STRUCTURAL APPLICATIONS OF FERRITIC STAINLESS STEELS (SAFSS)

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EUROPEAN COMMISSION

Research Programme of
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Abstract

The aim of the study was to collect up technical knowledge of ferritic stainless steels related to construction by utilizing standards and guidelines as well as publications, articles and reports generated in research projects. The comparison of ferritic hot and cold rolled flat products by applications in 2007 is presented based on the study of International Stainless Steel Forum (ISSF). As shown present legislation covering the use of stainless steels in structures makes little references to ferritic stainless steels. Eurocode 3 does not actively promote this family of materials in the same way as other grades. The study is made in co-operation with Finnish Constructional Steelwork Association (FCSA) and at first it was used in the preparation of a RFCS (Research Fund for Coal and Steel) funded project application for ferritic stainless steels in construction. The study was updated in December 2010 with some recently published papers.

1.0 Aim

The aim of this study was to gather knowledge related to ferritic stainless steel standards, design guidance and research reports for the needs of structural design in building industry. The volume information is based on the report done by ISSF in 2008. Figure 1 shows an estimation of the shares of the use of cold-rolled and hot-rolled ferritic stainless steels in different applications /1/.

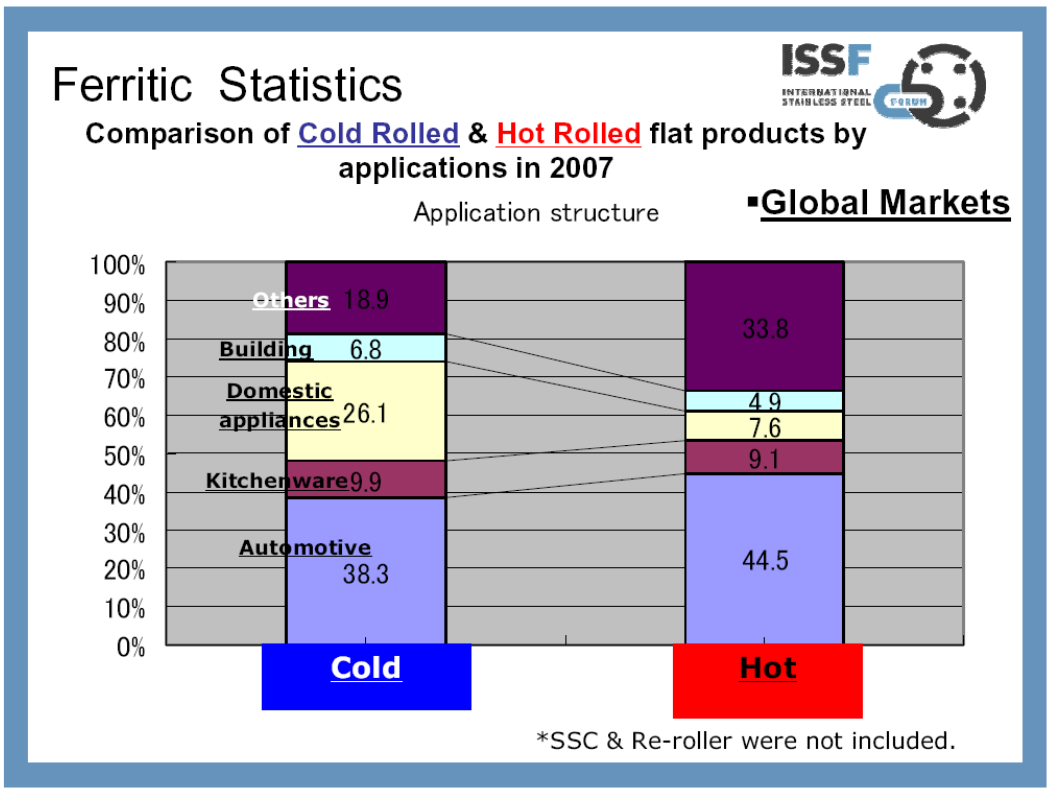

Figure1. Shares of cold- and hot rolled ferritic stainless steel grades in different applications /1/.

2.0 Ferritic grades in use

Ferritic stainless steels have increased their share among stainless steels during the last 3 years. According to a study conducted by ISSF /1/, the share of ferritic grades is estimated to have increased up to 33% in 2007 compared to 24% in 2004. The stable long term price level and generally lower price level compared to austenitic stainless steel grades have encouraged the growth of the share of ferritic grades. Ferritic stainless steel grades are alloyed with a minor quantity of nickel and, in the case of some grades, with molybdenum.

The term “alloy surcharge”, which is one part of the prices of stainless steel grades, is strongly influenced by the LME price of nickel in case of CrNi grades and by the additional cost of molybdenum in the case of CrNiMo grades. The LME price of nickel was extremely high during the period 2006 – 2008. As a result of this, the prices of austenitic grades increased, but the prices of ferritic grades remained more stable. This kind of an unforeseen price fluctuation has led the end users to compare the properties of the traditionally used austenitic grades to the more stable-priced ferritic grades in service situations.

The ISSF study /1/ showed that the use of stainless steel in the building sector is lesser compared to other studied sectors, which included automotive, kitchen ware, domestic appliances and others.

The ISSF publication ”Ferritic solution” /2/ presents the classification of ferritic grades, properties and joining. The wide range of applications from different sectors is presented in this publication.

Other reported ferritic stainless steel applications include:

- Bare ferritic stainless steels in interior and exterior applications (roofing, cladding)
- Coated ferritic stainless steels mainly for exterior use
- Painted ferritic stainless steels
- Profiles made of ferritic stainless steels

The use of ferritic stainless steel grades in these applications is favoured by their sufficient corrosion resistance, long term aesthetic appeal and lower price level compared to CrNi- and CrNiMo- stainless steels. The other advantageous properties are their suitability for coating and easy formability.

3.0 Ferritic stainless steel grades

3.1 Ferritic grades according to material standards and structural design standards

The following chapters present the material selection based on standards aimed for building industry applications.

3.1.1 Material standards EN 10088, structural design standard EN 1993-1-4, fire design standard EN 1993-1-2 and material toughness properties standard EN 1993-1-10

Stainless steel is determined according to standard *EN 10088-1, Stainless steels – Part 1: List of stainless steels* /3/: stainless steels are steels, with at least 10,5 % of chromium and at most 1,2 % of carbon.

Standard EN 10088-1 /3/ gives the chemical composition of ferritic corrosion resisting steels and ferritic heat resisting steels. Not all ferritic heat-resisting steels comply with the definition of stainless steel. *Standard EN 10088-2, Stainless steels – Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes* /4/ includes the technical delivery conditions for ferritic corrosion resisting steels but not to ferritic heat-resisting steels.

Standard *prEN 10088-4 Stainless steels - Part 4: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes /5/* and *prEN 10088-5 Stainless steels - Part 5: Technical delivery conditions for bars, rods, wire, sections and bright products of corrosion resisting steels for construction purposes /6/* includes the annex ZA, which is used for the CE-marking of these materials.

Table 1 shows the chemical composition of ferritic corrosion resisting steels according to standard EN 10088-2. Table 2 shows the mechanical strength values at room temperature to ferritic corrosion resisting steels. Ferritic corrosion resisting steels are categorised as follows:

Standard steels

Standard steel grades have relatively good availability and a wide range of application.

- EN 10088-2: 1.4003, 1.4512, 1.4516, 1.4000, 1.4002, 1.4016, 1.4510, 1.4511, 1.4113 and 1.4521
- prEN 10088-4: 1.4003, 1.4512, 1.4016, 1.4510, 1.4521, 1.4513, 1.4526 and 1.4509 (standard prEN 10088-4 tables 7-11 have no requirement to the value of impact energy, in CE-marking the value shall be declared)
- prEN 10088-5: 1.4003, 1.4016, 1.4523 (standard prEN 10088-5 tables 7-11 have no requirement to the value of impact energy, in CE-marking the value shall be declared)

Special steels

Special steel grades are meant for specialised uses and have a limited availability.

- EN 10088-2: 1.4520, 1.4595, 1.4513, 1.4017, 1.4589, 1.4526, 1.4590, 1.4509, 1.4592

Material in work hardened condition

- According to standard EN 10088-2 material 1.4016 is available in work hardened conditions C700, C850 also CP350 and CP500. (Standard EN 10088 does not forbid the delivery of other grades than 1.4016 in work hardened condition)
- Standard prEN 10088-4 does not give information on the availability of ferritic grades in work hardened condition.
- Standard prEN 10088-5 does not give information on the availability of ferritic grades in work hardened condition.

Table 1. Chemical composition of ferritic corrosion resisting steels according to EN 10088-2 /4/.

Teräksen nimike Steel designation		paino-% % by mass											
Nimike Name	Numero-tunnus Number	C max.	Si max.	Mn max	P max.	S max.	N max.	Cr	Mo	Nb	Ni	Ti	Muut Others
Standarditeräkset Standard grades													
X2CrNi12	1.4003	0,030	1,00	1,50	0,040	0,015	0,030	10,5…12,5	-	-	0,30...1,00	-	-
X2CrTi12	1.4512	0,030	1,00	1,00	0,040	0,015	-	10,5...12,5	-	-	-	[6x (C+N)]...0,65	-
X6CrNiTi12	1.4516	0,08	0,70	1,50	0,040	0,015	-	10,5...12,5	-	-	0,50...1,50	0,05...0,35	-
X6Cr13	1.4000	0,08	1,00	1,00	0,040	0,015[b]	-	12,0...14,0	-	-	-	-	-
X6CrAl13	1.4002	0,08	1,00	1,00	0,040	0,015[b]	-	12,0...14,0	-	-	-	-	Al: 0,10...0,30
X6Cr17	1.4016	0,08	1,00	1,00	0,040	0,015[b]	-	16,0...18,0	-	-	-	-	-
X3CrTi17	1.4510	0,05	1,00	1,00	0,040	0,015[b]	-	16,0...18,0	-	-	-	[4x(C+N) + 0,15] ...0,80[c]	-
X3CrNb17	1.4511	0,05	1,00	1,00	0,040	0,015	-	16,0...18,0	-	12 x C...1,00	-	-	-
X6CrMo17-1	1.4113	0,08	1,00	1,00	0,040	0,015[b]	-	16,0...18,0	0,90...1,40	-	-	-	-
X2CrMoTi18-2	1.4521	0,025	1,00	1,00	0,040	0,015	0,030	17,0...20,0	1,80...2,50	-	-	[4x(C+N) + 0,15] ...0,80[c]	-
Erikoisteräkset Special grades													
X2CrTi17	1.4520	0,025	0,50	0,50	0,040	0,015	0,015	16,0...18,0	-	-	-	0,30...0,60	-
X1CrNb15	1.4595	0,020	1,00	1,00	0,025	0,015	0,020	14,0...16,0	-	0,20...0,60	-	-	-
X2CrMoTi17-1	1.4513	0,025	1,00	1,00	0,040	0,015	0,020	16,0...18,0	0,80...1,40	-	-	0,30...0,60	-
X6CrNi17-1	1.4017	0,08	1,00	1,00	0,040	0,015	-	16,0...18,0	-	-	1,20...1,60	-	-
X5CrNiMoTi15-2	1.4589	0,08	1,00	1,00	0,040	0,015	-	13,5...15,5	0,20...1,20	-	1,00...2,50	0,30...0,50	-
X6CrMoNb17-1	1.4526	0,08	1,00	1,00	0,040	0,015	0,040	16,0...18,0	0,80...1,40	[7x(C+N)+0,10] ...1,00	-	-	-
X2CrNbZr17	1.4590	0,030	1,00	1,00	0,040	0,015	-	16,0...17,5	-	0,35...0,55	-	-	Zr ≥ 7x (C+N) + 0,15
X2CrTiNb18	1.4509	0,030	1,00	1,00	0,040	0,015	-	17,5...18,5	-	[3xC+0,30]...1,00	-	0,10...0,60	-
X2CrMoTi29-4	1.4592	0,025	1,00	1,00	0,030	0,010	0,045	28,0...30,0	3,5...4,5	-	-	[4x(C+N) + 0,15] ...0,80[c]	-

[a] Elements not listed in this table shall not be intentionally added to steel without the agreement of the purchaser except for finishing the cast. All precautions are to be taken to avoid the addition of such elements from scrap and other materials used in production which would impair mechanical properties and the suitability of the steel.

[b] Particular ranges of sulphur content may provide improvement of particular properties. For machinability, a controlled sulphur content of 0,015…0,030 % is recommended and permitted. For weldability, a controlled sulphur content of 0,008…0,030 % is recommended and permitted. For polishability, a controlled sulphur content of 0,015 % max. is recommended.

[c] Stabilisation may be used of titanium or niobium or zirconium. According to the atomic mass of these elements and the content of carbon and nitrogen, the equivalence shall be the following: Nb (% by mass) = Zr (% by mass) = 7/4 Ti (% by mass).

Table 2. The mechanical strength values of ferritic corrosion resisting steels at room temperature according to EN 10088-2.

Teräksen nimike / Steel designation: Nimike / Name	Numerotunnus / Numer	Tuotemuoto [a] / Product form [a]	Paksuus / Thickness mm max.	0,2 %-raja / 0,2 %-proof strength: $R_{p0,2}$ MPa[*)] min. (pitk.) (long.)	$R_{p0,2}$ MPa[*)] min. (poik.) (tr.)	Murtolujuus / Tensile strength: R_m MPa[*)]	Murtovenymä / Elongation after fracture: $A_{80\ mm}$ [b] < 3 mm thick % min. (pitk. + poik.) (long. + tr.)	A [c] ≥ 3 mm thick % min. (pitk. + poik.) (long. + tr.)	Raerajakorroosionkestävyys [d] / Resistance to intergranular corrosion [d]: toimitustilassa / in the delivery condition	hitsattuna / in the welded condition
Standarditeräkset / Standard grades										
X2CrNi12	1.4003	C	8	280	320	450...650	20		ei / no	ei / no
		H	13,5							
		P	25[e]	250	280		18			
X2CrTi12	1.4512	C	8	210	220	380...560	25		ei / no	ei / no
		H	13,5							
X6CrNiTi12	1.4516	C	8	280	320	450...650	23		ei / no	ei / no
		H	13,5							
		P	25[e]	250	280		20			
X6Cr13	1.4000	C	8	240	250	400...600	19		ei / no	ei / no
		H	13,5	220	230					
		P	25[e]	220	230					
X6CrAl13	1.4002	C	8	230	250	400...600	17		ei / no	ei / no
		H	13,5	210	230					
		P	25[e]	210	230					
X6Cr17	1.4016	C	8	260	280	450...600	20		kyllä / yes	ei / no
		H	13,5	240	260		18			
		P	25[e]	240	260	430...630	20			
X3CrTi17	1.4510	C	8	230	240	420...600	23		kyllä / yes	kyllä / yes
		H	13,5							
X3CrNb17	1.4511	C	8	230	240	420...600	23		kyllä / yes	kyllä / yes
X6CrMo17-1	1.4113	C	8	260	280	450...630	18		kyllä / yes	ei / no
		H	13,5							
X2CrMoTi18-2	1.4521	C	8	300	320	420...640	20		kyllä / yes	kyllä / yes
		H	13,5	280	300	400...600				
		P	12	280	300	420...620				
Erikoisteräkset / Special grades										
X2CrTi17	1.4520	C	8	180	200	380...530	24		kyllä / yes	kyllä / yes
X1CrNb15	1.4595	C	8	210	220	380...560	25		kyllä / yes	kyllä / yes
X2CrMoTi17-1	1.4513	C	8	200	220	400...550	23		kyllä / yes	kyllä / yes
X6CrNi17-1	1.4017	C	8	330	350	500...750	12		kyllä / yes	ei / no
X5CrNiMoTi15-2	1.4589	C	8	400	420	550...750	16		kyllä / yes	kyllä / yes
		H	13,5	360	380		14		kyllä / yes	kyllä / yes
X6CrMoNb17-1	1.4526	C	8	280	300	480...560	25		kyllä / yes	kyllä / yes
X2CrNbZr17	1.4590	C	8	230	250	400...550	23		kyllä / yes	kyllä / yes
X2CrTiNb18	1.4509	C	8	230	250	430...630	18		kyllä / yes	kyllä / yes
X2CrMoTi29-4	1.4592	C	8	430	450	550...700	20		kyllä / yes	kyllä / yes

[a] C = kylmävalssattu nauha, H = kuumavalssattu nauha, P = kuumavalssattu levy.

Standard EN 1993-1-4 Eurocode 3 – Design of Steel Structures, Part 1-4: General rules, Supplementary rules for stainless steels /7/ is valid for ferritic corrosion resisting steels 1.4003, 1.4016 and 1.4512.

Standard EN 1993-1-4 gives the following rules concerning the structural design with ferritic grades:

- 2.1.1 (1) part 1.4 should be applied to design ferritic stainless steels
- 2.1.1 (4) the design provisions are applicable for material of nominal yield strength up to and including 480 N/mm^2. (5) By testing higher strength may be taken account.
- 2.1.2 (2) Material ductility requirements are given according to EN 1993-1-1 (f_u/f_y >1,20, A > 12,5%, Ag > $15\varepsilon_y$)
- 2.1.2 (4) (5) For cold worked material the strength values should be given by testing
- 2.1.3 (1) The value of the modulus of elasticity E is 220 000 N/mm^2 for ferritic grades 1.4003, 1.4016 and 1.4512 (Table 2.1)
- 2.1.4 (2) the fracture toughness requirements (testing temperature and CVN-value) are given in standard EN 1993-1-10, Table 2.1.
- 4.2 (9) Ramberg-Osgood-curve coefficient n for ferritic grades 1.4003 n = 7 (longitudinal) n = 11 (transversal), 1.4016 n = 6 (long.) n = 14 (trans.), 1.4512 n = 9 (long.)
  n = 16 (trans.). (In longitudinal direction shape of the stress-strain curve is quite the same as for austenitic grades)
- 5.1 (5) Deformation caused work hardening and enhanced strength may be taken account for austenitic grades.
- 5.2.2 in tables 5.2 (compression loaded flat parts) the higher value of modulus of elasticity of ferritic grades has an effect on cross section class limiting values.
- 5.2.3 (1) the higher value of modulus of elasticity of ferritic grades has an effect on value of effective cross sectional area (cross section 4).

Standard EN 1993-1-2 /8/ annex C presents the rules for the fire design of stainless steels structures. For ferritic grades the following information is given:

- For grade 1.4003 the retention factors are given to calculate the effective yield strength, 2 % -proof strength (Table C.1). Other Ferritic grades use the retention factors determined for structural steels.
- C.3.1 The coefficient of thermal expansion is not given for ferritic grades. It is supposed that the value of structural steel can be used.
- C.3.1 Values of other thermal properties are supposed to be the same as for austenitic grades.

Standard EN 1993-1-10 /9/ (Material toughness and through-thickness properties) presents the rules for material selection taking into account the requirements for material toughness and through-thickness properties. Standard EN 1993-1-10 applies to structural steel. Standard EN 1993-1-4 includes a reference to table 2.1 concerning the impact strength and test temperature for ferritic grades. The impact strength requirement as CVN value is 27 J - 40 J at testing temperature. The maximum material thickness can be determined according to table 2.1, for example material thickness up to 15 mm requires CVN 27 J at temperature 0°C.

Standard EN 1993-1-10 /9/ Chapter 3 presents requirements for material through-thickness properties, when the steel plate is subjected to a risk of lamellar tearing. Typically the risk is present in thick plates with transversal welded parts. When the risk exists the plate material is selected according to standard EN 10164 or the welded area is inspected afterwards against lamellar tearing. The risk may exists with steel plates of thickness t =15 mm or over.

3.1.2 Australia/New Zealand, AS/NZS 4673:2001 /10/

Material selection is referenced to standards: AS 1449, ASTM 167, ASTM A176, ASTM A240, ASTM A276, ASTM A480, ASTM A 666, EN 10088 and JIS G4305

Standard AS/NZS 4673 has the following rules concerning the structural design with ferritic grades:

- 1.5.2.4 Enhanced strength of ferritic grades 409, 430, 439 and 1.4003 achieved by work hardening can be taken into account by theoretical determination as given in this chapter of the standard. The yield strength f_y is substituted by a theoretically calculated cross section average yield strength f_{ya}.
- 1.5.2.6 Stainless steel grades not included in this standard shall fulfil the requirements ($f_u/f_y > 1,08$, A> 10 % in 50 mm measuring length)
- Annex B (normative) gives the mechanical strength values (E, f_y, n, f_p and f_u) for compression- and tension stress in longitudinal and transversal directions. Table 3 (next page) shows the mechanical strength values. Mechanical strength values for material in cold worked condition are not given.

Table 3. Mechanical strength values according to standard AS/NZS 4673.

AS/NZS 4673:2001

Longitudinal tension			**409**	**1.4003**	**430**
Modulus of elasticity	E	N/mm^2	**185000**	**195000**	**185000**
Yield strength (0,2%-strength)	f_y	N/mm^2	**205**	**280**	**275**
Ramberg-Osgood coefficient	n		**11**	**9**	**8,5**
Proportional limit (0,01%-strength)	f_p	N/mm^2	**155**	**180**	**195**
Tensile strength	f_u	N/mm^2	**380**	**435**	**450**

Longitudinal compression			**409**	**1.4003**	**430**
Modulus of elasticity	E	N/mm^2	**185000**	**210000**	**185000**
Yield strength (0,2%-strength)	f_y	N/mm^2	**205**	**260**	**275**
Ramberg-Osgood coefficient	n		**9,5**	**7,5**	**6,5**
Proportional limit (0,01%-strength)	f_p	N/mm^2	**150**	**170**	**170**

Transversal tension			**409**	**1.4003**	**430**
Modulus of elasticity	E	N/mm^2	**200000**	**220000**	**200000**
Yield strength (0,2%-strength)	f_y	N/mm^2	**240**	**320**	**310**
Ramberg-Osgood coefficient	n		**16**	**11,5**	**14**
Proportional limit (0,01%-strength)	f_p	N/mm^2	**200**	**215**	**250**
Tensile strength	f_u	N/mm^2	**380**	**460**	**450**

Transversal compression			**409**	**1.4003**	**430**
Modulus of elasticity	E	N/mm^2	**200000**	**230000**	**200000**
Yield strength (0,2%-strength)	f_y	N/mm^2	**240**	**285**	**310**
Ramberg-Osgood coefficient	n		**16**	**11,5**	**15**
Proportional limit (0,01%-strength)	f_p	N/mm^2	**200**	**220**	**255**

- Annex C8 includes guidance to grade selection:

  C8.2.1 Ferritic grade 409 is used in mildly corrosive environment, where some staining and thickness loss is accepted. This grade is generally not available in thicknesses greater than 2 mm. It is not weldable for structural purposes. Grade 409 is mainly used in automotive exhaust systems and industrial equipments.

  C8.2.2 Ferritic grade EN 10088 1.4003 is widely available. This grade can be used in mildly corrosive environments, where some staining is accepted. The availability in the applicable thickness range is better. Grade 1.4003 is weldable for structural purposes using suitable welding procedures.

  C8.2.3 Ferritic grade 430 is widely available. This grade is mainly used for decorative purposes in indoor applications. Material is not reliable weldable for structural purposes. Thin material is available up to 1,6 mm, finish BA or No 4.

3.1.3 USA, SEI/ASCE 8-02 /11/

Structural Engineering Institute / American Iron and Steel institute (SEI/ASCE) Specification for the Design of Cold-Formed Stainless Steel Structural Members, SEI/ASCE 8-02 (ASCE Standard No. 8-02). Stainless steel grades included are according to standards ASTM A176-85a, ASTM A240-86, ASTM A276-85a and ASTM A666-84.

Standard SEI/ASCE 8-02 gives the following rules concerning the structural design with ferritic grades:

- 1.3.1: Note Maximum thickness for ferritic grade 409 is 3,8 mm, for ferritic grades 430 and 439 3,2 mm.
- 1.3.2: Other ferritic grades are allowed to be used according to this chapter.
- 1.3.3: Ductility requirements: f_u/f_y min. 1,08, Elongation min. 10 % within 2” measuring length.
- Stainless steel structural hollow sections are not included. Product standard for stainless steel structural hollow sections is ASTM A 554, which includes (version year 2003) ferritic grades MT-429, MT-430 and MT-430-Ti (weldeld stainless steel mechanical tubing).

3.1.4 South Africa, SABS 0162–4:1997 /12/

South Africa standard SABS 0162–4:1997 is valid for structures made of cold formed profiles. Stainless steel grades included are according to the standards ASTM 167, ASTM A176, ASTM A240, ASTM A276, ASTM A 666, DIN 5512-3 and Columbus specification 3CR12. Maximum material thickness is 25 mm. Material thickness of ferritic grades 409 is limited to 3,8 mm and grade 430 and 439 to 3,2 mm

Standard SABS 0162 has following rules concerning the structural design with ferritic grades:

- 4.2: Other than above mentioned grades shall fulfil at least one of the following requirements:
    - 4.2a): f_u/f_y min. 1,08, elongation min. 10 % within 2” measuring length
    - 4.2b) if steel grade does not fulfil 4.2a) it may be passed to application taking account the 1)material strength requirement, 2) structural testing, 3) modifications to structural design formulas
- 4.3 Mechanical strength values are given for ferritic grades 409, 430/439 and 3CR12, table 4 (next page).
- 5.3.1.3 Enhanced strength of ferritic grades 409, 430, 439 and 3CR12 achieved by work hardening can be taken into account in structural design of fully effective cross-sections. Enhanced yield strength can be calculated based on formulas given in chapter 5.3.2 of this standard. The determination can be based on material certificate mechanical strength values or measured values of cross-section flat parts.
- Standard gives guidance to design with RHS, SHS and CHS.

Table 4. Mechanical strength values of ferritic grades according to standard SABS 0162–4:1997.

SABS 0162-4:1997

Mechanical properties for longitudinal tension

			409	430, 439	3CR12
Modulus of elasticity	E	N/mm^2	186000	186000	197000
Yield strength (0,2 % - strength)	f_y	N/mm^2	207	276	252
Ramberg-Osgood coefficient [1)]	n				
Proportional limit (0,01% - strength)	f_p	N/mm^2	157	193	181
Tensile strength	f_u	N/mm^2	379	448	437

Mechanical properties for longitudinal compression

			409	430, 439	3CR12
Modulus of elasticity	E	N/mm^2	186000	186000	213000
Yield strength (0,2 % -strength)	f_y	N/mm^2	207	276	258
Ramberg-Osgood coefficient [1)]	n				
Proportional limit (0,01 % - strength)	f_p	N/mm^2	151	171	172

Mechanical properties for transverse tension

			409	430, 439	3CR12
Modulus of elasticity	E	N/mm^2	200000	200000	224000
Yield strength (0,2 % - strength)	f_y	N/mm^2	241	310	280
Ramberg-Osgood coefficient [1)]	n				
Proportional limit (0,01 % - strength)	f_p	N/mm^2	200	251	215
Tensile strength	f_u	N/mm^2	447	680	460

Mechanical properties for transverse compression

			409	430, 439	3CR12
Modulus of elasticity	E	N/mm^2	200000	200000	231000
Yield strength (0,2 % - strength)	f_y	N/mm^2	241	310	283
Ramberg-Osgood coefficient [1)]	n				
Proportional limit (0,01 % - strength)	f_p	N/mm^2	200	254	219

[1)] Coefficient n is not given.

3.1.5 Japan

Standard Design and Construction Specifications for Stainless Steel Structures
Stainless Steel Building Association of Japan, 1995 /13/ has not been published in English.

3.1.6 Germany, Zulassung Z-30.3-6 /14/ (renewing 2009)

Zulassung Z-30.3-6 includes ferritic grades 1.4003 and 1.4016 according to EN 10088-1.

Zulassung Z-30.3-6 has the following rules concerning the structural design with Ferritic grades:

- 2.1.2.3 For ferritic grades 1.4003 and 1.4016 fracture toughness values shall be measured at temperature -40°C (40 J).
- 3.2.2.2 (2) Grade 1.4003 is weldable when cold deformation is less than 5 %. If cold deformation is larger, welding may cause grain growth and decrease of fracture toughness.
- 4.3 Heat treatment is necessary for cold worked ferritic grades.
- 4.6.2 Grade 1.4003 welding energy is limited to a maximum value of 15 kJ/cm.
- Table 1 strength classification for ferritic grades
    - 1.4003: S235, S275, S355, S460
    - 1.4016: S235

3.1.7 Hong Kong, China, India

Hong Kong has not published a national structural design code for stainless steel structures. However, it may be possible to use the standards EN 1993, AS/NZS 4673 and SEI/ASCE-8-02 in Hong Kong. China has no national structural design code for stainless steel structures. In India, the structural design is often based on American or British standards.

3.2 Properties

The physical property values of ferritic grades EN 1993-1-4 and AS/NZS 4673 are shown in table 5 as given in the referenced standards.

Joining methods like bonding, spot welding and mixing of these, bond welding, are presented in final report ”Stainless steel in bus constructions, Contract No 7210-PR/176 1 July 1999 to 30 June 2002 ” Report EUR 20884 EN /15/. The results may be applicable to building industry applications. Joining using self drilling screws may be a useful method for thin sheet structures as expected easy drilling to ferritic grades, but no testing results were found for ferritic grades. Welding metallurgy and corrosion resistance have been discussed in literature elsewhere and it is expected that results for building industry applications are in existence as well.

Table 5. Physical properties of ferritic grades according to standards EN 1993-1-4 and AS/NZS 4673.

EN 1993-1-4	EN 10088-1				
Material	**Density [kg/m³]**	**Thermal expansion x10⁻⁶/C (0-100C)**	**Thermal conductivity W/mK (20C)**	**Specific thermal capacity J/kgK (20C)**	**Electrical resistivity Ωmm²/m**
1.4003	7700	10,4	25	430	0,60
1.4016	7700	10,0	25	460	0,60
1.4512	7700	10,5	25	460	0,60

AS/NZS 4673:2001					
Material	**Density [kg/m³]**	**Thermal expansion x10⁻⁶/C (0-100C)**	**Thermal conductivity W/mK (20C)**	**Specific thermal capacity J/kgK (20C)**	**Electrical resistivity nΩ.m**
409	7800	12	24,9	460	
1.4003	7800	10,8	31,0	480	570
410	7800	9,9	24,9	460	570
430	7800	10,4	26,1	460	600

Generally the welds meant for to structural applications shall fulfil the requirements for ductility, structural and corrosion resistance in heat affected zones and weld metal. These properties are related to the microstructure changes in the welded area. The changes are affected by heat cycles from welding, welded materials, alloying of welding consumables and post weld heat treatment of weld. The welding aspects to ferritic stainless steels are presented in the book ”Ruostumattomat teräkset ja niiden hitsaus” (“Stainless steels and their welding”), Antero Kyröläinen ja Juha Lukkari, 2002” pages 225–231, in Finnish /16/. The welding part in this chapter is based on that publication. Welding may decrease the ductility due to the grain growth and brittle martensite formation in HAZ. The ferrite content in the weld may be estimated using the diagram shown in figure 2 (/16/ s. 226 /Balmforth et al. 1998).

Austenitic consumables are recommended to welding of ferritic stainless steels. The chromium content of the consumable shall correspond to the chromium content of the base material. Applicable consumables are EN 23 12 L, EN 23 12 2 L, EN 19 9, EN 19 9 L, EN 18 8 Mn and EN 25 20.

Shielding gases that contain hydrogen should be avoided when welding ferritic grades because of risk of hydrogen cracking. Hot cracking does not normally occur when the weld is cooling as ferrite phase. Cold cracking may occur caused by low ductility combined to brittle behaviour after welding and stress acting on weld.

At ambient temperatures the brittle-like behaviour may be caused by hydrogen-, sigma and 475 °C brittlement.

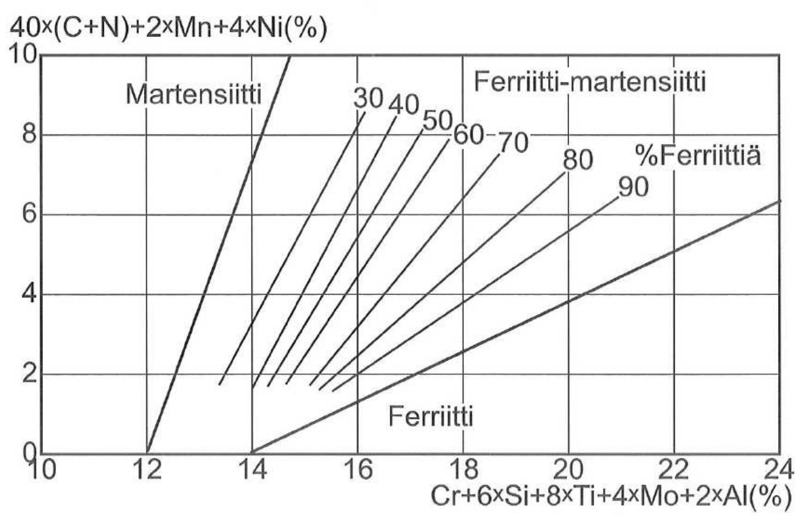

Figure 2. Diagram for the determination of ferrite and martensite contents of stainless steels (Ruostumattomat teräkset and niiden hitsaus /16/, p. 226 /Balmforth et al. 1998).

From the point of view of weldability, the ferritic grades are divided into three groups:

1. Non-stabilized ferritic grades (e.g. 1.4016)

   Because of the high carbon content of these steels (max. 0,10 %) the microstructure of HAZ may be coarse and brittle. If no consumable has been used, the weld is also expected to be brittle. The brittle material can be restored by heat treatments.

   These steels are susceptible to grain boundary corrosion. These grades are used in thicknesses under 2 mm.

2. Stabilized ferritic grades (e.g. 1.4512, 1.4510, 1.4521, 1.4526, 1.4002)

   Stabilization has been done by adding alloying elements titanium, niobium or aluminium. This prevents the sensitization to grain boundary corrosion and martensite formation. These ferritic grades have a ferrite microstructure at all temperatures. The grade 1.4512 may transform to martensite during the cooling phase.

   Some of these grades have a very low carbon content, max 0,03 % (1.4512, 1.4521).

   The weldability of these grades is better in comparison to non-stabilized grades. The grain growth in HAZ may be a problem causing decrease in ductility. A higher chromium content (20-30 % Cr) makes the material more prone to grain growth than less chromium alloyed stabilized grades are. Niobium stabilized ferritic grades have better impact strength compared to titanium stabilized.

3. Low carbon ferritic-martensitic grades (e.g. 1.4003, AISI 409_{mod})

   These steels have a very low carbon- and nitrogen content (0,01-0,02 %). Low carbon 12Cr ferritic grades have ductile welds as a result of ductile martensite forming in HAZ. The microstructure after welding may be estimated by use of the Kaltenhauser formula / /:

FF=%Cr+6x%Si+4x%Mo+8x%ti+2x%Al-40x(%C+%N)-4x%Ni-2x%Mn

When

FF < 8	the microstructure is fully martensite
8<FF<14	ferritic-martensite
FF>14	fully ferritic

The goal is to achieve a fully martensite microstructure in HAZ in order to guarantee sufficient ductility. Grade 1.4003 is applicable to structural purposes in low temperatures as well.

4.0 Structural testing and design recommendations

Technical research reports and proposed design methods for ferritic stainless steels are presented in the following. This information is based on a web-search.

For ferritic stainless steel structural hollow sections and welded joints, only a few testing results were available.

4.1 University of Sydney

1. Rasmussen et Al, “design of stiffened elements in cold-worked stainless steel sections”,2003, Research Report No R826 /17/

   This report gives the test results of open profiles and longitudinally stiffened C-profiles made of steel grades of 1.4003, AISI 409 and AISI 430 loaded in compression with local buckling being the expected failure mode. The familiar Winter formula is used to determine the effective cross section in profiles loaded in compression. It was estimated that the formula gives results that are about 10 % on the unconservative side in cases where the corner (stiffener) does not give enough support to flat parts. The deviation is estimated to be due to gradual yielding of the material. The formula given in standard EN 1993-1-4 is conservative.

   Research results used were:
   Kuwamura et al (2001) /18/ with grades of strength f_y=262/279 N/mm^2, f_u=439/486 N/mm^2, E=203000 N/mm^2. These are supposed to be ferritic grades (AISI 409 and 430, 1.4003). Austenitic grades (rectangular hollow sections) were of strength class CP350/C700 /38/.

2. Rasmussen et Al, ”Experimental Investigation of SS Roof Section in Bending”, 2005, Research Report No 847 /19/

   Testing of two different kinds of a roof sheet of ferritic grade 445 loaded in pure bending is presented. Roof sheets were:

- Monoclad- and
- Megaclad-roof sections,

fabricated by Stramit Building Industries in Australia.

The thickness were t=0,6 mm and outside dimensions 850 x 1700 mm. Material mechanical strength was (longitudinal tension):

Monoclad :
$f_{0,01}$ = 246 N/mm^2
$f_{0,2}$ = 346 N/mm^2
E_0 = 205 000 N/mm^2
n = 9

Megaclad :
$f_{0,01}$ = 260 N/mm^2
$f_{0,2}$ = 388 N/mm^2
E_0 = 193 000 N/mm^2
n = 7

All the specimens exceeded the ultimate bending moment corresponding to the proportional limit of the steel material, which shows that failure has occurred at gradual yielding part of the stress-strain curve. The ultimate bending moment to yield moment ratios were between 0,87 – 1,16. The effect of flange curling was studied. Results were used to calibrate a FE-model and for design guidance.

3. Rasmussen et Al, "design of stainless steel roofs", 2005, Research report No R851 /20/

   A proposal for roof sheet structural design guidance based on 2) and 4) is given. The design guidance takes account of the effect of flange curling on cross sectional values and critical buckling stress. Local buckling and distortional buckling failure modes were studied.

4. Rasmussen et Al, "experimental investigation distortional buckling of cold-formed stainless steel sections", 2005, Research Report no 844 /21/

   Testing of stiffened U-profiles of grades AISI 304, AISI 430 and 3CR12 to axial compression loading is presented. Profile dimensions were 106x90xt, 68x57xt, 55x55xt and 105x85xt, material thickness t=1,2mm and 2 mm. Failure mode studied was distortional buckling.

Table 6. Mechanical strength of tested grades (Research report no 844).

Material	Long. tension $f_{0,01}/f_y/f_u/n$ [N/mm^2]	Long. compression $f_{0,01}/f_y/n$ [N/mm^2]	Trans. tension $f_{0,01}/f_y/f_u/n$ [N/mm^2]	Trans. compression $f_{0,01}/f_y/n$ [N/mm^2]
304 (Flat)	138 / 251 / 703 / 5	164 / 242 / 8	186 / 255 / 727 / 9	187 / 254 / 10
304 (Corner)	300 / 570 / / 5	276 / 565 / 4		
430 (Flat)	190 / 291 / 451 / 7	170 / 271 / 6	238 / 307 / 472 / 12	228 / 391 11
430 (Corner)	326 / 452 / / 9			
3CR12 (Flat)	215 / 338 / 483 / 7	234 / 339 / 8	273 / 384 / 504 / 9	325 / 388 / 17
3CR12 (Corner)	425 / 544 / / 13	410 / 606 / 8		

5. Rasmussen et Al,"FEM and design of cold formed stainless steel section", 2005, Research Report 845 /22/

   Based on report 4 (Research report), 570 more results are calculated using the FE-method in order to prepare design guidance against distortional buckling. Material strength values were according to standard AS/NZS 4673(2001) corresponding to longitudinal compression, Corner radius values used were r/t=1,0 and 2,5. Corner yield strength of grade AISI 304 were 2,34 times the flat part yield strength when r/t=1,0 and 1,85 times, when r/t=2,5. Coefficient values to increase corner area yield strength were to grades AISI 430 and 3CR12 1,77 and 1,56. The stress-strain curve up to tensile fracture was modelled.

   Proposal to failure mode distortional buckling resistance is given in this report.

   Other conclusions have been made to succeed with FE-calculation:

   - non-linear stress-strain curve of stainless steel must be taken account
   - numerical analyses should be based on the compressive material properties for the longitudinal direction
   - anisotropy can be ignored
   - Corner areas and intermediate stiffeners carry significant loads and the model accuracy can be improved by enhanced corner yield strength

6. Rasmussen, Becque "Experimental Investigation of the interaction of local and overall buckling of stainless steel columns", Report 873, 2006 /23/

   Testing series included lipped channel sections of made of grades AISI 304, 430 and 3CR12, t=1,2 mm, length of 400 – 1800 mm and eccentricity of L_e/1500. Profiles were: 3CR12: 125x45x2 mm ("lip" 23 mm), 304: 144x24x2 mm (lip 24 mm) and 430: 80x33x1,13 mm (lip 22 mm). Pin ended columns were tested in axial compression loading. The studied failure mode was an interaction of local and flexural buckling.

   Table 7. Mechanical strength of tested grades (Research report no 873).

Material	Long. tension $f_{0,01}$,f_y/f_u/n [N/mm^2]	Long. compression $f_{0,01}$,f_y/n [N/mm^2]	Trans. tension $f_{0,01}$,f_y/f_u/n [N/mm^2]	Trans. compression $f_{0,01}$,f_y/n [N/mm^2]
304 (flat)	158 / 245 / 689 / 7	148 / 234 / 6,5	186 /250 / 700 / 10	183 / 247 / 10
(corner)	300 /552 / / 5	215 / 551 / 3		
430 (flat)	187 / 80 / 431 / 7,5	170 / 265 / 6,5	238 / 301 / 453 / 13	228 / 295 / 14,5
(corner)	264 / 440 / 6			
3CR12(flat)	215 / 328 / 475 / 7	217 / 328 / 7,5	280 / 378 / 489 / 10	325 / 379 / 19,5
(corner)	/527 /	270 / 571 / 4		

   Grades AISI 304 and 3CR12 have a stronger ability for work hardening, which is found by comparing the strength values of flats and corners. Ultimate axial loading to local buckling was studied by stub column tests. The test results are given.

7. Rasmussen, Becque "Experimental investigation of interaction of local and overall buckling of stainless steel I-columns", 2007, report R887 /24/

   Testing series included I-profiles of dimension 125x48x1,2 mm (back-to-back by screw jointed C-profiles) made of grades AISI 304 and 404, length of 500 –

3000 mm and eccentricity of L_e/1500. Pin ended columns were loaded by axial compression loading. The studied failure mode was combined local and flexural buckling. Material strength measured by coupon testing is shown in table 8.

Table 8. Material mechanical strength values (Research report no 887).

Material	Long. tension $f_{0,01}/f_y/f_u/n$ [N/mm^2]	Long. compression $f_{0,01}/f_y/n$ [N/mm^2]	Trans. tension $f_{0,01}/f_y/f_u/n$ [N/mm^2]	Trans. compression $f_{0,01}/f_y/n$ [N/mm^2]
304 Flat	127 / 259 / 689 / 4	84 / 243 / 3	177 / 262 / 682 / 7,5	114 / 250 / 4
304 Corner	257 / 387 / / 7,5			
404 Flat	231 / 302 / 450 / 11	210 / 290 / 9,5	272 / 310 / 451 / 22,5	236 / 325 / 9,5
404 Corner	199 / 376 / / 4,5			

Work hardening of ferritic grade AISI 404 in corner region was less compared to austenitic grade AISI 304 (50%) as result of brake pressing of profiles. The coefficient n value of ferritic grade 404 decreased remarkably as a result of the decreased value of the proportional limit and the increased value of the yield strength. The effect of work hardening to austenitic grade 304 was different.

The resistance of I-profiles made of AISI 404 was higher compared to I-profiles of AISI 304. This was explained by higher yield strength and a less non-linear stress-strain relation. The non-linear stress-strain behaviour of the corner area did not obviously influence the behaviour of the whole cross section. The result has been used to verify the FE-calculation and further to develop design guidance.

8. Rasmussen, Becque ”Numerical investigation and design methods for SS columns failing by interaction of local and overall buckling, R888, 2008 /25/

   A design proposal for interaction of local and overall buckling is presented for open profiles and RHS/SHS/CHS based on testing and FE-calculation results. EN 1993 seems to be safe for austenitic structural hollow sections. There may be differences in design formulas between open profiles and structural hollow sections, but also between ferritic and austenitic grades.

9. Rasmussen, Lecce , “Nonlinear Flange Curling in Wide Flange Sections”, Journal of Constructional Steel Research, Journal of Constructional Steel Research, 2008 /39/

   The article presents the phenomenon and design formulas of flange curling causing larger deformations in wide flange sections under compression and tension. The basic equations to calculate the wide flange deflection and average stress have been performed by Winter. The formulas were studied by Bernard for thin walled roof sections. The results for stainless steel roof sections are reported by R847 /19/ and R851 / X/

10. Becgue, Lecce, Rasmussen “ The direct strength method for stainless steel compression members”,2008, /40/

   The article presents the direct strength method DSM formulas for austenitic and ferritic stainless steel section in compression. The studied grades were 304, 430, 3CR12 and 404. The research reports related are R873 /23/, R886/24/ and R888 /25/.

The design formulas are presented for local, distortional and overall buckling which are suitable for Eurocode: The slenderness value (depending on failure mode; local, distortional, overall buckling) is calculated based on elastic buckling load related to failure mode. The elastic failure mode is calculated using the software developed for this purpose (eg. finite strip), not calculating the effective widths as the basis of Eurocode.

The calculation of local and overall buckling does not separate the types of stainless steels. When it concerns the distortional buckling different equation is given austenitics compared to ferritics.

Loading eccentricity used in member compression testing was L/1500.

(to calculation method proposed by DSM makes the resistance calculation more simple compared to Eurocode method based on effective width calculation).

11. M. Lecce &K.J.R. Rasmussen, Design of Wide-flange Stainless Steel Sections in Bending", Advanced Steel Construction, Vol. 5, No. 2, 2009, pp. 164-174.

    The article presents the designing with DSM to thin wall roof sections (named MEGACLAD and MONOCLAD) of ferritic stainless steel. The expected failure modes under pure bending loading are local or distortional buckling of wide flange when it is under compression loading. The equations given by AISI "North American Specification for the design of Cold-Formed Steel Structural Members,2007" were compared with the one developed for distortional buckling of ferritic stainless steel and Winter formula for local buckling. The elastic failure loads were determined using software Thinwall. The elastic failure loads were determined for original cross-section but also for deformated cross section after flange curling. The reports /2/ and /3/ shows the testing and development of design.
    It is shown that for the ferritics developed equation to take account the distortional failure mode and the Winter formula to take account the local buckling are more suitable for predicting the failure moments than equations presented by AISI. (AISI equations are developed for carbon steel.)

12. J. Becque & K.J.R. Rasmussen, Experimental Investigation of Local-overall Interaction Buckling of Stainless Steel Lipped Channel Columns", Journal of Constructional Steel Research, Vol. 65, Nos 8-9, 2009, pp 1677-1684. /42/

    Article shows the results of compression tests of lipped channel section of material 304, 430 and 3CR12 for interaction of local and overall buckling. Report Rxxx

    The global imperfection used is L/1500. Test results showed sensitivity to eccentricity. The reduction in capacity was 12-17% compared to concentric testing.

13. J. Becque & K.J.R. Rasmussen, Numerical Investigation of Local-overall Interaction Buckling of Stainless Steel Lipped Channel Columns", Journal of Constructional Steel Research, Vol. 65, Nos 8-9, 2009, pp 1685-1693./43/

    Article shows the results of numerical investigation made based on testing /43, R873/. Parametric FE-method was used.

It is shown that Eurocode gives conservative results in whole of the range in overall and cross sectional slenderness. Eurocode (combined axial and bending member resistance) is quite much conservative when cross sectional slenderness value is low.

14. J. Becque & K.J.R. Rasmussen, Experimental Investigation of the Interaction of Local and Overall Buckling of Stainless Steel I-Columns", Journal of Structural Engineering, American Society of Civil Engineers, Vol. 135, No. 11, 2009, pp. 1340-1348./44/

    Article shows the experimental results of compression loaded stainless steel I-sections (back-to-back channels connected with sheet metal screws) to interaction of local and overall buckling. The article is based on report R873.

    Cold-formed channels were used to manufacture I-profile of 126x97m of thickness 1,2mm.

    The global imperfection used was L/1500.

    The testing showed the interaction of local and overall buckling. The numerical investigation is shown in /15/.

15. J. Becque & K.J.R. Rasmussen, Numerical Investigation of the Interaction of Local and Overall Buckling of Stainless Steel I-Columns", Journal of Structural Engineering,American Society of Civil Engineers, Vol. 135, No. 11, 2009, pp. 1349-1356./45/

    Article shows the results of numerical investigation made based on testing /44, R873/. Parametric FE-method was used.

    It is shown that design codes AS/NZS 4673 (Australian and New Zealand code) gives unconservative results when cross sectional slenderness is increased. Eurocode is conservative when cross sectional slenderness value is low (λ_s=1,0).

    The global imperfection used was L/1500.

16. B. Rossi, J-P. Jaspart & K.J.R. Rasmussen, Combined Distortional and Overall Flexural-torsional Buckling of Cold-formed Stainless Steel Sections: Experimental Investigations, Journal of Structural Engineering, American Society of Civil Engineers, April 2010, pp. 354-360. /46/

    The article shows the experimental results for compression loaded members, fixed end condition, which sectional dimensions are chosen to be sensitive to distortional and overall flexural-torsional buckling. The lipped channel sections were made of ferritic stainless steel 1.4003 (3CR12) by press braking.

    The interaction of distortional and overall flexural-torsional buckling was found for columns with intermediate lengths.

17. B.Rossi, J-P. Jaspart & K.J.R. Rasmussen, Combined Distortional and Overall Flexural-torsional Buckling of Cold-formed Stainless Steel Sections: Design, Journal of Structural Engineering, American Society of Civil Engineers, April 2010, pp. 361-369. /47/

The article shows the results of numerical calculation based on tests reported /46/. It is also shown the effect of fixed ends on short columns distortional buckling stress. Normally the pinned end condition is used, but gives quite much conservative results.

Also the Eurocode equation for flexural-torsional buckling is compared with testing results and AS/NZS methods. All these method gave quite much conservative results.

The interaction equations are given for ferritic and austenitic grades.

4.2 South-African Universities

1. Van der Berg, "The effect of non-linear stress-strain behaviour of tainless steel on member capacity", 2000, (JCSR) /26/

   This article is a compilation of developments in research and design guidance for ferritic and austenitic grades carried out during a number of years prior to the publication of the article.

   The mechanical strength values for structural ferritic grades are given:

	409	**430**	**3CR12**	
E_0 [GPa]	186	195	197	(Longitudinal tension)
f_y [N/mm^2]	224	323	293	
f_p [N/mm^2]	167	241	212	
f_u [N/mm^2]	389	498	461	
E_0 [GPa]	191	202	207	(Longitudinal compression)
f_y [N/mm^2]	229	331	301	
f_p [N/mm^2]	167	225	211	

   The resistance calculations against stability failure modes (local buckling, shear buckling and overall buckling) of stainless steel structures take the non-linear behaviour when calculating the critical elastic stress into account by using the so-called η-parameter. The η-value is equal to the E_s/E_0 or E_t/E_o, when the applied stress exceeds the proportional limit (f_p).

   The design formulas for overall buckling, distortional buckling and lateral torsional buckling are presented.

2. Klopper&Laubscher, "The lateral torsional buckling strength of hot-rolled 3CR12 beams", 2006 /27/

   The testing of hot rolled profiles IPE AA 100x55x11 mm, U 127x64x15 mm, U 152x76x18 mm of material 3CR12 loaded by 4-point bending test is presented. Results are compared to standards SANS 10162 and ENV 1993. Profile strength values are determined by stub column compression tests; IPE AA f_y= 380 N/mm^2, f_p=249 N/mm^2, U 127x64 f_y=316 N/mm^2, f_p=230 N/mm^2, U 152x76 f_y=327 N/mm^2, f_p=252 N/mm^2. By comparing to ultimate moment to SANS

10162, it has been concluded that some further research is needed to guarantee the applicability of yield strength value of f_y =300 N/mm^2.

3. Laubcsher, Van der Merwe, ”Structural design in hot-rolled 3CR12 sections”, 2003 /28/

The research plan consisted of a study of the structural behaviour of U-, L- and IPE-profiles, welded and bolted connections and also of rebars of 3CR12. However, the availability of analysis results is not known.

4.3 Spanish Universities

1. Lopes, Vila Real, Simoes da Silva, Mirambell, “Numerical modelling of the lateral-torsional buckling of stainless steel I-beams: Comparison with Eurocode 3” aug. 21-23.2006, Sanya, Hainan, China /29/

2. Vila Real, Lopes, Simoes da Silva, Franssen, ”Lateral-torsional buckling of stainless steel I-beams in case of fire”, Journal of Constructional Steel Research 64 (2008), s. 1302-1309 /30/

   The lateral-torsional buckling resistance is determined to stainless steel grades 1.4301, 1.4003, 1.4571, 1.4401 and 1.4462 using material model given by standard EN 1993-1-2 for the welded I-profiles of dimension IPE 220, HEA 500 and IPE 500. The authors propose a modification to structural resistance calculation of standard EN 1993-1-2 method depending on steel grade (1.4301, 1.4003).

3. Estrada, I., Real, E., Mirambell, E., “General behaviour and effect of rigid and non-rigid end post in stainless steel plate girders loaded in shear. Part 1: Experimental study”, Journal of Constructional Steel Research 63(2007) 970-984 /31/

   Research was done by using austenitic grade 1.4301.

4. Estrada, I., Real, E., Mirambell, E., “General behaviour and effect of rigid and non-rigid end post in stainless steel plate girders loaded in shear. Part 2: Extended numerical study and design proposal”, Journal of Constructional Steel Research 63(2007) 985-996 /32/

   Research was done by using austenitic grade 1.4301.

4.4 Welds and welded joints

The following research articles present the structural behaviour of welds in ferritic stainless steel grades. There exists only very few public research publications, which are dealing with ferritic grades. The main grade studied was 1.4003. Data on welded joints in structural ferritic stainless hollow sections or other profiles were not found.

1. Research Center of the Belgium welding institute, www.bil-ibs.be/eng /33/

E. Deleu (Ferritic stainless steel X2CrNi12 with improved weldability for structural applications, Stainless Steel World 2005 ss. 160-166) has studied the ferritic-martensitic grade weldability to structural applications with material of chemical composition as shown below:

	C	Si	Mn	P	S	Cr	Ni	N(ppm)	
1.4003	<0,015	±0,45	±1,00	±0,02	±0,001	±11,5	±0,50	±100	
cast	0,014	0,45	0,99	0,021	0,001	12,32	0,44	61	(t=12 mm)

f_y = 497 N/mm^2
f_u = 633 N/mm^2
A = 37 %
Hardness = 172 HB
Microstructure 60% ferrite and 40 % tempered martensite.
Impact strength -20°C 100 J – 180 J.

Material thickness varied between 6 mm, 12 mm, 20 mm and 30 mm. Article includes a discussion on the selection of the weld consumables for ferritic stainless steel grades. The research method was the simulation of welding and heat treatment works using estimated material temperature cooling rates but also producing real welds to measure and compare certain parameters to simulated ones.

It was concluded after the simulation that certain properties in HAZ (e.g. impact toughness, hardness) depend on the grain size after heat cycle. The heat treatment simulation showed that no increase in impact strength occurred in HAZ if the heat treatment temperature exceeded 1100°C, the impact strength in this case was less than 10 J. Real welds achieved much higher impact strength values (table 9) in areas close to the fusion line compared to the simulated values.

Table 9. Impact strength values at temperature of -20^{0}C for submerge weld of thickness 8 mm.

Consumable	Notch location	Impact strength (-20^{0}C)	
		Measured / average [J]	Measured / average [J/cm^2]
ER309L	weld	36-32-33 / 34	60-53-55 / 56
	fusion line	44-36-41 / 40	73-60-68 / 67
ER316L	weld	39-39-37 / 38	65-65-62 / 64
	fusion line	77-53-85 / 72	128-88-142 / 119

2. Akita Masayuki & al, Fatigue Behaviour of Welded Joints in Ferritic Stainless Steel SUS 444, Transactions of the Japan Society of Mechanical Engineers, A, vol. 71;No.705;page.769-774(2005), language Japanese. http://sciencelinks.jp/j-east/article/200514/000020051405A0496660.php /34/

Research was concentrated on fatigue and crack growth properties of weld made in ferritic grade SUS 444. Fatigue testing showed remarkable decrease of fatigue life compared to the base material. Testing was continued with annealed welds and by cut out weld reinforcement Cut out weld reinforcement improved the fatigue life to the level of that of the base material. Cut out reinforcement decreased the value of stress concentration which improved the fatigue properties. The annealing of weld had only a minor effect on fatigue life, which was explained by the fact that the small sized specimen had no welding residual stress at all to be released by annealing. Only the abstract of the article was available in English and included no information about the weld reinforcement or the fatigue life.

3. Project Stainless steel in bus constructions /15/

   European research project "Stainless steel in bus constructions" included austenitic grades and ferritic grade 1.4003. The project included corrosion and mechanical testing of welds. Thicknesses of plate material of grade1.4003 were t=1,5 mm and 3,0 mm with 2B-surfaces. HF-welded structural hollow sections of grade 1.4003 were CHS 2,0x45 mm, SHS 1,5x40x40 mm and 3,0x100x100 mm. Table 10 shows the results of weld mechanical testing. Project included also impact strength and fatigue testing, whose results are not shown in this report.

Table 10. Mechanical strength of MAG-welded joint for plates-(butt weld) and structural hollow section joints (fillet weld, transversal flange) (table 1 and 2, page 96 of original document)

Grade	Thickness [mm] and surface	Specimen (BM=base material, W=weld)	$R_{p0,2\%}$ [N/mm^2]	R_m [N/mm^2]	A [%][2)]	Location of failure (BM=base material, W=weld T= base metal(not HAZ))
1.4003[1)]	1,46 2B	BM	389	478	30,1	BM
1.4003[1)]	1,46 2B	W	385	465	21,9	BM
1.4003[1)]	1,46 2B	W	384	463	22,8	BM
1.4003	3,0 2B	BM	429	557	23,6	BM
1.4003	3,0 2B	W	335	452	23,4	BM
1.4003	3,0 2B	W	335	451	23,4	BM
1.4003	40x40x1,5	W	306	342	11,7	T
1.4003	40x40x1,5	W	310	340	10,5	T
1.4003	40x40x1,5	W	305	345	18,5	T
1.4003	40x40x1,5	W	310	340	16,6	T
1.4003	40x40x1,5	W	312	341	15,4	T

Hardness testing was done to welds and the results showed that the weld and HAZ have hardness values that are higher compared to the base material. The hardness values of structural hollow section joints are not mentioned.

Table 11. Mechanical strength of PPAW-welds, plate and structural hollow section butt weld. (table 10 and 11, pages 107 and 108 of original report).

Code	Grade	Thickness and surface	Specimen (BM=base material, W=weld)	$R_{p0,2\%}$ [N/mm^2]	R_m [N/mm^2]	Location of failure (BM=base material, W=weld T= base material)
N (base metal)	1.4003[1)]	1,5 2B	BM	372	469	BM
N (weld)	1.4003[1)]	1,5 2B	W		463	BM
N (weld)	1.4003[1)]	1,5 2B	W		443	BM
O (base metal)	1.4003	3,0 2B	BM	367	463	BM
O (weld)	1.4003	3,0 2B	W		445	BM
O (weld)	1.4003	3,0 2B	W		445	BM
R (base metal)	1.4003	40x40x1,5	BM	429	497	BM
R (weld)	1.4003	40x40x1,5	W		427	W
R (weld)	1.4003	40x40x1,5	W		445	W
R (base metal)	1.4003	100x100x3	BM	451	492	BM
R (weld)	1.4003	100x100x3	W		280	W
R (weld)	1.4003	100x100x3	W		275	W

4. Euroinox, Design Manual 3. version /35/

   EuroInox Design Manual presents the structural design formulas for austenitic and duplex grades. The ”Commentary”-part includes a reference to the doctoral dissertation of van der Merwe.

4.5 VTT (Technical Research Centre of Finland)

VTT has developed software for material selection with consideration of the corrosion risk and design life.

In project KORRKONS /36/, VTT has developed software for the estimation of the risk to pitting corrosion in evaporated conditions (chloride and sulphite including liquids). For the software, the ferritic grade 1.4003 was tested. The estimation method and software are presented in conference paper: Carpen, L. et al, A Tool and Methods for Predicting Pitting Corrosion Risk of Stainless Steels in Evaporated Conditions, 6th European Stainless Steel Conference, 2008, Helsinki

In project ENNUS-TERÄS /37/, software has been developed to estimate the design life of steel structures taking into account the type of material, structural details, maintenance etc. Ferritic grades 1.4016 (facade material) and 1.4509 (structural material) are included.

5.0 Conclusions

The aim of this study was to gather knowledge related to ferritic stainless steel structural design standards, material selection, research results and the variety of products already produced using ferritic grades. It can be concluded that ferritic grades are used in facades (cladding, roofing) as bare and coated surface finishes. Fabricators of structural hollow sections and profiles are marketing ferritic grades, but their share in building industry applications was unclear. The availability of open- and I-profiles made of ferritic grades was not confirmed through this study. Open profiles and I-profiles made of other metal grades (e.g. structural steel, aluminium) are extremely common in building detailing.

Ferritic stainless steel grades should be classified to structural purposes:

1) weldable
2) other

The number of ferritic stainless steel grades included in different standards varies. European standard EN 1993-1-4 includes only few ferritic grades compared to other standards. Standard EN 1993-1-4 should include all ferritic grades according to standards EN 10088-4 and 5.

Design strength values have some deviations. Standard EN 1993-1-4 classifies the design strength based on the tensile value determined in the direction transversal to rolling, other standards give strength values in both longitudinal- and transversal directions, compression and tension loadings.

The enhanced strength in e.g. profiled sheets can be theoretically determined according to standard AS/NZS 4673, but European standard EN 1993-1-4 does not give formulas to determine enhanced strength. Typical mechanical strength values at room temperature of ferritic grades seem to be higher compared to values given by standards. There may be a need to check the strength values given by EN 10088 or the value of material safety factor used in design formulas. A proposal has been put forth to check the strength values given by different standards. The research related to structural design with ferritic grades carried out so far has targeted methods for taking into account the non-linear behaviour in structural resistances.

Based on USA structural design methods (USA, Australia, South Africa) the non-linearity of the stress-strain curve is taken into account by using the so-called tangent modulus approach in failure modes related to stability checks. In Europe, the tangent modulus approach is not used. The standard EN 1993-1-4 formulas related to failure modes of stability in ferritic stainless steel structures may need some further validation against testing in the cases of flexural buckling, local buckling, compression and bending of loaded beams. The austenitic grades have been tested with above mentioned tests and supported the validity of the given formulas when using the non-linear stress-strain curve.

The resistance calculation of a beam loaded in compression and bending differs from that of structural steel beams presented in EN 1993-1-1. The effective cross section is related to the failure mode in local buckling. The limits of cross section classes and effective cross sectional areas are determined in the same way as for austenitic grades. The testing could confirm whether the cross section limits for ferritic grades are closer to the values of austenitic grades or structural steels. From the point of view of a structural designer, the question may arise if there exist possibilities in the steel mill to influence the non-linearity of the ferritic grade stress-strain curve.

The ferritic grades 1.4003 and 3CR12 are recommended for structural purposes because of their good weldability. Ferritic grades AISI 430 and 409 are weldable up to thicknesses 3,2 and 3,8 mm (AS/NZS 4673: up to 2,0 mm). Standard EN 1993-1-4 does not give information on the weldability of ferritic grades for structural purposes. It should be noted that only very few research results were available for welded joints for structural purposes. Welded joints in structural hollow sections and in other profiles should be checked for ferritic grades. Standard EN 1993 differs from Australia, USA and South Africa norms concerning the structural design of the weld. Euro Inox - Design Manual presents a weld design method which is close to these norms, but differs from the method given in standard EN 1993-1-4. The Euro Inox method checks the joint resistance in the base material, HAZ and the weld material. Further research of welded joints should concentrate on giving support to the method presented by Euro Inox Design Manual. The target may be to develop the design formulas in time for them to be ready for the next version of EN 1993-1-4. Fracture toughness and plate Z-value (for transversal welds) determination is given in standard EN 1993-1-10 for structural steels. The applicability of these should be checked for ferritic grades.

Testing results for bolted or screw joints were not found for ferritic grades. It is supposed that the formulas given by EN 1993 are applicable to ferritic grades. The standard EN ISO 3506 includes ferritic bolts as well, but their availability is not known. The bolts used with ferritic grades may be selected among the austenitic ones.

The standard EN 1993-1-2 covers the structural design in fire situation and the mechanical strength values are given for stainless steel grades. The European standard may be the only one for structural fire design of stainless steel structures. The ferritic grade 1.4003 has the mechanical strength values for structural fire design given by the standard EN 1993-1-2. The values of other ferritic grades are missing. The temperature of ferritic grade steels may increase differently during the fire compared to austenitic steel. The deviation, if there is any, may come from the phase transformation of ferritic grades at certain temperature areas and the ferritic grade steels' surface emissivity may be different. Also the value of thermal elongation is not known through the whole scope of the temperature variation. Thermal elongations may cause additional forces, which should be taken account during periods of temperature increase and cooling when fire design is based on real fires. The fire resistant coatings may extend the fire resistance period also for ferritic structures, but no testing on these has been performed.

Ferritic stainless steel-concrete composite structures have not been studied. Ferritic grades may be used as rebar and composite column or beam surfaces.

Table A.1 of the standard EN 1993-1-4 should be completed with ferritic grades. Another tool for grade and surface quality selection could be KORRKONS-type software to estimate the staining/pitting corrosion risk in given environments.

Finally, the ferritic grades should be validated for applications where traditional stainless steel grades have been used but also for new applications of stainless steels. The following issues should be checked:

1. Corrosion resistance (to staining) compared to CrNi-, CrNiMo-, CrMn-grades and duplex grades
2. Long term sustainability compared to galvanised steel, aluminium, copper and painted structural steel
3. Applicable coating methods to ferritic grades
4. Structural resistance in load bearing structures; mechanical strength values, checking the applicability of existing structural design formulas, structural behaviour in low temperatures, resistance of welded joints.

Conclusions based on the articles added in December 2010 /39-47/:

- Direct strength method (DSM) used by Australian research and design quide might be practical to study and maybe include to European design guidances (EN 1993-1-4, Euroinox Design manual)
- Eurocode design formulas seem to be in safe side, but there exist some points which should be considered:

1) The material properties are determined by tensile/compression tests for plate material, which was used to manufacture the sections. The 0,2% strength value is quite the same as earlier research and standards expect. The value of modulus of elasticity for ferritic grade 1.4003 was 40% lower compared to standard; E=180 GPa. This may cause conclusions made in articles /46,47/, as it was mentioned that Eurocode flexural-torsional buckling resistance is quite much in safe side.

2) Global imperfection used was L/1500. The Eurocode formulas are based on L/1000. Eurocode should be in safe side because of this. Eurocode proposes global imperfections according to EN 1993-1-1 table 5.1 (recommended values, NDP) for FE-calculation.

3) Eurocode uses 0,2% strength to determine cross sectional slenderness, which might be different form AS/NZS.

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