GRISPE PLUS

VALORISATION OF KNOWLEDGE
FOR SPECIFIC PROFILED STEEL SHEETS

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DESIGN MANUAL FOR CORRUGATED SHEETING

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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 corrugated steel sheets as developed in the European 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 corrugated steel sheets is based on tests carried out within the European GRISPE project (2013-2016).

The background of this method can be found in the GRISPE project's deliverables D2.5.

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.

Chapter 2 outlines the preliminary considerations that must be taken into account during the predesign phases and the minimum technological requirements that have to be respected including support frame, profiles characteristics and fixing.

Chapter 3 gives the basic technological requirements.

Chapter 4 lists the materials properties of the profiles and of the fasteners.

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

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

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

Chapter 8 gives practical examples of the new design method.

A bibliography and the amendment proposal for EN 1993-1-3 is included.

PREFACE

This Design manual have been carried out with the support of RFCS funding n°754092.

This new 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 Thibault RENAUX and has been discussed in a GRISPE PLUS working group composed by the following members:

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FIGURES & TABLES

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

Figure 1.1.1	JORIS IDE
Figure 1.1.2	JORIS IDE
Figure 1.2.1	JORIS IDE
Figure 1.2.2	Copy of EN 1993-4-1
Figure 1.2.3	Copy of StBK-N5
Figure 1.3.1	KIT / JORIS IDE
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Table 1.3	KIT
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Figure 6.3.1.1	Copy of StBK-N5
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Figure 8.2	JORIS IDE
Figure 8.4.3.1	JORIS IDE
Figure 8.4.3.2	Copy of StBK-N5
Figure 8.5.2	JORIS IDE

CONTENT

SCOPE OF THE PUBLICATION

The aim of this publication is to present the new design method for corrugated steel sheets, in accordance with [1] that has been proposed for inclusion in [2].

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 [1].

NOTATIONS

In addition to notations of EN 1993-1-3, the following symbols are used:

I_y:	moment of inertia [mm4/mm]
R:	curvature radius |mm]
W_y:	section modulus [mm^3/mm]
η:	coefficient of detailed method for calculate bending moment resistance [-]
σ_{elr}:	buckling stress [N/mm²]
σ_c:	reduced stress [N/mm²]

1. INTRODUCTION

1.1. Type of corrugated steel sheets

This design manual deals with corrugated steel sheets (see Figure 1.1.1 below). Corrugated steel sheets have a continuous curvature instead of flat sections like trapezoidal profiles.

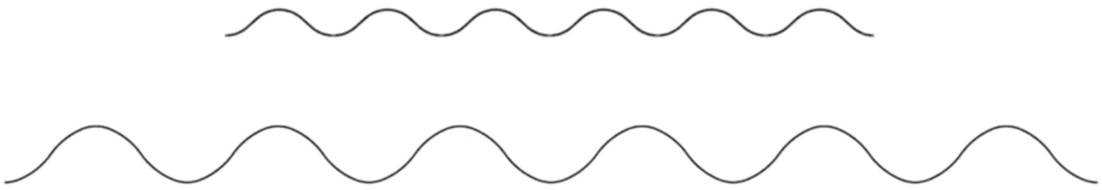


Figure 1.1.1 *– Typical geometry of corrugated steel sheets.*

Two modes of fixing are currently used in Europe: fastening in the crest or fastening in the valley, like Figure 1.1.2 below:

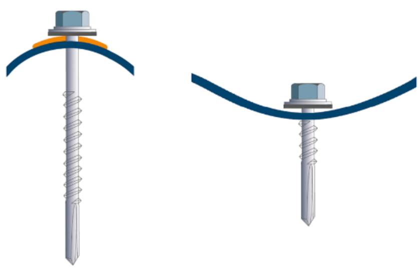


Figure 1.1.2 *- Fastening in the crest (left part) and fastening in the valley (right).*

1.2. State of the art

The standard [2] doesn't cover the design of corrugated steel sheet, one of the oldest cold formed steel sheets used to daily realize cladding and roofing envelop of building in Europe.

Therefore, it seems necessary to provide the engineer with design tools that avoids resorting to test campaigns. It was the aim of one of the parts of GRISPE Project.

Conventional bending theory can be used to design a corrugated steel sheet, because no local buckling is expected due to the continuous curvature of such product.

Based on a classical analyze of geometrical inertia, it's first possible to establish a method to determine the moment of area of a typical geometry of corrugated steel sheets, like in Figure 1.1.1, considering the following parameters:

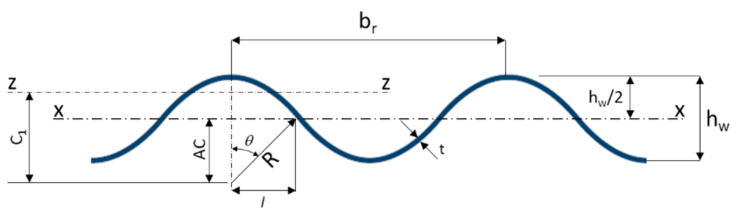


Figure 1.2.1 *– Geometrical parameters for classical moment of area of corrugated sheet.*

The moment of area can be determinate applying:

- Radius of curvature: $R = 5 \cdot h_w / 4$;
- Length $l = h_w$;
- Angle θ: $\sin\theta = l/R$;
- Distance between center of gravity of the arc ('z-z' axis) and arc center: $C_1 = (R \cdot \sin\theta)/\theta$;
- Distance between the arc center and the axis 'x-x': $AC = R - (h_w/2)$;
- And finally, the moment of area for a quarter of the gross section:

$$I'_{xx} = R^3 \cdot \left(\frac{\theta + \sin\theta \cdot \cos\theta}{2} - \frac{(\sin\theta)^2}{\theta}\right) + (R \cdot \theta)\left[C_1 - \left(R - \frac{h_w}{2}\right)\right]^2$$

And therefore, the section modulus is obtained by:

$$W_{xx} = \frac{4 \cdot I'_{xx} \cdot t}{b_R \cdot h_w/2}$$

In the German standard [3], some static characteristics are given, in a parameter range of the height/radius ratio where no buckling is expected.

In article [4], we can find a calculation which is developed from the comparison with FE calculations. This procedure, corresponding to the usual procedure for buckling problems, contains parameters developed from the comparison with FE calculations and allowing to calculate a reduction factor χ to be applied for determine the bearing stress of a cylinder segment. It remains to check whether corrugated profiled sheets fit into the curvature of field of CTICM study. The different steps are shown in the following:

- Parameter of curvature: $Z = b^2/(R \cdot t)$, with b the arc length (width of corrugated sheet), R the radius of curvature and t the thickness;

- Euler critical stress:

$$\sigma_E = \frac{\pi^2 \cdot E}{12(1-\upsilon^2)} \cdot \left(\frac{t}{b}\right)^2;$$

- Buckling coefficient:

$$k_c^{(Z)} = \frac{k_c^{plate}}{2}\left(1 + \sqrt{1 + \frac{48 \cdot (1-\upsilon^2)}{\pi^4 \cdot \left(k_c^{plate}\right)^2} \cdot Z^2}\right) \text{ and } k_c^{plate} = 4;$$

- Critical buckling stress:

$$\sigma_{cr}^{(Z)} = k_c^{(Z)} \cdot \sigma_E;$$

- Reduced slenderness: $\bar{\lambda} = \sqrt{f_y/\sigma_{cr}^{(Z)}}$;

- Intermediate parameters for the reduction factor χ: $\overline{\lambda_0} = 0{,}33$, $\beta = 0{,}73$ and α_Z given by a table in function of Z;

- Reduction factor:

$$\chi = \frac{2\beta}{\beta+\bar{\lambda}+\sqrt{(\beta+\bar{\lambda})^2-4\beta\left(\bar{\lambda}-\alpha_Z(\bar{\lambda}-\bar{\lambda}_0)\right)}};$$

- Bearing stress: $\sigma_u = \chi \cdot f_y$.

An example of the proposed calculation method is given to illustrate.

The standard [5], Eurocode standard for silos, gives relations to determine the stiffness, the second moment of area and the moment resistance, for corrugated sheets as follow:

- Stiffness for axial compression:

$$C_y = Et\left(1+\frac{\pi^2 d^2}{4l^2}\right);$$

- Second moment of area: $I_y = 0{,}13 \cdot t \cdot d^2$ with notation from shell structures and $I_x = 0{,}13 \cdot t \cdot h_w^2$ in [2] notation type;
- With the following geometrical parameter:

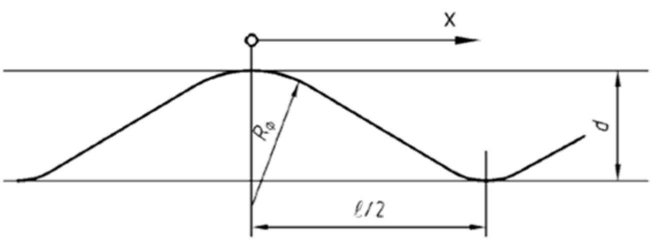


***Figure 1.2.2** – Geometrical parameters for EN 1993-4-1.*

We can deduce that moment resistance $M_{c,Rd}$ can be obtained with the following relation:

$$M_{c,Rd} = \frac{0{,}13 \cdot t \cdot h_w^2}{\frac{h_w}{2}} \cdot \frac{f_{yb}}{\gamma_{M0}} = \frac{0{,}26 \cdot t \cdot h_w \cdot f_{yb}}{\gamma_{M0}}$$

The Swedish code [6] contains an approach to determine the ultimate bending moment for corrugated profiles with sinusoidal or similar cross section, considering local buckling aspect.

Depending of the ratio between the curvature radius r and the thickness t of the sheet, calculation of the characteristic moment is different.

If $r/t \leq 0{,}04 \cdot E/f_{yb}$: the cross section needs not be checked for the local buckling and the characteristic bending moment is determined with: $M_{c,Rk} = W_y \cdot f_{yb}$.

If $r/t > 0{,}04 \cdot E/f_{yb}$: the characteristic bending moment should be calculated using a reduced compressive stress applying following steps:

- Coefficient η:$\eta = 0{,}19 + 0{,}67/\sqrt{1 + r/(100 \cdot t)}$;
- Reduced buckling stress: $\sigma_{elr} = 0{,}60 \cdot \eta \cdot E \cdot t/r$;
- Slenderness ratio: $\alpha = \sqrt{f_{yb}/\sigma_{elr}}$;
- For $\alpha \leq 0{,}30$: $\sigma_c = f_{yb}$;
- For $0{,}30 < \alpha < 1{,}10$: $\sigma_c = (1{,}126 - 0{,}419 \cdot \alpha) \cdot f_{yb}$;
- For $1{,}10 \leq \alpha$: $\sigma_c = \frac{0{,}8}{\alpha^2} \cdot f_{yb}$.

And finally: $M_{c,Rk} = W_y \cdot \sigma_c$.

Figure 1-2-3 below presents the evolution of the ultimate compressive stress in function of the slenderness ratio used in [6]:

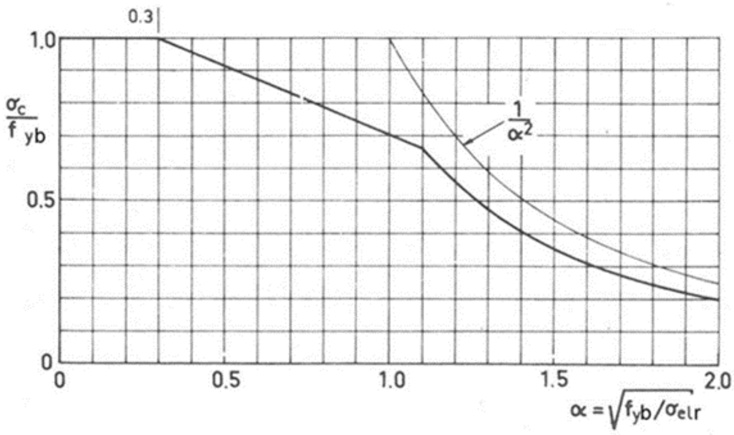


Figure 1.2.3 *– Ultimate compressive stress with respect to local buckling of the cylinder part of the profile.*

The moment of inertia, which is used to calculate deformations in serviceability limit state, should be calculated using the same procedure as for bending moment, but with reduced stress $f_{yb}/1{,}5$.

1.3. Main results of GRISPE

The aim of the GRISPE project was to develop a design model to calculate the load-bearing capacity between support and on support, and under local loads (end support resistance).

Two types of profiles representative of the mostly used corrugated steel sheets were selected for testing:

- 18 mm depth with radius of 23 mm and 76 mm pitch as showed in Figure 1.3.1 below:

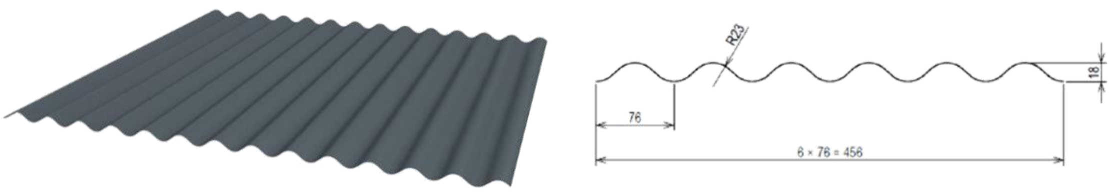


Figure 1.3.1 *– Small corrugated steel sheet selected for testing.*

- 46 mm depth with radius of 29,25 mm and 150 mm pitch as showed in Figure 1.3.2 below:

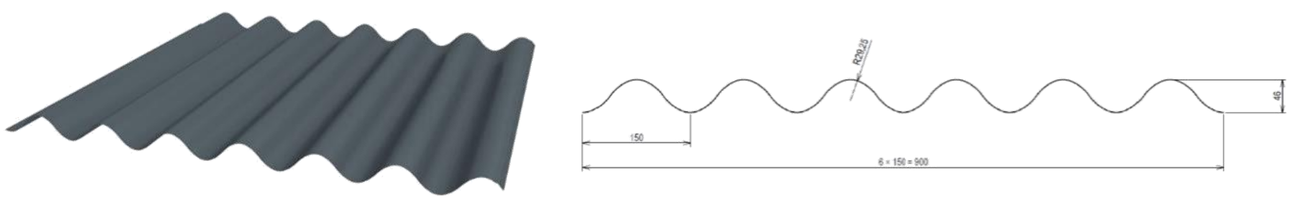


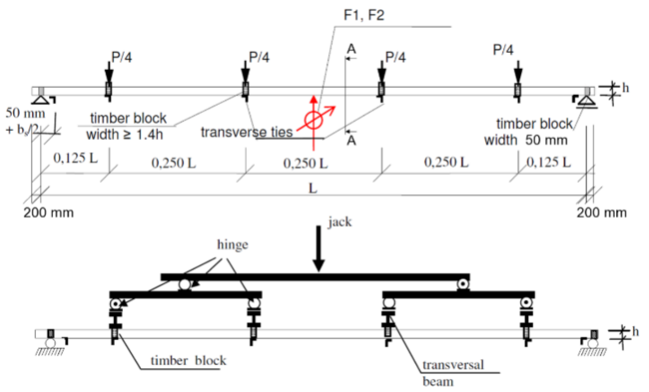
Figure 1.3.2 *– Big corrugated steel sheet selected for testing.*

A total of 95 corrugated sheeting tests were carried out to determine the bending moment capacity and the load bearing capacity in span and at intermediate supports (combination of bending moment and support reaction), and including single span tests for load case “gravity loading” (positive bending), internal support tests for load case “gravity loading” and “uplift loading” and end support tests and shear tests for load case “gravity loading” for the determination of the characteristic values of the end support resistance.

Type of test	Thickness [mm]	Support width [mm] / Fastening	Span [mm]		Number of tests	
			18/76	46/150	18/76	46/150
Single span test with gravity loading	0.63	-	1500	2000	3	6
	1.00	-	2000	3000	3	3
Internal support tests with gravity loading	0.63	10	400	600	2	2
			800	1000	2	2
		40	400	600	2	2
			800	1000	2	2
	1.00	10	400	600	2	2
			1000	1200	2	2
		40	400	600	2	2
			1000	1200	2	2
Internal support tests with uplift loading	0.63	valley	400	600	2	2
			800	1000	2	2
		crest	400	600	2	2
			800	1000	2	2
	1.00	valley	400	900	2	2
			1000	1400	2	2
		crest	400	900	2	2
			1000	1400	2	2
End support tests with gravity loading	0.63	-	1000	1050	4	3
	1.00	-	1000	1050	4	3
Shear test	0.63	-	1000	1000	1	1

Table 1.3 *– Tests campaign performed during GRISPE project.*

Internal support tests for load case “uplift loading” were dived in two series: one for fixing in the crest and the other for fixing in valley (see paragraph 1.1).



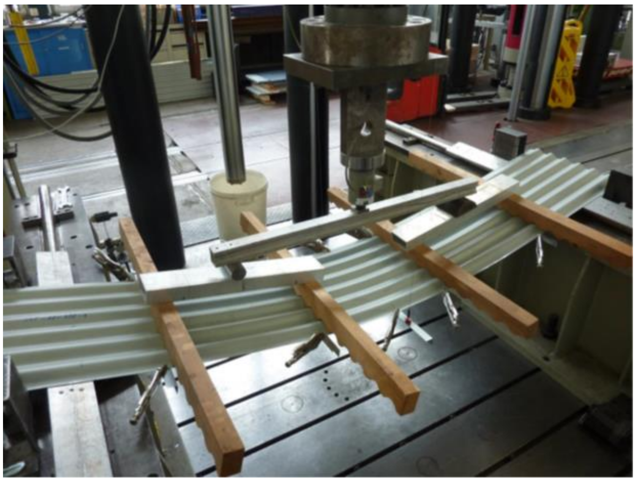


Figure 1.3.3 *– Schematic test setup and failure example for single span test.*

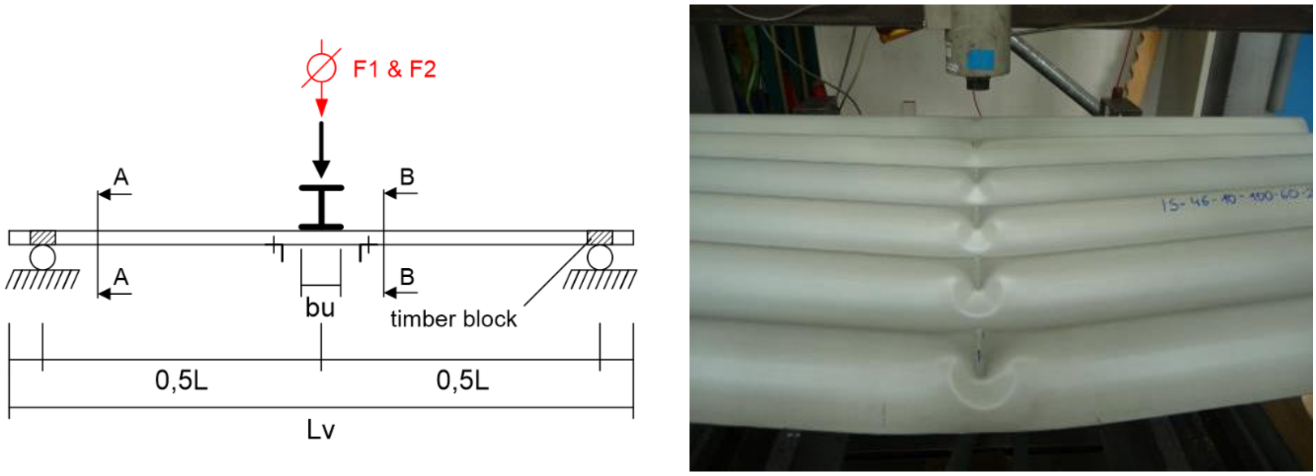


Figure 1.3.4 *– Schematic test setup and failure example for internal support test with gravity loading.*

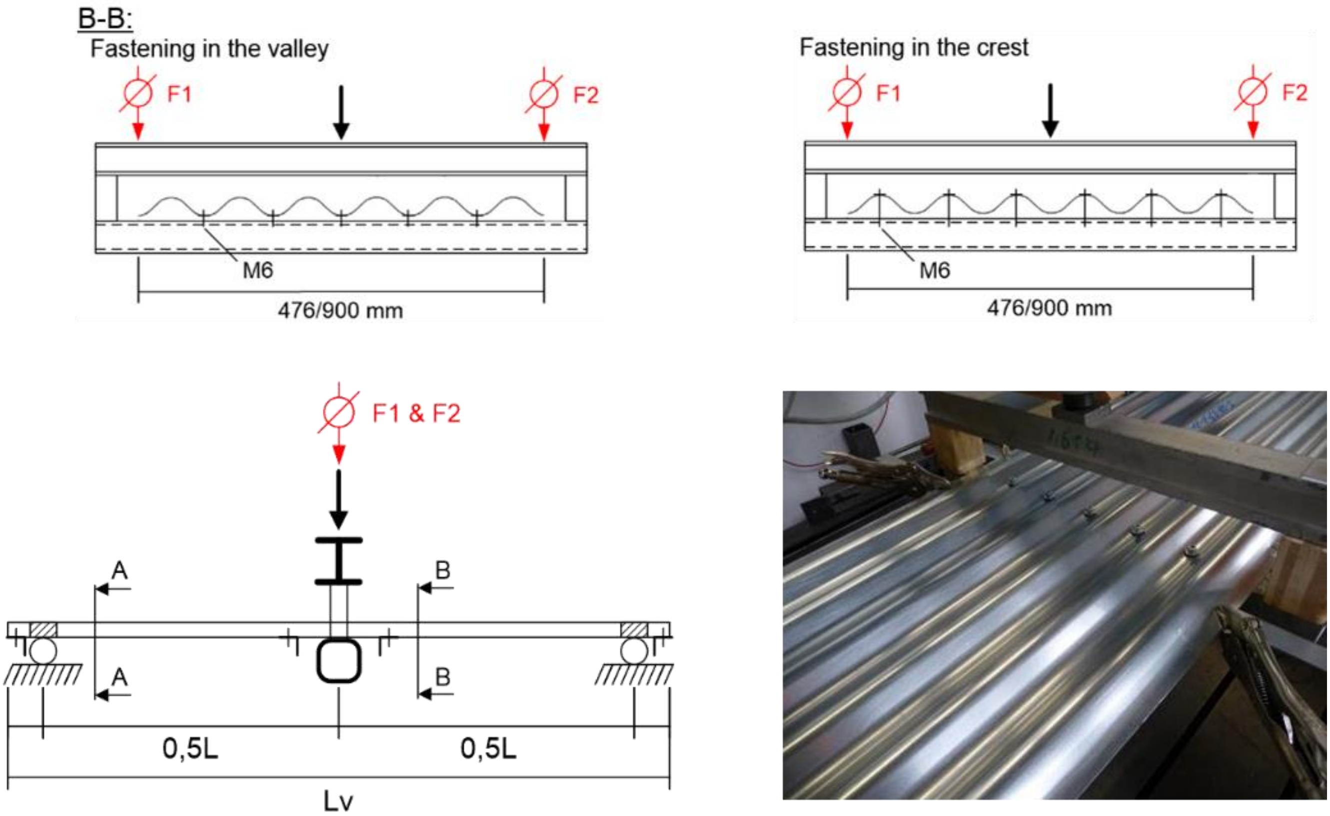


Figure 1.3.5 *– Schematic test setup and failure example (fixing in valley) for internal support test with uplift loading.*

A series of tensile tests were also integrated in the experimental plan to determine the material properties of the samples. The analysis and interpretation of the tests focused on the load bearing capacity / characteristic values of corrugated profiles with sinusoidal or similar cross section.

For the strength under the shear load, the project proved experimentally, that on the current profiles tested, the shear resistance is always superior to the resistance at support (i.e. not critical).

For the behavior in simple bending in pression, two formulas were proposed:

- one considering EN 1993-4-1 art 4.4, based on an equivalent bending property (flexural stiffness)
- and one based on a Swedish method (buckling stress).

An Excel sheet was developed to allow the design of the corrugated profile in bending with these two methods.

For the behaviour of the profile on intermediate support, the results did not point to a clear rule as too many parameters interfere on the behaviour and more tests are necessary to reach a viable conclusion. The reduction of the ultimate bending moment is influenced by the following parameters:

- R/t-ratio of the part of the cross section which is in contact with the support;
- Pitch of the cross section and the length of the wave;
- Width and type of support;
- Size of the support reaction/load, location and direction of the load.

The fact that the load/support reaction acts as pressure or as tension, plays a very important role. If the support reaction acts as a tension force on the cross section, there is no effect on the bending moment.

For the end support capacity and shear capacity the results were too disparate to support a general design rule.

In summary: GRISPE project proposed 2 methods for bending in span and in the case of all other situations, the project concluded that the number of parameters that influence the behaviour on support was too big and consequently many more tests were necessary to determine a safe design method.

It was decided that the calculation method developed for bending in span, isostatic behaviour of sheet, could be transferred to the Eurocodes.

1.4. General design requirements and rules

The following design method only offers a way for the calculation of the design resistance M_{Rd} of corrugated steel sheets on 2 supports according to [7], its amendment [8] and corrigendum [9]. Design values of the effects of actions have to be evaluated in conformity to every relevant part of [10] and its corrigendum [11], [12] and its corrigendum [13] and amendment [14], [15] and its corrigendum [16] and amendment [17].

The succeeding procedure respects general rules given in [18] and its corrigendum [19] and amendment [20] and the basis of design defined in part 2 of [2] and its corrigendum [21].

2. PRELIMINARY CONSIDERATION

2.1. Field of application of the new design method

This manual presents a design method for determine the resistance of corrugated steel sheets compliant to [1].

This method is established in the scope of minimum technological dispositions, see following paragraphs.

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 cold formed members comply with [2] and [21].

2.2. Minimum technological dispositions of the frame

The corrugated steel sheet must be put on 2 supports under uniformly distributed loads.

Corrugated steel sheet directly in contact with a concrete support is not allowed.

2.3. Minimum technological dispositions of the corrugated steel sheet

Profiled sheets have within the permitted tolerances a constant nominal thickness over their entire length and may have either a uniform cross section or a tapering cross section along their length.

Corrugated steel sheets have a continuous curvature instead of flat sections like trapezoidal profiles.

The thickness, t, is a steel design thickness (the steel core thickness extracted minus tolerance if needed as specified in clause 3.2.4 of EN [2]), if not otherwise stated.

The corrugated steel sheet must present all the following parameters:

- Ratio $r/t \leq 0{,}1 \cdot E/f_{yb}$;
- Pitch: $76\,mm \leq p \leq 150\,mm$;
- Height: $18\,mm \leq h \leq 46\,mm$;
- Minimal steel core thickness of 0,55 mm,

3. BASIC TECHNOLOGICAL REQUIREMENTS

3.1. Supports

Supports comply with [18] to [20] for steel material or with [22] to [25] for timber material.

3.2. Profiles sheet and CE marking

Profile steel sheet are CE marked according to [1].

4. MATERIAL PROPERTIES

4.1. Corrugated steel sheet

The material properties should satisfy the requirements given in [2], section 3 with a minimum steel grade of S 320 GD + Z.

4.2. Fasteners

The material properties should satisfy the requirements given in [2], section 8.

4.3. Safety factors

The safety factors should satisfy the requirements given in [2], section 2.

5. ACTION LOADS AND COMBINATIONS

Action loads and combinations should be taken into account and determined according:

- [8] and [9] for basis and load combinations,
- [10] and [11] for self-weight and imposed loads,
- [12] to [14] for snow loads,
- [15] to [17] for wind loads.

6. BASIS OF THE DESIGN

6.1. Principles

This new design method is given to calculate the bending stiffness and moment resistance of a corrugated steel sheet with sinusoidal or similar cross section.

6.2. Field of application of the new design method

This new design method is for corrugated steel sheets on 2 support received uniformly distributed load.

6.3. Design procedure

6.3.1. Generally applicable design procedure

This procedure is established with respect to local buckling in the compressed area.

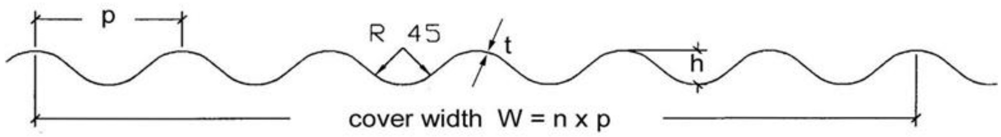


***Figure 6.3.1.1** – Typical cross section*

Two situations can occur:

- If $R/t \leq 0{,}04 \cdot E/f_{yb}$: the cross section needs not be checked for the local buckling and the characteristic bending moment is determined with: $M_{c,Rk} = W_y \cdot f_{yb}$;
- If $R/t > 0{,}04 \cdot E/f_{yb}$: the characteristic bending moment should be calculated using a reduced compressive stress σ_c: $M_{c,Rk} = W_y \cdot \sigma_c$.

With:

- Slenderness ratio: $\lambda = \left(f_{yb}/\sigma_{elr}\right)^{0,5}$;
- Buckling stress: $\sigma_{elr} = 0{,}60 \cdot \eta \cdot E \cdot t/R$;
- Coefficient η:$\eta = 0{,}19 + 0{,}67/(1 + R/(100 \cdot t))^{0,5}$;

- For $\lambda \leq 0{,}30$: $\sigma_c = f_{yb}$;
- For $0{,}30 < \lambda < 1{,}10$: $\sigma_c = (1{,}126 - 0{,}419 \cdot \lambda) \cdot f_{yb}$;
- For $\lambda \geq 1{,}10$: $\sigma_c = (0{,}8/\lambda^2) \cdot f_{yb}$.

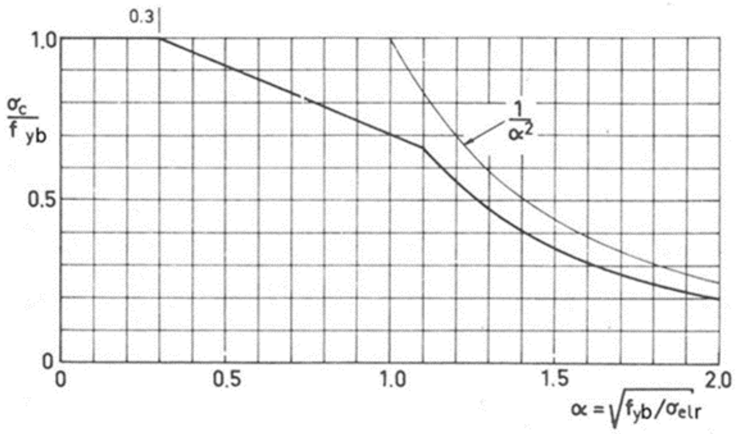


***Figure 6.3.1.2** – Ultimate compressive stress with respect to local buckling of the cylinder part of the profile.*

The moment of inertia, which is used to calculate deformations in serviceability limit state, should be calculated considering the characteristic bending moment but with reduced stress $f_{yb}/1{,}5$.

6.3.2. Simplified procedure for restricted application range

If the conditions:

- Corrugated steel profile as single span girder and,
- Uniformly distributed loads and,
- Ratio $R/t \leq 0{,}1 \cdot E/f_y$ and,
- Steel core thickness $t_{cor} \geq 0{,}55\,mm$ and,
- Profile height $18\,mm \leq h \leq 46\,mm$ and,
- Profile pitch $76\,mm \leq p \leq 150\,mm$,

Are met, the following simplified procedure may be adopted:

- Moment of inertia per unit width: $I_y = 0{,}13 \cdot t \cdot h^2$;
- Section modulus per unit width: $W_y = 0{,}26 \cdot t \cdot h$;
- Characteristic bending moment: $M_{c,Rk} = W_y \cdot f_{yb}$

7. SPECIFIC DESIGN CONSIDERATION

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

- For fire: it should be considered national regulations in agreement with EN 1991-1-2 and EN 1993-1-2;

- For seismic: it should be considered national regulations in agreement with EN 1998-1;
- For environmental aspect: it should be considered national regulations;
- For thermal: it should be considered national regulations in agreement with EN 1991-1-5;
- For acoustic: it should be considered national regulations.

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

8. DESIGN EXAMPLE

8.1. Description of frame and loading assumption

These design example deals with a simple pitch roof application of a building for which the steel frame is composed of IPE 80 beam with current span of 1,15 m and a verification located in areas H and I according 7.2.4 of EN 1991-1-4.

Pitch roof is constituted by a corrugated steel of 0,64 mm nominal thickness.

8.1.1. Information for the building

The building of 16 m height, building 1, is located in an industrial area near Oostende (Belgium) with simple pitch roof of 45°.

The fundamental value of the basic wind velocity $v_{b,0}$ is 26 m.s^{-1}.

Terrain category is assumed to be 0.

Directional factor c_{dir} and season factor c_{season} are fixed to 1. Orography factor $c_0(z)$ is taken to 1.

The recommended value of 1 is considered for the turbulence factor k_I.

For the air density ρ, the recommended value is applied: ρ = 1,25 kg/m^3.

Location of the building in a windswept topography: C_e = 0,8 according [12].

Snow load shape coefficient μ_i of 0,8.

8.1.2. Loading assumption

This design example doesn’t deal with mounting phase. In service phase, loads are provided by wind effects and dead loads.

Snow loads are neglected due to characteristic value of snow load on the ground s_k at sea level of 0,2 kN/m² according [12] and a combination factor Ψ_0 of 0,5 according the Belgium national annex of [12] (s= $\mu_i \cdot C_e \cdot C_t \cdot s_k$ = 0,064 daN/m² for the exact application).

Determination of wind action according [15] to [17]

Basic wind velocity $v_b = c_{dir} \cdot c_{season} \cdot v_{b,0} = 1{,}00 \cdot 1{,}00 \cdot 26 = 26$ m.s^{-1}.

Mean wind $v_m(z)$:

- Terrain category 0: z_0 = 0,003 m and z_{min} = 1 m;
- $z_{0,II}$ = 0,05 m;

- Terrain factor $k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0{,}07} = 0{,}19 \cdot \left(\frac{0{,}003}{0{,}05}\right)^{0{,}07} = 0{,}156$;
- Roughness factor $c_r(z) = k_r \cdot ln\left(\frac{z}{z_0}\right) = 0{,}156 \cdot ln\left(\frac{16}{0{,}003}\right) = 1{,}339$;
- $v_m(z) = c_r(z) \cdot c_0(z) \cdot v_b = 1{,}339 \cdot 1{,}00 \cdot 26 \approx 34{,}8\, m.s^{-1}$;

Wind turbulence $I_v(z) = \frac{k_l}{c_0(z) \cdot ln(z/z_0)} = \frac{1{,}00}{1{,}00 \cdot ln(16/0{,}003)} = 0{,}117$

Peak velocity pressure $q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = [1 + 7 \cdot 0{,}117] \cdot \frac{1}{2} \cdot 1{,}25 \cdot 34{,}8^2 \approx 1{,}38\, kN/m^2$

Pressure coefficients for mono pitch roof:

- θ = 45°;
- External pressure coefficients $c_{pe,10}$:
    - Zone H:
        - Wind at 0°: 0,6;
        - Wind at 180°: -0,7;
        - Wind at 90°: -1,0;
    - Zone I: -0,9;
- Internal pressure coefficient c_{pi} = +0,2/-0,3;
- Global coefficient $c_{p,net}$:
    - For wind pressure effect: $c_{p,net}$ = 0,9;
    - For wind suction effect: $c_{p,net}$ = -1,2.

Wind loads W_{50}:

- For pressure effect: W_{50}^+ = 1,24 kN/m²
- For suction effect: W_{50}^- = - 1,65 kN/m²

Loads combination according [8], [9] and Belgium national annex of [8]

The most severe combination in pressure effect is: $Q^+ = 1{,}50 \cdot W_{50}^+ + 1{,}35 \cdot g_0 = 1{,}50 \cdot 1{,}24 + 1{,}35 \cdot 0{,}061 \approx 1{,}94$ kN/m²

The most severe combination in suction effect is: $Q^- = 1{,}50 \cdot W_{50}^- + g_0 = 1{,}50 \cdot (-1{,}65) + 0{,}061 \approx -2{,}41$ kN/m²

For g_0 see paragraph 8.2.

For the verification of the deformation at SLS: $Q_{SLS} = W_{50}^+ + g_0$ = 1,30 kN/m².

8.2. Description of corrugated steel sheet

The corrugated steel sheet is a 76 mm pitch sinusoidal section of 18 mm height and 0,64 mm nominal steel thickness.

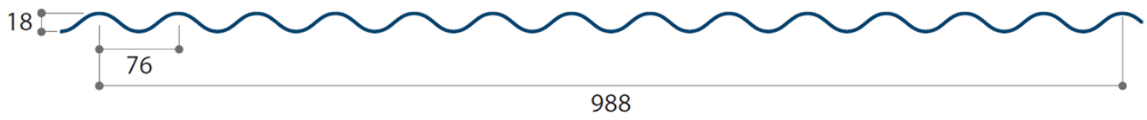


Figure 8.2 *– 76.18 corrugated steel sheet.*

The corrugated profile is in steel grade S 320 GD + Z 275 in 0,65 mm nominal thickness. Self-weight g_0 of profile is 0,060 kN/m².

The safety factor γ_{M0} is taken to 1,00.

8.3. Verification using simplified approach

8.3.1. Loading application

It's considering 1 span of 1m15 length under uniform distributed loading.

For wind pressure effect, the application of load combination, see paragraph 8.1.2, drives to: an applied moment on span $M_{c,Ed} = (Q^+ \cdot L^2)/8 = (1{,}94 \cdot 1{,}15^2)/8 = 0{,}321$ kNm/m.

For wind suction effect, the application of load combination, see paragraph 8.1.2, drives to: an applied moment on span $M_{c,Ed} = (Q^- \cdot L^2)/8 = (2{,}41 \cdot 1{,}15^2)/8 = 0{,}399$ kNm/m.

For service limit states, in application of a classical criterion of L/150, the maximal deflection is 7,67 mm.

8.3.2. Application of the simplified method

Based on nominal thickness, the design thickness t = 0,60mm.

Before applying the simplified method, it's necessary to verify if $R/t \leq 0{,}1 \cdot E/f_{yb}$:

- $R = 5h_w/4 = 22{,}5\ mm$;
- $R/t = 37{,}50$;
- $0{,}1 \cdot E/f_{yb} = 0{,}1 \cdot \frac{210\,000}{320} = 65{,}625$.

The criterion is verified and we can apply the simplified method:

- Moment of inertia per unit width: $I_y = 0{,}13 \cdot t \cdot h^2 = 0{,}13 \cdot 0{,}60 \cdot 18^2 = 25{,}27\ \ mm^4/mm$;
- Section modulus per unit width: $W_y = 0{,}26 \cdot t \cdot h = 0{,}26 \cdot 0{,}60 \cdot 18 = 2{,}81\ \ mm^3/mm$;
- Characteristic bending moment: $M_{c,Rk} = W_y \cdot f_{yb} = 2{,}808 \cdot 320 = 0{,}899\ \ kN.m/m$.

Consequently, the bending design resistance is: $M_{c,Rd} = 0{,}899\ kN.m/m$.

It's assumed that, considering the symmetry of the sinusoidal section of the sheet that the values of the bending design resistance under downward loading and for uplift loading, are the same.

<u>Verification of the resistance and deformation</u>

Under downward loading: Moment in span: $\frac{M_{c,Ed}}{M_{c,Rd}} = \frac{0{,}321}{0{,}899} = 0{,}357\ \leq 1{,}00$;

For uplift loading: Moment in span: $\frac{M_{c,Ed}}{M_{c,Rd}} = \frac{0,399}{0,899} = 0,444 \leq 1,00$.

The resistance of the corrugated steel sheet at ULS is verified.

The deflection of the corrugated steel sheet on 2 support is determined by:

$$y = \frac{5 \cdot (W_{50}^{+} + g_0) \cdot L^4}{384 \cdot E \cdot I_y} = 8,57\ mm$$

Deflection criterion of L/150 isn't respected because the deflection of the corrugated steel sheet (y = 8,57 mm) exceeds the maximum allowed value of 7,67 mm.

In addition, fasteners can be verified according [2], section 8.

8.4. Verification using detailed approach

8.4.1. Corrugated steel sheet

The corrugated steel sheet is the same that the product described at paragraph 8.2.: 76 mm pitch and 18 mm height.

The corrugated profile is in steel grade S 320 GD + Z 275 in 0,65 mm nominal thickness. Self-weight g_0 of profile is 0,060 kN/m².

The safety factor γ_{M0} is taken to 1,00.

8.4.2. Loading application

We resume the loadings described in paragraph 8.3.1 in order to study the interest of the detailed method compared to the simplified method.

8.4.3. Application of detailed method

Based on nominal thickness, the design thickness t = 0,60 mm.

At this step, we need to verify if $R/t \leq 0,04 \cdot E/f_{yb}$:

- $R = 5h_w/4 = 22,5\ mm$;
- $R/t = 37,50$;
- $0,04 \cdot E/f_{yb} = 0,04 \cdot \frac{210000}{320} = 26,25$.

$R/t > 0,04 \cdot E/f_{yb}$ and the characteristic bending moment should be calculated using a reduced compressive stress σ_c: $M_{c,Rk} = W_y \cdot \sigma_c$.

<u>Determination of the moment of inertia and section modulus</u>

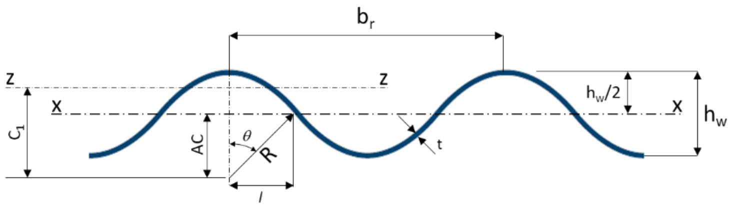


***Figure 8.4.3.1** – Geometrical parameter to determine the moment of inertia and the section modulus.*

Radius of curvature: $R = 5 \cdot h_w/4 = 22{,}5\, mm$;

Length $l = h_w = 18\, mm$;

Angle θ: $\sin\theta = l/R = 18/22{,}5$ and $\theta = 0{,}927\, rad$;

Distance between center of gravity of the arc ('z-z' axis) and arc center:

$$C_1 = (R \cdot \sin\theta)/\theta = \frac{22{,}5 \cdot \sin 0{,}927}{0{,}927} = 19{,}41\, mm;$$

Distance between the arc center and the axis 'x-x':

$$AC = R - (h_w/2) = 22{,}5 - 0{,}5 \cdot 18 = 13{,}5\, mm;$$

And finally, the moment of area for a quarter of the gross section:

$$I'_{xx}/t = R^3 \cdot \left(\frac{\theta + \sin\theta \cdot \cos\theta}{2} - \frac{(\sin\theta)^2}{\theta}\right) + (R \cdot \theta)\left[C_1 - \left(R - \frac{h_w}{2}\right)\right]^2$$

$$\frac{I'_{xx}}{t} = 22{,}5^3\left(\frac{0{,}927 + \sin 0{,}927 \cdot \cos 0{,}927}{2} - \frac{(\sin 0{,}927)^2}{0{,}927}\right) + (22{,}5 \cdot 0{,}927)[19{,}41 - 13{,}5]^2$$
$$= 882{,}48\ mm^3/mm$$

And the moment of inertia per width is:

$$I_{xx} = \frac{4 \cdot I'_{xx} \cdot t}{b_R} = \frac{4 \cdot 882{,}48 \cdot 0{,}60}{76} = 27{,}87\ mm^4/mm$$

The section modulus is given by:

$$W_y = \frac{4 \cdot I'_{xx} \cdot t}{b_R \cdot h_w/2} = \frac{4 \cdot 882{,}48 \cdot 0{,}60}{76 \cdot 9} = 3{,}10\ mm^3/mm$$

<u>Determination of the bending moment resistance calculating the reduced stress</u>

Coefficient

$$\eta = 0{,}19 + 0{,}67/(1 + R/(100 \cdot t))^{0{,}5} = 0{,}19 + 0{,}67/(1 + 22{,}5/(100 \cdot 0{,}60))^{0{,}5} = 0{,}761;$$

Buckling stress:

$$\sigma_{elr} = 0{,}60 \cdot \eta \cdot E \cdot t/R = 0{,}60 \cdot 0{,}763 \cdot 210\,000 \cdot 0{,}60/22{,}5 = 2558{,}23\ N/m^2;$$

Slenderness ratio:

$$\lambda = \left(f_{yb}/\sigma_{elr}\right)^{0{,}5} = (320/2558{,}23)^{0{,}5} = 0{,}354;$$

As $0{,}30 < \lambda < 1{,}10$, the reduced stress is given by:

$$\sigma_c = (1{,}126 - 0{,}419 \cdot \lambda) \cdot f_{yb} = (1{,}126 - 0{,}419 \cdot 0{,}354) \cdot 320 = 312{,}9\ N/mm^2$$

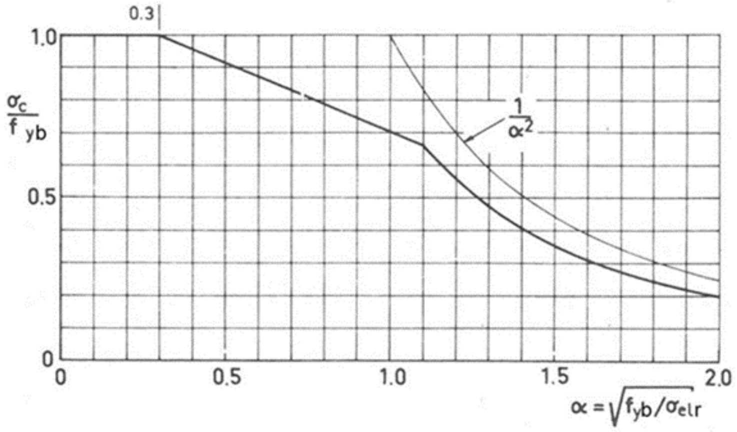


Figure 8.4.3.2 *– Ultimate compressive stress with respect to local buckling of the cylinder part of the profile.*

The characteristic bending moment is:

$$M_{c,Rk} = W_y \cdot \sigma_c = 3{,}15 \cdot 313{,}33 = 0{,}969\ kN.m/m$$

Consequently, the bending design resistance is: $M_{c,Rd} = 0{,}969\ kN.m/m$.

It's assumed that, considering the symmetry of the sinusoidal section of the sheet that the values of the bending design resistance under downward loading and for uplift loading, are the same.

For the moment of inertia to use in SLS: $W_{y,SLS} = M_{c,Rk}/(f_{yb}/1{,}5) = 4{,}54\ mm^3/mm$, and $I_{y,SLS} = W_{y,SLS} \cdot (h_w/2) = 40{,}87\ mm^4/mm$.

<u>Verification of the resistance and deformation</u>

Under downward loading: Moment in span: $\frac{M_{c,Ed}}{M_{c,Rd}} = \frac{0{,}321}{0{,}969} = 0{,}331\ \leq 1{,}00$;

For uplift loading: Moment in span: $\frac{M_{c,Ed}}{M_{c,Rd}} = \frac{0{,}399}{0{,}969} = 0{,}412\ \ \leq 1{,}00$.

The resistance of the corrugated steel sheet at ULS is verified. The detailed method represents a gain of approximatively 8 % compared to the simplified method.

For SLS, the deflection of the corrugated steel sheet on 2 support is determined by:

$$y = \frac{5 \cdot (W_{50}^{+} + g_0) \cdot L^4}{384 \cdot E \cdot I_{y,SLS}} = 5{,}30\, mm$$

Deflection criterion of L/150 is respected because the deflection of the corrugated steel sheet (y = 5,30 mm) doesn't exceed the maximum allowed value of 7,67 mm.

In addition, fasteners can be verified according [2], section 8.

8.5. Software verification

8.5.1. Software information

An Excel software is available on GRISPE plus website (www.grispeplus.eu).

8.5.2. Validation of the example

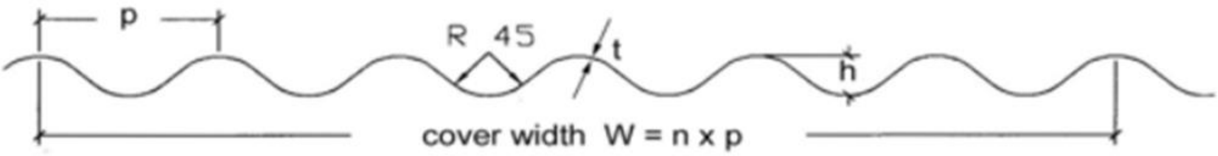
Input date are first the geometrical parameters:

- Radius of curvature: R = 22,5 mm for us example;
- Height of corrugated profile: h = 18 mm;
- Pitch: p = 76 mm.

Secondly, it's necessary to implement the Young Modulus (E = 210 000 N/mm²), the Yield stress (f_{yb} = 320 N/mm²) and the section modulus (W_y = 3150 mm3/m given at paragraph 8.4.3).

Please fill in the red cells

results



R	22,50	[mm]	E	210 000,00	[N/mm²]
t_{cor}	0,61	[mm]	f_{yb}	320,00	[N/mm²]
h	18,00	[mm]	W_y	3 150,00	[mm³/m]
p	76,00	[mm]			

Generally applicable design procedure with respect to local buckling in the compressed area

R/t 36,885246 [-] ≤ $0{,}04 \cdot E/f_{yb}$ 26,25 [-]

slenderness ratio α [-]	buckling stress σ_{clr} [N/mm²]	coefficient η [-]	compressive stress σ_c [N/mm²]
0,350	2 605,245	0,763	313,329

$M_{c,Rk}$ 0,987 [kNm/m]

Simplified procedure for restricted application range

Check conditions (all most be fulfilled):

single span girder		true/false?
uniformly distributed loads		true/false?
ratio R/t 36,885246 [-]	≤ $0{,}1 \cdot E/f_{yb}$ 65,625 [-]	true
steel core thickness $t_{cor} \geq 0{,}55$ mm		true
profile height 18 mm ≤ h ≤ 46 mm		true
profile pitch 76 mm ≤ p ≤ 150 mm		true

$M_{c,Rk}$ 0,914 [kNm/m]

***Figure 8.5.2** – Excel tab for corrugated steel sheet.*

Comparison between analytical result and Excel software

Both methods are validated due to the exactly correspondence on all parameters and precisely the following results:

- Slenderness ratio;
- Buckling stress;
- η coefficient;
- Compressive stress;
- Bending characteristic moment for detailed method and simplified method.

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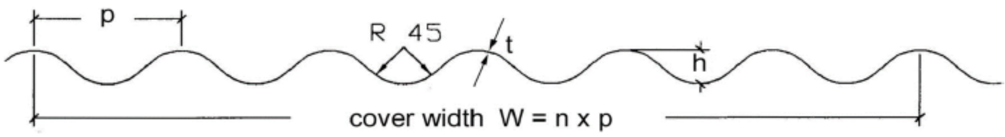
ANNEX: AMENDMENT PROJECT SUBMITTED TO CEN

AM-1-3-2013-75	
Subject	Load bearing capacity / characteristic values of corrugated profiles with sinusoidal or similar cross section
Clause No/ Subclause No/ Annex	
Reason for Amendment	No design rules by calculation available in EN 1993-1-3
Proposed Change	In order to calculate the bending stiffness and the ultimate bending moment for corrugated profiles with sinusoidal or similar cross section, two approaches are proposed **1. Generally applicable design procedure with respect to local buckling in the compressed area**  **Fig nn:** Typical cross section, definition of parameters σ • If $R/t \leq 0{,}04 * E / f_{yb}$: The cross section needs not be checked for local buckling

characteristic bending moment: $M_{c,Rk} = W_y * f_{yb}$

- If $R/t > 0{,}04 * E / f_{yb}$: The characteristic bending moment should be calcula ed using the reduced compressive stress σ_c $M_{c,Rk} = W_y * \sigma_c$

with:

slenderness ratio: $\lambda = (f_{yb} / \sigma_{elr})^{0,5}$

buckling stress $\sigma_{elr} = 0{,}60 * \eta * E * t / R$

coefficient η $\eta = 0{,}19 + 0{,}67 / (1 + R / (100 * t))^{0,5}$

for $\lambda < 0{,}30$ $\sigma_c = f_{yb}$

for $0{,}30 < \lambda < 1{,}10$ $\sigma_c = (1{,}126 - 0{,}419 * \lambda) * f_{yb}$

for $1{,}10 \geq \lambda$ $\sigma_c = (0{,}8 / \lambda^2) * f_{yb}$

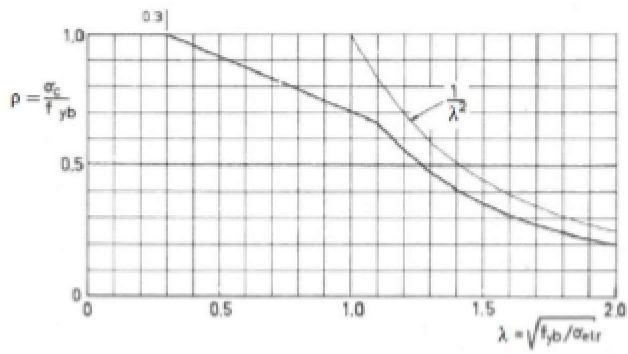


Fig nn: ultimate compressive stress with respect to local buckling of the cylindric part of the profile

The moment of inertia, which is used to calculate deformations in serviceability limit state, should be calculated using the same procedure as for bending moment, but with reduced stress $f_{yb} / 1{,}5$.

2. Simplified procedure for restricted application range

If the conditions

- profile installed as single span girder and
- uniformly distributed loads and
- ratio $R/t \leq 0{,}1 * E / f_{yb}$ and
- steel core thickness $t_{cor} \geq 0{,}55$ mm and
- profile height 18 mm $\leq h \leq$ 46 mm and
- profile pitch 76 mm $\leq p \leq$ 150 mm

are met, the following simplified procedure may be adopted:

	moment of inertia per unit width $I_y = 0,13 * t * h^2$ section modulus per unit width $W_y = 0,26 * t * h$ characteristic bending moment: $M_{c,Rk} = W_y * f_{yb}$
Background Information	[1] D2.5 WP2 Background and draft annexes for EN 1993-1-3 for corrugated sheets, 31.12.2015, KIT [2] StBK-N5 Swedish Code for Light-Gauge Metal Structures, March 1982, SBI [3] EN 1993-4-1 Tanks