GRISPE PLUS

VALORISATION OF KNOWLEDGE FOR SPECIFIC PROFILED STEEL SHEETS

WP N°: 3
WP Title: eLectures: Interactive electronic lectures
Deliverable N°: D3.1
Deliverable Title: Perforated profiles
Deliverable Date: 31st of March 2018

The GRISPE PLUS project has received financial support from the European Community's Research Fund for Coal and Steel (RFCS) under grant agreement N° 754092"

Author(s)		
Sokol Palisson Consultants, Anna Palisson		
Drafting history		
DRAFT N° 1 –DATE:		
DRAFT N° 2- DATE:		
FINAL- DATE: 31st of March		
Dissemination Level		
PU	*Public-Open*	
PP	*Restricted to the Commission Services, the Coal and Steel Technical Groups and the European Committee for Standardisation (CEN)*	
RE	*Restricted to a group specified by the Beneficiaries*	
CO	*Confidential, only for Beneficiaries (including the Commission services)*	

D3.1 PERFORATED PROFILES

RFCS funded – agreement N° 754092

Disclaimer notice

and

EU acknowledgement of support

Disclaimer notice

By making use of any information or content in this manual (Part 1 and Part 2) you agree to the following:

No warranties

All the information or content provided in this manual is provided "as is" and with no warranties. No express or implies warranties of any type, including for example implied warranties of merchantability or fitness for a particular purpose, are made with respect to the information or content, or any use of the information or content in this manual.

The authors make no representations or extend no warranties of any type as to the completeness, accuracy, reliability, suitability or timeliness of any information or content in this manual.

Disclaimer of liability

This manual is for informational purposes only. It is your responsibility to independently determine whether to perform, use or adopt any of the information or content in this manual.

The authors specifically disclaim liability for incidental or consequential damages and assume no responsibility or liability for any loss or damage suffered by any person as a result of the use or misuse of any of the information or content in this manual.

The authors will not be liable to you for any loss or damage including without limitation direct, indirect, special or consequential loss or damage, or any loss or damage whatsoever arising from loss of data or loss of business, production, revenue, income, profits, commercial opportunities, reputation or goodwill, arising out of, or in connection with, the use of the information or content in this manual.

The authors do not represent, warrant, undertake or guarantee that the use of the information or content in this manual will lead to any particular outcome or results.

Reasonableness

By using this manual, you agree that the exclusions and limitations of liability set out in this disclaimer are reasonable. If you do not think they are reasonable, you must not use this manual.

Severability

If any part of this disclaimer is declared unenforceable or invalid, the remainder will continue to be valid and enforceable.

"The information and views set out in this manual (Part 1 and Part 2) are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information or views contained therein"

EU acknowledgement of support

The GRISPE project has received financial support from the European Community's Research Fund for Coal and Steel (RFCS)under grant agreement No75 4092

SUMMARY

The purpose of this design manual is to present a new method of design by calculation for perforated profiles, as developed in the European project GRISPE PLUS.

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 perforated profiles, is based on tests carried out within the European GRISPE project (2013-2016).

The background of this method is described in Annex 1.

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, including in particular the verification of the field of application of the new design method;

Chapter 3 states the 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 specifies the determination of actions and combinations

Chapter 6 gives the basis of the design

Chapter 7 lists the specific design consideration not covered by the manual

Chapter 8 explains in detail the software developed for perforated profiles

Chapter 9 gives an application of the new design method.

Chapter 10 gives the auto-control of the software

A bibliography and an Annex are 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 PALISSON Anna and has been discussed in a GRISPE PLUS working group composed by the following members:

Mickael BLANC	France
Silvia CAPRILI	Italy
David IZABEL	France
Markus KUHNENNE	Germany
Anna PALISSON	France
Valérie PRUDOR	France
Irene PUNCELLO	Italy
Dominik PYSCHNY	Germany
Thibaut RENAUX	France
Daniel SPAGNI	France

Corresponding members have included:

SOKOL	Léopold	France

Figures

The figures have been produced by the following companies

Figure 1.1.1 – JORIS IDE

Figure 1.1.2 – KIT

Figure 1.1.3 – KIT

Figure 1.3.1 to Figure 1.3.12 – KIT

Figure 2.2.1.1 – Copy of EN 1993-1-3

Figure 2.2.2.1 – Copy of EN 1993-1-3

Figure 6.2.1 - Sokol Palisson Consultants

Figure 6.2.2 - Sokol Palisson Consultants

Figure 6.3.2.1 – Copy of EN 1993-1-3

Figure 8.1 – Sokol Palisson Consultants

CONTENT

SCOPE OF THE PUBLICATION

The aim of this publication is to present the new design method for perforated 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:

t : design thickness

t_{nom} : nominal thickness

t_{eff}: effective thickness

h_w : profile height

h_a : height of the part of the web above the stiffener

h_{sa} : height of the web stiffener

d_s : height of the flange stiffener

d : diameter of the perforations

a : spacing between the centers of the perforations

f_{yb} : yield strength

E : Young's modulus

t_{red} : reduced thickness

b_{pi} : widths of plane cross section parts

$b_{i,eff}$: effective width

A_g : area of the gross cross-section

A_{eff} : effective area

z_G : position of the neutral axis

σ_{xx} : stress

χ_d : reduction factor for the distortional buckling resistance

$M_{c,Rd}$: resistance moment

M_{span} : span resistance moment

e_c : distance from the compressed flange and the position of the neutral axis

s_{per}: slant height of the perforated portion of the web

s_n : width of the part of the web between the compressed flange and the position of the neutral axis

s_{eff} : effective cross section for the web

W_{eff} : effective section modulus

$R_{w,Rd}$: local transverse resistance

1. INTRODUCTION

1.1. Type of profiled steel sheets

This design manual deals with steel profiles (Figure 1.1.1) with perforations arranged in square, in the flanges (Figure 1.1.2) or in the webs (Figure 1.1.3).

Figure 1.1.1 *– Steel profile*

Figure 1.1.2 *– Steel profile with perforations arranged in squares in the upper flanges*

Figure 1.1.3 *– Steel profile with perforations arranged in squares in the webs*

1.2. State of the art pre-GRISPE

Perforated profiles are increasingly used in the internal skin of the building envelope to improve the acoustic performance. The cold form steel companies have developed, for this kind of application, different types, geometries and distribution of perforations on the profile web and flange

European standard EN 1993-1-3, Chapter 10.4 only covers plane walls with equilateral triangular perforation pattern while many sheeting with different distribution of perforations exist on the market.

Several studies exist on sheets with triangular pattern perforations [1], [2], [3], [4], [5]. As far as quadratic pattern perforations are concerned, some initial research carried out at KIT in Germany [2], [3] gives some useful information on the effective width and web crippling resistance, but it was based on numerical computer analysis that doesn't lead directly to the analytical formulation and needs to be extended to cover the solutions currently present on the market.
Therefore the one way to design sheeting with quadratic pattern perforations is to determine resistance values by testing, which takes a long time and is expensive.

1.3. Main results of GRISPE

In order to determine and compare the resistance values of steel profiles with and without perforations, an extensive programme of 224 tests was performed according to EN 1993-1-3 Annex A on steel trapezoidal profiles (Figure 1.3.1 to Figure 1.3.4):

- with perforations arranged in squares in the webs
- with perforations arranged in squares in the flanges
- without perforations

Moreover 48 local testing on coupons without and with perforations arranged in square and perforations arranged in triangle were performed in order to determine their influence on local behaviour.

The analysis of these local testing allowed to define effective thickness for sheeting with perforations arranged in square as a function of effective thickness for sheeting with perforations arranged in triangle and to adapt to a perforation arranged in square, the formulas defined in EN 1993-1-3 for perforation arranged in triangle. These innovative formulas could be validated by a detailed analysis of the global testing experimental results. Calculations methods have been developed to determine span moment resistance, web crippling resistance and moment – reaction resistance of the profile with perforations (in the flange or in the web) arranged in square which could not be determined before.

Figure 1.3.1 *– Single span test on profile without perforation*

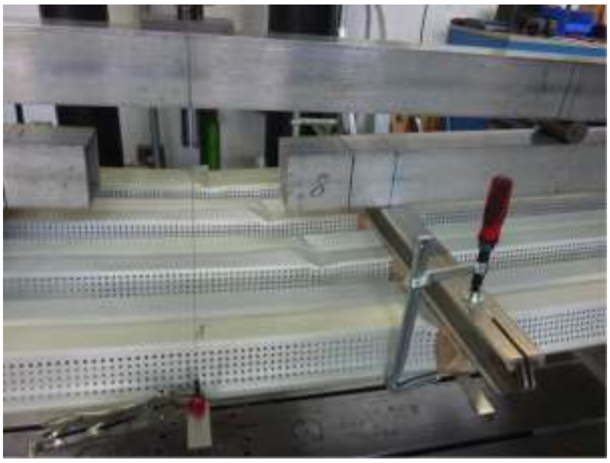


Figure 1.3.2 *– Single span test with web perforation*

Figure 1.3.3 *– Single span test on profile with flange perforation*

***Figure 1.3.4** – Single span test on profile with total perforation*

***Figure 1.3.5** – End support test on profile without perforation*

***Figure 1.3.6** – End support test on profile with web perforation*

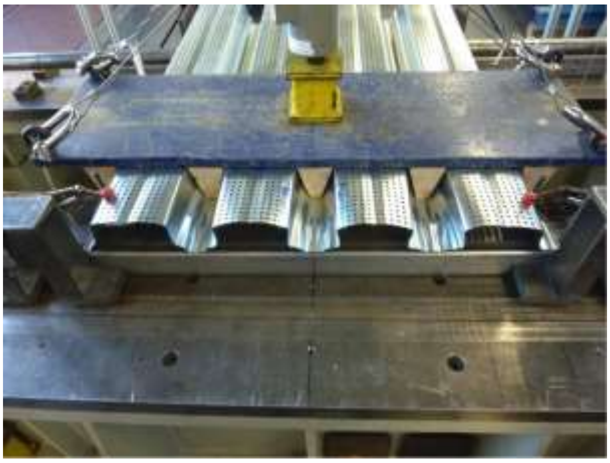


Figure 1.3.7 *– End support test on profile with flange perforation*

Figure 1.3.8 *– End support test on profile with total perforation*

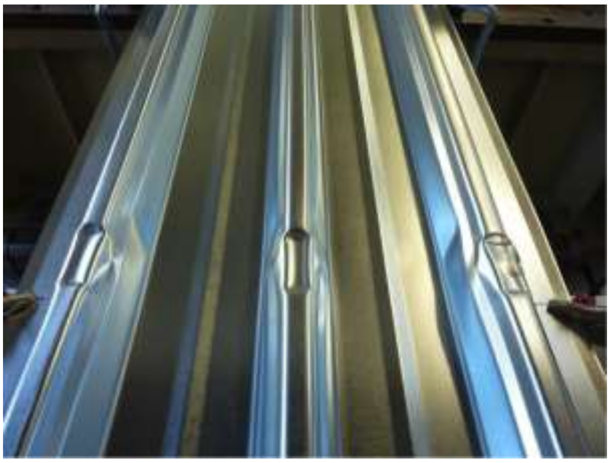


Figure 1.3.9 *– Profile without perforation after internal support testing*

***Figure 1.3.10** – Profile with web perforation after internal support testing*

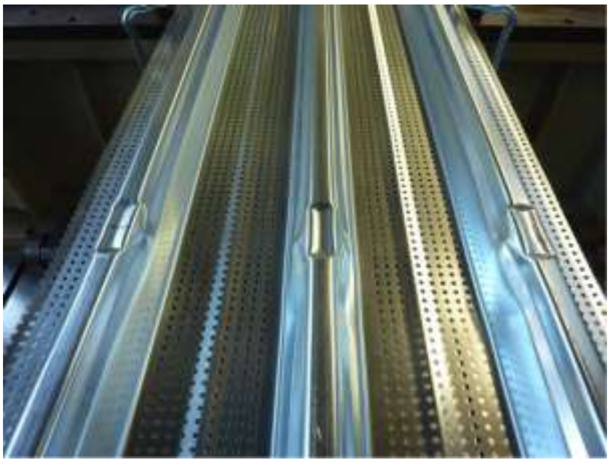


***Figure 1.3.11** – Profile with flange perforation after internal support testing*

***Figure 1.3.12** – Profile with total perforation after internal support testing*

1.4. General design requirements and rules

(1) The design of perforated profiles should be 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 CONSIDERATION – PRE-DESIGN

2.1. Field of application of the new design method

This manual gives design requirements for steel profiles with perforations arranged in squares in the webs or in the flanges. The execution of steel structures made of sheeting is covered in EN 1090.

This manual gives methods for design by calculation. This method applies within stated ranges of material properties and geometrical proportions.

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.

2.2. Technological dispositions of the profile sheet

2.2.1. Form of sections

(1) 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.

(2) The cross-sections of profiled sheets essentially comprise a number of plane elements joined by curved elements.

(3) Examples of cross-sections for sheets are illustrated in figure 2.2.1.1.

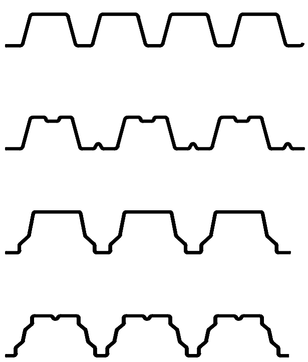


Figure 2.2.1.1 *– Example of profiles sheets*

(4) Cross-sections of sheets may either be unstiffened or incorporate longitudinal stiffeners in their webs or flanges, or in both.

2.2.2. Cross-section dimensions

The cross-section dimensions should satisfy the general requirements given in EN 1993-1-3, section 1.5.3.

(1) 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 1993-1-3), if not otherwise stated.

(2) The provisions for design by calculation given in this design manual should not be applied to cross-sections outside the range of width-to-thickness ratios *b/t*, *h/t*, *c/t* and *d/t* given in Table (Table 5.1 of EN 1993-1-3).
(3)

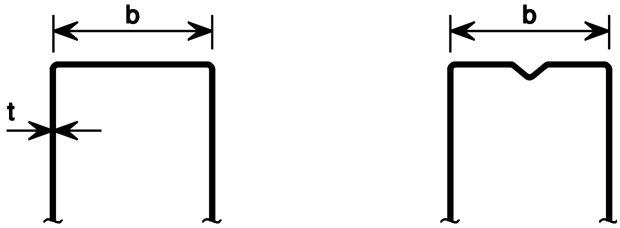
	$b/t \le 500$
	$45° \le \phi \le 90°$ $h/t \le 500 \sin\phi$

***Table 2.2.2.1** – Checking of geometrical proportions*

3. BASIC TECHNOLOGICAL REQUIREMENTS

Profiled sheet and CE marking

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

4. MATERIAL PROPERTIES

Steel sheet

The material properties should satisfy the requirements given in EN 1993-1-3, section 3.

The usual types of steel are the grades S320GD + ZA and S350GD + ZA

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

5. ACTION LOADS AND COMBINATIONS

The actions and combinations which should be taken into account must be determined according to EN 1991-1-6 Eurocode 1: Actions on the structures, Part 1-6 : General actions – Actions during execution, 2005, and the National Annexes.

6. BASIS OF THE DESIGN

6.1. Principles

This new design method is given to calculate for sheeting with perforations arranged in squares in the webs or in the flanges:

- The resistance to bending moment
- The resistance to local load or support reaction
- The resistance to combined bending moment and local load or support reaction

6.2. Field of application of the new design method

This new design method is for sheeting with perforations arranged in squares (Figure 6.2.1) in the webs or in the flanges (Figure 6.2.2).

Range of validity: $0.2 \leq d/a \leq 0.9$

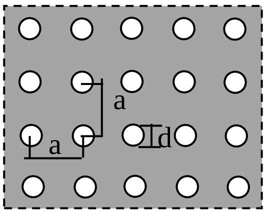


Figure 6.2.1 – *Perforations arranged in squares*

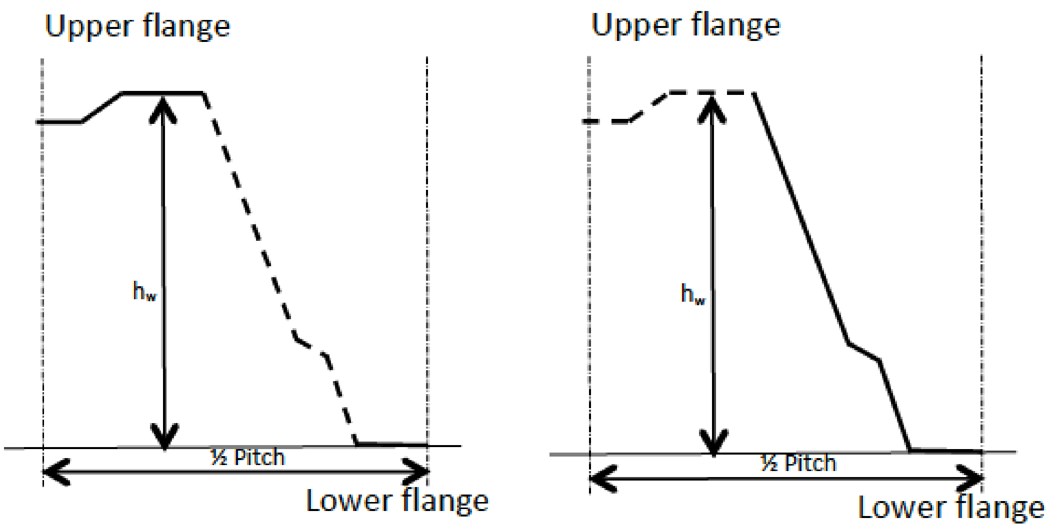


Figure 6.2.2 – *Sheeting with perforations in the web (on the left) or in the flange (on the right)*

6.3. Design procedure

6.3.1. Gross section of perforated sheeting with perforations arranged in squares

Gross section properties are calculated using EN 1993-1-3 Section 5.1, but replacing t by $t_{a,eff}$ obtained from: $t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{a}\right)$

where:
d is the diameter of the perforations;
a is the spacing between the centers of the perforations (Figure 6.2.1).

6.3.2. Effective section of perforated sheeting with perforations arranged in squares

Effective section properties are calculated using EN 1993-1-3 Section 5, but replacing t by $t_{b,eff}$ obtained from: $t_{b,eff} = t\sqrt[3]{1{,}18\left(1 - d/a\right)}$

where:
d is the diameter of the perforations;
a is the spacing between the centers of the perforations (Figure 6.2.1).

6.3.3. Resistance moment of sheeting with perforations arranged in squares

The design moment resistance of a cross-section for bending about one principal axis $M_{c,Rd}$ is determined according to EN 1993-1-3 "6.1.4 Bending moment", as follows:

$$M_{c,Rd} = W_{eff}\, f_{yb} / \gamma_{M0}$$

The effective section modulus W_{eff} should be based on an effective cross-section that is subject only to bending moment about the relevant principal axis, with a maximum stress $\sigma_{max,Ed}$ equal to f_{yb} / γ_{M0}, allowing for the effects of local and distortional buckling as specified in Section 5.5. and in 7.1

6.3.4. Local load or support reaction of a web with perforations arranged in squares

Local transverse resistance of a web of a sheeting with perforations of the web arranged in squares is calculated according to the formula (6.18) of EN 1993-1-3

$$R_{w,Rd} = \alpha t^2 \sqrt{f_{yb} E}\,\left(1 - 0{,}1\sqrt{r/t}\right)\left[0{,}5 + \sqrt{0{,}02\, l_a / t}\right]\left(2{,}4 + (\phi/90)^2\right)/\gamma_{M1} \qquad (6.18)$$

but replacing t by $t_{c,eff}$ obtained from: $t_{c,eff} = t\left[1 - (d/a)^2 s_{per} / s_w\right]^{3/2}$

Where: s_{per} is the slant height of the perforated portion of the web;

s_w is the total slant height of the web.

6.3.5. Combined bending moment and local load or support reaction with perforations arranged in squares

(1) In case of sheeting with with perforations arranged in squares the equations (6.28a), (6.28b) and (6.28c) of EN 1993-1-3 may be used with:

$M_{c,Rd}$ = resistance moment determined according to 6.3.3

$R_{w,Rd}$ = local transverse resistance determined according to 6.3.4

(2) Cross-sections subject to the combined action of a bending moment M_{Ed} and a transverse force due to a local load or support reaction F_{Ed} should satisfy the following:

$$M_{Ed} / M_{c,Rd} \leq 1$$

$$F_{Ed} / R_{w,Rd} \leq 1$$

$$\frac{M_{Ed}}{M_{c,Rd}} + \frac{F_{Ed}}{R_{w,Rd}} \leq 1,25$$

7. SPECIFIC DESIGN CONSIDERATION

Situations not covered by the present Manual

Fire

Seismic

Environmental aspect

Thermal

Acoustic

Others

8. EXPLANATION OF THE "WEB PERFORATIONS – SPAN – END SUPPORT"" SOFTWARE CALCULATION

This software allows to calculate span moment resistance and end support reaction for a profile with one stiffener in the upper flange, with one stiffener in the web and with perforations arranged in squares in the web.

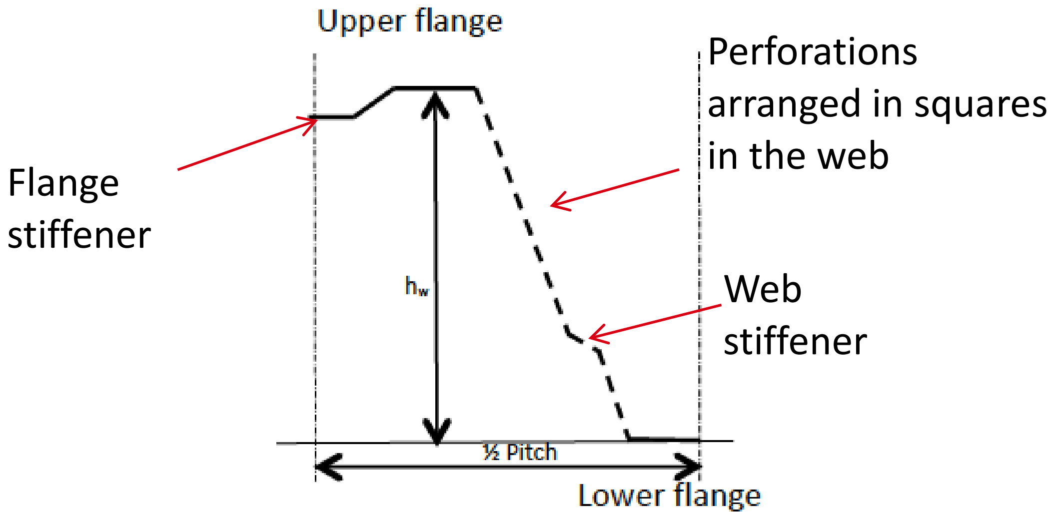


Figure 8.1. *- Steel sheeting with a stiffener in the upper flange, a stiffener in the web and with perforations arranged in squares in the web*

8.1. DATA

All the red cells have to be filled with the profile dimensions (*Figures 8.1.1 and 8.1.2*): internal bend radius R, angles θ, angle of the web relative to the flanges ϕ, design thickness t, nominal thickness t_{nom}, the pitch, web height h_w, height of the part of the web above the stiffener h_a, height of the web stiffener h_{sa}, height of the flange stiffener d_s, yield strength f_{yb}, Young's modulus E, diameter of the perforations *d*; spacing between the centers of the perforations *a*, slant height of the perforated portion of the web s_{per}:

R1 (mm)	θ_1 (rad)	R2$_{sup}$ (mm)	R2$_{inf}$ (mm)	θ_2 (rad)	R3 (mm)	θ_3 (rad)	ϕ (rad)

t_{nom} (mm)	t (mm)	Pitch (mm)	h_w (mm)	h_a (mm)	h_{sa} (mm)	d_s (mm)

f_{yb} (N/mm²)	E (N/mm²)	γ_{M0}	a (mm)	d (mm)	s_{per} (mm)

Table 8.1.1 *- Excel cells to be filled with the profile dimensions*

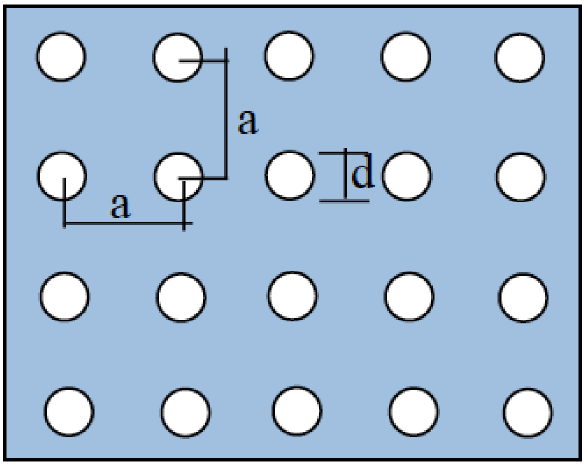


Figure 8.1.1 *- Perforation pattern*

Fill the red cells of the following table with dimensions (b_{pi}) of all elements of ½ pitch. The element numbers are given in the Figure 8.1.2. The length of the elements are measured from the midpoints « P » of the adjacent corner elements as indicated in Figure 8.1.3.

Element	b_{pi} (mm)
1	
2	
3	
4	
5	
6	
7	

Table 8.1.2 *- Excel cells to be filled with the elements dimensions*

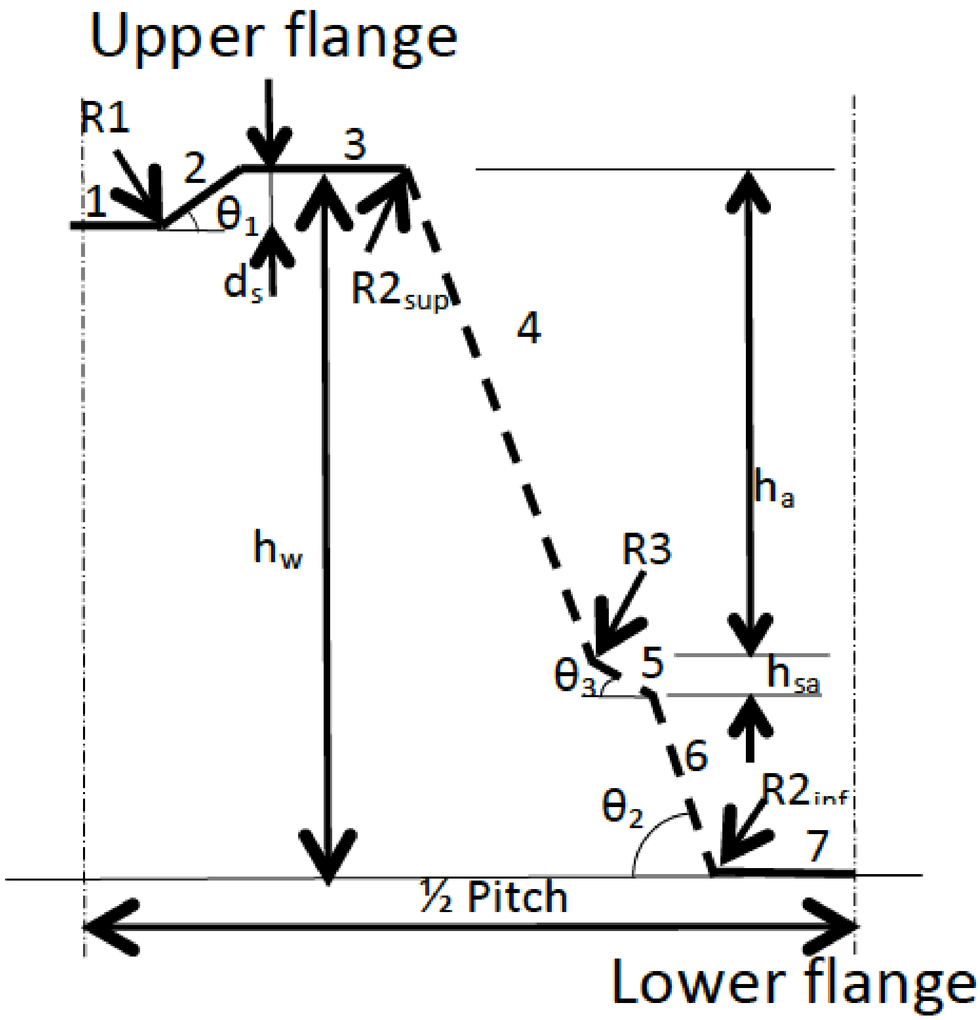


Figure 8.1.2 *- Element numbers and data*

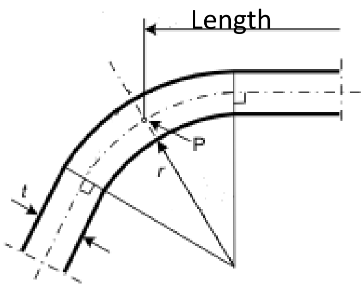


Figure 8.1.3 *- Length of the elements measured from the midpoints « P »*

8.2. Checking of geometrical proportions

Fill the red cell of the following table with dimensions (b)

The software automatically displays the checking of geometrical proportions

	b=	
	b/t=	
	θ_2=	
	h/t=	
	500sin(θ2)=	
r <	$0{,}04\ t\ E\ /\ f_y$	

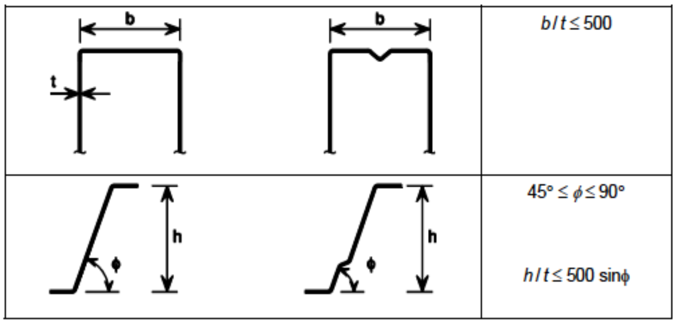


Table 8.2.1 *- Automatic checking of geometrical proportions*

8.3. RESULTS

The software automatically displays the results:

- ⇨ span moment resistance **M_{span}= xxx kNm/m**
- ⇨ end support reaction **$R_{endsupport}$= xxx kN/m**

9. DESIGN EXAMPLE

This example shows how to deal with steel profiles with perforations arranged in squares in the webs, when determining the bending capacity and the web-crippling resistance of a sheeting with one stiffener in the upper flange and one stiffener in the web.

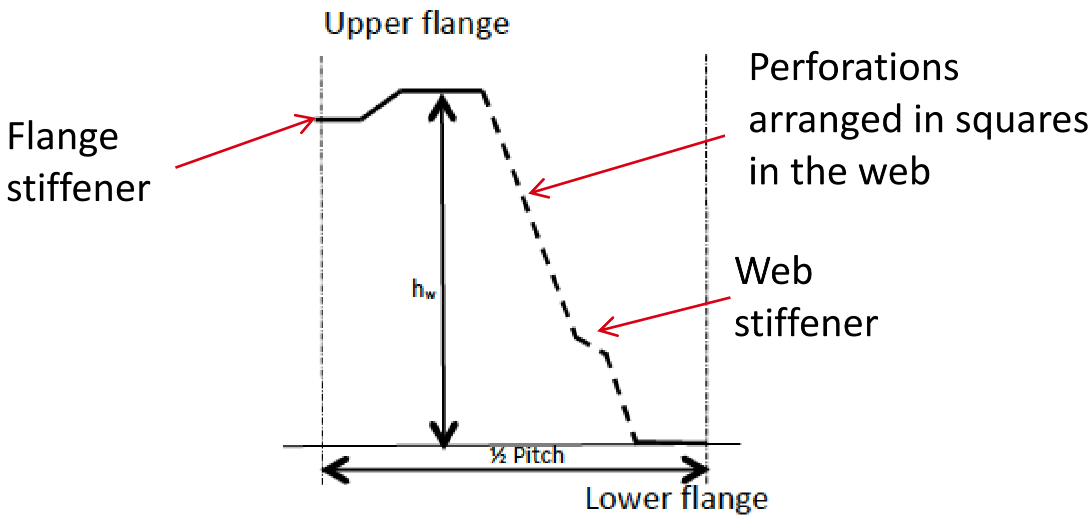


Figure 9.1 *- Steel sheeting with one stiffener in the flange, one stiffener in the web and perforations arranged in squares in the web.*

9.1. Sheeting cross section

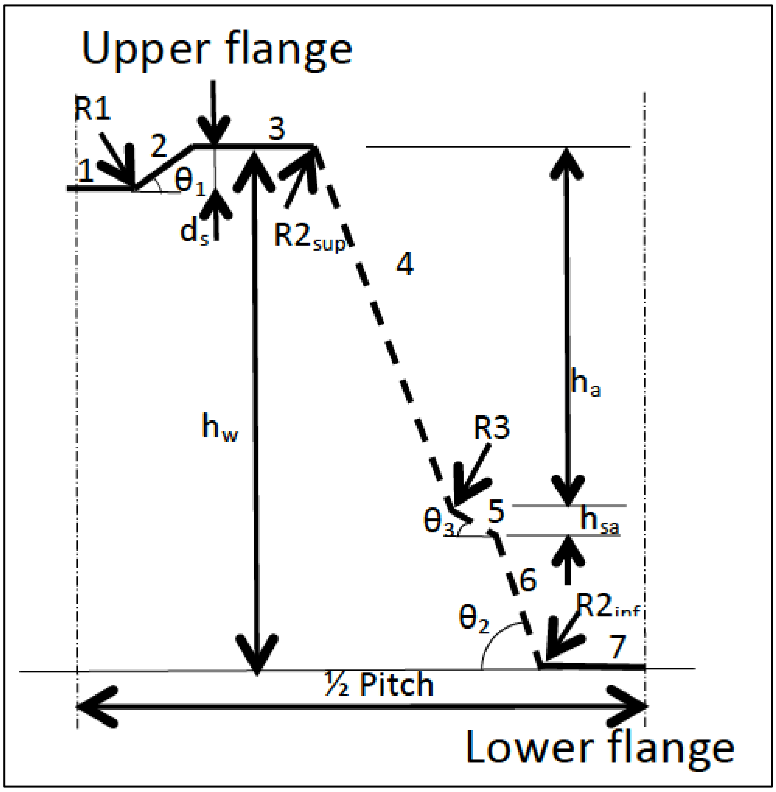


Figure 9.1.1 *- Sheeting cross section*

9.1.1. Sheeting values

The example is based on the calculation of span moment resistance value of a profile with the following data:

R1 (mm)	θ_1 (rad)	$R2_{sup}$ (mm)	$R2_{inf}$ (mm)	θ_2 (rad)	R3 (mm)	θ_3 (rad)	ϕ (rad)
0	0.22	6	6	1.31	3	0.99	1.27

t_{nom} (mm)	t (mm)	Pitch (mm)	h_w (mm)	h_a (mm)	h_{sa} (mm)	d_s (mm)
0.75	0.71	195	73	45	9	3

f_{yb} (N/mm²)	E (N/mm²)	γ_{M0}	a (mm)	d (mm)	s_{per} (mm)
320	210000	1	11.30	5.00	46.64

Table 9.1.1.1 *- Sheeting data*

Element	b_{pi} (mm)
1	0.00
2	15.30
3	47.50
4	45.44
5	10.34
6	18.52
7	12.00

Table 9.1.1.2 *- Elements dimensions*

9.1.2. Checking of geometrical proportions

b = 125; t = 0.71; h = 73; f_y = 320

	b=	125.00
	b/t=	176.06
	θ_2=	75.00
	h/t=	102.82
	500sin(θ2)=	482.96
r <	$0{,}04\ t\ E\ /\ f_y$	18.64

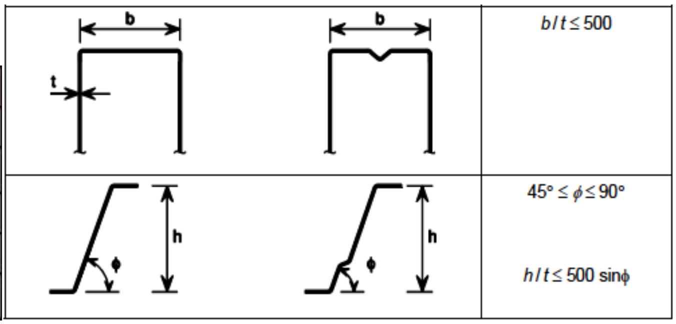


Table 9.1.2.1 *- Checking of geometrical proportions*

9.1.3. Perforations dimensions

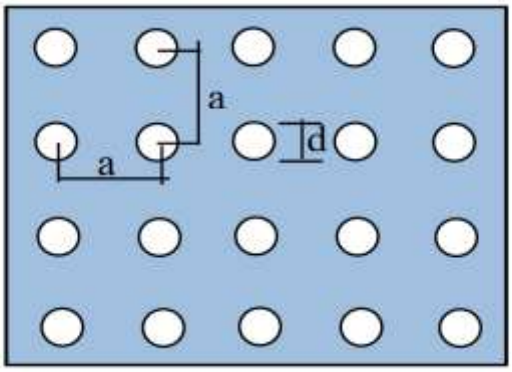


Figure 9.1.3.1 *- Perforations dimensions*

d/a = 0.4
Range of validity checked : $0.2 \leq d/a \leq 0.9$

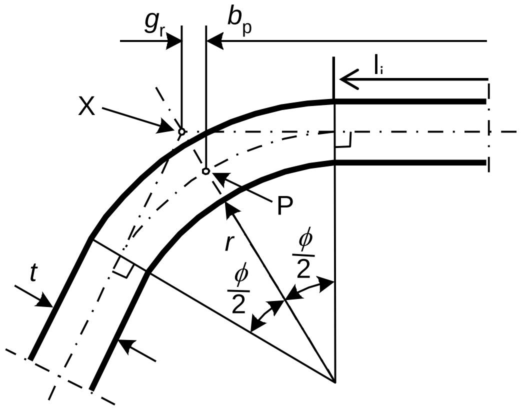
9.2. Calculation of A_g the area of the gross-section

Gross section properties are calculated using EN 1993-1-3 Section 5.1, but replacing web thickness t by $t_{a,eff}$ obtained from: $t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{a}\right)$

where:
d is the diameter of the perforations;
a is the spacing between the centers of the perforations (Figure 9.1.3.1).

A_g is the sum of the areas of each element (length x t)

length = $l_i = b_p - r_m \times \sin\pi/4$



(a) midpoint of corner or bend

X is intersection of midlines

P is midpoint of corner

$r_m = r + t/2$

Figure 9.2.1 *- Notional widths of plane cross section parts b_p allowing for corner radii*

Element	l_i (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
1	0.0	0.0	70.0	0.00	-18.5
Corner 1_{inf}	0.0	0.0	70.0	0.00	-18.5
2	15.3	10.9	71.5	776.56	-20.0
Corner 1_{sup}	0.0	0.0	73.0	0.00	-21.5
3	43.8	31.1	73.0	2272.61	-21.5
Corner 2_{sup}	7.9	5.6	71.4	398.30	-19.9
4	40.4	17.0	50.5	858.37	1.0
Corner 3_{sup}	3.0	1.3	28.0	35.18	23.5
5	7.5	3.2	23.5	74.03	28.0
Corner 3_{inf}	3.0	1.3	19.0	23.87	32.5
6	13.4	5.7	9.5	53.77	42.0
Corner 2_{inf}	7.9	5.6	1.6	8.77	49.9
7	8.3	5.9	0.0	0.00	51.5
TOTAL		87.4		4501.5	51.5

Table 9.2.1 - *Elements dimensions*

A_g = 87.4 mm²

Position of the neutral axis: $z_G = S / A_g$ = 51.5 mm

9.3. Calculation of the effective area A_{eff} of the section

Effective section properties are calculated using EN 1993-1-3 Section 5, but replacing web thickness t by $t_{b,eff}$ obtained from:

$$t_{b,eff} = t \sqrt[3]{1{,}18\left(1 - d / a\right)}$$

where:
d is the diameter of the perforations;
a is the spacing between the centers of the perforations (Figure 9.1.3.1).

A_{eff} is the sum of the effective areas of each element.

9.3.1. Step 1

Upper flange effective area

The upper flange has one stiffener. The effective cross-section of the flange is calculated according to EN 1993-1-3 § "5.5.3.4.2 Flanges with intermediate stiffeners".

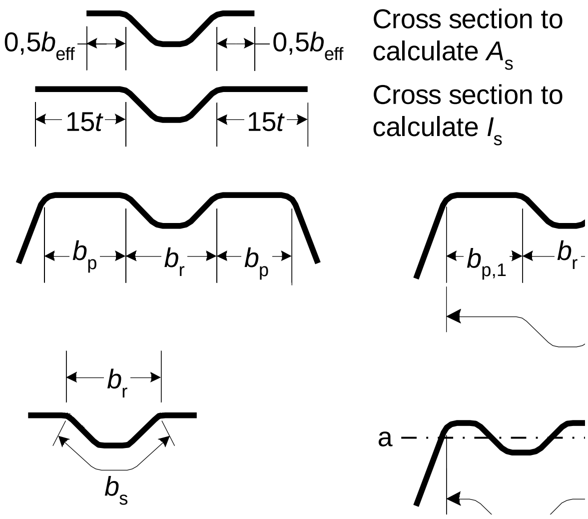


Figure 9.3.1.1 *- Flange with two stiffeners*

stress in the upper flange is $\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G = 134$ N / mm²

$b_p = 47.5$ mm

$\lambda_p = b_p/t/(28.4\ \varepsilon k_\sigma^{1/2})$ with $\varepsilon=(235/ f_{yb})^{1/2}$

$\psi=\sigma_2/ \sigma_1= 1$ ➔ Coefficient $k_\sigma=4$

$\lambda_p=1.374$

$\lambda_{pred}= \lambda_p \times \sqrt{\frac{\sigma\ com}{fy/\gamma M0}}$ ➔ $\lambda_{pred1}= 0.888$

$\lambda_{pred} > 0.673$ ➔ $\rho = \frac{1-0{,}055(3+\psi)/\bar{\lambda}_{p,red}}{\bar{\lambda}_{p,red}} + 0{,}18\frac{(\bar{\lambda}_p - \bar{\lambda}_{p,red})}{(\bar{\lambda}_p - 0{,}6)}$ ➔ $\rho = 0.96$

$b_{eff}= \rho * b_p = 45.6$ ➔ $0{,}5\ b_{eff} = 22.8$ m

<u>Stiffener of the upper flange:</u>

The cross section of the stiffener is calculated according to EN 1993-1-3 § "5.5.3.3 Plane elements with intermediate stiffeners »

Calculation of critical buckling stress $\sigma_{cr,s}$

$$\sigma_{cr,s} = \frac{4{,}2\, k_w E}{A_s}\sqrt{\frac{I_s\ t^3}{4\ b_p^2\ (2\ b_p + 3\ b_s)}}$$

$b_s = 30.6$ mm, $b_p = 47.5$ mm

Calculation of A_s

Element	l_i (mm)	A_i(mm²)
plane part	22.81	16.19
Corner 1 $_{sup}$	0.00	0.00
2	15.30	10.86
Corner 1 $_{inf}$	0.00	0.00
1	0.00	0.00
Corner 1 $_{inf}$	0.00	0.00
2	15.30	10.86
Corner 1 $_{sup}$	0.00	0.00
plane part	22.81	16.19
TOTAL		54.1

***Table 9.3.1.1** - Elements lengths and areas*

A_s = 54.1 mm²

Calculation of I_s

Element	l_i (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)	h	I_i(mm⁴)
plane part	10.65	7.56	0.00	0.00	0.88	0.71	6.23
Corner 1 $_{sup}$	0.00	0.00	0.00	0.00	0.88	0.00	0.00
2	15.30	10.86	1.50	16.29	-0.62	3.30	13.95
Corner 1 $_{inf}$	0.00	0.00	3.00	0.00	-2.12	0.00	0.00
1	0.00	0.00	3.00	0.00	-2.12	0.71	0.00
Corner 1 $_{inf}$	0.00	0.00	3.00	0.00	-2.12	0.00	0.00
2	15.30	10.86	1.50	16.29	-0.62	3.30	13.95
Corner 1 $_{sup}$	0.00	0.00	0.00	0.00	0.88	0.00	0.00
plane part	10.65	7.56	0.00	0.00	0.88	0.71	6.23
TOTAL		36.8		32.6	0.88		40.4

***Table 9.3.1.2** - Elements lengths and moment areas*

I_s = 40.4 mm^4

$$l_b = 3{,}07 \sqrt[4]{\frac{I_s\, b_p^2\,(2\,b_p + 3\,b_s)}{t^3}}$$

l_b = 254.9

s_w = 73.7

$l_b / s_w = 3.5 \geq 2 \rightarrow \quad k_w = k_{wo}$

$$k_{wo} = \sqrt{\frac{s_w + 2\,b_d}{s_w + 0{,}5\,b_d}}$$

k_{wo} = 1.54

critical buckling stress $\sigma_{cr,s}$ = 74 N/mm²

$$\bar{\lambda}_{d} = \sqrt{f_{yb}/\sigma_{cr,s}}$$

$$\bar{l}_{d} = 1{,}77$$

$$\bar{\lambda}_{d} \geq 1{,}38 \Rightarrow \chi_{d} = \frac{0{,}66}{\bar{\lambda}_{d}}$$

reduction factor for the distortional buckling resistance χ_d = 0,317

Reduced thickness $t_{red} = c_d t \frac{f_{yb}/g_{M0}}{s_{com,Ed}}$

Reduced thickness t_{red} = 0.54 mm

Web Effective area

The web effective area is calculated according to "5.5.3.4.3 Webs with up to two intermediate stiffeners" of EN 1993-1-

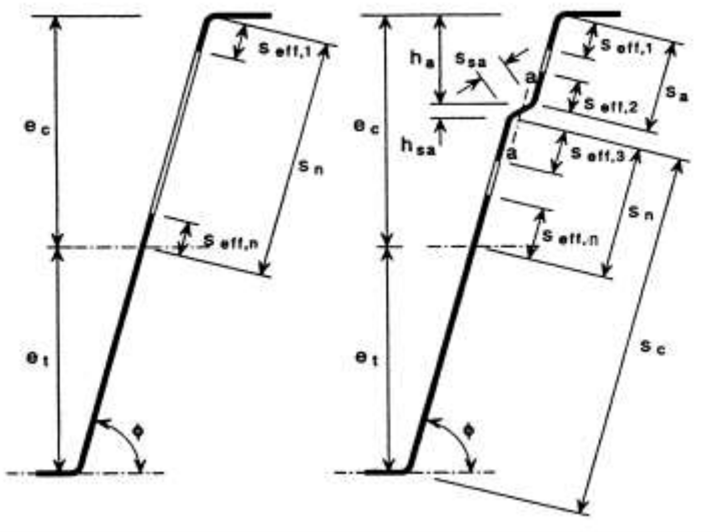


Figure 9.3.1.2 *- Web effective area*

As z_g = 51.5 mm and h_a = 45 mm the web stiffener is below the neutral axis therefore the stiffener is not compressed and the effective width of the web is calculated as a web without a stiffener.

$e_c = h_w - z_G$=21,5 mm ➔ s_n = 21,3 mm

$\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G$ = 134 N / mm²

effective section properties refined iteratively ➔

$$s_{\text{eff},0} = 0{,}95t\sqrt{\frac{E}{\gamma_{M0}\sigma_{\text{com,Ed}}}}$$

➔ $s_{\text{eff},0} = 22{,}0$ mm

$s_{\text{eff},1} = s_{\text{eff},0}$ ➔ $s_{\text{eff},1} = 22.0$ mm

$s_{\text{eff},n} = 1.5\ s_{\text{eff},0}$ ➔ $s_{\text{eff},n} = 33.0$ mm ➔ $s_{\text{eff},1} + s_{\text{eff},n} \geq s_n$ the entire web is effective

$s_{\text{eff},1} = 0{,}4s_n$

$s_{\text{eff},n} = 0{,}6s_n$

Lower flange effective area

Lower flange in this case is in tension ➔ all width is effective

Total effective area

Calculation of A_{eff}

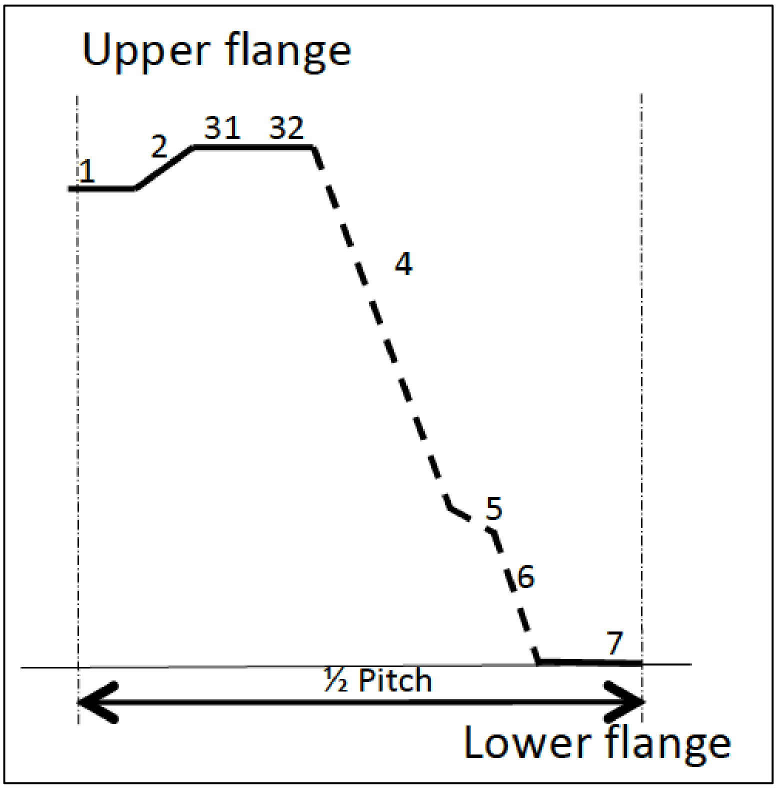


Figure 9.3.1.3 *- Elements numbers*

Element	l_i (mm)	t_{eff} (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
1	0.0	0.54	0.00	70.00	0.00	-21.94
Corner 1_{inf}	0.0	0.54	0.00	70.00	0.00	-21.94
2	15.3	0.54	8.24	71.50	589.16	-23.44
Corner 1_{sup}	0.0	0.54	0.00	73.00	0.00	-24.94
31	23.8	0.54	12.79	73.00	933.91	-24.94
32	19.2	0.71	13.60	73.00	992.85	-24.94
Corner 2_{sup}	7.9	0.71	5.58	71.43	398.30	-23.36
4	40.4	0.58	23.53	50.50	1188.30	-2.44
Corner 3_{sup}	3.0	0.58	1.74	28.00	48.70	20.06
5	7.5	0.58	4.36	23.50	102.48	24.56
Corner 3_{inf}	3.0	0.58	1.74	19.00	33.05	29.06
6	13.4	0.58	7.84	9.50	74.44	38.56
Corner 2_{inf}	7.9	0.71	5.58	1.57	8.77	46.49
7	8.3	0.71	5.93	0.00	0.00	48.06
TOTAL			90.9		4370.0	48.1

Table 9.3.1.3 *- Elements lengths and areas*

A_{eff} = 90.9 mm²

Position of the neutral axis of the effective section: z_G = 48.1 mm

9.3.2. <u>Iteration: : Next Steps</u>

In the next steps the new position of the neutral axis of the effective section is taken to calculate the new σ_{com} .

<u>The upper flange effective area</u> is calculated as in step 1 but taking the new σ_{com} calculated with new position of the neutral axis z_c

<u>Web Effective area</u> is calculated as in step 1 but In the next step the new position of the neutral axis of the effective section is taken to calculate the new σ_{com} .

<u>Lower flange effective area</u>

Lower flange in this case is in tension ➔ Lower flange in this case is in tension ➔ all width is effective

All the values of steps 2, 3 and 4 are indicated in following table. The convergence is considered satisfactory at step 4, the iteration stops at step 4.

		2nd step	3rd step	4th step
Upper flange	σ_{com}	166	177	179
	ρ	0.875	0.851	0.844
	$0,5\ b_{1,eff}$	20.78	20.20	20.05
Upper flange stiffener	$\sigma_{cr,s}$	77.75	79.02	79.35
	χ_d	0.33	0.33	0.33
	t_{red}	0.45	0.42	0.42
Web	e_c	24.9	26.0	26.2
	s_n	24.9	25.9	26.2
	$s_{eff,0}$	19.7	19.1	19.0
	$s_{eff,1}$	19.7	19.1	19.0
	$s_{eff,n}$	29.6	28.7	28.4
	$s_{eff,1} + s_{eff,n}$	49.3	47.8	47.4
		entire web is effective	entire web is effective	entire web is effective
	$s_{eff,1}$	0,4sn	0,4sn	0,4sn
	$s_{eff,n}$	0,6sn	0,6sn	0,6sn
Total effective Area	A_{eff}	87.3	86.4	86.1
Position of neutral axis	z_c	47.0	46.8	46.7

***Table 9.3.2.1** – Steps 2, 3, 4 values*

9.4. Calculation of span moment resistance

The span moment resistance is calculated with step 4 data

Element	l_i (mm)	t_{eff} (mm)	A_i (mm²)	z(mm)	S_i (mm³)	z0(mm)	h	I_i (mm⁴)
1	0.0	0.42	0.0	70.00	0.00	-23.29	0.71	0.00
Corner 1_{inf}	0.0	0.42	0.0	70.00	0.00	-23.29	0.00	0.00
2	15.3	0.42	6.4	71.50	455.37	-24.79	3.30	3918.40
Corner 1_{sup}	0.0	0.42	0.0	73.00	0.00	-26.29	0.00	0.00
31	23.8	0.42	9.9	73.00	721.84	-26.29	0.71	6832.62
32	19.2	0.71	13.6	73.00	992.85	-26.29	0.71	9397.89
Corner 2_{sup}	7.9	0.71	5.6	71.43	398.30	-24.71	0.00	3405.73
4	40.4	0.58	23.5	50.50	1188.30	-3.79	38.98	3316.80
Corner 3_{sup}	3.0	0.58	1.7	28.00	48.70	18.71	0.00	609.15
5	7.5	0.58	4.4	23.50	102.48	23.21	6.27	2364.40
Corner 3_{inf}	3.0	0.58	1.7	19.00	33.05	27.71	0.00	1335.93
6	13.4	0.58	7.8	9.50	74.44	37.21	12.98	10961.71
Corner 2_{inf}	7.9	0.71	5.6	1.57	8.77	45.14	0.00	11363.27
7	8.3	0.71	5.9	0.00	0.00	46.71	0.71	12933.53
TOTAL			86.1		4024.1	46.7		66439.4

***Table 9.4.1**– Step 4 data*

$$M_{c,Rd} = W_{eff}\, f_{yb} / \gamma_{M0}$$

For ½ pitch I_{eff} =66439 mm^4

For the profile I_{eff} = 681 mm^3

v = max (46,7;26,3)=46,7 mm

$W_{eff} = I_{eff} / v = 14.6 \text{ mm}^3$

M_{span} = 4,7 kNm/m

9.5. Calculation of end support reaction

Local transverse resistance of a web of a sheeting with web perforations arranged in squares is calculated according to the usual formula (6.18) of EN 1993-1-3

$$R_{w,Rd} = \alpha t^2 \sqrt{f_{yb} E} \left(1 - 0{,}1\sqrt{r/t}\right)\left[0{,}5 + \sqrt{0{,}02\, l_a / t}\right]\left(2{,}4 + (\phi/90)^2\right)/\gamma_{M1} \quad (6.18)$$

but replacing t by $t_{c,eff}$ obtained from:

$$t_{c,eff} = t\left[1 - (d/a)^2 s_{per} / s_w\right]^{3/2}$$

Where: s_{per} is the slant height of the perforated portion of the web;

s_w is the total slant height of the web.

In this case the reaction at end support is with $c \leq 1{,}5\, h_w$ clear from a free end therefore this is Category 1

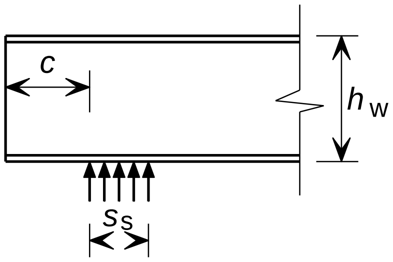


***Figure 9.5.1 -** Reaction at end support with $c \leq 1{,}5\, h_w$: Category 1*

For Category 1 for sheeting profiles α = 0,075 and l_a = 10mm

As the is stiffened the resistance is multiplied by the factor $\kappa_{a,s}$ given by:

$\kappa_{a,s} = 1{,}45 - 0{,}05\, e_{max} / t$ but $\kappa_{a,s} \leq 0{,}95 + 35\,000\, t^2\, e_{min} / (b_d^2\, s_p)$

where:

b_d is the developed width of the loaded flange, see figure 6.10;

e_{min} is the smaller eccentricity of the folds relative to the system line of the web;

s_p is the slant height of the plane web element nearest to the loaded flange, see figure 6.10.

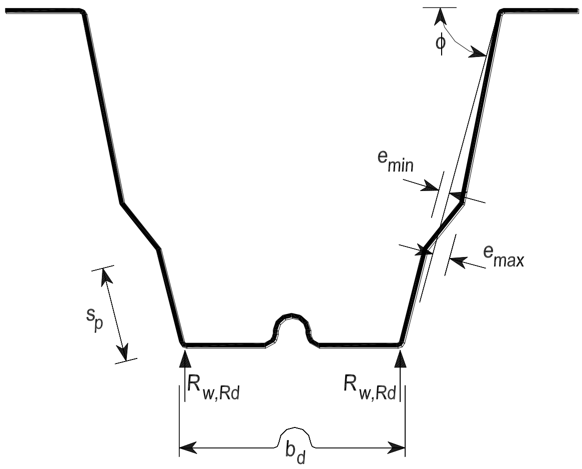


Figure 9.5.2 - *Stiffened webs*

t = 0,71 mm

r = 5 mm

$\phi = 72$

$e_{min} = 0.804$ mm

$b_d = 24$

$\kappa_{a,s} = 1.278$

Per web : $R_{w,Rd}$ = 713 N

Pitch = 195

Per meter: **$R_{w,Rd}$ = 6,5 kN/m**

10. AUTO-CONTROL OF THE SOFTWARE

The auto control is based on the previous example.

10.1. Calculation of span moment resistance:

The calculated span moment resistance in the previous example is

M_{span} = 4.7 kNm/m

The result of the software is M_{span}= 4.7 kNm/m

The results are the same

10.2. Calculation of end support resistance:

The calculated span moment resistance in the previous example is **$R_{w,Rd}$ = 6.5 kN/m**

The result of the software is $R_{endsupport}$= 6.5 kN/m

The results are the same

11. BIBLIOGRAPHY

[1] Baik S.C, Han H.N, Lee S.H, Oh K.H, Lee D.N, Plastic behaviour of perforated sheets under biaxial stress state, LNT J. Mech. Sc., vol39, No7, pp781-793, 1997.

[2] Misiek T. and Saal H. Load bearing capacity of perforated trapezoidal sheeting, stability and ductility of steel structure, Rio de Janeiro, Brazil, Sept. 2010.

[3] Kathage K., Misiek T., Saal H., Stiffness and critical buckling load of perforated sheeting, Thin-Walled Structures, 44, 2006.

[4] Lee Y.C., Chen F.K., Yield criterion for a perforated sheet with a uniform triangular pattern of round holes and a low ligament ratio, NTU Publ., Febr. 1999.

[5] Degtyarev V.V, Degtyareva N.V., Eleastic stability of uniformally compressed plates perforated in triangular pattern, Thin-Walled Structures, 52, 2012,

Annex 1

Background of the new design method for steel profiles with perforations arranged in squares.

D3.1	GRISPE WP3 Background document	Anna PALISSON (Sokol Palisson Consultants)
D3.2	GRISPE WP3 Test programme definition	Anna PALISSON (Sokol Palisson Consultants)
D3.3	GRISPE Test report	Christian FAUTH (KIT)
D3.4	GRISPE WP3 Test analysis and interpretation	Anna PALISSON (Sokol Palisson Consultants)
D3.5	GRISPE WP3 Background guidance for EN 1993-1-3 to design of sheeting with perforations or with a hole	Anna PALISSON (Sokol Palisson Consultants)