GRISPE PLUS

VALORISATION OF KNOWLEDGE FOR SPECIFIC PROFILED STEEL SHEETS

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DESIGN MANUAL FOR CURVED PROFILES

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FINAL VERSION

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SUMMARY

The purpose of this design manual is to present a new method of design by calculation for curved profiles, as developed in the European project GRISPE PLUS basing on previous results achieved in the positively concluded research project GRISPE.

The manual is based on the Eurocode principles in general and more specifically on the EN 1993-1-3 and EN 1993-1-5 Eurocodes.

This new method of design by calculation for curved profiles is based on tests carried out within the European GRISPE project (2013-2016).

The background of this method is described in Annex 1.

More in details:

Chapter 1 details the type of profiles concerned, the state of the art, the main research results of GRISPE and the general design requirements and rules (state of the art and introduction).

Chapter 2 outlines the preliminary considerations that must be taken into account during the pre-design phases, including considerations about the verification of the field of application of the new design method.

Chapter 3 states the basic technological requirements that have to be respected including support frame, profiles characteristics and assemblies.

Chapter 4 lists the materials properties of the profiles.

Chapter 5 gives the actions that must be considered in the design (self-weight, etc.) and their combinations.

Chapter 6 explains in detail the proposed design method (principles, field of application, and description of how to apply the new formula).

Chapter 7 lists the specific design considerations not covered by the manual (Fire, Seismic, Environmental aspect, Thermal, Acoustic).

Chapter 8 gives practical examples.

A bibliography is included.

IMPORTANT REMARK

The experimental data have been obtained and provided by Rainer Holz, IFL –ING LEICHTBAU and by Daniel Ruff and Christian Fauth, KIT –KARLSRUHE INSTITUTE OF TECHNOLOGY

PREFACE

This Design manual has been developed out with the support of RFCS funding n°**754092.**

The design method has been presented at the evolution group of EN 1993-1-3 in 2016-2017 and is being considered for inclusion into the Eurocodes.

This Design manual has been written by Walter Salvatore, Silvia Caprili and Irene Puncello basing on experimental data and considerations already performed in the positively concluded research project GRISPE; the design manual has been discussed in a GRISPE PLUS working group composed by the following members:

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FIGURES AND TABLES

The figures and tables have been produced by the following companies/sources:

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SCOPE OF THE PUBLICATION

The aim of this publication is to present the new design method for curved profiles that has been proposed for inclusion in Eurocode EN 1993-1-3.

This design manual deals with currently occurring situations.

For specific issues (e.g. opening) or for exceptional situations (seismic, fire, etc.) it is necessary to follow the relevant clauses of the Eurocodes and/or EN 1090-4.

NOTATIONS

The following symbols are used in the following:

t_N	design thickness
R	curvature radius
b	arc length
L	span length
f	height
β	buckling length coefficient
α[°]	curvature angle
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
$maxN_{dD}$	ideal buckling force
$ultN_{dD}$	critical buckling force
α	slenderness ratio
L_{cr}	buckling length
i_{ef}	radius of gyration of the effective cross section
σ_{cd}	design compressive stress
A_{ef}	area of the effective cross section for axial compression
σ_{elg}	eulerian compressive stress for the gross section
A_g	area of the gross section
$M_{c,Rk,F}$	characteristic bending moment in span
$F_{u,k}$	characteristic load
b_V	width of the test specimen
L_V	span length
L	length of the test specimen
s	mid length of the arch
g	self-weight of the test specimen
f_{max}	vertical deflection at midspan
F_u	test failure load
$C_{f,i}$	overall stiffness of the specimen
C_f	mean value of all tests of the same subset, considered representative for a family
f_{eq}	equivalent vertical deflection at midspan, representative for a family
C_{ind}	spring stiffness of the horizontal support
f_{yk}	characteristic yield strength

1. INTRODUCTION

1.1. Type of profiled steel sheets concerned

This design manual deals with steel curved profiles.

Generally, this kind of profiles might be obtained by three different curving processes:

- Roll forming (see Figure 1-1)
- Crushing of the inner flange (see Figure 1-2)
- In situ bending process (see Figure 1-3)

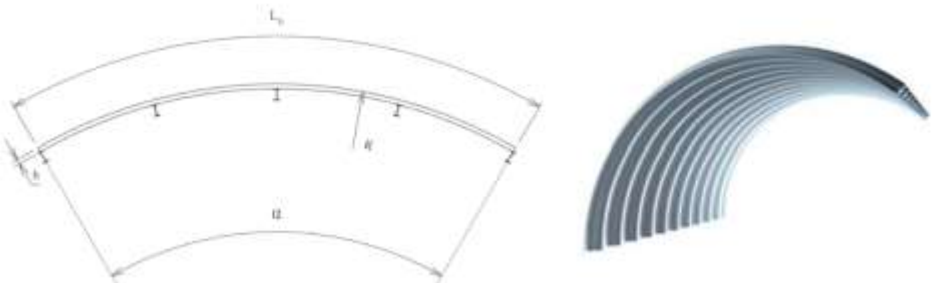


Figure 1-1 Curved profile by roll forming (variant A).

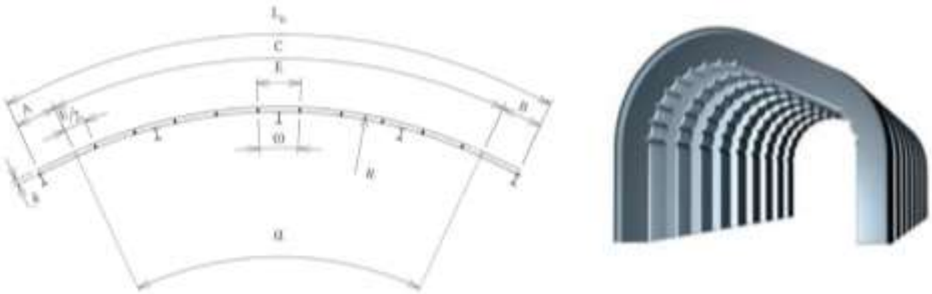


Figure 1-2 Curved profile by crushing of the inner flange (variant B).

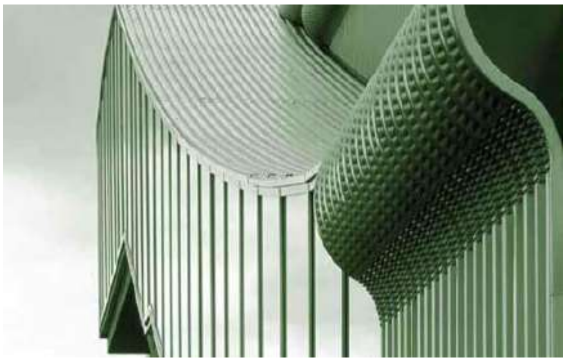


Figure 1-3 Curved profile by bending on site (variant C).

In the current design manual only the structural performance of **curved profiles obtained through a continuous roll-forming process (VARIANT A)** will be analysed. The structural performance shall be evaluated with reference to the bearing capacity of the corresponding flat profiles.

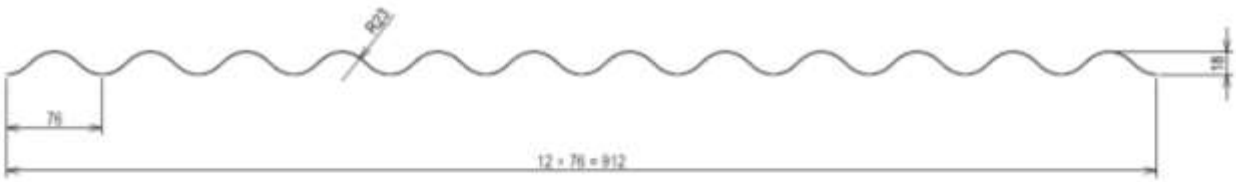


Figure 1-4: Cross- section of the sinusoidal profile.

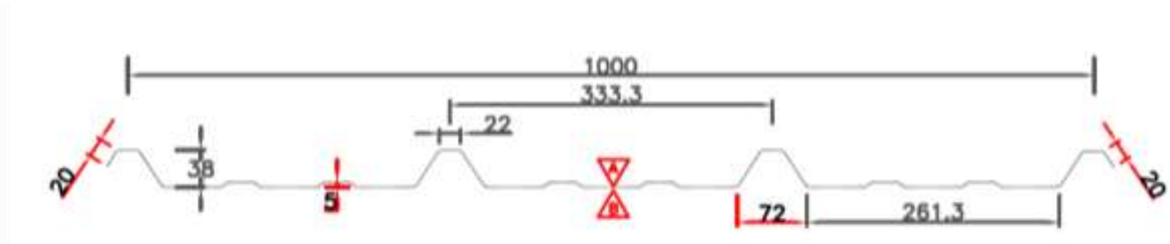


Figure 1-5: Cross- section of the trapezoidal profile.

1.2. State of the art ante-GRISPE research project

The bending load bearing capacity of profiles achieved by crushing of the inner flange (Variant B) is not relevant for the aims of GRISPE research project since the profiles obtained in such a way are usually associated to small span length.

At the same time, the profiles achieved through the 'in situ bending process' (Variant C) can be simply designed according to EN 1993-1:2005 for flat profiles, since the bending radius is very large. For them, no change is expected in the bearing capacity compared to conventional profiles.

In this design manual, as previously said, there will be a focus on profiles achieved though roll forming (Variant A).

The influence of residual stresses from the manufacturing was examined in the past at the research centre of steel, timber and masonry in Germany through the execution of a wide experimental test campaign. A variety of tests according to DIN 18807-2 on curved trapezoidal profiles from different producers were performed. The bending radius was varied between 4 m and 19 m and the supports were not both fixed in the tests. The measured difference in bending bearing capacity between a flat profile and a curved profile was between zero and ten percent.

Data presented in the current scientific literature refer to variation of the bearing capacity of curved profiles respect to flat profiles around by 20% (narrow flange in compression) to 30% (wide flange in compression) [1].

It is worthy to note that if both supports are fixed, the bending theory is no longer applicable, since the profile behaves like an arch.

1.3. Main results of GRISPE research project

As previously said, the study focuses on profiles curved during manufacturing by bending/roll-forming. The roll-forming process involves the continuous bending of a long strip of sheet metal (typically a coiled steel) into the desired cross-section. The strip passed through sets of rolls mounted on consecutive stands, each set performing only an incremental part of the bending, until the desired cross-section (profile) is obtained. This process is used for producing constant-profile parts with long lengths and in large quantities. A simple scheme of the procedure is presented in the following Figure 1-6.

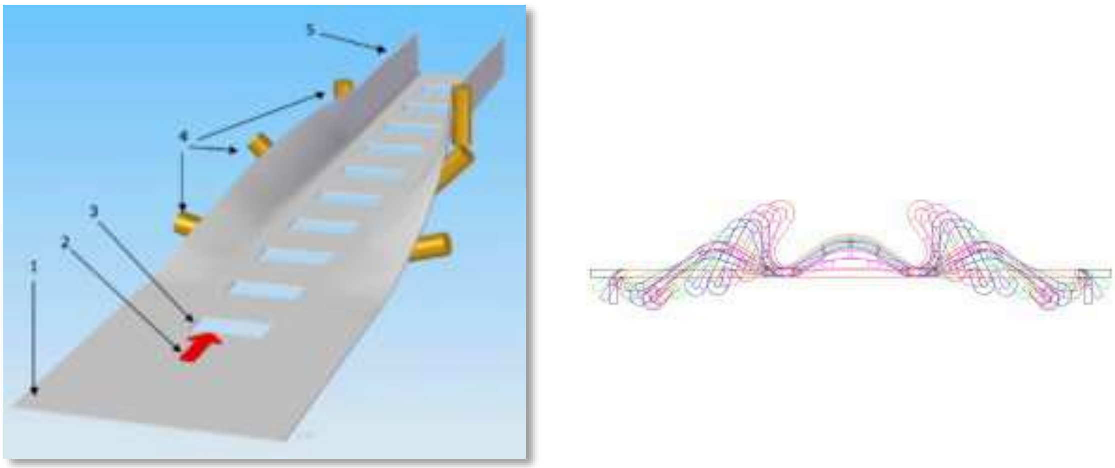


Figure 1-6 Roll-forming process.

The roll-formed sections own some advantages over the ones obtained by extrusion process: components can be lighter, with thinner walls and stronger, having been work hardened in a cold state. Furthermore, the roll forming process is more rapid than extrusion process.

The effects of the process on the material's properties are minimal. The physical and chemical properties virtually don't change, but the process may cause work-hardening, micro-cracks, or thinning at bends when discussing the mechanical properties of the material, conditions that shall be properly accounted for.

What was investigated in GRISPE project was the modification of the structural performance (bearing capacity) of the obtained curved profile with respect to flat profiles (plastic deformations developing in the extreme fibres of the cross section may alter the bearing capacity) for different bending radii.

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. Two different cross sections of the profile were tested: **sinusoidal profiles** provided by Bacacier (profile 18/76) see Figure 1-4 and **trapezoidal profiles** with stiffeners provided by Arcelor Mittal construction France (profile 39/333) see Figure 1-5. For each profile shape, profiles of 0.63 and 1.0 mm of nominal thickness were provided.

Two different configurations were selected for the execution of the experimental tests, respectively for the analysis of the structural performance of the curved profile under only bending actions and under the condition of combined bending and axial forces.

In the following Table 1 the performed tests are summarized.

Figure 1-7 explain the parameter of a curved profile.

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.

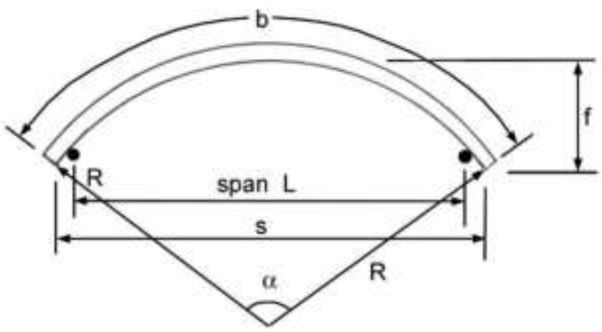


Figure 1-7: Parameters of the curved profiles.

In the first configuration (i.e. only bending actions), the ultimate bending moment and the effective moment of inertia were determined by load tests with curved single span sheets, loaded with two or four vertical line loads to simulate uniformly distributed load (see Figure 1-8 and Figure 1-9). The test specimens were placed on supports which were movable in the horizontal direction. Therefore, no axial forces can appear in the apex of the curved specimen where the bending moment becomes a maximum. The radius of curvature was varied to analyse the influence on the internal stresses and on the bending moment capacity of the profile.

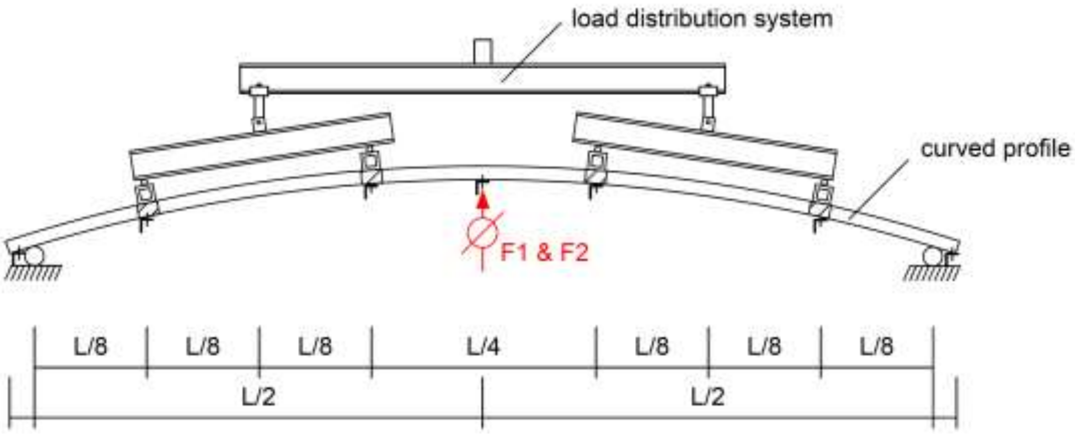


Figure 1-8: Test setup single span tests.

Figure 1-9: Picture of the test setup single span tests.

In the second configuration (i.e. bending and axial forces), the curved profiles were placed on horizontally fixed supports (see Figure 1-10 and Figure 1-11) . In this way, the profiles worked as an arch and were stressed by bending moments and axial compression forces. These tests were executed to verify the design formula for combined bending moment/axial compression given by EN 1993-1-3. Because this formula is valid for trapezoidal sheets, these tests were not done with the sinusoidal profile. By varying the span of the specimen, different slopes were achieved with consequently different ratios bending moment/axial compression.

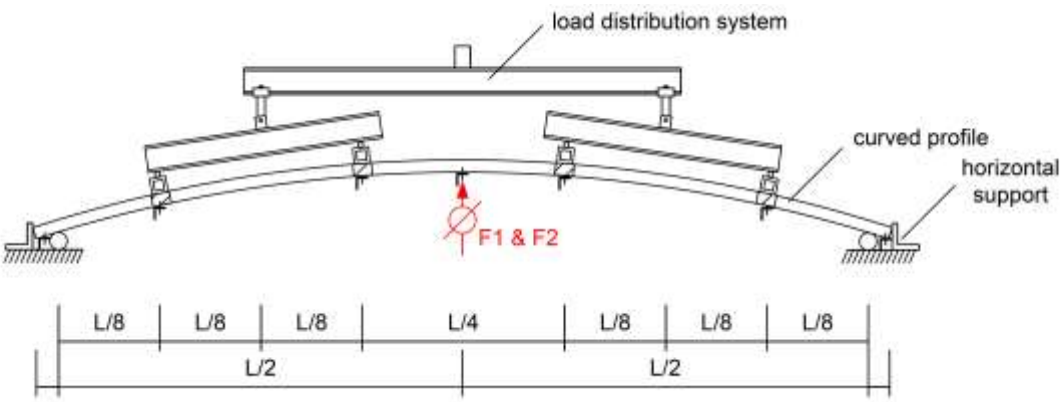


Figure 1-10: Picture of the test setup single span tests (profile 18/76).

Figure 1-11: Picture of the test setup single span test with horizontal support (profile 39/333).

Basing on the results of experimental tests on above mentioned specimens, for curved profiles with only bending actions it can be proposed to reduce the bending moment capacity by 10 % compared to the bending moment capacity of the flat profiles.

For curved profiles with horizontal support (arch: M+N), on the other hand, additional considerations shall be performed stating what resulted from the experimental evidence. First of all, it was noted that the influence of the horizontal displacements (in this second configuration not allowed) cannot be conservatively neglected: higher displacements are related to lower internal forces. As a consequence, the design methodology shall take directly into account the presence of the horizontal support, and the corresponding structural scheme becomes hyper-static. It is the suggested to use the following design procedure:

1. The internal forces of the arch (bending moments, axial forces) should be evaluated using the gross cross section values A_g and J_g of the profiled sheeting.
2. The horizontal displacement at supports may not be neglected. As greater 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 an opportune horizontal spring. The spring stiffness, which depends on the substructure and the fixing of the profiled sheeting, should be 'adjusted' in order to meet the calculated horizontal displacements with the real (experimental) 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.

1.4. General design requirements and rules

(1) The design should be executed in accordance with the general rules given in EN 1993-1-1.

(2) Appropriate partial factors shall be adopted for ultimate limit states and serviceability limit states according to EN 1993-1-3.

2. PRELIMINARY CONSIDERATIONS: PRE-DESIGN

2.1. Field of application of the new design method

This manual presents a design method to determine the strength of curved profiles.

This manual gives method to design by calculation.

This manual does not cover load arrangement for loads during execution and maintenance.

The calculation rules given in this manual are only valid if the tolerances of the cold formed members comply with EN 1993-1-3.

The calculation rules are based on the elaboration of experimental data on the previously described curved profiles specimens.

The design procedure is valid for profiles which are curved during fabrication by bending or rollforming. It is not valid for profiles which are curved by bending during erection or by crushing the inner flange of the cross section.

The slendeness ratio alpha should not be limited to 1 as required in DIN 18807 for straight profiles.

Horizontal displacement at supports may be modelized by horizontal springs. Horizontal displacement leads to higher bending moments in the arch. The spring stiffness should be aligned to the horizontal stiffness of the substructure including the deformations in the fixing of the arch profile. As smaller the spring stiffness as greater the bending moments; estimation of the spring stiffness on the "weak" side leads to a safer design.

3. BASIC TECHNOLOGICAL REQUIREMENTS

3.1. Requirements concerning profiled sheets and CE marking

Steel profiles shall be CE marked, according to the standard EN 14782 (non-structural) or EN 1090-1 (if structural).

4. MATERIAL PROPERTIES

4.1. Steel sheets

If not further specified, the material properties used in calculation have to satisfy requirements defined within section 3 of EN 1993-1-3.

The thickness tolerances should satisfy the requirements given in EN 1993-1-3, section 3.2.4.

- steel core thickness t_{cor} = 0,58 mm
- yield stress $f_{y,k}$ = 408,3 N/mm^2

Detailed information concerning the profiles characteristics are contained in 8.1.

5. ACTION LOADS AND COMBINATIONS

The actions and combinations which should be taken into account must be determined according to:

EN 1990 Eurocode 0: basis of structural design

EN 1991-1-1: 2005 Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings

EN 1991-1-3: 2005- Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads

EN 1991-1-6: 2005 Eurocode 1: Actions on structures - Part 1-6: General actions - Actions during execution"

6. BASIS OF THE DESIGN

6.1. Principles

The new design method can be used to determine:

- Mid span bending resistance, in the configuration of single span element without horizontal supports.
- Bending moment-axial compression interaction, in the configuration of single span element with horizontal supports.

In order to apply this design method, the profile should be symmetrical loaded.

6.2. Field of application of the new design method

The following design procedure may be used to evaluate the bearing capacity of curved profiles.

During the experimental tests performed in GRISPE project, profiles with different thicknesses, span length and curvature radius have been tested, as well as described in Table 1.

The internal forces of the arch (bending moments, axial forces) should be calculated using the gross cross section values A_g and J_g of the profiled sheeting

The design model is verified for arches with symmetric loading.

The horizontal displacement at supports may not be neglected.

The field of application is the same as the one given for the interactive formula given in DIN 18807, part 3, section, item 3.3.6.1.

6.3. Design procedure

6.3.1. Single span configuration without horizontal supports: calculation of bending moment capacity

The curving process by bending or by roll-forming creates plastic deformations in the extreme fibres of the cross section. This leads to internal stresses in the cross section which can influence the bending capacity of the cross section itself. The test results have shown, on the other hand, that the influence is rather small and furthermore not uniform:

- For the profiles with thickness equal to 1.0 mm, the curvature doesn't influence the bending moment capacity of the curved profile respect to the flat one.
- For the profiles with thickness equal to 0.63 mm, the bending moment capacity is affected by the application of curvature in both senses:

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

With respect to this behaviour and considering the low sensitivity of the bending moment capacity, it is proposed – conservatively - to reduce the bending moment capacity of the corresponding flat profile by 10 % (see eq .6.1). This reduction factor shall be considered as an additional safety factor to cover the indifferent scattering; it is not a mechanically based coefficient.

$$M_{c,Rk,F}(curved\ profile) = 0{,}9 \cdot M_{c,Rk,F}(flat\ profile) \qquad 6(1)$$

6.3.2. Single span configuration with horizontal supports: calculation of bending moment capacity

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

In case of compression force and bending action, the following equation 6(2) is provided:

$$\frac{N_D}{N_{dD}} \cdot \left[1 + 0{,}5 \cdot \alpha \left(1 - \frac{N_D}{N_{dD}}\right)\right] + \frac{M}{M_d} \leq 1 \qquad 6(2)$$

Being:

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 the slenderness ratio being defined as:

$$\alpha = \frac{L_{cr}}{i_{eff} \cdot \pi} \cdot \sqrt{\frac{f_{y,k}}{E}} \qquad 6(3)$$

Where:

L_{cr} buckling length. The formulation is commonly accepted since provided, for instance, by DIN 18 800 part 2 (see Figure 6-2).

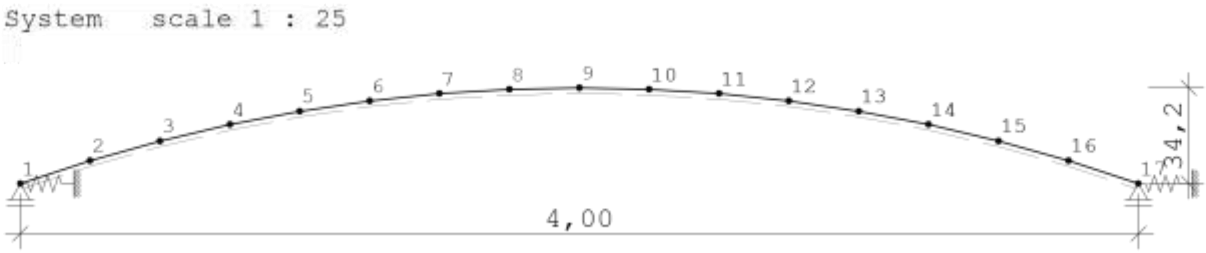
i_{ef} radius of gyration of the effective cross section

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

Hereafter, the DIN-procedure for combined bending moment/axial compression modified to 'adapted' to the case of curved profiles is described in detail step by step.

1. <u>Determination of the internal forces of the arch under characteristic failure load.</u>

   This step (1) can be done calibrating a simple model basing on the results of experimental tests. The calibration allows to assume a representative stiffness of the horizontal springs positioned in correspondence of the two ends of the profile (see Figure 6-1).Figure 6-1: Example of simple model with horizontal spring (Source Rainer Holts grispe project).



SECTION PROPERTIES

Cross-sect. No.	Mat	Profile Name	I (cm4)	A (cm2)	Aq (cm2)	h (cm)	S top (cm3)	S bot (cm3)
1	1	Arcelor 3	9.77	6.58	0.000	0.00	0.000	0.000

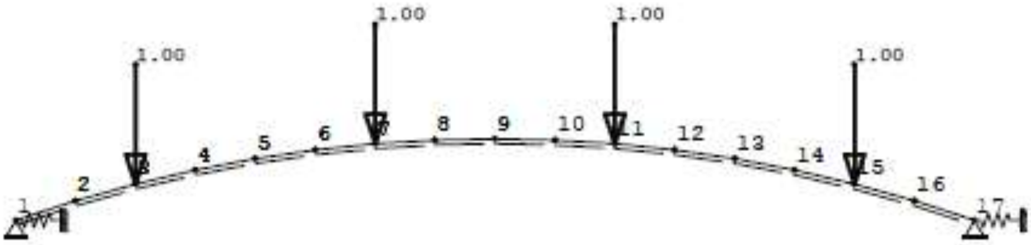


Figure 6-1: Example of simple model with horizontal spring (Source Rainer Holts grispe project).

For example, taking into account experimental data previously presented, a simple model representative of the structural configuration of the curved profile shall be elaborated. To simplify, the circle-shaped arch can be approximated by a polygon. The two end supports at the ends are equipped with springs in the horizontal directions to allow and control the horizontal deflections, while the supports are fixed in the vertical direction. The characteristic failure load is applied according to the performed experimental tests (for example with 4 equal vertical line loads at 0,125 L – 0,25 L – 0,25 L – 0,25 L – 0,125 L) and the self-weight of the profile is neglected. Obviously, for the calibration procedure, in case of different loading schemes, the model shall be opportunely updated.

Calculation of internal forces is done for the system representing the considered subset under characteristic failure load. Each subset consists of several identical tests with different individual failure loads and different individual deflection values. A common deflection value shall be evaluated from the tests, representing the whole subset: this representative value is not then directly the deflection of an individual test (for example, it can be the mean deflection at characteristic failure load, as assumed in the following). For example, taking into consideration the results coming from previous tests, the following procedure can be adopted.

For each i-th test, the vertical deflection at midspan f_{max} and the corresponding (individual) failure load F_u (test) allow the determination of an individual "*stiffness parameter*", as in the following:

- Overall stiffness of the i-th specimen

$$C_{f,\,i} = F_u/f_{max} \qquad 6(4)$$

- Mean value of all tests of the same subset, considered as representative for this family

$$C_f = Mean\ (C_{f,i}) \qquad 6(5)$$

Using the overall stiffness value of the family (C_f), a midspan deflection under characteristic failure load can be evaluated, which is considered as representative for this family.

Since the internal forces of the arch are calculated for the unit width, the result should be multiplied with the width of the test specimen.

$$f_{eq} = F_{u.k} / C_f * b_V \qquad 6(6)$$

Calculating the arch with a software used to realize the model, the spring stiffness of the horizontal supports is varied and finally locked to a value, for which the calculated midspan deflection under characteristic failure load corresponds to the deflection f_{eq} according to Table 2. This spring stiffness of the horizontal support is the above mentioned C_{ind}.

After the calibration of the model basing on what above presented, the evaluation of the internal forces is possible.

test no. SSP-H-39-…	F_u kN	deflection f_{max} at mid-span (mm)	L m	b_V m	overall stiffness specimen $C_{f,i}$ (kN/mm)	mean value stiffness C_f	repr. deflection (mm) for $F_{u,k}$, width 1 m
217-063-1	9,12	18,0	3,00	0,667	0,507	0,444	16,6
217-063-2	8,95	23,5	3,00	0,667	0,381		
380-063-1	9,49	17,6	4,00	0,667	0,539	0,589	14,4
380-063-2	11,43	19,2	4,00	0,667	0,595		
380-063-3	11,03	17,4	4,00	0,667	0,634		
576-063-1	5,67	23,6	5,00	0,667	0,240	0,329	13,4
576-063-2	5,17	14,1	5,00	0,667	0,367		
576-063-3	6,83	18,0	5,00	0,667	0,379		

Table 2: Representative midspan deflection at characteristic load level $F_{u,k}$.

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 (see Figure 6-1).

Buckling length $L_{cr} = s_K$ $=: s_K = \beta \cdot s$,

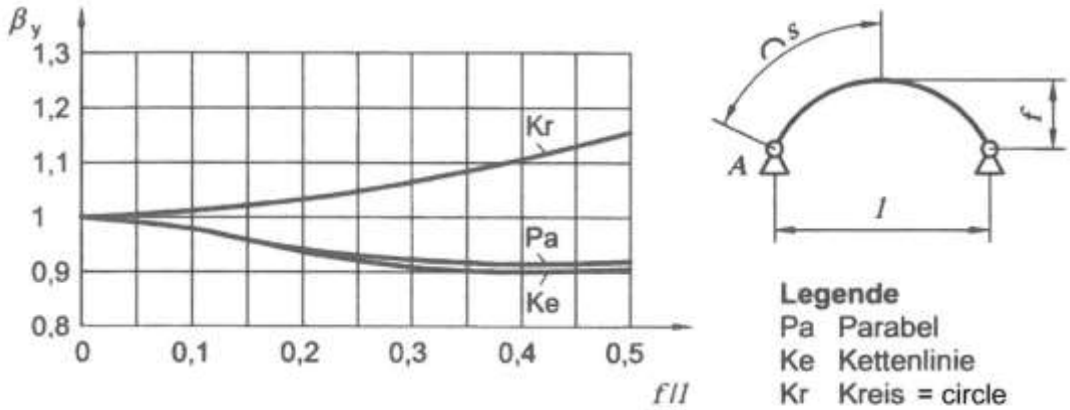


Figure 6-2: buckling length following DIN 18 800 - 2.

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

$$N_{dD} = min(\sigma_{cd} \cdot A_{ef}; 0{,}8 \cdot \sigma_{elg} \cdot A_g) \qquad 6(7)$$

Being:

- σ_{cd} design compressive stress
- A_{ef} area of the effective cross section for axial compression
- σ_{elg} Eulerian compressive stress for the gross section
- A_g area of the gross section

4. Calculation of the bending moment/axial compression interaction, according to DIN 18807

$$\frac{N_D}{N_{dD}} \cdot \left[1 + 0{,}5 \cdot \alpha\left(1 - \frac{N_D}{N_{dD}}\right)\right] + \frac{M}{M_d} \leq 1 \qquad 6(8)$$

Being:

- 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

According to DIN 18807, the slenderness value previously defined by equation 6(3) should be limited to 1.
Basing on the results of GRISPE, a modified DIN procedure is proposed without the limitation of α to a value equal to 1; in this way, the results achieved are a little bit more conservative than the one obtained through the pure DIN approach.
Calibration of the method was done with symmetric loading only.

7. SPECIFIC DESIGN CONSIDERATIONS

7.1. Situations not covered by the present Manual

The following issues are not covered by the present design manual:

- For fire: national regulations in agreement with EN 1991-1-2 and EN 1993-1-2 and their national annex shall be considered.
- For seismic: national regulations in agreement with EN 1998-1 and their national annex shall be considered.
- For environmental aspects: national regulations shall be considered.
- For thermal: national regulations in agreement with EN 1991-1-5 and their national annex shall be considered.
- For acoustic: it should be considered national regulations.

And for all other subjects not clearly identified higher or lower.

8. DESIGN EXAMPLE

8.1. Explanation of the design procedure

The presented design procedure allows to calculate span moment resistance for a curved profile, obtained by roll forming process applied to a flat sheet. Two different configurations have been taken in account:

- Single span without horizontal supports (profile stressed by bending moment only), see Figure 8-1.
- Single span with horizontal supports (profile stressed by a combination of bending moment and axial forces), see Figure 8-2.

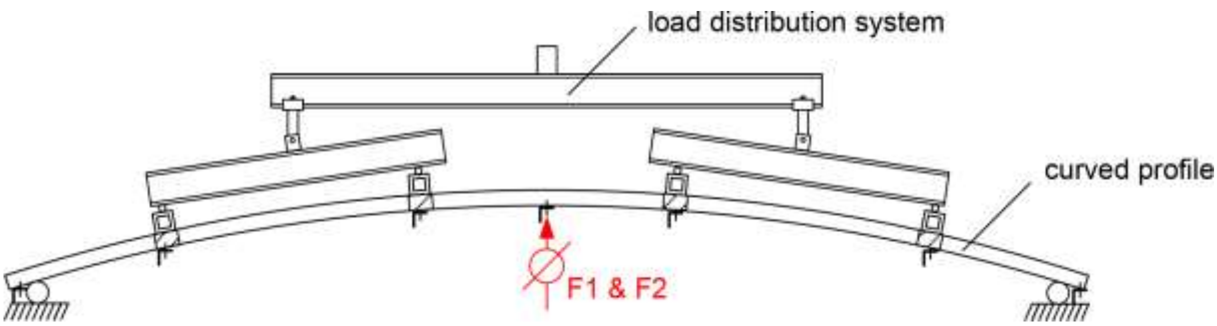


Figure 8-1: Configuration of single span without horizontal supports.

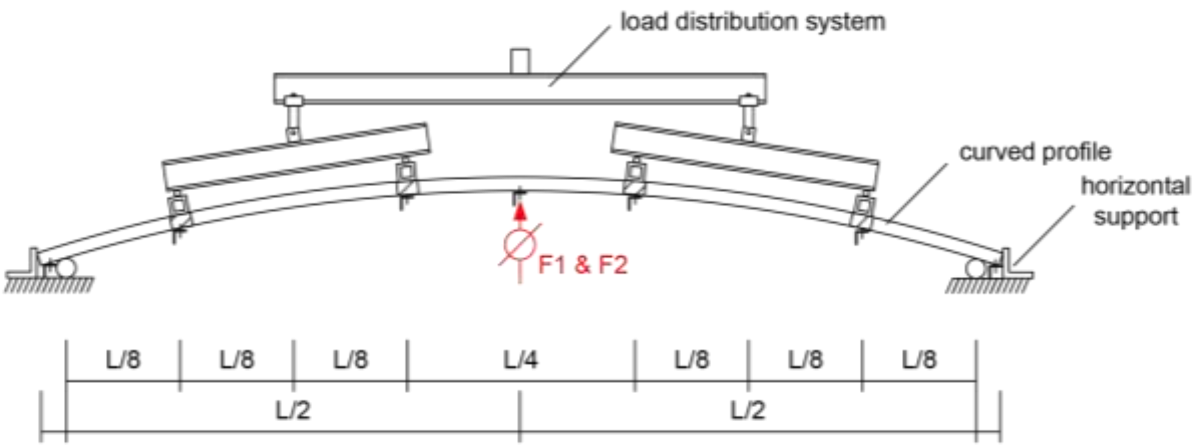
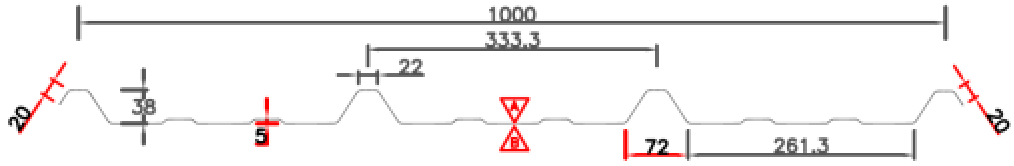


Figure 8-2: Configuration of single span with horizontal supports.

In the following paragraphs, the assessment of the bearing capacity of the described configurations, is presented in detail considering a profile with the following characteristics:



- Profile: Arcelor 39/333
- test family: H-39-380-63
- span length of the arch: 4.0 m
- height of the arch: 342 mm
- width of the arch: 1 m
- radius of curvature: 6.02 m
- characteristic failure load (applied load in the calculation): 12.77 kN/m
- self- weight of the profile: 0.095 kN/m^2
- length of the profile: 4.20 m
- section properties of the gross cross section

  area A_g = 6.58 cm^2/m

  moment of inertia J_g = 9.77 cm^4/m

  radius of gyration i_g = 1.218 cm
- section properties of the effective cross section for axial compression

  area A_{ef} = 1.89 cm^2/m

  moment of inertia J_{ef} = 5.21 cm^4/m

  radius of gyration i_{ef} = 1.660 cm
- The bending resistance of the profile is given by the steel sheet producer

  load bearing values positive bending moment M_d^+= 1.093 kNm/m

  negative bending moment M_d^- = 1.426 kNm/m

8.1.1. Single span without horizontal supports

In the case of single span *without* horizontal supports, the load generates bending moments and shear forces in the profile; axial forces are, on the other hand, negligible.

The load is applied by 4 lines load at 0,125 L – 0,25 L – 0,25 L – 0,25 L – 0,125 L and, due to the isostatic load distribution system, all 4 lines load are equal.

According to what have been proposed by GRISPE because of the experimental test campaign, the bearing capacity of the curved profile could be evaluated as the 90% of the bearing capacity of the correspondent flat profile.

The maximum bending moment in span of a flat profile could be evaluated using the following equation:

$$M_{c,Rk,F} = \frac{F_{u,k}}{b_v} \cdot \frac{L}{8} + g \cdot L_v \cdot [2L - L_v]/8$$

Being:

$M_{c,Rk,F}$ characteristic bending moment in span (kNm/m)

$F_{u,k}$ characteristic load in kN (including preload)

b_V width of the test specimen

L_V length of the test specimen

L span length (here: L = 2,00 or 3,00 or 4,00 m)

g self-weight of the profile

According to the characteristics of the example-profile above mentioned, the following value can be achieved for the 'original' flat profile:

$$M_{c,Rk,F} = \frac{12.77}{1} \cdot \frac{4}{8} + 0.095 \cdot 4.20 \cdot [2 \cdot 4 - 4.20]/8 = 6.57\text{kN/m/m}$$

This value shall be introduced in the excel table in the correspondent red cell. In this way, the value of the bearing capacity of the correspondent curved profile is automatically displayed by the excel file, being simply evaluated by applying a reduction of 10% to the flat one.

$M_{c,Rk,F}(curved\ profile) = 0,9 \cdot M_{c,Rk,F}(flat\ profile)$					
$M_{c,Rk,F,flat\ profile}$	6.57	[kNm/m]	$M_{c,Rk,F,curved\ profile}$	5.91	[kNm/m]

8.1.2. Single span with horizontal supports

In the case of single span with horizontal supports, a multistep approach, as described in details hereafter, shall be adopted. As already explained in the design manual, the solution of the problem in this load/restraint condition needs to be solved as a hyper-static problem. With horizontal displacements restrained, the curved profile behaves like an arch.

Step 1: Determination of the internal forces of the 'arch' under characteristics failure load.

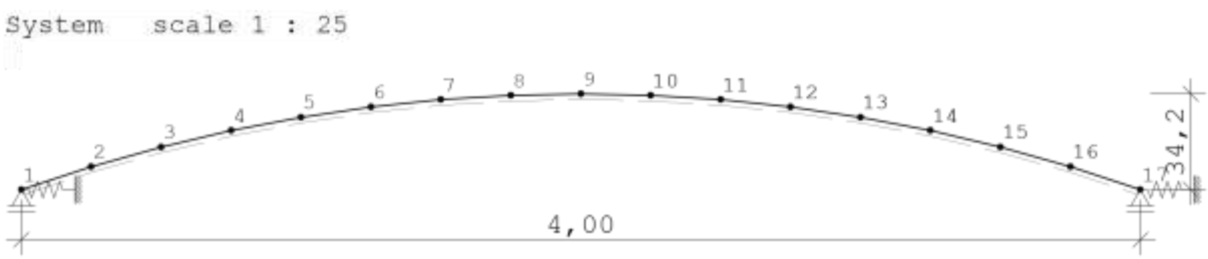


Figure 8-3: Geometric model dimensions.

The circle-shaped arch is approached by a polygon made up of 16 straight sections; nodes are recalled with no. from 1 to 17 (see Figure 8-3 and Figure 8-4). The calculation refers to 1.0 m unit width of the profile. The supports at the ends (nodes 1 and 17) are equipped with springs in the horizontal direction to allow and control horizontal deflections; the supports are fixed in the vertical direction. The characteristic failure load is applied as 4 equal vertical line loads at 0,125 L – 0,25 L –0,25 L – 0,25 L – 0,125 L (in correspondence of nodes 3, 7, 11 and 13). The self-weight of the profile is neglected.

Since the internal forces of the arch depend on the horizontal displacement at supports, it is crucial to adopt the correct spring stiffness, when the internal forces are calculated. Considering the influence of the spring stiffness on the internal forces, the spring stiffness should be estimated "on the weak side" to obtain a conservative condition for the design. Neglecting the horizontal displacements at supports leads to internal forces which are too favourable, and consequently to an unsafe design. The spring stiffness is thus chosen in a way that the calculated vertical displacement at summit fits the vertical displacement measured in the tests.

Calculation of internal forces is done for a system, which represents the considered subset under characteristic failure load. A common deflection value has to be developed from the tests which represent the subset family. Please note that this representative value is not directly the deflection of an individual test.

For each test, the vertical deflection at midspan f_{max} and the corresponding (individual) failure load F_u (test) define an individual "stiffness parameter":

Overall stiffness of the specimen

$$C_{f,i} = F_u / f_{max}$$

The mean value of all tests of the same subset is considered as representative for this family.

$$C_f = \text{Mean}\ (C_{f,i})$$

Using the overall stiffness value of the family, a midspan deflection under characteristic failure load can be calculated, which is considered as representative for this family.

Since the internal forces of the arch are calculated for the unit width, the result should be multiplied by the width of the test specimen.

$$f_{eq} = F_{u.k} / C_f * b_V$$

Test setup/ span	Cross section	Spring stiffness at support C_f [kN/m/cm]	Failure load [kN/m]	Dislacement		Support reactions [kN/m]		M/N values [kN/m/m, kN/m]		
								at load point near to summit		at support
				f_h (support)	f_v (summit)	R_h	R_v	max M	corresp N	max N
1/3.00m	gross	fixed	11.03	0.00	0,11	20.46	5.52	0.17	20.62	21.19
		68.00	11.03	0.28	1.67	18.81	5.52	0.49	18.98	19.60
		20.00	11.03	0.79	4.55	15.76	5.52	1.08	15.94	16.65
		10.00	11.03	1.28	7.33	12.82	5.52	1.65	13.01	13.80
	effective	fixed	11.03	0.00	0.41	20.35	5.52	0.19	20.51	21.08
		88.00	11.03	0.22	1.66	19.64	5.52	0.33	19.80	20.40
		20.00	11.03	0.88	5.33	17.57	5.52	0.73	17.74	18.39
		10.00	11.03	1.55	9.08	15.46	5.52	1.14	15.64	16.35
2/4.00m	gross	fixed	12.77	0.00	0.08	19.13	6.39	0.35	19.35	20.16
		62.00	12.77	0.30	1.45	18.64	6.39	0.40	18.87	19.70
		20.00	12.77	0.88	4.10	17.69	6.39	0.71	17.92	18.80
		10.00	12.77	1.64	7.56	16.45	6.39	1.11	16.69	17.62
	effective	fixed	12.77	0.00	0.39	19.09	6.39	0.26	19.31	20.13
		79.00	12.77	0.24	1.44	18.88	6.39	0.33	19.11	19.93
		20.00	12.77	0.91	4.51	18.29	6.39	0.51	18.53	19.37
		10.00	12.77	1.76	8.33	17.56	6.39	0.75	17.80	18.68

3/5.00m	gross	fixed	6.62	0.00	0.02	9.23	3.31	0.16	9.36	9.81
		29.00	6.62	0.31	1.34	9.01	3.31	0.26	9.14	9.60
		20.00	6.62	0.45	1.91	8.91	3.31	0.30	9.04	9.50
		10.00	6.62	0.86	3.67	8.61	3.31	0.43	8.74	9.22
	effective	fixed	6.62	0.00	0.23	9.22	3.31	0.16	9.35	9.80
		33.00	6.62	0.28	1.33	9.12	3.31	0.21	9.09	9.70
		20.00	6.62	0.45	2.07	9.05	3.31	0.24	9.18	9.63
		10.00	6.62	0.89	3.91	8.88	3.31	0.31	9.01	9.48

Table 3 : Internal forces and deflections of the arches under characteristic failure load

Green coloured lines: spring stiffness at support adapted to the midspan-deflection in test.
Red marked line: example configuration considered in the detailed calculation.

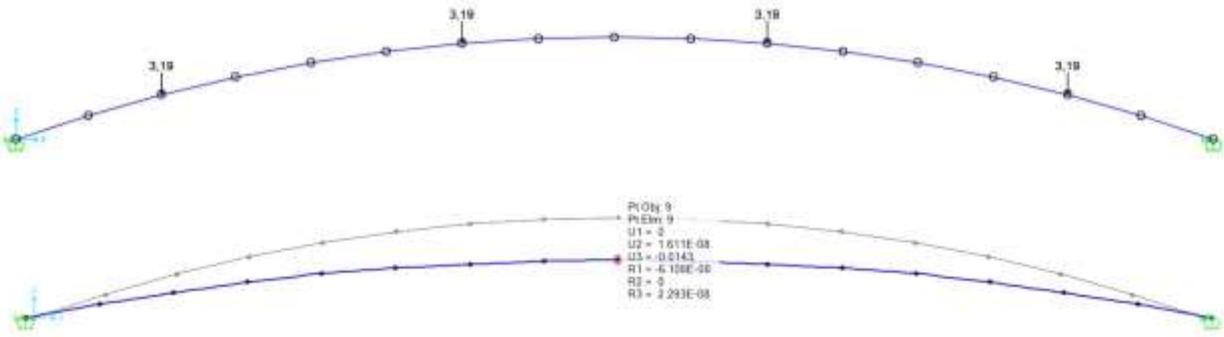


Figure 8-4: Example of simple model with horizontal springs.

Calculating the arch with a software, the spring stiffness of the horizontal support is varied and finally locked to a value, for which the calculated midspan deflection under characteristic failure load corresponds to the deflection f_{eq}. This spring stiffness of the horizontal support is the above mentioned C_{ind}.

The failure load in the analysed example has a value of 12.77kN/m as could be seen in the Table 3. In the model this value it is applied in four points, resulting in the following value:

$$F_{u,\ nodes} = 12.77/4 = 3.19\text{kN}$$

The vertical deflection at midspan for the current example has a value equal to:

$$f_v = 1.45 \text{ cm}$$

This value is reached by the model, by adopting the spring stiffness of the horizontal support as

$$C_f = 62 \text{ kN/m/cm}$$

In the calibrated model, taking in account the section with maximum bending moment (in the load point near to summit) the following values are achieved:

$$M = 0.40 \text{ kNm/m}$$

$$N_D = 18.87 \text{ kN/m}$$

Those values have to be insert in the correspondent red cells of the excel table.

f_{yb}	408.3	[N/mm^2]	$N_{c,Ed}$	18.87	[kN/m]

E	210000	[N/mm^2]	$M_{c,Ed}$	0.40	[kNm/m]
L_{cr}=β s	207.9	[cm]	$M_{c,Rd}$	1.09	[kNm/m]
A_g	6.58	[cm^2/m]			
i_g	1.22	[cm]			
A_{ef}	1.89	[cm^2/m]			
i_{ef}	1.66	[cm]			

Step2: Determination of the buckling length $L_{cr.}$

The buckling length of a circle-shaped arch can be found in the literature, for instance DIN 18800-2 provides the following expression:

arch length *b*

height/span-ratio *f/L*

buckling length coefficient *β = f (height/span-ratio f/L) from diagram*

buckling Length $L_{cr} = \beta * s = \beta * b/2$

s is the mid length of the arch, as represented in Figure 8-4.

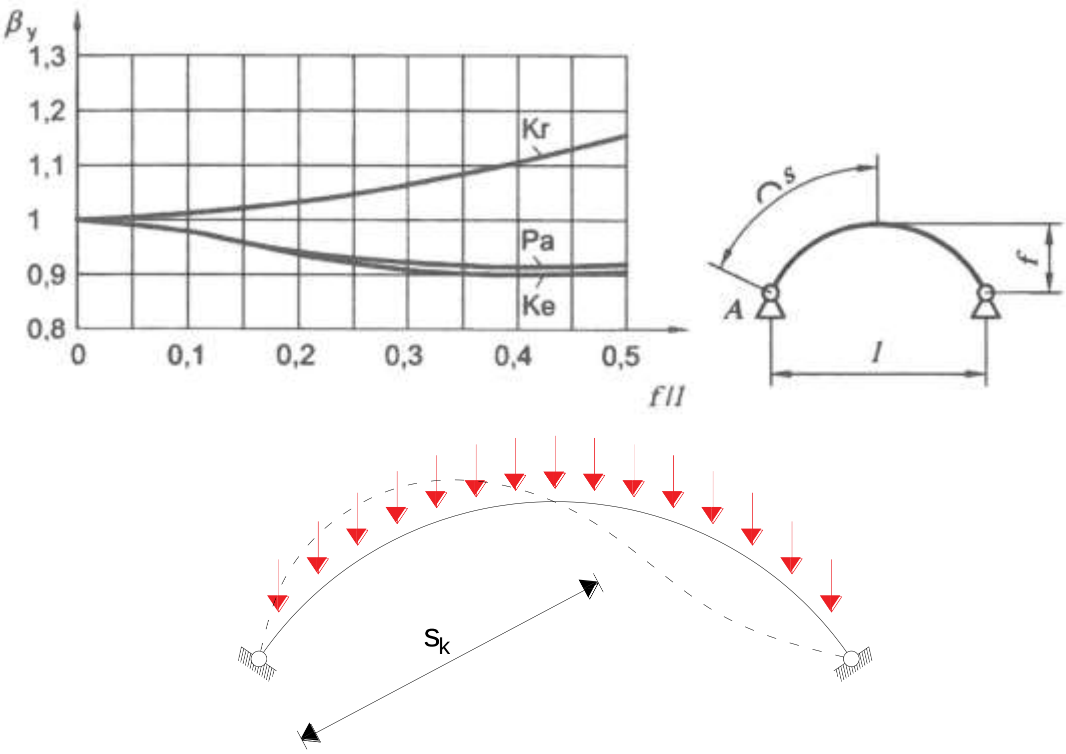


Figure 8-5: buckling length coefficient b from DIN 18800 – 2.

For instance, we can use the following data:

arch height *f = 342 mm*

span *L = 4000 mm*

slope at support *α/2 = 0,338*

radius of curvature *R = 4000 / (2 * sin 0,338) = 6024 mm* arch length *b = 6024 * 2 * 0,338 = 4072 mm*

height/span-ratio *f/L = 342 / 4000 = 0,085*

buckling length coefficient *β = 1,02*

buckling length L_{cr} *= 1,02 * 4072 / 2 = 2079 mm*

The buckling length value has to be insert in the correspondent red cell of the excel table.

f_{yb}	408.3	[N/mm²]	$N_{c,Ed}$	18.87	[kN/m]
E	210000	[N/mm²]	$M_{c,Ed}$	0.4	[kNm/m]
L_{cr}=β s	207.9	[cm]	$M_{c,Rd}$	1.09	[kNm/m]
A_g	6.58	[cm²/m]			
i_g	1.22	[cm]			
A_{ef}	1.89	[cm²/m]			
i_{ef}	1.66	[cm]			

Step 3: Determination of the design resistance of compressive force N_{dD}

$$N_{dD} = \min(\sigma_{cd} \cdot A_{ef}; 0.8 \cdot \sigma_{elg} \cdot A_g$$

Ideal buckling force:

$$maxN_{dD} = 0.8 \cdot \sigma_{elg} \cdot A_g$$

$$maxN_{dD} = 0.8 \cdot \frac{\pi^2 \cdot E \cdot J_g}{L_{cr}^2}$$

$$maxN_{dD} = 0.8 \cdot \frac{\pi^2 \cdot 210000 \cdot 9.77}{207.9^2}$$

$$maxN_{dD} = 37.47kN$$

Critical buckling force:

$$ultN_{dD} = \sigma_{cd} \cdot A_{ef}$$

Slenderness ratio:

$$\alpha = \frac{L_{cr}}{i_{ef} \cdot \pi} \cdot \sqrt{\frac{f_{yk}}{E}}$$

$$\alpha = \frac{207.9}{1.66 \cdot \pi} \cdot \sqrt{\frac{408.3}{210000}} = 1.758$$

Buckling curve from DIN 18807:

α	$\sigma_{cd}/\beta s$
α≤ 0.30	1.00
0.30 < α ≤ 1.85	1.126 -0.419 α

1.85< α	1.2/ α ²

$$\frac{\sigma_{cd}}{f_{yk}} = 1.126 - 0.419 \cdot 1.758 = 0.390$$

$$\sigma_{cd} = 0.390 \cdot 408.3 = 159.0\ N/mm^2$$

critical buckling force:

$$ultN_{dD} = 15.9 \cdot 1.8895 = 30.06\ kN/m$$

decisive design resistance:

$$N_{dD} = 30.06\ kN/m$$

The values of slenderness ratio, ideal buckling force, reduction factor and critical buckling force are automatically displayed by the excel file, once the red cells have been filled in with all the required data.

f_{yb}	408.3	[N/mm²]	$N_{c,Ed}$	18.87	[kN/m]
E	210000	[N/mm²]	$M_{c,Ed}$	0.40	[kNm/m]
L_{cr}=β s	207.9	[cm]	$M_{c,Rd}$	1.09	[kNm/m]
A_g	6.58	[cm²/m]			
i_g	1.22	[cm]			
A_{ef}	1.89	[cm²/m]			
i_{ef}	1.66	[cm]			

Slenderness ratio α [-]	Ideal buckling force [kN/m]	Reduction factor χ [-]	Critical buckling force [kN/m]
1.76	37.45	0.39	30.05
$N_{c,Rd}$	30.05 [kN/m]		
$N_{c,Ed}$ / $N_{c,Rd}$	0.63 [-]		
$M_{c,Ed}$ / $M_{c,Rd}$	0.37 [-]		

Step 4: interaction bending moment/ axial compression

According to DIN 18807, the slenderness value α = 1,758 should be limited to 1, but hereafter, the calculation with the modified procedure DIN 18807 is proposed: the modification consists in not limiting the value of the coefficient α in the M-N-interaction formula.

$$\frac{N_D}{N_{dD}} \cdot \left[1 + 0.5 \cdot \alpha \left(1 - \frac{N_D}{N_{dD}}\right)\right] + \frac{M}{M_d} \leq 1$$

$$\frac{18.87}{30.06} \cdot \left[1 + 0.5 \cdot 1.758 \left(1 - \frac{18.87}{30.06}\right)\right] + \frac{0.40}{1.093}$$

$$= 0.628 \cdot [1 + 0.5 \cdot 1.758(1 - 0.628)] + 0.366$$

=0.833+0.366=1.20>1

The M-N interaction is automatically displayed by the excel file.

Interaction formula	$\frac{N_{c,Ed}}{N_{c,Rd}} \cdot \left[1 + 0.5 \cdot \alpha \cdot \left(1 - \frac{N_{c,Ed}}{N_{c,Rd}}\right)\right] + \frac{M_{c,Ed}}{M_{c,Rd}} =$	1.20>1.0

The formula confirms well that with the loading of 4 loads of 3.19kN, so 12.77kN, the arch collapses as seen during the tests.

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[15] R. HOLZ, GRISPE – WP2: Curved Profiles – D2.2 Test program definition, 2016

[16] R. HOLZ, GRISPE – WP2: Curved Profiles – D2.4 Test analysis and interpretation,2016

Annex 1

Background of the new design method for curved profiles.

D2.1	GRISPE WP2 Background document	Christian FAUTH (KIT)
D2.2	GRISPE WP1 Test programme definition	Rainer HOLZ (IFL)
D2.3	GRISPE Test report of curved profiles	Christian FAUTH (KIT)
D2.4	GRISPE WP1 Test analysis and interpretation	Rainer HOLZ (IFL)
D2.5	GRISPE Background guidance for EN 1993-1-3 to design of sheeting with embossments and indentations	Christian FAUTH (KIT)