tubular joints without undertaking experimental and numerical investigation. It is recommended that this work is undertaken in the future to enable design rules to be proposed.

The final topic covered in this report related to fatigue in welded ferritic steel connections. From the tests carried out, it appears that the guidance for carbon steel can be applied to ferritic stainless steel, but only a few details have been tested and the information is not in the public domain. Additionally the tests have generally been on grade 1.4003 only, although it is unlikely that the other ferritic grades will behave very differently. To ensure good fatigue performance it is necessary to control the microstructure to ensure that localised corrosion at the welds does not occur which in turn might have an adverse impact on the fatigue performance.

As with all welded structures, it is essential that good design is adopted together with good fabrication and inspection, including choosing constructional details which are fatigue resistant.

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