Brunel University London

Standardised material properties for numerical parametric studies of structural stainless steel elements

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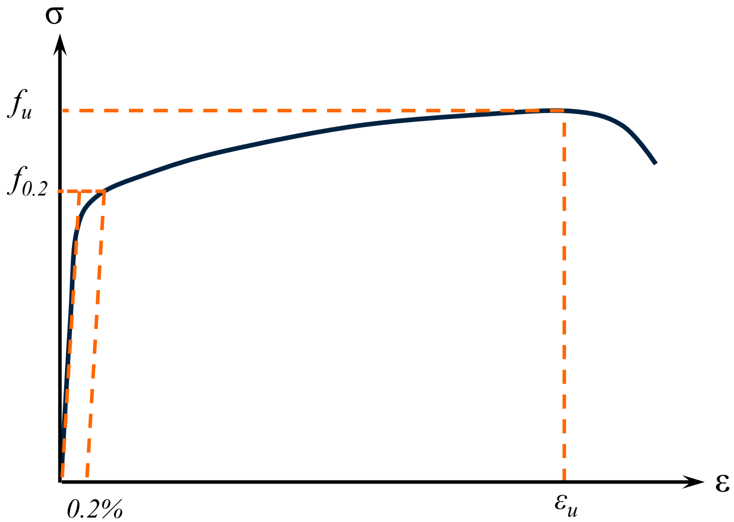
Presentation outline

- Overview and current practice for material modelling in numerical studies
- Proposals for modelling stress-strain response of stainless steels in numerical parametric studies
  1) Proposed standardised average material properties
  2) Proposed predictive models for material properties of cold-formed stainless steel sections
- Key conclusions

Stainless steel material modelling overview

- Numerical modelling has become a common tool for analysis and design of stainless steel structures
- Accurate description of the material stress-strain response is a crucial aspect of numerical modelling of steel structures
- The two-staged Ramberg-Osgood model is commonly used to describe the stress-strain response of stainless steels



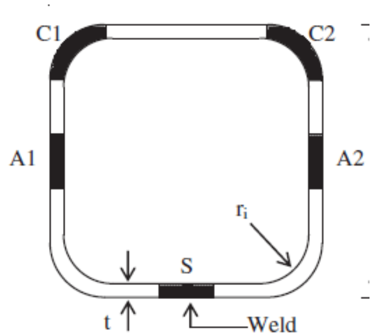
$$\varepsilon = \frac{f}{E} + 0.002\left(\frac{f}{f_{0.2}}\right)^{n} \text{ for } \sigma \leq \sigma_{0.2}$$

$$\varepsilon = \frac{f - f_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{t,0.2} - \frac{f_u - f_{0.2}}{E_{0.2}}\right)\left(\frac{f - f_{0.2}}{f_u - f_{0.2}}\right)^{m} \text{ for } \sigma > \sigma_{0.2}$$

Key input R-O model parameters

Key input parameters to construct full Ramberg-Osgood curves
$f_{0.2}$, f_u, E, n and m

1. For validation of numerical models against experimental results
→ Values from measured stress strain curves (coupon tests)



2. For design through computational analysis
→Characteristic values from design specifications (e.g. EC3 Part 1.4)

Type of stainless steel	Grade	Product form: Cold rolled strip, Nominal thickness t: $t \leq 8$ mm, f_y N/mm²	Cold rolled strip, $t \leq 8$ mm, f_u N/mm²	Hot rolled strip, $t \leq 13,5$ mm, f_y N/mm²	Hot rolled strip, $t \leq 13,5$ mm, f_u N/mm²	Hot rolled plate, $t \leq 75$ mm, f_y N/mm²	Hot rolled plate, $t \leq 75$ mm, f_u N/mm²
Ferritic steels	1.4003	280	450	280	450	250 c	450 c
	1.4016	260	450	240	450	240 c	430 c
	1.4512	210	380	210	380	-	-

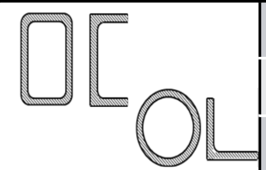
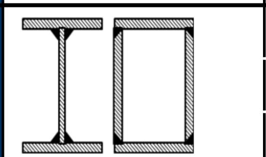
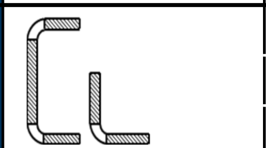
3. For parametric studies conducted in research studies
→ Values representative of real structural sections (grade, section geometry, production route)

?

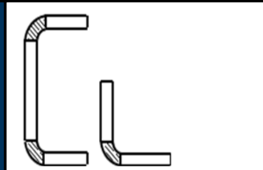
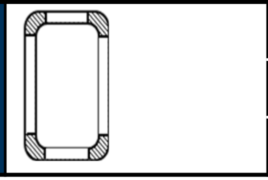
Database of material test results

- Typical values for $f_{0.2}$, f_u, E, n and m from a comprehensive database of material tests were sought – literature test programmes
- The collected test data were grouped based on:
  - Types of stainless steel:
    - **Austenitic (A)**
    - **Duplex (D)**
    - **Ferritic (F)**
  - Types of product that exhibit similar characteristics:

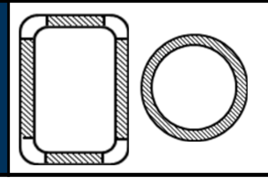
Group I: Hot-rolled sections, hot-rolled plates and sheets and cold-formed sheets

Material type	Structural sections	Grade
Hot-rolled sections		A D F
Hot-rolled plate/sheet (to form welded profiles)		A D F
Cold-rolled sheet/flat regions of press-braked sections		A D F

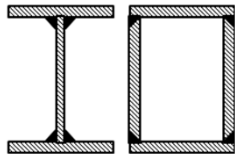
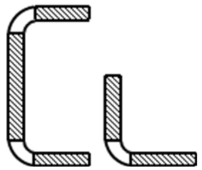
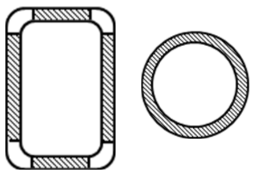
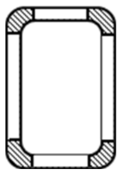
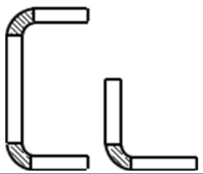
Group II: Corner regions of cold-formed box-sections and press-braked sections

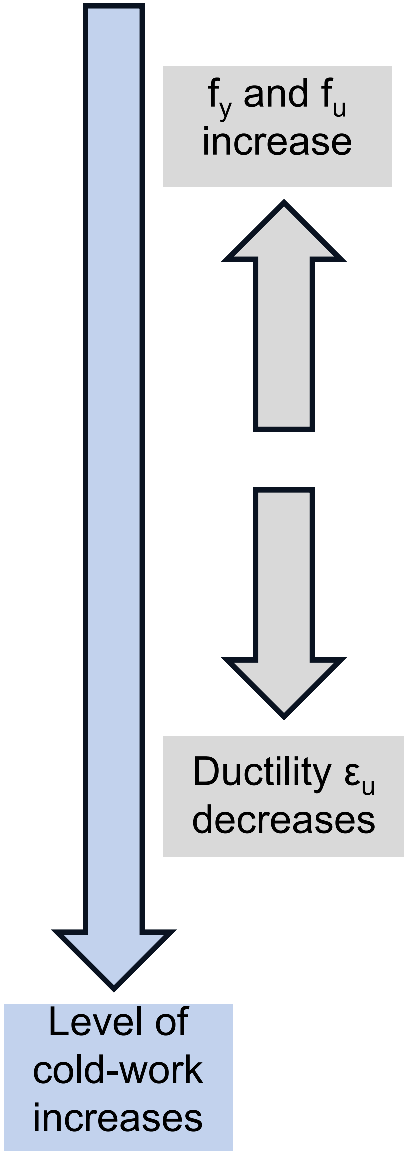
Material type	Structural sections	Grade
Corner regions of cold-formed box sections		A D F
Corner regions of press-braked sections		A D F

Group III: Flat faces of cold-formed box sections, curved walls of cold-formed CHS

Material type	Structural sections	Grade
Corner regions of press-braked sections		A D F

Proposed standardised average material properties

Material type	Structural sections	Grade	Basic material properties				
			f_y	f_u	ε_u	n	m
Hot-rolled sections		A	280	580	0.50	9.1	2.3
		D	530	770	0.30	9.3	3.6
		F	320	480	0.16	17.2	2.8
Hot-rolled plate/sheet (to form welded profiles)		A	280	580	0.50	9.1	2.3
		D	530	770	0.30	9.3	3.6
		F	320	480	0.16	17.2	2.8
Cold-rolled sheet/flat regions of press-braked sections		A	280	580	0.50	9.1	2.3
		D	530	770	0.30	9.3	3.6
		F	320	480	0.16	17.2	2.8
Flat faces of cold-formed box-sections/curved walls of cold-formed CHS		A	460	700	0.20	7.1	2.9
		D	630	780	0.13	7.5	4.8
		F	430	490	0.06	11.5	4.6
Corner regions of cold-formed box sections		A	640	830	0.20	6.4	7.1
		D	800	980	0.03	6.1	6.7
		F	560	610	0.01	5.7	6.8
Corner regions of press-braked sections		A	640	830	0.20	6.4	7.1
		D	800	980	0.03	6.1	6.7
		F	560	610	0.01	5.7	6.8



Statistical data – Material strength f_y and f_u

Collected statistics on material data from key European stainless steel producers and literature for **Mean** and **Scatter** of yield strength and ultimate tensile strength

Material type	Product type	Source	No. of tests n	Thickness range (mm)	$f_{y,mean}$ (N/mm^2)	σ (N/mm^2)	COV	$f_{y,mean}/f_{y,min}$	$f_{y,k}/f_{y,min}$
Austenitic	C	[5]	2572	2.49-6.35	312	15.2	0.049	1.34	1.24
		Producer	-	-	314	22.9	0.073	1.34	1.19
	H	[7,8]	-	4.0	290	-	-	1.37	-
		Producer	-	-	326	25.3	0.078	1.54	1.35
	P	[6]	>3000	5.0-50	294	20.6	0.070	1.38	1.23
		[7,8]	-	15	283	-	-	1.33	-
		Producer	1368	-	309	33.0	0.107	1.44	1.20
		Producer	-	-	293	28.8	0.099	1.40	1.19
	Average				308			1.40	1.23
Duplex	C	[5]	239	2.49-6.35	586	26.5	0.045	1.17	1.09
		[9]	-	1.0	650	-	-	1.27	-
		Producer	5749	0.4-3.5	631	27.3	0.043	1.28	1.19
		Producer	-	-	610	30.9	0.052	1.26	1.16
		Producer	-	<6.4	550	7.5	0.014	1.04	1.01
	H	[9]	-	4.0	595	-	-	1.27	-
		Producer	-	-	591	49.0	0.087	1.33	1.16
		Producer	-	<10	549	12.2	0.022	1.14	1.10
	P	[6]	>300	5.05-50	524	19.6	0.037	1.14	1.07
		[9]	-	15	505	-	-	1.11	-
		Producer	-	-	520	18.2	0.035	1.19	1.13
	Average				570			1.20	1.12
Ferritic	C	Producer	-	-	331	19.0	0.059	1.29	1.17
		Producer	-	-	349	21.4	0.062	1.45	1.31
		Producer	-	>10	358	19.3	0.054	1.51	1.38
		Producer	438	1.25-2.0	352	16.9	0.048	1.21	1.12
	H	Producer	-	-	354	34.0	0.097	1.46	1.25
		Producer	-	-	371	26.4	0.071	1.33	1.18
	P	Producer	-	-	347	37.0	0.107	1.39	1.16
	Average				352			1.38	1.22

Over-Strength Ratio

$$OSR = \frac{f_{y,mean}}{f_{y,nominal}}$$

Coefficient of Variation

$$COV = \frac{\text{Standard deviation}}{f_{y,mean}}$$

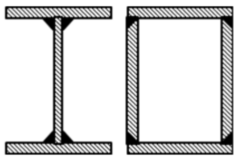
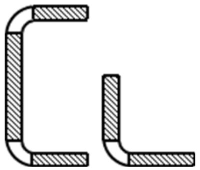
Statistical data vs Collected data

Over-strength ratio and **COV** for yield strength f_y

Grade	$f_{y,mean}/f_{y,nom}$	COV
Austenitic	1.3	0.060
Duplex	1.1	0.030
Ferritic	1.2	0.045

Over-strength ratio and **COV** for ultimate tensile strength f_u

Grade	$f_{u,mean}/f_{u,nom}$	COV
Austenitic	1.1	0.035
Duplex	1.1	0.035
Ferritic	1.1	0.050

Material type	Structural sections	Grade	f_y	f_u
Hot-rolled sections		A	280	580
		D	530	770
		F	320	480
Hot-rolled plate/sheet (to form welded profiles)		A	280	580
		D	530	770
		F	320	480
Cold-rolled sheet/flat regions of press-braked sections		A	280	580
		D	530	770
		F	320	480

	$f_y/f_{y,min}$	$f_u/f_{u,min}$
Austenitic	1.17-1.40	1.05-1.16
Duplex	1.01-1.18	1.03-1.18
Ferritic	1.07-1.29	1.07-1.17

The proposed f_y and f_u values tie in with the over-strength factors

Section specific material properties

- The proposed material properties correspond to average measured values across a range of products and section geometries
- For cold-formed sections:
  - The material properties will in fact be cross-section specific
  - Since the level of cold-work, which influences the resulting stress-strain curve, is dependent on the section geometry
- Section specific material properties may be determined from predictive models for:
  - Press-braked sections and
  - Cold-formed tubular sections
- Due to the dependency on section geometry, the section specific material properties will sometimes be above the basic (average) values and sometimes below

Predictive models for cold-formed sections

Mechanically based predictive models developed and verified against collated tests; two step process:

1. Estimate plastic strain induced during section forming using simple geometric relationships (t and R)
2. Determine stress corresponding to this plastic strain from material model to use as enhanced yield strength

ANNEX B Strength enhancement of cold formed sections

1. Afshan, S., Rossi, B. and Gardner, L. (2013). Strength enhancements in cold-formed structural sections – Part I: Material testing. Journal of Constructional Steel Research. 83, 177-188.
2. Rossi, B., Afshan, S. and Gardner, L. (2013). Strength enhancements in cold-formed structural sections – Part II: Predictive models. Journal of Constructional Steel Research. 83, 189-196.

Enhanced flat, corner and CHS strength

f_{yc} is the predicted enhanced yield strength of the corner region and is calculated as:

$$\boxed{f_{y,cf} = K(\varepsilon_c + \varepsilon_{t,0.2})^{n_p} \quad \text{but} \quad f_y < f_{y,cf} < f_u}$$ Enhanced corner strength

$$\boxed{\varepsilon_c = t/2(2r_i + t)}$$ Corner strain

f_{yf} is the predicted enhanced yield strength of the section flat face and is calculated as:

$$\boxed{f_{y,cf} = K(\varepsilon_f + \varepsilon_{t,0.2})^{n_p} \quad \text{but} \quad f_y < f_{y.cf} < f_u}$$ Enhanced flat strength

$$\boxed{\varepsilon_c = [t/900] + [\pi t/2(b + h - 2t)]}$$ Flat strain

f_{yCHS} is the predicted enhanced yield strength of a CHS and is calculated as:

$$\boxed{f_{y,cf} = K(\varepsilon_{CHS} + \varepsilon_{t,0.2})^{n_p} \quad \text{but} \quad f_y < f_{y,cf} < f_u}$$ Enhanced CHS strength

$$\boxed{\varepsilon_{CHS} = t/2(d - t)}$$ CHS strain

Predictive models for f_u and ε_u (From Annex A of SSDM)

- Ultimate tensile stress

$$f_{u,cf} = \frac{f_{y,cf}}{[0.2 + 185 f_{y,cf}/E]}$$

For austenitic and duplex grades

$$f_{u,cf} = \frac{f_{y,cf}}{[0.46 + 145 f_{y,cf}/E]}$$

For ferritic grade

- Strain at ultimate tensile stress

$$\varepsilon_{u,cf} = 1 - \frac{f_{y,cf}}{f_{u,cf}}$$

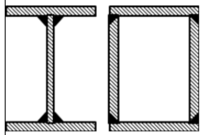
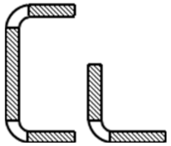
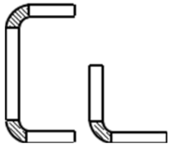
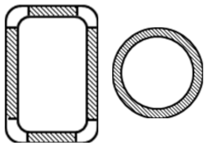
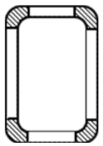
For austenitic and duplex grades

$$\varepsilon_{u,cf} = 0.6\left[1 - \frac{f_{y,cf}}{f_{u,cf}}\right]$$

For ferritic grade

I. Arrayago, E. Real, and L. Gardner. Description of stress-strain curves for stainless steel alloys. Materials and Design, 87:540–552, 2015.

Conclusions and summary

Material type	Structural sections	Grade	Basic material properties					Section specific material properties*			Geometric imperfections	Residual stress model
			f_y	f_u	ε_u	n	m	$f_{y,cf}$	$f_{u,cf}$	$\varepsilon_{u,cf}$		
Hot-rolled sections		A	280	580	0.50	9.1	2.3	–	–	–	[25] and [26]	[47]
		D	530	770	0.30	9.3	3.6					
		F	320	480	0.16	17.2	2.8					
Hot-rolled plate/sheet (to form welded profiles)		A	280	580	0.50	9.1	2.3	–	–	–	[48]	[48]
		D	530	770	0.30	9.3	3.6					
		F	320	480	0.16	17.2	2.8					
Cold-rolled sheet/flat regions of press-braked sections		A	280	580	0.50	9.1	2.3	–	–	–	[25]	[25]
		D	530	770	0.30	9.3	3.6					
		F	320	480	0.16	17.2	2.8					
Corner regions of press-braked sections		A	640	830	0.20	6.4	7.1	Eq. (3)	Eq. (11)	Eq. (13)	[25]	[25]
		D	800	980	0.03	6.1	6.7					
		F	560	610	0.01	5.7	6.8		Eq. (12)	Eq. (14)		
Flat faces of cold-formed box-sections/curved walls of cold-formed CHS		A	460	700	0.2	7.1	2.9	Eq. (4) Eq. (5)	Eq. (11)	Eq. (13)	[25]	[25]
		D	630	780	0.13	7.5	4.8					
		F	430	490	0.06	11.5	4.6		Eq. (12)	Eq. (14)		
Corner regions of cold-formed box sections		A	640	830	0.20	6.4	7.1	Eq. (3)	Eq. (11)	Eq. (13)	[25]	[25]
		D	800	980	0.03	6.1	6.7					
		F	560	610	0.01	5.7	6.8		Eq. (12)	Eq. (14)		

*n and m values for section specific material properties may be taken as those given under basic material properties in rows 4-6.

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Predictive models for f_y - principle

Strength enhancement (and loss of ductility) due to cold-working: