GRISPE PLUS

VALORISATION OF KNOWLEDGE
FOR SPECIFIC PROFILED STEEL SHEETS

Curved profiles

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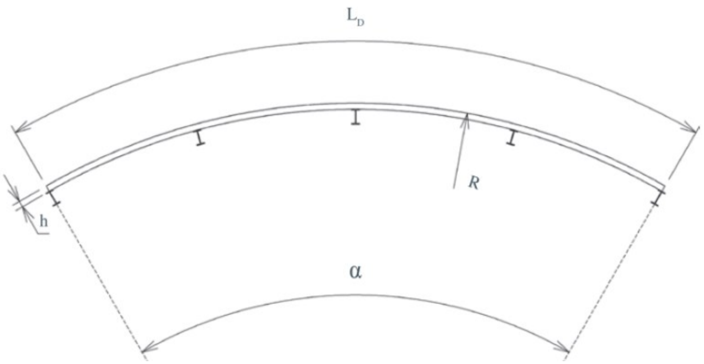
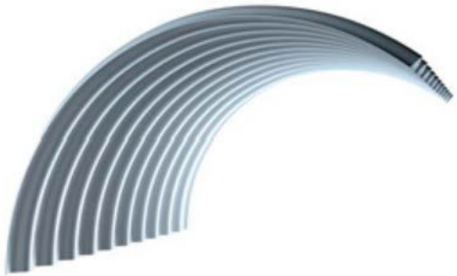
The project has received financial support from the European Community (RFCS programme) under grant agreement No 754092

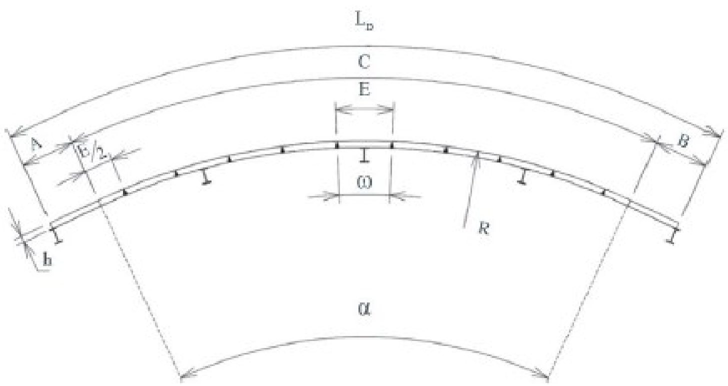
Curved profiles

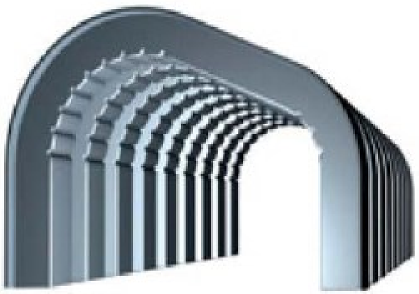
CURVED PROFILES can be obtained through three different processes:



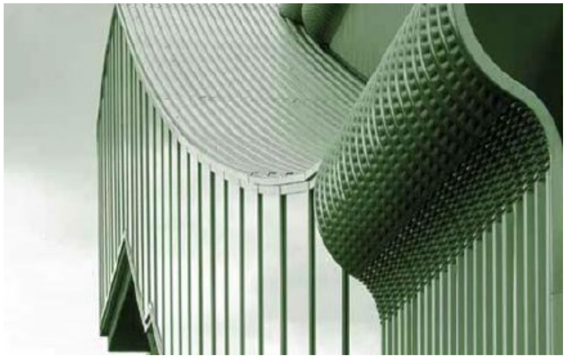


ROLL FORMING – Variant A





BY CRUSHING OF THE INNER FLANGE – Variant B



THROUGH IN SITU BENDING PROCESS – Variant C

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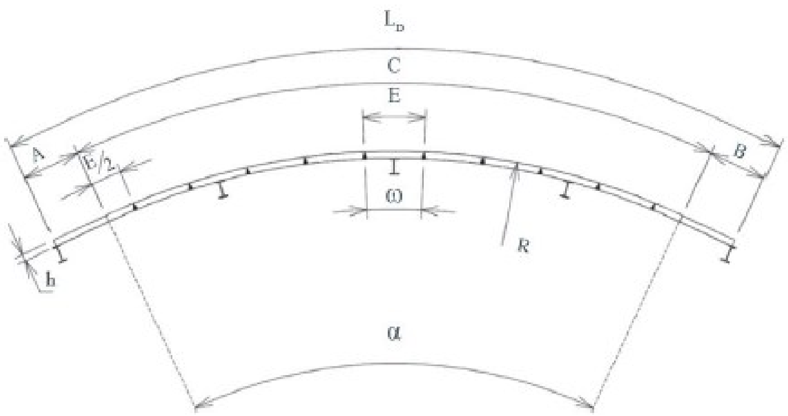
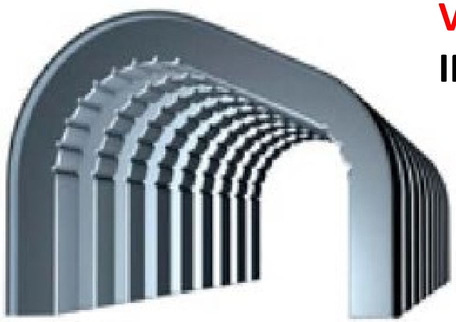
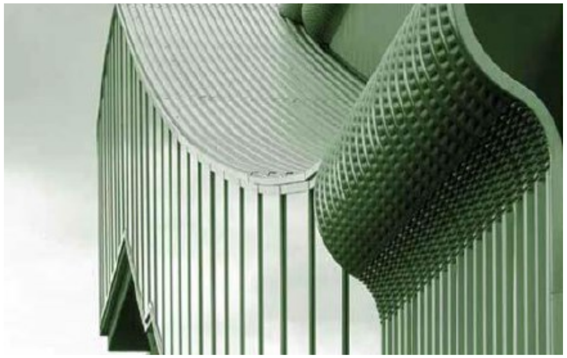




Variant B - CRUSHING OF THE INNER FLANGE

- This case (**VARIANT B**) is usually associated to <u>small span length</u> when adopted, and consequently not considered in the present research project.

THROUGH IN SITU BENDING PROCESS – Variant C



- This case (**VARIANT C**) is usually associated to <u>large curvature/bending radius</u> applied to the profile. The design can be consequently executed following the standard prescriptions imposed by **<u>Eurocode 3 (EN1993-1:2005)</u>** for flat profiles.

Variants B and C were then not considered in the main framework of GRISPE project

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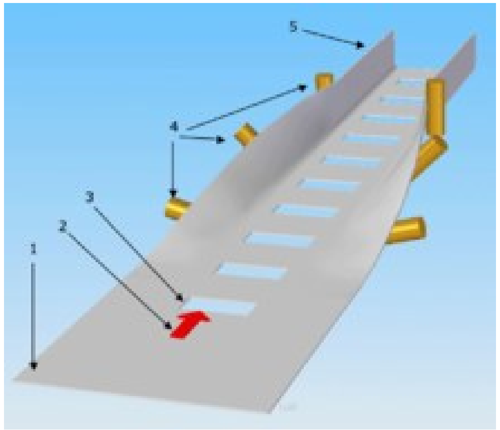
Curved profiles

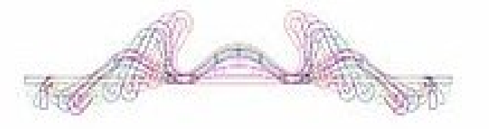
MAIN FOCUS OF GRISPE RESEARCH PROJECT

Investigation of the structural performance of **curved profiles obtained through a continuous roll-forming process (VARIANT A)**. <u>The structural performance shall be evaluated with reference to the bearing capacity of the corresponding flat profiles</u>.

ROLL-FORMING process



https://en.wikipedia.org/wiki/File:Roll_forming.png



https://en.wikipedia.org/wiki/File:Flower_Pattern.jpg

- Type of rolling process involving the <u>**continuous bending of a long strip of sheet metal (typically coiled steel) into a desired cross-section**</u>.
- The strip passed through sets of rolls mounted on consecutive stands, each set performing only an **incremental part** of the bend, until the desired cross-section (profile) is obtained.
- Roll forming is used for producing constant-profile parts with long lengths and in large quantities.-
- Roll-formed sections advantages over **extrusion** process: <u>**components can be lighter, with thinner walls and stronger**</u>, having been work hardened in a **cold state**. <u>The roll forming process is more rapid than extrusion process</u>.

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Curved profiles

MAIN FOCUS OF GRISPE RESEARCH PROJECT

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ROLL-FORMING 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.
- 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)**

Data presented in the current scientific literature refer to variation of the bearing capacity of curved profiles respect to flat profiles around **10%/20%/30%**

Two situations investigated in GRISPE:

- **BENDING CAPACITY**
- **BENDING+AXIAL CAPACITY**

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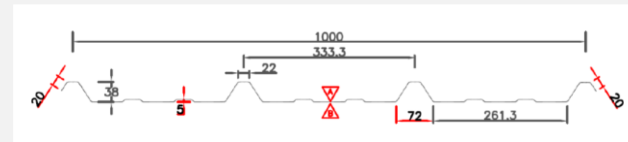
Curved profiles

To evaluate the modifications induced by the roll-forming process on the bearing capacity of flat profiles (into curved ones), the following methodology was adopted inside GRISPE research project.

1

SELECTION OF THE TYPOLOGIES OF PROFILES

- Trapezoidal and sinusoidal sheets



2

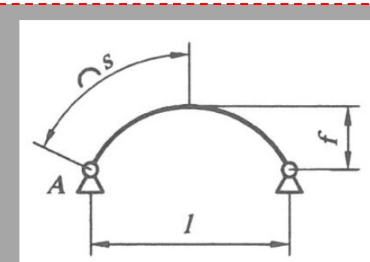
ORGANIZATION OF THE EXPERIMENTAL TESTS' CAMPAIGN

- Definition of the test setup
- Definition of the loading history to be applied
- Execution of tests with two different configurations
- Interpretation of results

3

ELABORATION OF DESIGN MODELS AND GUIDELINES

- Simple indications for design of curved profiles (M; M+N)
- Comparison with prescriptions proposed by DIN standards



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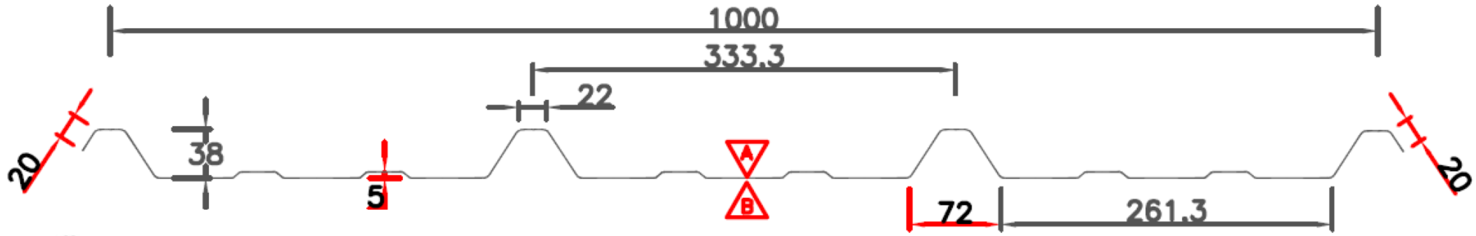
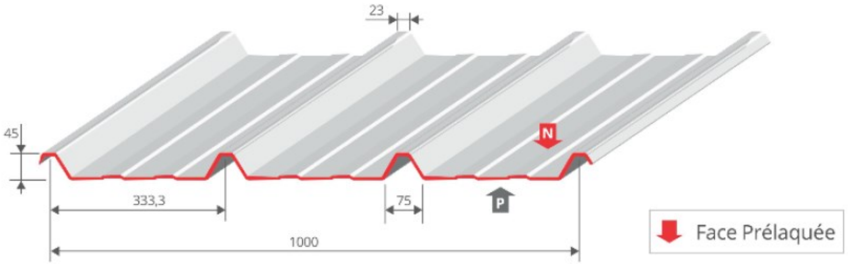
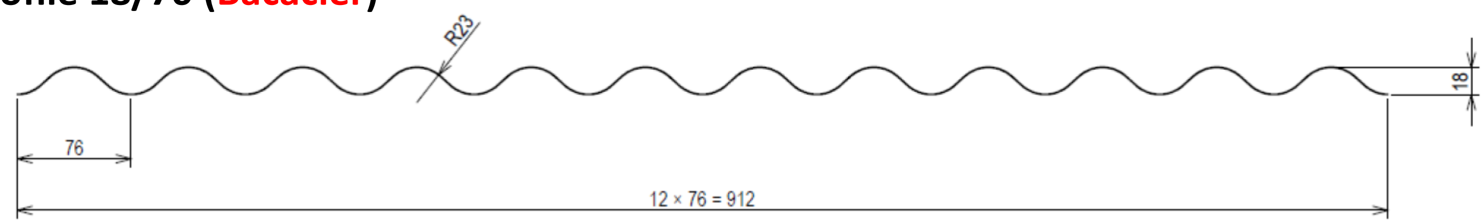
Curved profiles

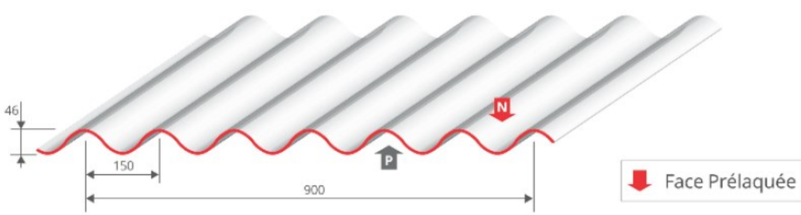
Trapezoidal profile with stiffener 39/333 (Arcelor Mittal)





Sinusoidal profile 18/76 (Bacacier)





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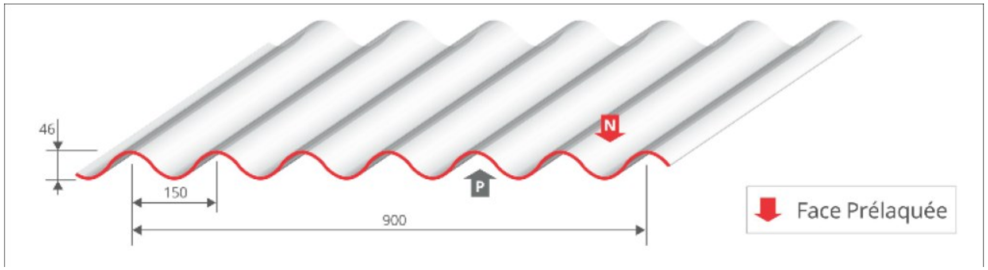
Curved profiles

- **Trapezoidal profile 39/333 (Arcelor Mittal)**

- **Sinusoidal profile 18/76 (Bacacier)**



The tested specimens manufactured by Bacacier and Arcelor Mittal consist of **steel sheetings** according to **EN 10346:2009**, which are formed to curved corrugated sheets and curved trapezoidal sheets using the following section heights and overall widths by **roll-forming**:

Type of profile	Steel grade according to EN 10346:2009	Height [mm]	Width [mm]	Thickness [mm]
Bacacier 18/76	S320GD	18	912	0,63 and 1,00
Arcelor Mittal 39/333	S320GD	39	1000	0,63 and 1,00

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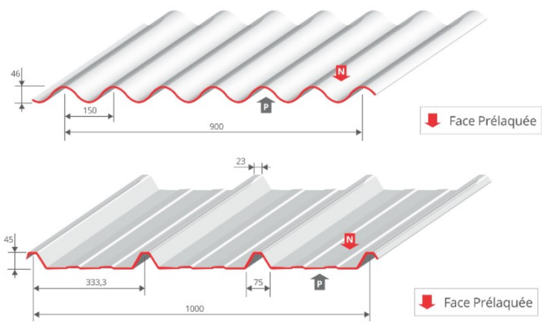
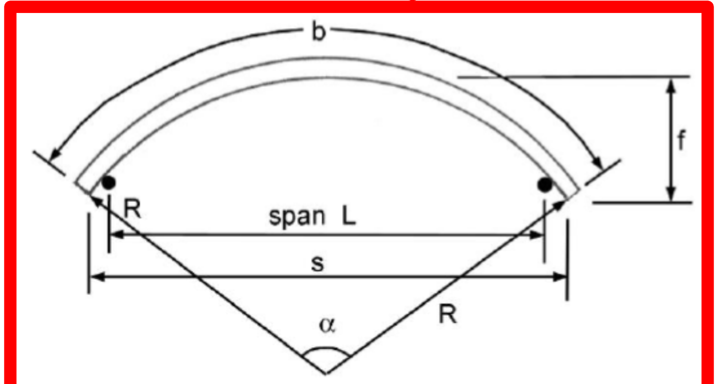
Curved profiles

A wide test program was performed to determine the **<u>load-bearing capacity of curved profiles in bending for different bending radii.</u>**





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

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Curved profiles

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**.

BENDING ACTIONS:
SINGLE SPAN TESTS

- Evaluation of the **mid-span bearing capacity** of the curved profile (with reference to the original flat one).
- Definition of an opportune scheme for restraints
- Application of a uniformly distributed loading action

A

COMBINED BENDING AND AXIAL ACTIONS:
SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS

- Evaluation of the **mid-span bearing capacity** of the curved profile (with reference to the original flat one).
- Definition of an opportune scheme for restraints (arch system, M+N)
- Application of a uniformly distributed loading action

B

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Curved profiles

PRELIMINARY CHARACTERIZATION OF MATERIAL PROPERTIES

- 3 specimens per sheet and per thickness were worked out, from coupons extracted by the tested trapezoidal sheets or directly delivered by the producer.
- **Tensile tests were executed according to EN 6892-1:2009.**
- The determination of the yield strength $\mathbf{R_{p0.2}}$ and the tensile strength $\mathbf{R_m}$ was based upon the measured sheet thickness without zinc coating.

Profile	Nominal thickness t_N [mm]	Core thickness t_K [mm]	Yield strength $R_{p0,2}$ [N/mm²]	Tensile strength R_m [N/mm²]	Elongation at fracture $A_{L=80mm}$ [%]
18/76	0.63	0.53	330	456	26.2
		0.53	329	457	26.0
		0.52	329	456	25.4
	1.00	0.99	342	387	29.3
		1.00	346	387	27.6
		0.99	358	392	27.9
39/333	0.63	0.58	406	430	27.6
		0.58	411	430	26.4
		0.58	408	431	27.0
	1.00	0.96	379	425	24.7
		0.96	384	427	24.5
		0.95	382	426	25.4

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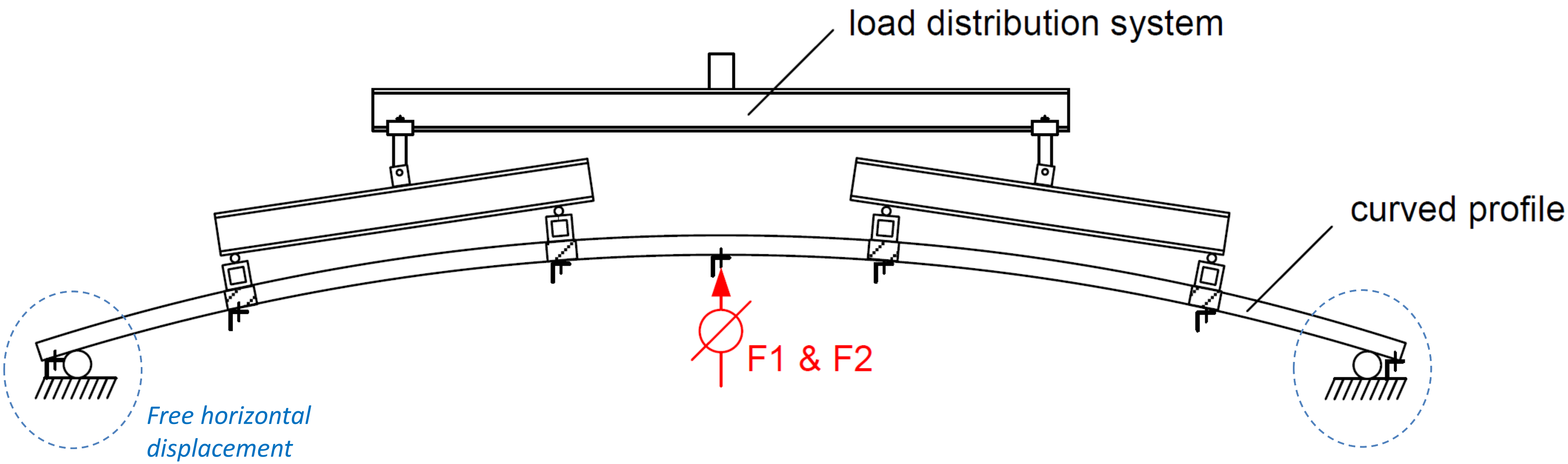
Curved profiles

SELECTION OF THE TESTING CONFIGURATIONS

BENDING ACTIONS: SINGLE SPAN TESTS



- **Determination of MID-SPAN MOMENT RESISTANCE:** **Single span tests** for load case "gravity loading" (positive bending) were performed with uniformly distributed load simulated by **four line loads**.
- The load was introduced into the valleys of the corrugated sheets or the bottom flanges of the trapezoidal sheets via **transverse steel sections and timber blocks**. The transverse steel sections were clamped with the profile.
- The test specimens are placed on supports which are **movable in horizontal direction**. Therefore, **no axial forces can appear in the apex of the curved specimen** where the bending moment becomes a maximum.

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Curved profiles

SELECTION OF THE TESTING CONFIGURATIONS

BENDING ACTIONS: SINGLE SPAN TESTS

Trapezoidal sheet 39/333

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SELECTION OF THE TESTING CONFIGURATIONS

BENDING ACTIONS: SINGLE SPAN TESTS

Sinusoidal sheet 18/76

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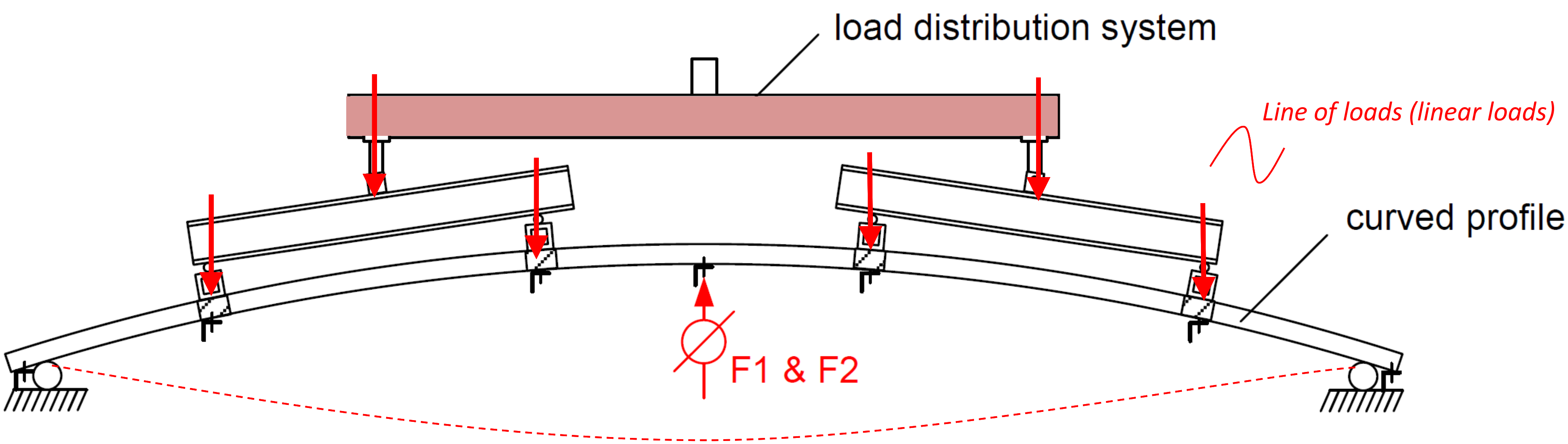
SELECTION OF THE TESTING CONFIGURATIONS

BENDING ACTIONS: SINGLE SPAN TESTS



- In order to reduce the friction between the transverse steel beams at the supports of the load distribution system oil was used.
- The load was applied in **deflection-control** with a speed **of 6 mm/min to 15 mm/min**. The load was measured continuously using a load cell with a maximum capacity of 50 kN.
- The deflections were measured continuously in mid-span by two trip **wire displacement sensors**, under the bottom flanges.

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TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

CORRUGATED SHEETS 18/76

Test	Span [mm]	t_N [mm]	b [mm]	Measured t_N incl. zinc coating [mm]	Measured height f [mm]		Measured width b [mm]	Preload [kN]	F_{max} [kN]
SSP-18-0-063-1[1)]	2000	0.63	2200	0.57	0	0	894	0.29	3.71
SSP-18-0-063-2[1)]				0.56	0	0	895		4.07
SSP-18-0-063-3[1)]				0.56	0	0	890		3.91
SSP-18-30-063-1[1)]			2201	0.59	40	47	890	0.29	3.97
SSP-18-30-063-2[1)]				0.55	40	48	892		3.93
SSP-18-61-063-1[1)]			2204	0.56	45	56	888		4.11
SSP-18-61-063-2[1)]				0.56	48	60	890		4.01
SSP-18-154-063-1[2)]			2229	0.56	120	115	890	0.49	4.98
SSP-18-154-063-2[2)]				0.55	120	120	895		4.86
SSP-18-0-100-1[1)]	3000	1.00	3200	1.00	0	0	887	0.35	-
SSP-18-0-100-2				-	-	-	-	-	-
SSP-18-64-100-1[2)]			3203	0.99	75	60	885	0.49	-
SSP-18-64-100-2[2)]				0.99	70	70	885		-
SSP-18-64-100-3[2)]				0.99	64	60	885		-
SSP-18-64-100-4[2)]				0.99	60	65	885		-
SSP-18-129-100-1[2)]			3214	1.01	110	120	885	0.49	-
SSP-18-129-100-2[2)]				1.00	110	125	885		-
SSP-18-129-100-3[2)]				0.99	90	85	885		-
SSP-18-334-100-1[2)]			3292	1.00	320	300	885	0.80	-
SSP-18-334-100-2[2)]				1.00	325	295	885		-
SSP-18-334-100-3[2]				1.00	315	300	885		-

- Failure occurred by **local buckling of the crest** (corrugated sheets) in the span generally for thickness 0.63 mm.
- Failure by **plastic deformation** occurred in all tests of the corrugated sheets (profile 18/76) with a nominal thickness of **t_N = 1.00 mm**, none F_{max} value is then determined.

The load Fmax indicates the failure load including preload, but without self-weight of the test specimen

*1) test setup for flat profiles, 2) test setup for curved profiles, *) test setup for curved profiles without oil at supports of the load distribution system*

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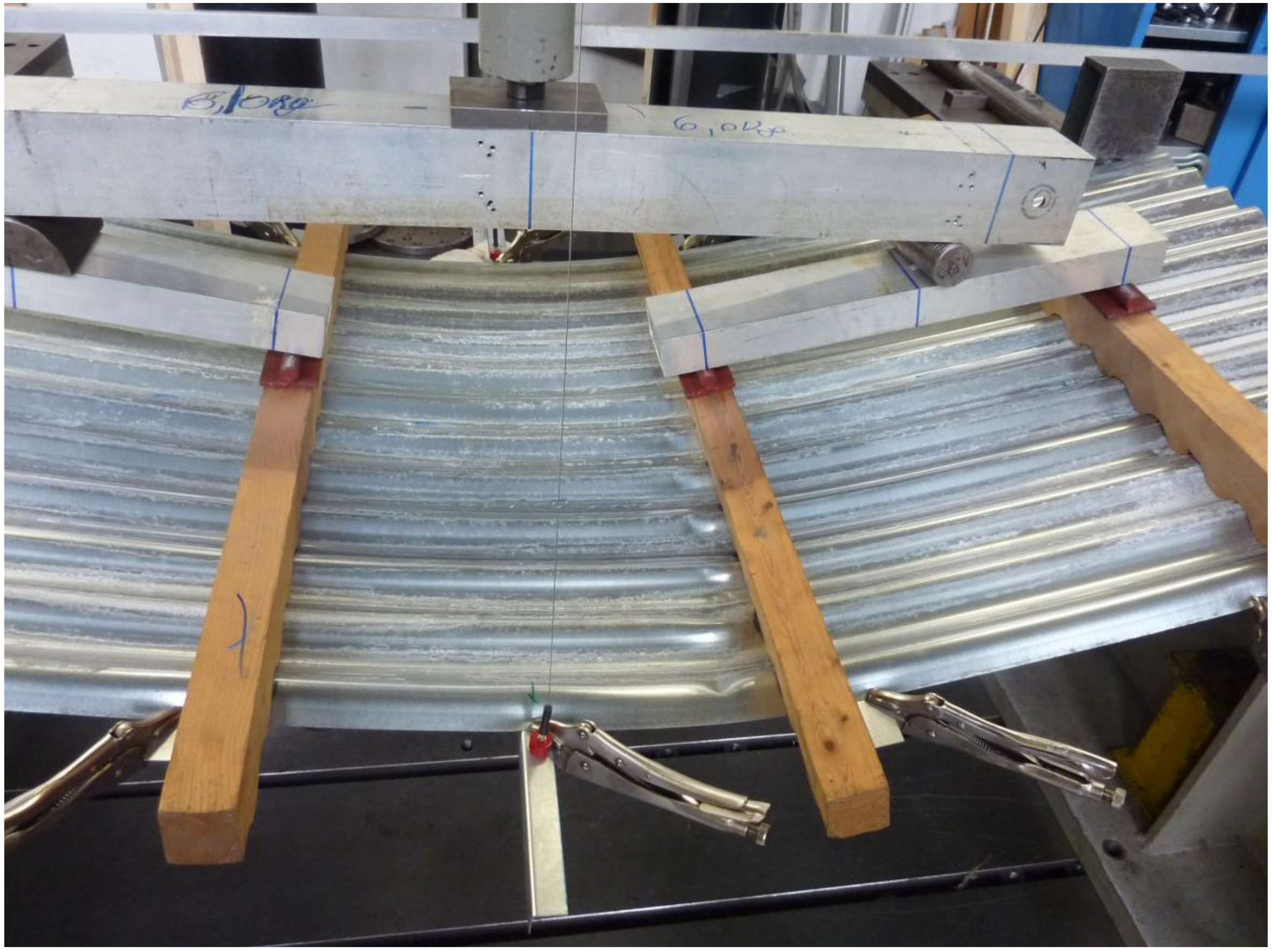
Curved profiles

TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS



CORRUGATED SHEETS 18/76

- Failure mode (**local buckling**) of profile 18/76, t_N = **0.63 mm**

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Curved profiles

TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

CORRUGATED SHEETS 18/76

- Failure mode (**plastic deformation)** of profile 18/76 t_N **= 1.00 mm**

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TESTS’ RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

CORRUGATED SHEETS 18/76

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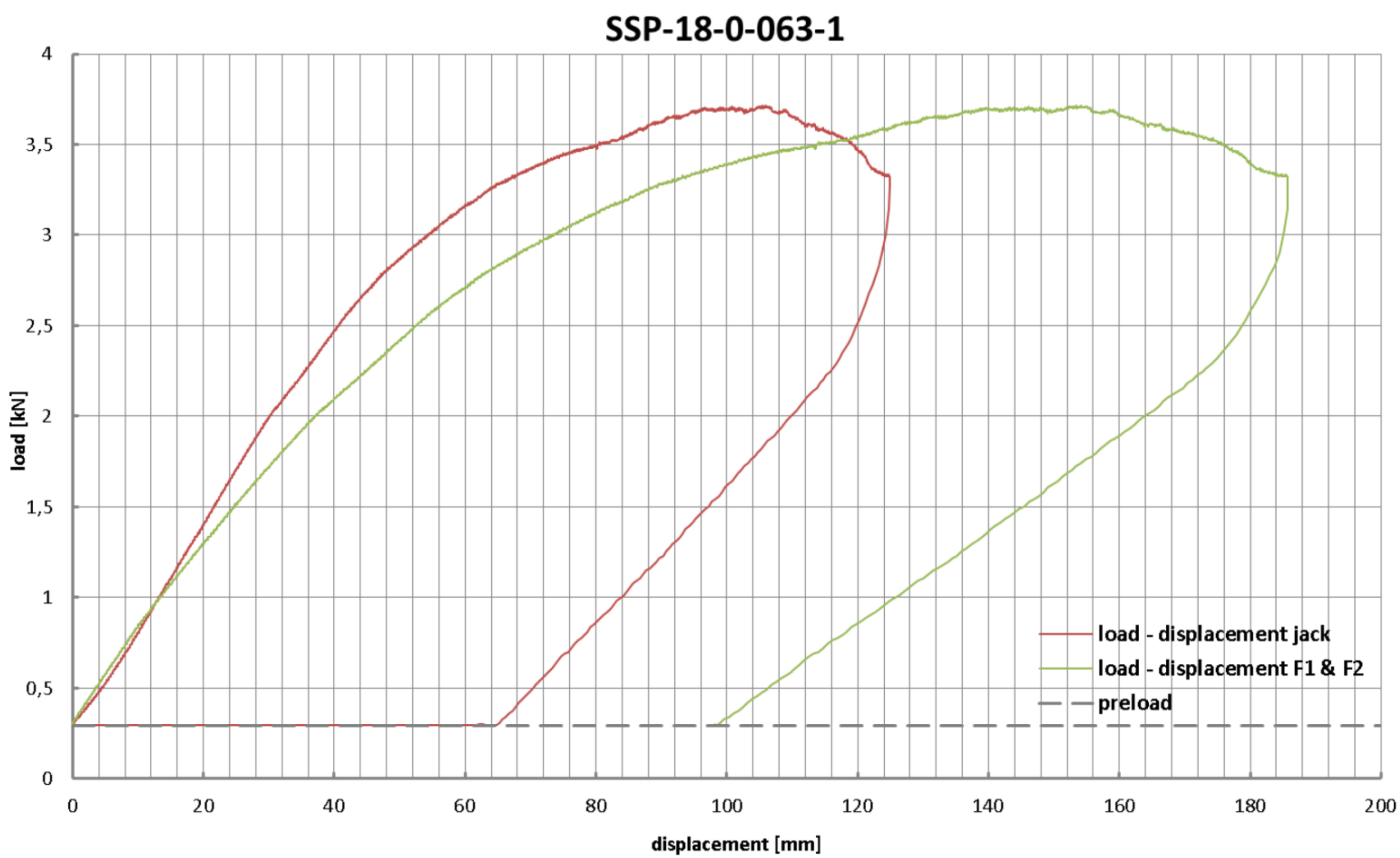
TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

Load-deflection curve (local buckling occurred – 0.63 mm)

CORRUGATED SHEETS 18/76



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Curved profiles

TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

Test	Span [mm]	t_N [mm]	b [mm]	Measured t_N incl. zinc coating [mm]	Measured height f [mm]		Measured width b [mm]	Preload [kN]	F_{max} [kN]
SSP-39-0-063-1[1)]	3000	0.63	3200	0.66	0	0	668	0.43	2.09
SSP-39-0-063-2[1)]				0.65	0	0	660		2.03
SSP-39-0-063-3[2)]				0.65	0	0	670	0.40	1.85
SSP-39-64-063-1[1)]			3203	0.66	37	34	660	0.43	1.92
SSP-39-64-063-2[1)]				0.66	34	32	663		1.96
SSP-39-129-063-1[1)]			3214	0.65	116	116	663	0.48	1.84
SSP-39-129-063-2[1)]				0.65	116	120	661		1.85
SSP-39-217-063-1[2)]			3239	0.64	205	200	670	0.49	1.61
SSP-39-217-063-2[2)]				0.66	205	205	670		1.56
SSP-39-217-063-3[2)]				0.68	210	210	668		1.65
SSP-39-0-100-1[1)]	4000	1.00	4200	1.02	0	0	665	0.71	2.80
SSP-39-0-100-2[1)]				1.01	0	0	668		2.81
SSP-39-111-100-1[1)]			4208	1.01	74	82	668		2.78
SSP-39-111-100-2[1)]				1.02	74	80	668		2.72
SSP-39-223-100-1[2)]			4232	1.02	190	190	670	0.49	2.81
SSP-39-223-100-2[2)]				1.03	190	190	670		2.82
SSP-39-380-100-1[2)]			4291	1.03	320	327	670	0.49	2.82
SSP-39-380-100-2[2)]				1.04	325	315	670		2.85

Trapezoidal Sheet 39/333

Failure occurred by **local buckling of upper flange** (trapezoidal sheets) in the span; in this case no problem of plastic deformation like in the case of sinusoidal sheet.

The load F_{max} indicates the failure load including preload, but without self-weight of the test specimen

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Curved profiles

TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS

Trapezoidal Sheet 39/333

- Failure mode (**local buckling of the upper flange**) of profile 39/333 with arch stitch h = 217 mm

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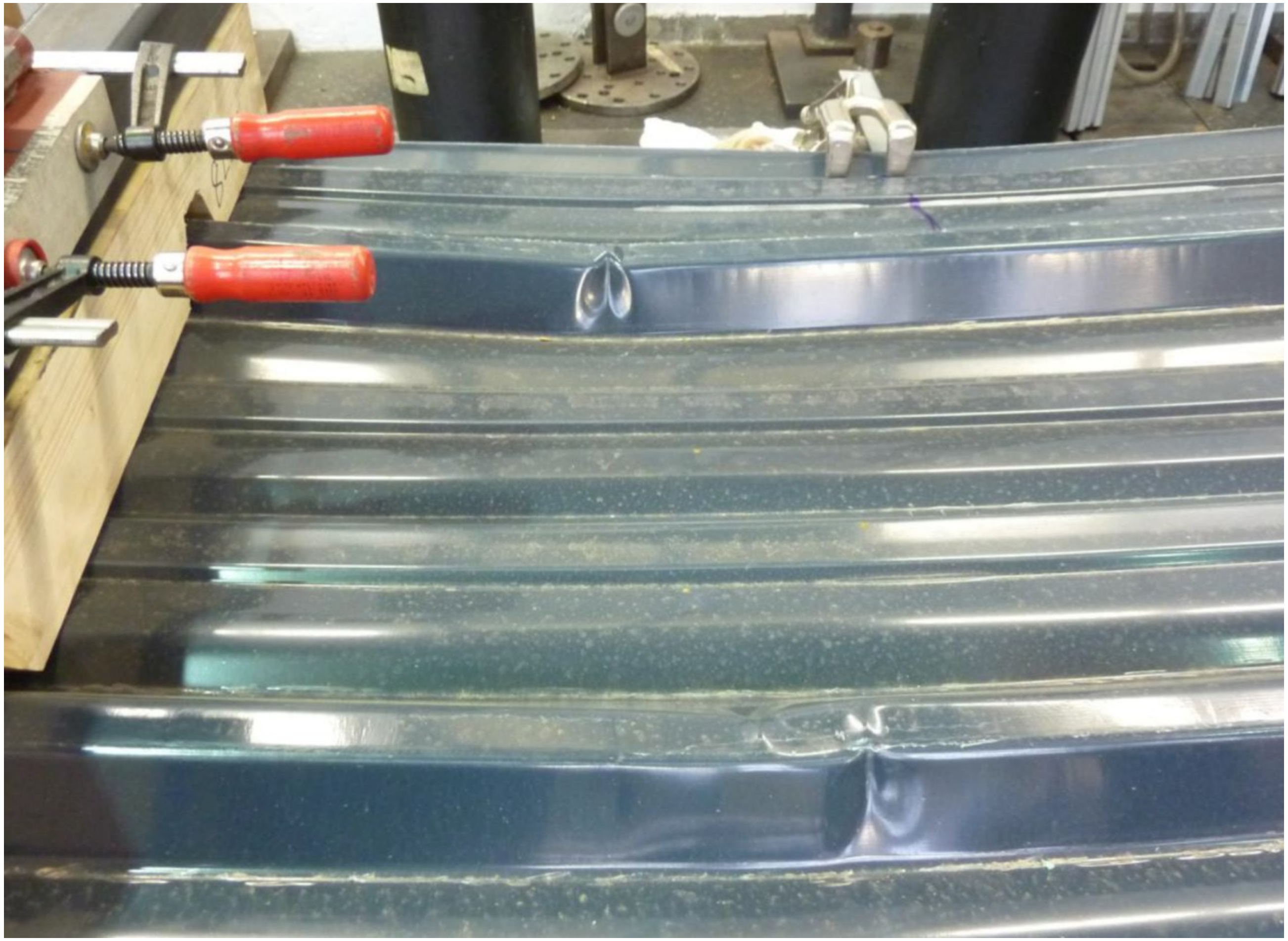
TESTS' RESULTS AND INTERPRETATION

BENDING ACTIONS: SINGLE SPAN TESTS



Trapezoidal Sheet 39/333

- Failure mode (**local buckling of the upper flange**) of profile 39/333

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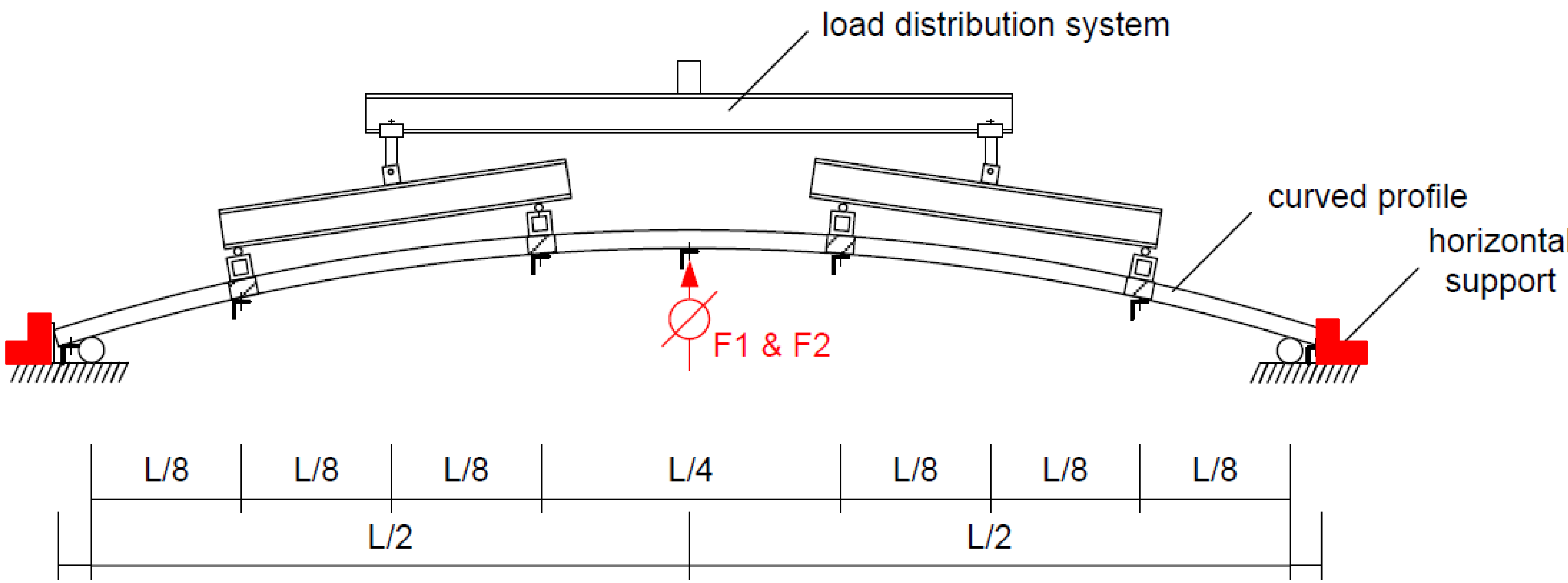
Curved profiles

SELECTION OF THE TESTING CONFIGURATIONS

COMBINED BENDING AND AXIAL ACTIONS: SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS



- Tests performed on curved profiles placed on **horizontally fixed supports**.
- The profile works as an **ARCH**, stressed by **bending moments and axial combined forces**.
- By varying the span of the specimen, different slopes are performed and consequently **different ratios bending moment/axial compression**.

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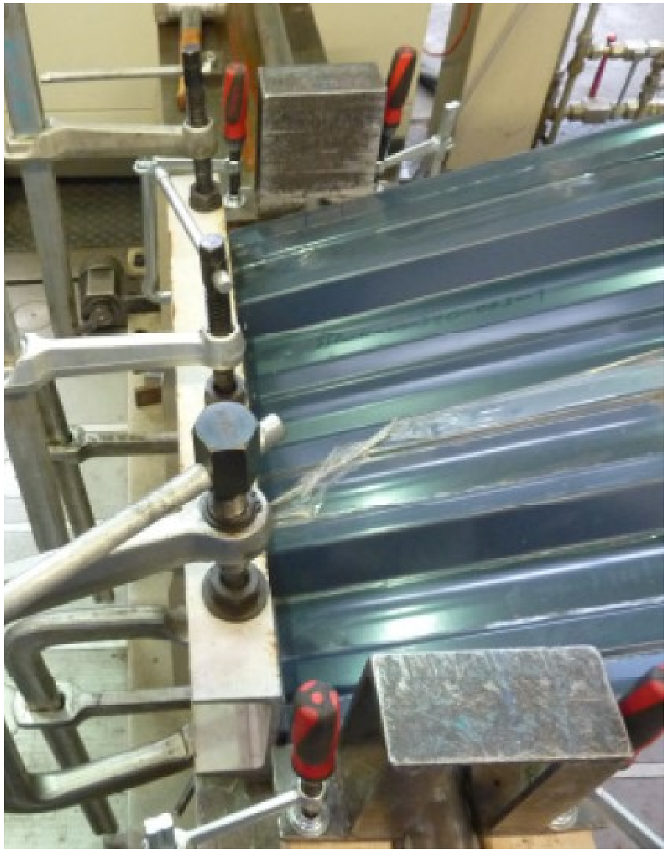
Curved profiles

SELECTION OF THE TESTING CONFIGURATIONS

COMBINED BENDING AND AXIAL ACTIONS:
SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS



The project has received financial support from the European Community (RFCS programme) under grant agreement No 754092

Curved profiles

TESTS' RESULTS AND INTERPRETATION

COMBINED BENDING AND AXIAL ACTIONS: SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS

Results of single span tests of profile 39/333 with horizontal support

Test	Span [mm]	Measured t_N incl. zinc coating [mm]	Measured height f [mm]		Measured width b [mm]	Preload [kN]	F_{max} [kN]
SSP-H-39-217-063-1[1)]	3000	0.66	200	210	670	0.49	9.12
SSP-H-39-217-063-2[1)]		0.66	205	210	670		8.95
SSP-H-39-380-063-1[1)]	4000	0.66	330	350	670	0.49	9.49
SSP-H-39-380-063-2[1)]		0.66	340	350	670		11.43
SSP-H-39-380-063-3[1)]		0.66	335	345	370		11.03
SSP-H-39-576-063-1[1)]	5000	0.65	460	465	665	0.49	5.67
SSP-H-39-576-063-2[1)]		0.67	450	455	668		5.17
SSP-H-39-576-063-3[1)]		0.67	460	465	665		6.83

Plastic deformations were observed in correspondence of the horizontal supports were the sheet is fixed

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TESTS' RESULTS AND INTERPRETATION

COMBINED BENDING AND AXIAL ACTIONS: SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS

Trapezoidal Sheet 39/333

- Failure mode (**buckling of the arch**) for arch stitch h = 217 mm and h = 380 mm

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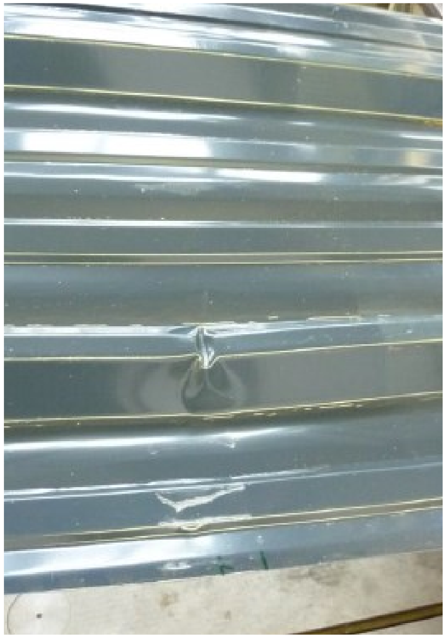
TESTS' RESULTS AND INTERPRETATION

COMBINED BENDING AND AXIAL ACTIONS: SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS

Trapezoidal Sheet 39/333

- Failure mode for specimen SSP-H-576-063-1, side view



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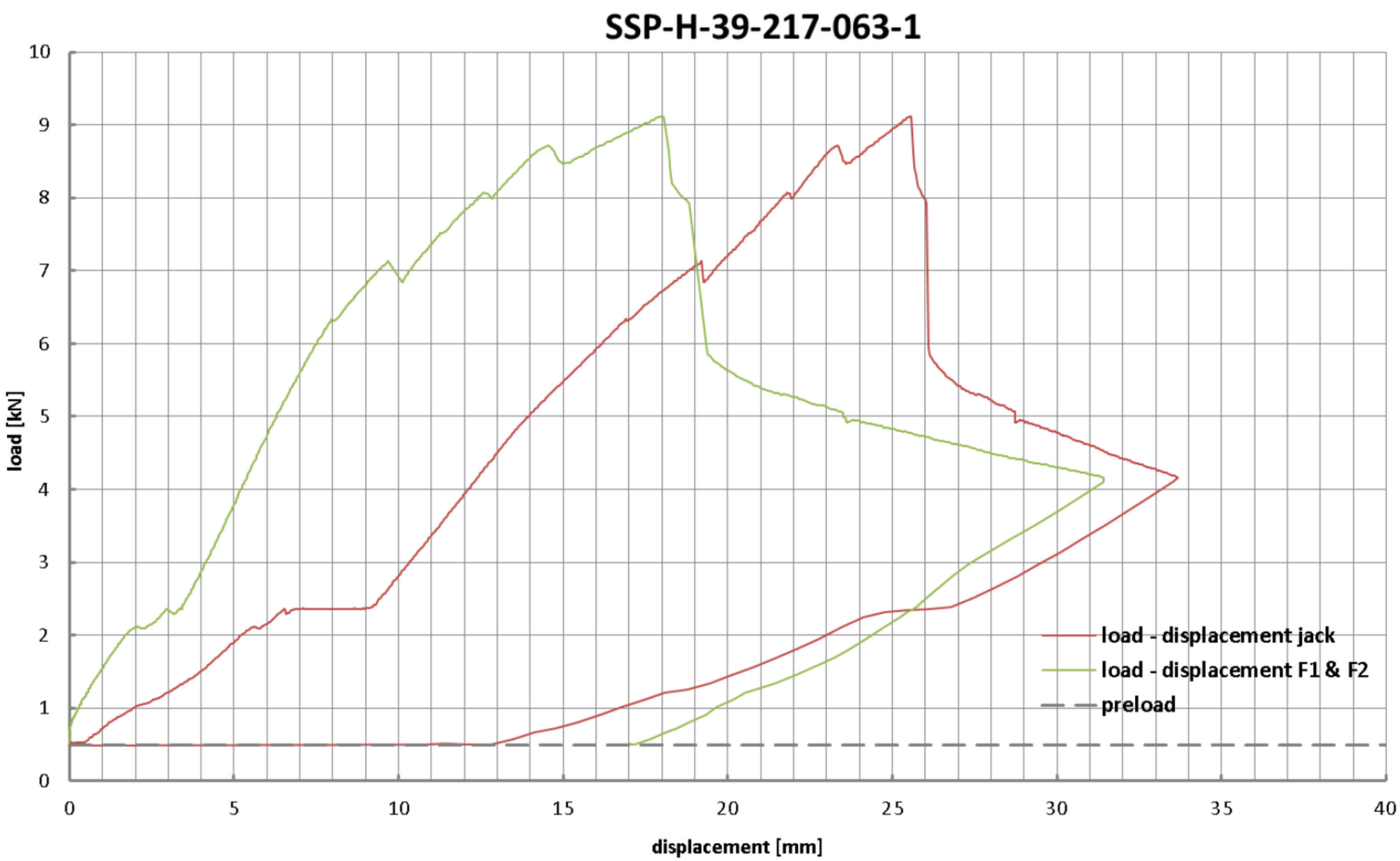
Curved profiles

TESTS' RESULTS AND INTERPRETATION

COMBINED BENDING AND AXIAL ACTIONS: SINGLE SPAN TESTS WITH HORIZONTAL SUPPORTS

Load-Deflection curve



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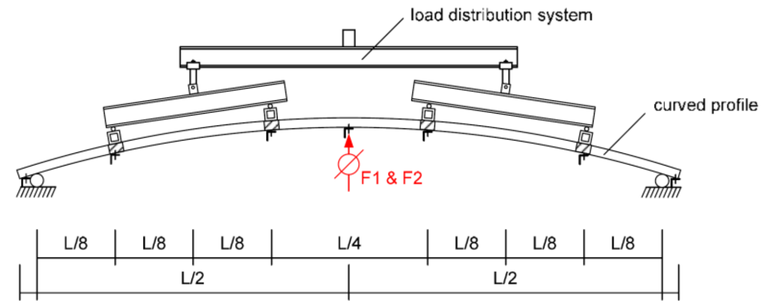
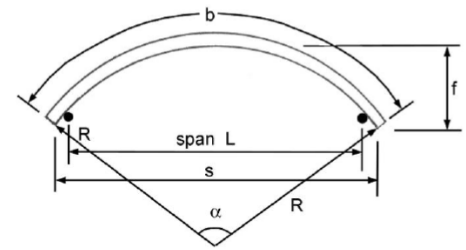


SPECIMENS SUBJECTED TO ONLY BENDING ACTIONS

Evaluation of the mid-span bending resistance

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



- $M_{c,Rk,F}$ *characteristic bending moment in span (kNm/m)*
- $F_{u,k}$ *characteristic load in kN (including preload)*
- b_V *width of the specimen (here: b_V = 0,912 or 1,00 m)*
- L_V *length of the specimen (here: L_V = 2,20 or 3,20 or 4,20 m)*
- *L span length (here: L = 2,00 or 3,00 or 4,00 m)*

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

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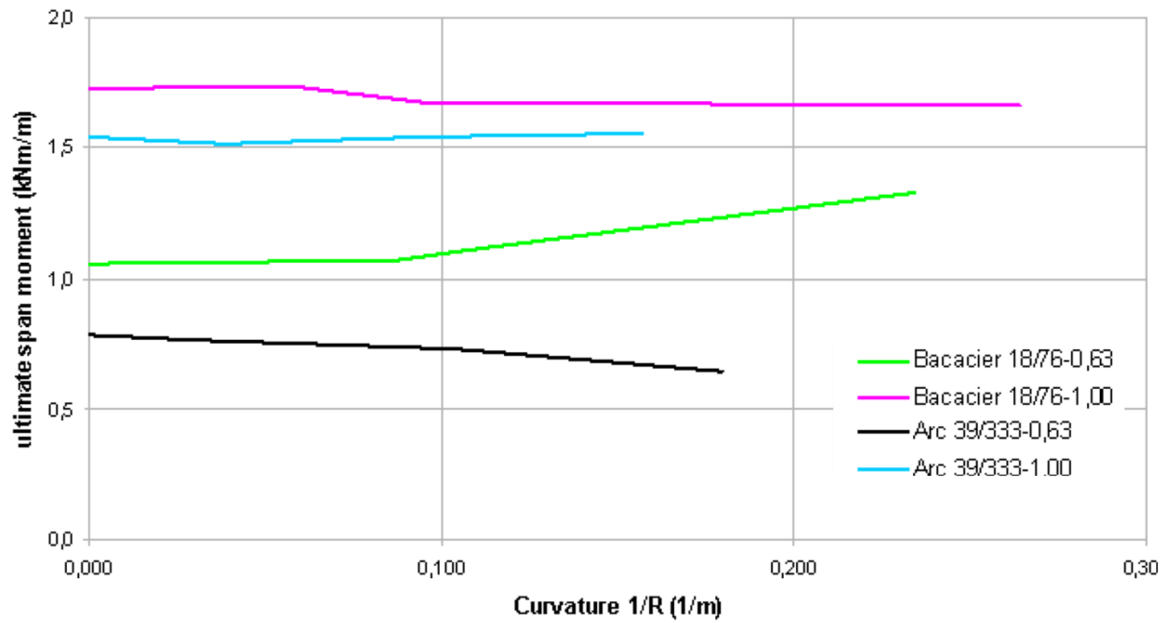
Curved profiles

SPECIMENS SUBJECTED TO ONLY BENDING ACTIONS



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

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Curved profiles

SPECIMENS SUBJECTED TO ONLY BENDING

Design proposition for curved profiles: conclusions coming from the analysis of tests 'results

1. The curving process by bending or by roll-forming creates **plastic deformations in the extreme fibres of the cross section**. This generates internal stresses that can influence the bending moment capacity of the profile. Anyway, **test results evidenced a rather small and not uniform influence on the bearing capacity.**
2. **For the profiles with thickness 1,0 mm, the curvature (1/R) doesn't change the bending moment capacity**.
3. **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

4. 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.

$$M_{c,Rk,F}\,(\text{curved profiles}) = 0.90 \cdot M_{c,Rk,F}\,(\text{flat profiles})$$

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Curved profiles

SPECIMENS SUBJECTED TO ONLY BENDING ACTIONS

Design proposition for curved profile conclusions concerning tests 'results

Comparison between the values directly derived from experimental tests on curved profiles and assumed design value (design proposition elaborated in GRISPE)- the design proposition for bending is **CONSERVATIVE**

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

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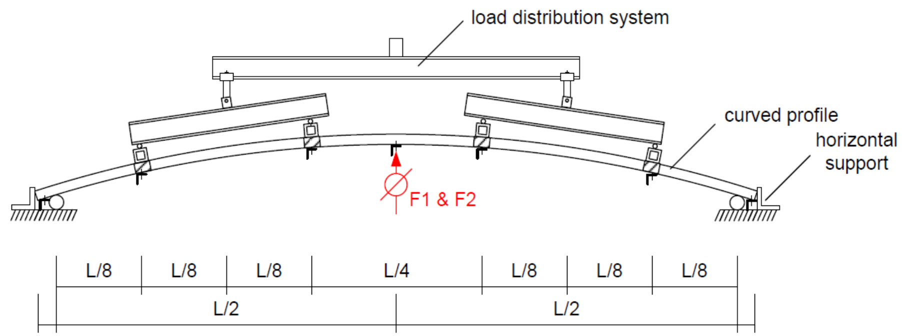
Curved profiles

SPECIMENS SUBJECTED TO COMBINED M+N

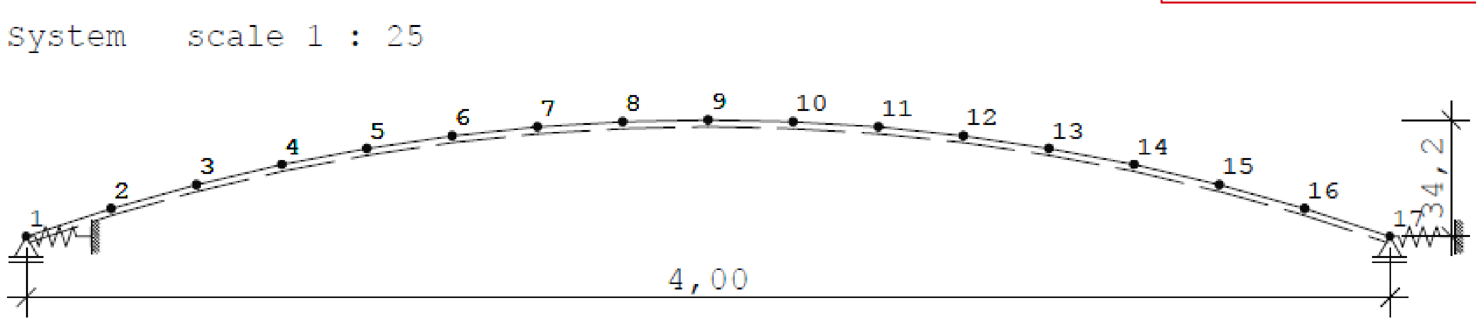
- The static system of the test specimen is **hyperstatic**; the internal forces don't depend only upon the applied load, but also on the **stiffness parameters** of the beam and its supports.
- The statistic evaluation is applied on the failure loads in order to determine an individual characteristic (failure) load for each subset.



The problem in this case is more complicated and shall be solved in an indirect way, since the internal forces depend on several factors that are not immediately known, such as:

- **EA and EJ of the profile section**
- **K (C) of the horizontal restraints positioned at the ends of the profile.**

NUMERICAL SIMULATIONS



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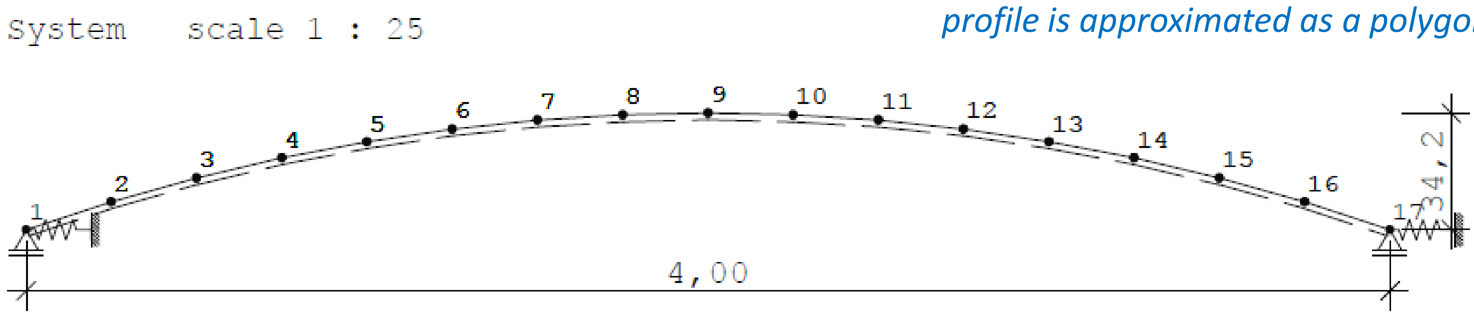
Curved profiles

SPECIMENS SUBJECTED TO COMBINED M+N

MODEL for SIMULAIONS: The curved profile is approximated as a polygonal line



PARAMETERS CONSIDERED IN THE NUMERICAL SIMULATIONS

- **Spring stiffness of the horizontal support**
  - fixed (C = ∞)
  - C = 20 kN/m/cm
  - C = 10 kN/m/cm
  - Cind (29 > 88 kN/m/cm)

Note: neglecting the displacements at the ends leads to unsafe values (bending underestimated)

The spring stiffness Cind is different for each arch; this value is calibrated according to the condition, that the calculated vertical deflection at summit is the same as measured in the test family.

- **Cross section properties**
  - gross cross section Ag , Jg
  - effective cross section Aef , Jef

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Curved profiles

CALIBRATION OF SUPPORT STIFFNESS

1. For each test **the deflection at mid span** is evaluated, as well as the **ultimate load corresponding to failure;** as a consequence, the overall stiffness of the specimen $\mathbf{C_{f,i}}$ can be evaluated as:

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

2. The mean value of the stiffness of the specimens achieved form tests $\mathbf{C_f}$ is considered as representative for this family and can be evaluated as:

$$C_f = \mathrm{mean}(C_{f,i})$$

3. 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 with the width of the test specimen.

$$f_{eq} = F_{u,k} / C_f \cdot b_v$$

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		
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		

*Calculating the arch with the 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 feq**. **This spring stiffness of the horizontal support is the above mentioned Cind.***

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Curved profiles

SPECIMENS SUBJECTED TO COMBINED M+N: Evaluation of internal M/N forces

Test setup/ span	Cross section	spring stiffness at support (kN/m/cm)	Failure load (kN/m)	displacements (cm) f_h (support)	displacements (cm) f_v (summit)	support reactions (kN/m) R_h	support reactions (kN/m) R_v	M- / N-values (kNm/m, kN/m) at load point near to summit: max M	M- / N-values (kNm/m, kN/m) at load point near to summit: corresp N	M- / N-values (kNm/m, kN/m) at support: max N
1 / 3,00 m	gross	fixed	11,03	0,00	0,11	20,46	5,52	0,17	20,62	21,19
		68,0	11,03	0,28	1,67	18,81	5,52	0,49	18,98	19,60
		20,0	11,03	0,79	4,55	15,76	5,52	1,08	15,94	16,65
		10,0	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
		88,0	11,03	0,22	1,66	19,64	5,52	0,33	19,80	20,40
		20,0	11,03	0,88	5,33	17,57	5,52	0,73	17,74	18,39
		10,0	11,03	1,55	9,08	15,46	5,52	1,14	15,64	16,35
2 / 4,00 m	gross	fixed	12,77	0,00	0,08	19,13	6,39	0,25	19,35	20,16
		62,0	12,77	0,30	1,45	18,64	6,39	0,40	18,87	19,70
		20,0	12,77	0,88	4,10	17,69	6,39	0,71	17,92	18,80
		10,0	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
		79,0	12,77	0,24	1,44	18,88	6,39	0,33	19,11	19,93
		20,0	12,77	0,91	4,51	18,29	6,39	0,51	18,53	19,37
		10,0	12,77	1,76	8,33	17,56	6,39	0,75	17,80	18,68
3 / 5,00 m	gross	fixed	6,62	0,00	0,02	9,23	3,31	0,16	9,36	9,81
		29,0	6,62	0,31	1,34	9,01	3,31	0,26	9,14	9,60
		20,0	6,62	0,45	1,91	8,91	3,31	0,30	9,04	9,50
		10,0	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
		33,0	6,62	0,28	1,33	9,12	3,31	0,21	9,09	9,70
		20,0	6,62	0,45	2,07	9,05	3,31	0,24	9,18	9,63
		10,0	6,62	0,89	3,91	8,88	3,31	0,31	9,01	9,48

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Curved profiles

DIN 18807 APPROACH FOR THE EVALUATION OF M/N INTERACTION

In case of compression force the following equation can be applied:

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

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

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

PROBLEM

- In the **M-N-interaction formula**, the coefficient α should be limited to 1 if **α > 1**.
- Anyway, 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 organizing it into 4 different steps.**

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Curved profiles

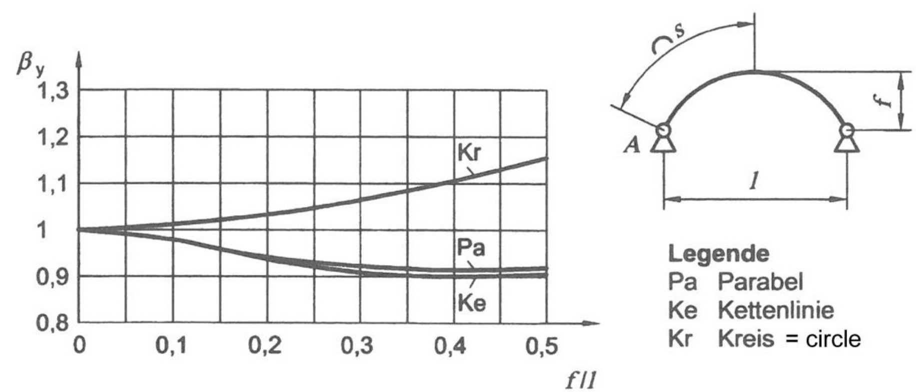
DIN 18807 APPROACH FOR THE EVALUATION OF M/N INTERACTION

- **Step 1**: **Determination of the internal forces of the arch under characteristic failure load (= design load)** under consideration of the horizontal spring stiffness C at the supports (M and N depends on C).

Test setup/ span	Cross section	spring stiffness at support (kN/m/cm)	Failure load	displacements (cm)		support reactions (kN/m)		M- / N-values (kNm/m, kN/m)		
								at load point near to summit		at support
			(kN/m)	f_h (support)	f_v (summit)	R_h	R_v	max M	corresp N	max N
1 / 3,00 m	gross	fixed	11,03	0,00	0,11	20,46	5,52	0,17	20,62	21,19
		68,0	11,03	0,28	1,67	18,81	5,52	0,49	18,98	19,60
		20,0	11,03	0,79	4,55	15,76	5,52	1,08	15,94	16,65
		10,0	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
		88,0	11,03	0,22	1,66	19,64	5,52	0,33	19,80	20,40
		20,0	11,03	0,88	5,33	17,57	5,52	0,73	17,74	18,39
		10,0	11,03	1,55	9,08	15,46	5,52	1,14	15,64	16,35
2 / 4,00 m	gross	fixed	12,77	0,00	0,08	19,13	6,39	0,25	19,35	20,16
		62,0	12,77	0,30	1,45	18,64	6,39	0,40	18,87	19,70
		20,0	12,77	0,88	4,10	17,69	6,39	0,71	17,92	18,80
		10,0	12,77	1,64	7,56	16,45	6,39	1,11	16,69	17,62

Evaluation of the values of M and N corresponding to the failure load

- **Step 2**: **Determination of the buckling length Lcr**. The buckling length of a circle-shaped arch can be found in the literature, for instance DIN 18800 part 2:



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Curved profiles

DIN 18807 APPROACH FOR THE EVALUATION OF M/N INTERACTION

Step 3: **Determination of design resistance to compressive axial force**

$$N_{d,D} = min\left(\sigma_{cd} \cdot A_{ef}; 0{,}8\sigma_{elg} \cdot A_g\right)$$

Ideal buckling force

$$maxN_{dD} = 0{,}8 \cdot \sigma_{elg} \cdot A_g = 0{,}8 \cdot \frac{\pi^2 \cdot E \cdot J_g}{L_{cr}^2}$$

Critical buckling force

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

Slenderness ratio

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

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: **Final interaction M/N and final assessment**

$$\frac{N_D}{N_{d,D}} \cdot \left[1 + 0{,}5 \cdot \alpha \cdot \left(1 - \frac{N_D}{N_{d,D}}\right)\right] + \frac{M_D}{M_{d,D}} \leq 1$$

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Curved profiles

For curved profiles with only bending actions it is 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) 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 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 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**.

Please note that the design model is verified only for arches with symmetric loading.

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Thank you
for your attention

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