GRISPE

Guidelines and **R**ecommendations for **I**ntegrating **S**pecific **P**rofiled steel sheets in the **E**urocodes
(**GRISPE**)

Working Package 2

Background and draft annexes for EN 1993-1-3 for curved profiles

31st October 2015

Deliverable D 2.5

Guidelines and Recommendations for Integrating Specific Profiled Steels sheets in the Eurocodes (GRISPE)

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D 2.5 WP2 Background and draft annexes for EN 1993-1-3 for curved profiles		***Due date : 31.10.2015*** ***Completion date: 31.12.2015***

1. Introduction

There are three forms of curved profiles. The difference between the three forms is the method of curving. The shaping can be done by roll forming, by crushing of the inner flange or by bending on site. In the GRISPE Project variant A (bending by rollforming) was investigated.

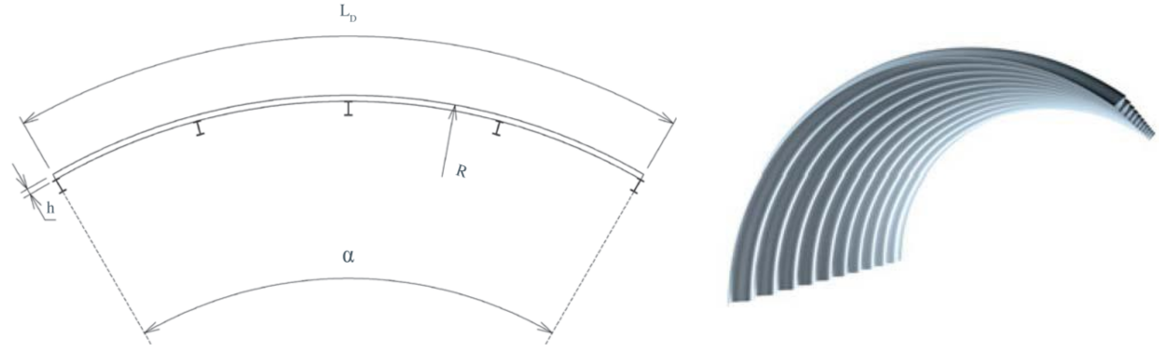


Fig. 1: curved profile by roll forming (variant A)

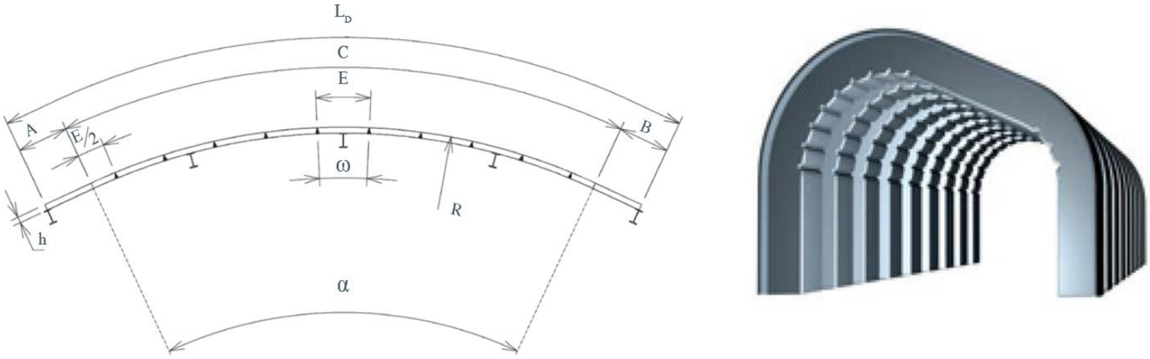


Fig. 2: curved profile by crushing the inner flange (variant B)

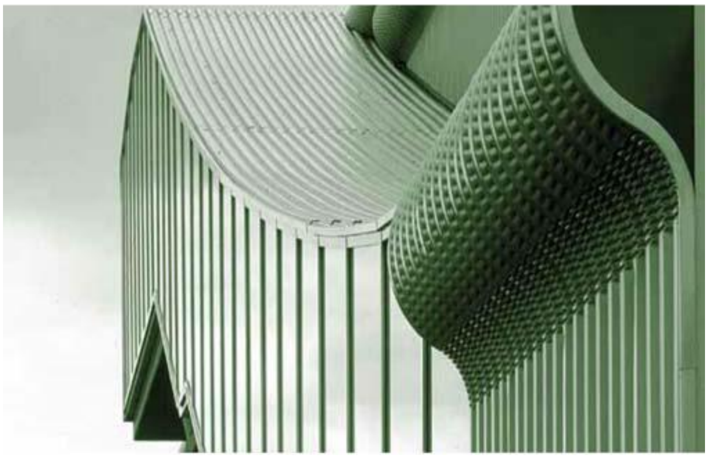


Fig. 3: curved profile by bending on site (variant C)

The failure of these profiles in bending occurs normally through plastic deformation (corrugated sheets with small slenderness) or through local buckling (corrugated sheets with large slenderness or trapezoidal sheets).

The aim of the GRISPE project is to develop a design model to calculate the load-bearing capacity in bending for different bending radii. Therefore single span tests for load case gravity loading with different bending radii were performed.

In the test report D 2.3 [3] the test range and the results are documented. The tests are evaluated and the ultimate bending moment was determined in D 2.4 [4].

2. Acquired data through GRISPE project

In the GRISPE project a large test program was performed to determine the load-bearing capacity of curved profiles in bending for different bending radii. In the following table the performed tests are documented.

Type of test	Profile	R [m]	b [mm]	Span L [mm]	s [mm]	f [mm]	α [°]	Number of tests
Single span positive bending test	18/76 $t_N = 0.63$ mm	∞	2200	2000	2200	0	0	3
		20.0	2201			30	6.31	2
		10.0	2204			61	12.63	2
		4.0	2229			154	31.92	2
	18/76 $t_N = 1.00$ mm	∞	3200	3000	3200	0	0	1
		20.0	3203			64	9.18	4
		10.0	3214			129	18.41	3
		4.0	3292			334	47.16	3
	39/333 $t_N = 0.63$ mm	∞	3200	3000	3200	0	0	3
		20.0	3203			64	9.18	2
		10.0	3214			129	18.41	2
		6.0	3239			217	30.93	3
	39/333 $t_N = 1.00$ mm	∞	4200	4000	4200	0	0	2
		20.0	4208			111	12.05	2
		10.0	4232			223	24.24	2
		6.0	4291			380	40.98	2
Single span positive bending test with horizontal support	39/333 $t_N = 0.63$ mm	6.0	3239	3000	3200	217	30.93	2
		6.0	4291	4000	4200	380	40.97	3
		6.0	5300	5000	5129	576	50.61	3

Table 1: Tests performed

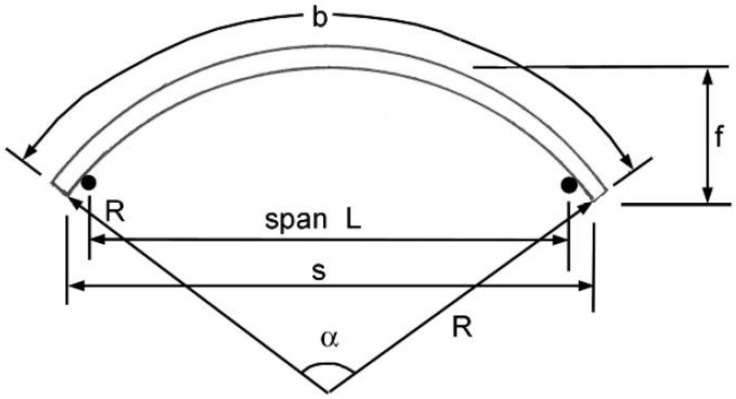


Fig. 4: Parameters of the curved profiles

Two different profiles in two thicknesses (different d/r-ratio) were tested. They are shown in Figure 4 and 5.

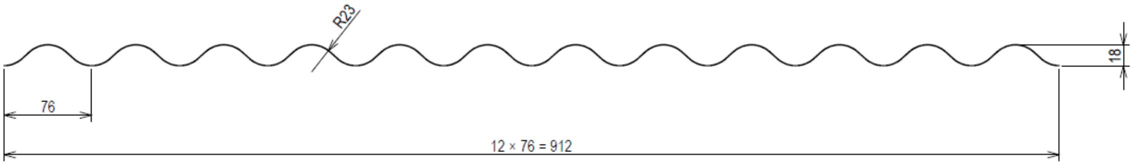


Fig. 5: Cross section of the profile 18/76

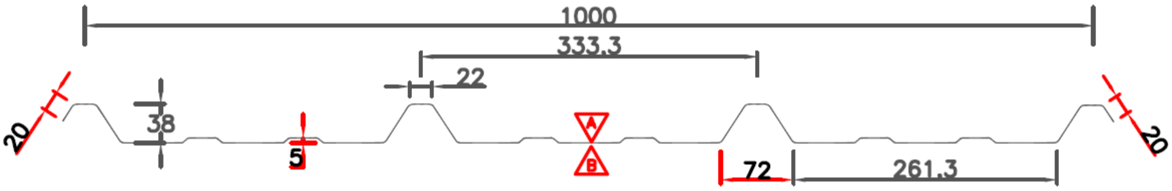


Fig. 6: Cross section of the profile 39/333

Detailed information of the test setups and the test results are documented in [3] and [4]. The test setup and main results of the interpretation and analysis of the test results are listed again in this document. They are as follows:

<u>Single span tests:</u>

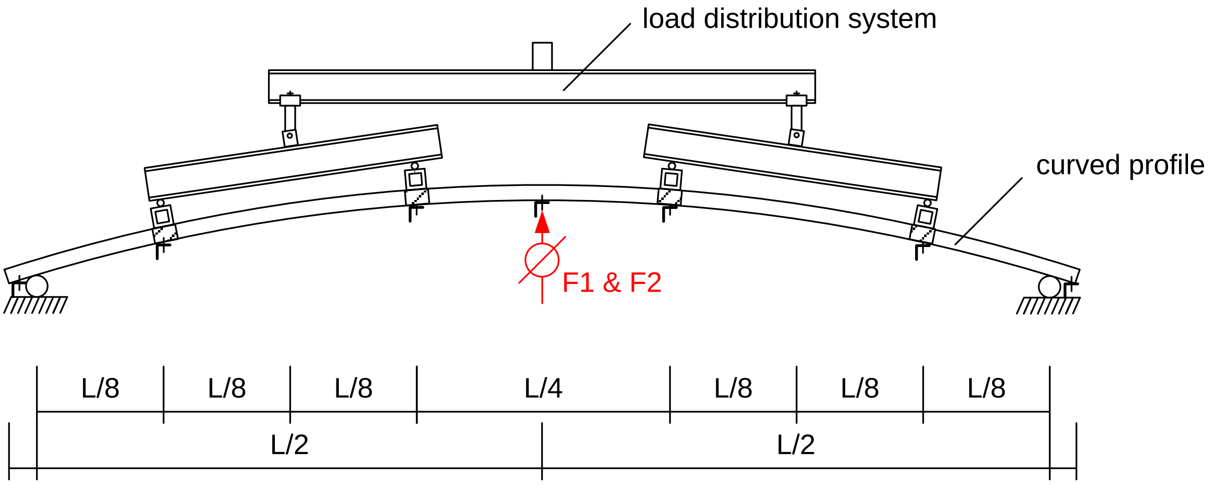


Fig. 7: Test setup single span tests

Fig. 8: Picture of the test setup single span tests (profile 18/76)

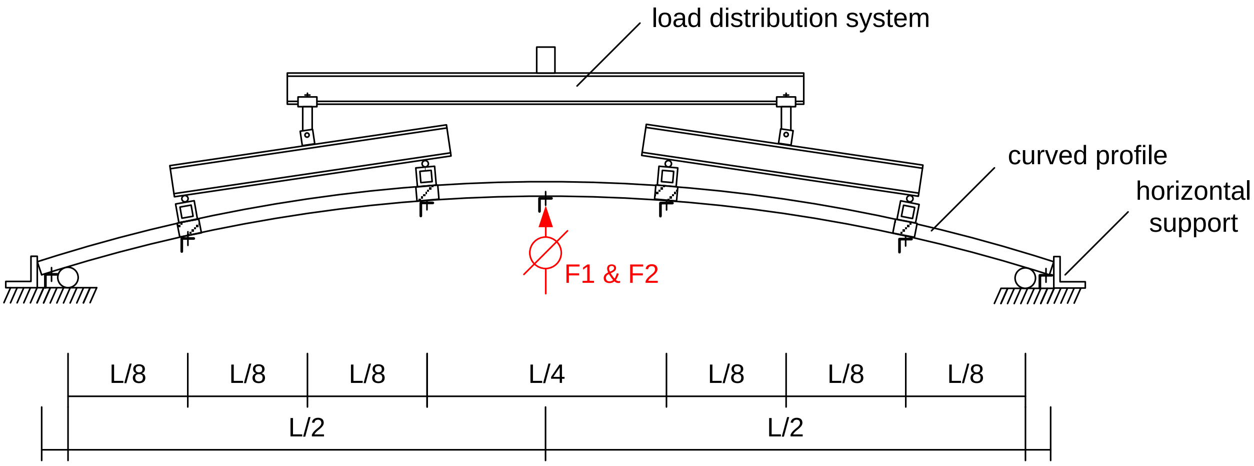


Fig. 9: Test setup single span tests

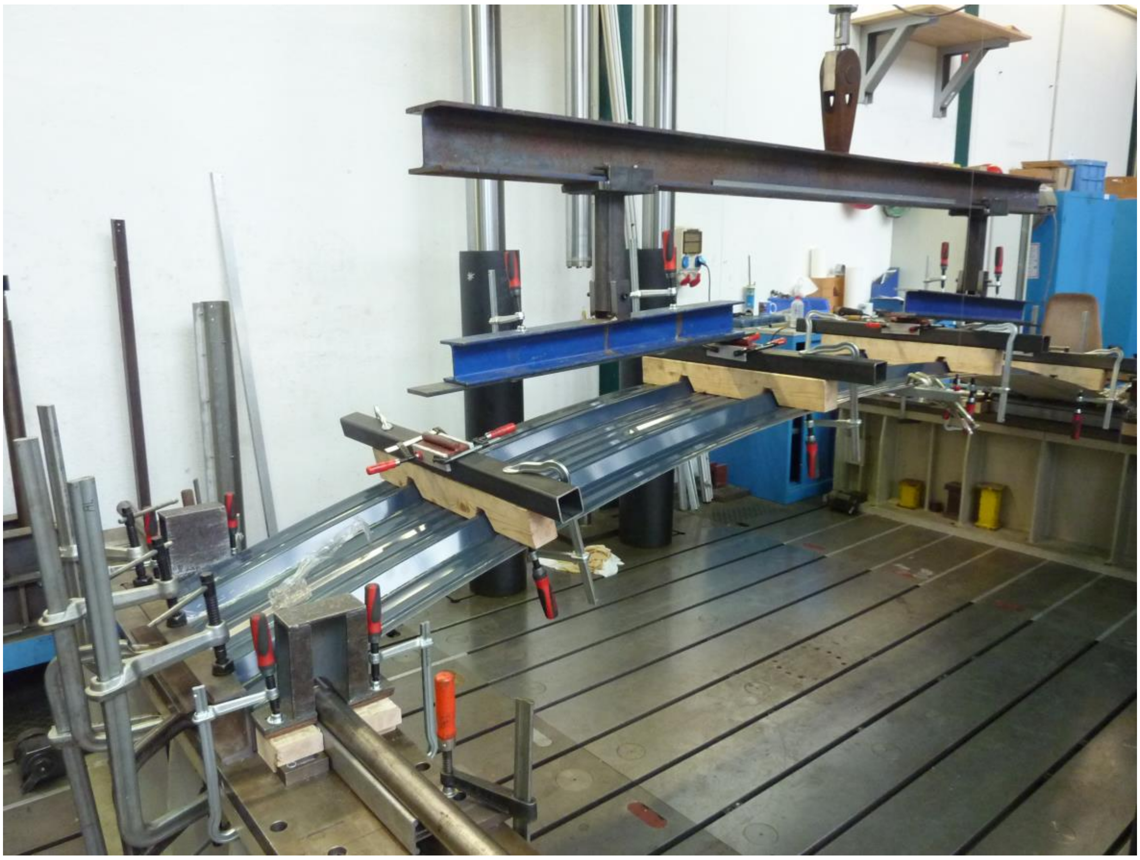


Fig. 10: Picture of the test setup single span test with horizontal support (profile 39/333)

Bacacier 18/76-0,63			Bacacier 18/76-1,00			Arcelor 39/333-0,63			Arcelor 39/333-1,00		
R m	1/R 1/m	$M_{c,Rk,F}$ kNm/m	R m	1/R 1/m	$M_{c,Rk,F}$ kNm/m	R m	1/R 1/m	$M_{c,Rk,F}$ kNm/m	R m	1/R 1/m	$M_{c,Rk,F}$ kNm/m
flat	0,000	1,057	flat	0	1,727	flat	0	0,785	flat	0	1,539
11,5	0,087	1,071	17,2	0,058	1,736	32,9	0,030	0,767	25,8	0,039	1,513
9,6	0,104	1,100	10,6	0,094	1,674	9,7	0,103	0,733	10,6	0,094	1,544
4,3	0,234	1,327	3,8	0,264	1,661	5,6	0,180	0,647	6,4	0,157	1,554

Table 2a: Test results of the single span tests without horizontal support [4]

Profile - thickness	Radius m	span L m	char. load $F_{u,k}$ kN/m
Arcelor 39/333 - 0,63	**5,56**	3,00	**11,027**
	6,02	4,00	**12,767**
	7,04	5,00	**6,615**

Table 2b: Test results of the single span tests with horizontal support [4]

The determination and calibration of the spring stiffness (horizontal support) and the comparison of the different interaction formulas are documented in [4].

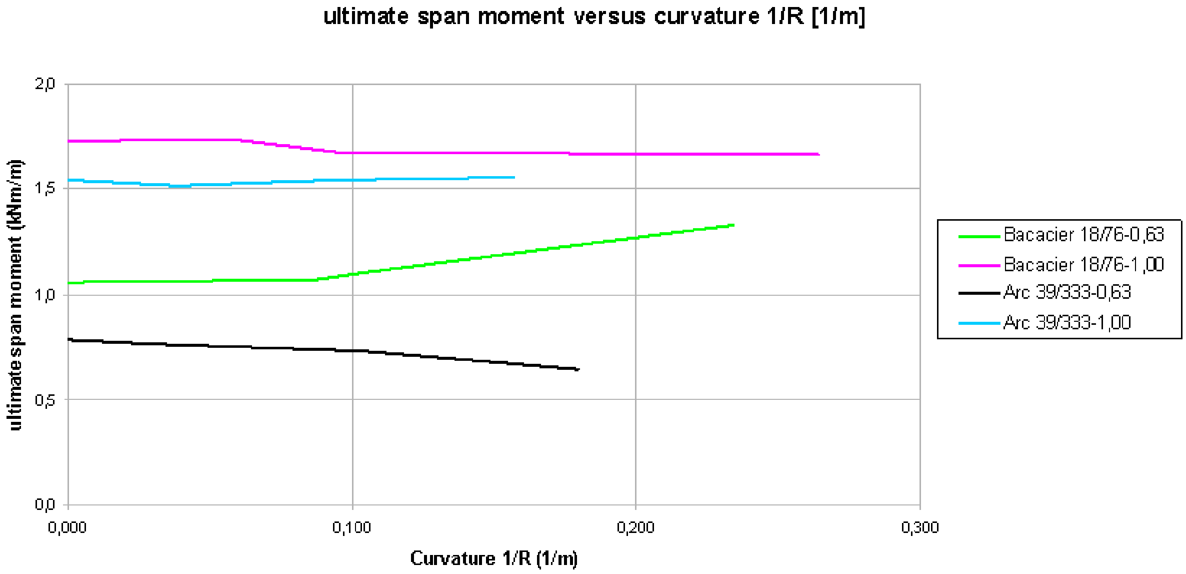


Fig. 11: Graphic view of the test results, bending moment versus curvature 1/R
More detailed information of the analysis and interpretation of the test results are documented in [4].

3. Calculation method for curved profiles

Curved profiles

The curving process by bending or by roll-forming creates plastic deformations of the cross section in the extreme fibres of the cross section. This leads to internal stresses in the cross section which can influence the bending moment capacity of the cross section. But the test results show, that the influence is rather small and furthermore not uniform: For the profiles with thickness 1,0 mm, the curvature doesn't change the bending moment capacity. For the profiles with thickness 0,63 mm, the bending moment capacity is affected in both senses:

+ 25 % for the sinusoidal profile 18/76
- 15 % for the trapezoidal profile 39/333

With respect to this indifferent behaviour and regarding the low sensitivity of the bending moment capacity it is proposed to reduce the bending moment capacity by 10 % compared to the bending moment capacity of the flat profile. This reduction factor is an additional safety factor to cover the indifferent scattering; it is not a mechanically based coefficient.

$$\mathbf{M_{c,Rk,F}\ (curved\ profile) = 0{,}9 * M_{c,Rk,F}\ (flat\ profile)}$$

A comparison of the test results and the design proposition is shown in table 3:

profile	nominal thickness t (mm)	radius of curvature R (m)	charact. bending moment (test value) $M_{c,Rk,F}$ (kNm/m)	design proposition 0,9 * $M_{c,Rk,F\,(flat)}$ (kNm/m)	ratio design/test
Bacacier 18/76	0,63	flat	1,057		
		11,5	1,071	0,951	0,89
		9,6	1,100	0,951	0,86
		4,3	1,327	0,951	0,72
	1,00	flat	1,727		
		17,2	1,736	1,554	0,89
		10,6	1,674	1,554	0,93
		3,8	1,661	1,554	0,94
Arcelor 39/333	0,63	flat	0,785		
		32,9	0,767	0,707	0,92
		9,7	0,733	0,707	0,96
		5,6	0,647	0,707	1,09
	1,00	flat	1,539		
		25,8	1,513	1,385	0,92
		10,6	1,544	1,385	0,90
		6,4	1,554	1,385	0,89

Table 3: Comparison characteristic bending moment (test) and design proposition [4]

Other properties of the profile, in particular the resistance against punctual loads and the moment of inertia are not touched in a considerable way. The values of the flat profile remain valid also for curved profiles.

Curved profiles with horizontal support (arch tests):

M-N-interaction according to DIN 18807(proposed design formula, different formulas are documented in [4])

DIN 18807 contains design rules for trapezoidal sheeting under combined bending moments and axial compression forces. It is checked, if this procedure can also be adopted for curved profiles with arch effect.

In case of compression force the following is applied

$$\frac{N_D}{N_{dD}} \cdot \left[1 + 0{,}5 \cdot \alpha \left(1 - \frac{N_D}{N_{dD}}\right)\right] + \frac{M}{M_d} \leq 1$$

with

N_D	design value of compressive force
M	design value of bending moment
M_d	design resistance of bending moment
N_{dD}	design resistance of compressive force

and

slenderness ratio $$\alpha = \frac{L_{cr}}{i_{ef} * \pi} \cdot \sqrt{\frac{f_{y,k}}{E}}$$

with

L_{cr}	buckling length
i_{ef}	radius of gyration of the effective cross section

In the **M-N-interaction formula**, the coefficient α should be limited to 1 if $\alpha > 1$. But this limit is not valid, when the slenderness ratio α is used to determine the ultimate compressive stress with respect to overall buckling.

Hereafter, the DIN-procedure for combined bending moment / axial compression, adapted to curved profiles is described in detail step by step. As far as explicite calculations are presented, they refer to the test setup no. 2, span 4 m, as example (see red marked line in table 9 in [4]).

- **Step 1**

Determination of the internal forces of the arch under characteristic failure load (= design load) like executed in chapter 5.2.4 in [4] under consideration of the horizontal spring stiffness C at the supports (M and N depends on C).

- **Step 2**

Determination of the buckling length L_{cr}

The buckling length of a circle-shaped arch can be found in the literature, for instance DIN 18 800 part 2:

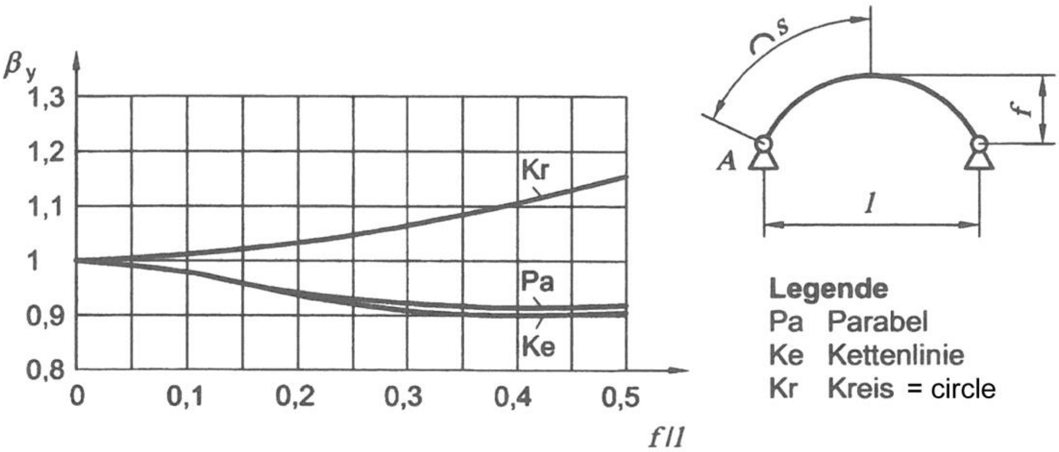


Fig. 12: buckling length coefficient b (from DIN 18800)

- **Step 3**

Determination of the design resistance of compressive force N_{dD}

$$N_{dD} = \min (\sigma_{cd} * A_{ef} \,;\, 0{,}8\, \sigma_{elg} * A_g)$$

In the calculations hereafter, the expressions max N_{dD} and ult N_{dD} are used.

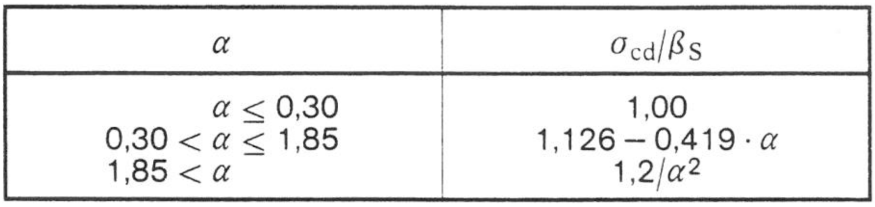
Ideal buckling force $\quad maxN_{dD} = 0{,}8 \cdot \sigma_{elg} \cdot A_g$

$$= 0{,}8 \cdot \frac{\pi^2 \cdot E \cdot J_g}{L_{cr}^2}$$

Critical buckling force $\quad ultN_{dD} = \sigma_{cd} \cdot A_{ef}$

slenderness ratio $\alpha = \frac{L_{cr}}{i_{ef}*\pi} \cdot \sqrt{\frac{f_{y,k}}{E}}$

Buckling curve from DIN 18807:



α	σ_{cd}/β_S
$\alpha \leq 0{,}30$	1,00
$0{,}30 < \alpha \leq 1{,}85$	$1{,}126 - 0{,}419 \cdot \alpha$
$1{,}85 < \alpha$	$1{,}2/\alpha^2$

- **Step 4**

Interaction bending moment / axial compression
According to DIN 18807, the slenderness value α should be limited to 1. This limitation is <u>not</u> proposed in this design procedure.

$$\frac{N_D}{N_{dD}} \cdot \left[1 + 0{,}5 \ \cdot \alpha \left(1 - \frac{N_D}{N_{dD}}\right)\right] + \frac{M}{M_d} \leq 1$$

4. Conclusion

For curved profiles it is proposed to reduce the bending moment capacity by 10 % compared to the bending moment capacity of the flat profile.

For curved profiles with horizontal support (arch) it is proposed to use the following design procedure:

1. The internal forces of the arch (bending moments, axial forces) should be calculated using the gross cross section values Ag and Jg of the profiled sheeting.

2. The horizontal displacement at supports may not be neglected. As grater the displacement is estimated, the internal forces become more unfavourable. Therefore it is necessary to take into account the horizontal displacement by modelling the support with a horizontal spring. The spring stiffness, which depends on the substructure and the fixing of the profiled sheeting, should be adjusted, that the calculated horizontal displacements meet the real values. To avoid unsafe design, the spring stiffness should not be over-estimated. Under-estimation of the spring stiffness leads to an over-estimation of the horizontal displacements and in consequence to a design on the safe side.

3. The bending moment – axial compression – interaction should be calculated with the interaction formula of DIN 18807, but without limitation of α to 1.

4. The design model is verified for arches with symmetric loading. If it is also applicable for arches with not symmetric loading, should be researched in another project.

5. References

[1] EN 1993-1.3: Eurocode 3 – Design of steel structures. Part 1.3: General rules – supplementary rules for cold-formed members and sheeting
[2] Deliverable D 2.1: Background Document. KIT, 30.11.2013
[3] Deliverable D 2.3: Test report. Curved Profiles. KIT, 31.05.2015
[4] Deliverable D 2.4: Curved profiles Test analysis and interpretation. IFL, 31.10.2015