GRISPE PLUS

VALORISATION OF KNOWLEDGE FOR SPECIFIC PROFILED STEEL SHEETS

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D3.1 HOLED PROFILES

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SUMMARY

The purpose of this design manual is to present a new method of design by calculation for holed 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 holed 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:

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Figures

The figures have been produced by the following companies

Figure 1.1.1 – JORIS IDE and Sokol Palisson Consultants

Figure 1.1.2 – JORIS IDE and Sokol Palisson Consultants

Figure 1.3.1 – KIT

Figure 1.3.2 – KIT

Figure 1.3.3 – 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 8.1 – Sokol Palisson Consultants

Figure 8.1.1 - Sokol Palisson Consultants

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Calculation of span moment resistance

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ANNEX 1

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 : dimension of the hole

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_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

1. INTRODUCTION

1.1. Type of profiled steel sheets

This design manual deals with steel profiles with a circular (Figure 1.1.1) or a square hole (Figure 1.1.2) in the flange.

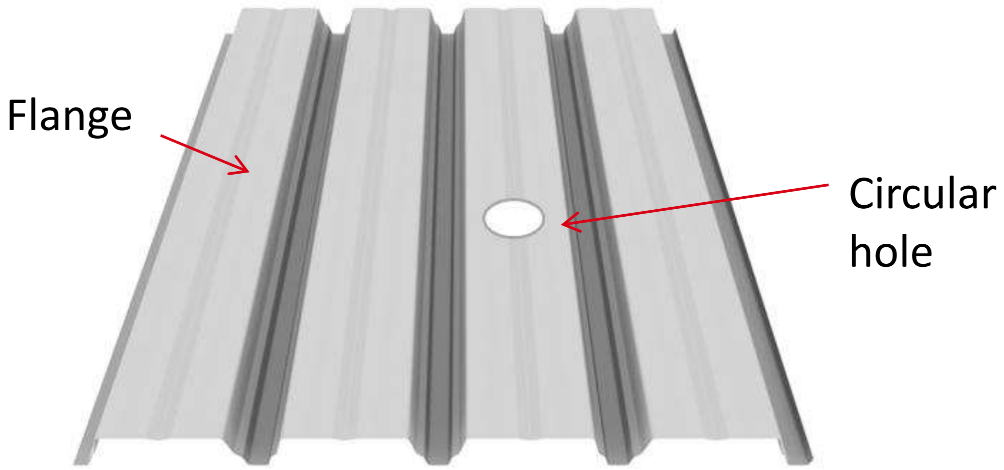


Figure 1.1.1 *– Steel profile with a circular hole*

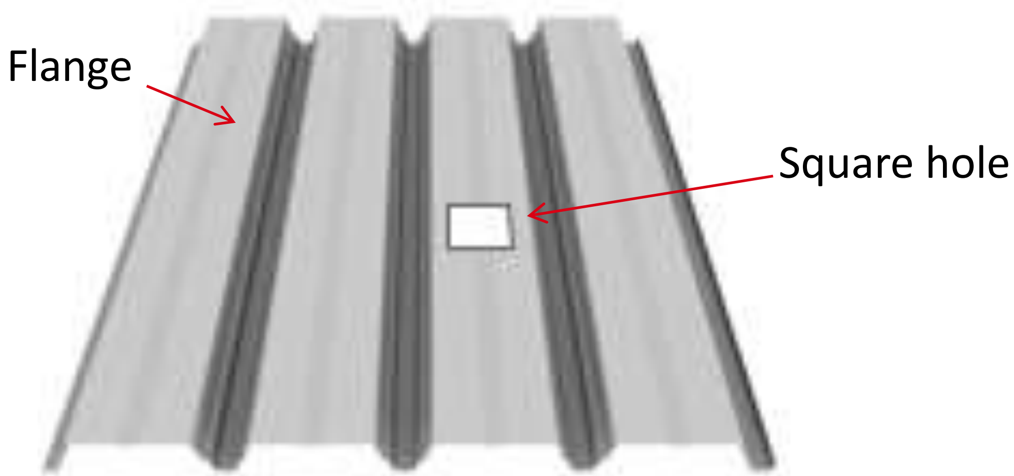


Figure 1.1.2 *– Steel profile with a square hole*

1.2. State of the art pre-GRISPE

In the context of construction site working conditions it is also often necessary to drill or cut holes in the flange of sheeting for the passage of services.

There is therefore a danger of improvised methods on the work site resulting in reduced structural safety and robustness. The holes reduce the strength capacity of the sheeting globally and locally and have an impact on its bending resistance and consequently on the safety. A formula for the buckling of plates with openings is available in the literature [1] while the German DIN 18807-3 provides solutions for some specific distribution and position of the holes [2] for which the IFBS has also provided some practical applications [3] but it's for holes with reinforcement. The US Council on Tall Buildings and Urban Habitat [4] reviewed the Dutch (SIS 1991), American (Heagler 1987) and Canadian approach. Penetration holes in the form of small square or round openings for the passage of services such as rainwater evacuation are always made in roofs [5]. Several studies on steel sheeting with holes [3], [4], [6], [7], [8] deal only with the effect of holes on local buckling and post buckling of plates subjected to compression or shear loading. Therefore there are no studies which establishes for sheeting with holes the moment resistance under flexion. Moreover European standard EN 1993-1-3 does not provide any information about moment resistance calculation.

The only option for manufacturers to design a profile with a hole is to carry out expensive and time consuming tests.

1.3. Main results of GRISPE

In order to determine and compare the resistance values of steel profiles with and without a hole, an extensive programme of 48 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 a circular hole in the flange
- with a square hole in the flange
- without a hole

A calculations method has been developed, checked and validated, to determine span moment resistance of a profile with a circular or a square hole in the upper flange..

Figure 1.3.1 *– Single span test on profile without a hole*

Figure 1.3.2 *– Single span test on profile with a circular hole*

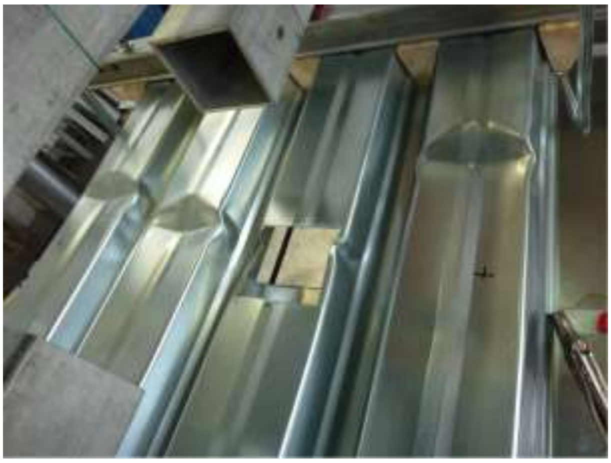


Figure 1.3.3 *– Single span test on profile with a square hole*

1.4. General design requirements and rules

(1) The design of holed 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 a circular or a square hole in the upper flange. The execution of steel structures made of sheeting is covered in EN 1090-4.

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 1.2.

NOTE: All rules in this manual relate to the main axis properties, which are defined by the main axes y - y and z - z for symmetrical sections and u - u and v - v for unsymmetrical sections as e.g. angles and Zed-sections. In some cases the bending axis is imposed by connected structural elements whether the cross-section is symmetric or not.

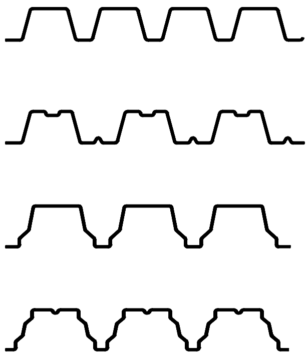


Figure 2.2.1.1 *– Example of profiles sheets*

(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)

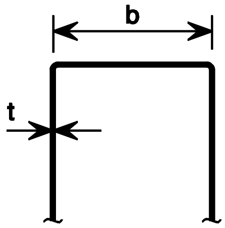
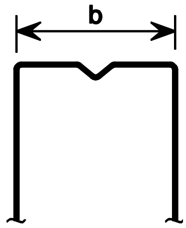
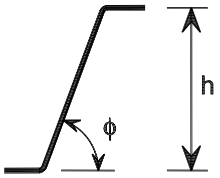
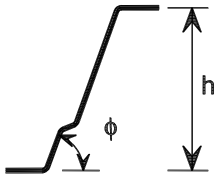
		$b/t \leq 500$
		$45° \leq \phi \leq 90°$ $h/t \leq 500 \sin\phi$

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 their National Annexes.

6. BASIS OF THE DESIGN

6.1. Principles

This new design method is given to calculate the resistance to bending moment for sheeting with a circular or a square hole in the compressed flange

6.2. Field of application of the new design method

This new design method is for sheeting with circular Figure (6.2.1) or square hole (Figure 6.2.2) in a flange.

Range of validity:

a) trapezoidal profiled sheets;

b) no more than two holes by span in a flange, with minimum distances according to the Figure 6.2.1;

c) only uniformly distributed loads are permitted.

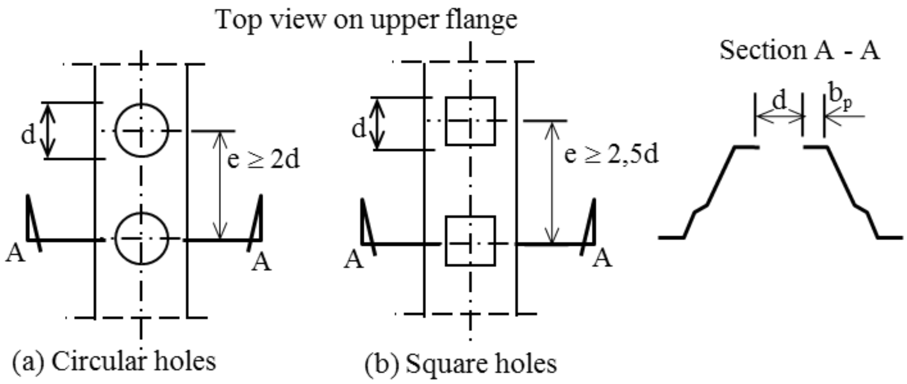


Figure 6.2.1 *– Perforations arranged in squares*

6.3. Design procedure

6.3.1. Effective section of a sheeting with a hole in a flange

In case of a circular or square hole in the compressed upper flange, the effective width of the flange parts adjacent to the webs may be determined considering them as as outstand elements of width b_p

6.3.2. 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

7. SPECIFIC DESIGN CONSIDERATION

Situations not covered by the present Manual

- **Fire**
- **Seismic**
- **Environmental aspect**
- **Thermal**
- **Acoustic**
- **Others**

8. EXPLANATION OF THE "HOLE – SPAN"" SOFTWARE CALCULATION

This software allows to calculate span moment resistance for a profile with a hole in one upper flange, with one stiffener in the others upper flanges and with one stiffener in the webs.

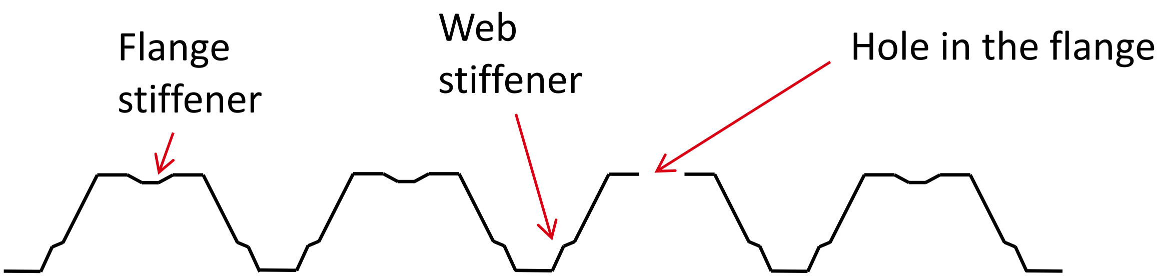


***Figure 8.1 -.** Steel sheeting a hole in a flange and with a stiffener in the others upper flanges and a stiffener in the webs*

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, 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, dimension of the upper flange b0, dimension of the hole *d*:

R1 (mm)	θ_1 (rad)	$R2_{sup}$ (mm)	$R2_{inf}$ (mm)	θ_2 (rad)	R3 (mm)	θ_3 (rad)

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

f_{yb} (N/mm²)	E (N/mm²)	γ_{M0}	b0 (mm)	d (mm)

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

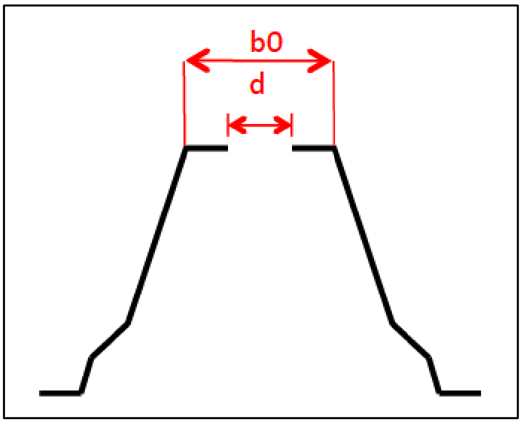


***Figure 8.1.1** – Hole dimension*

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*

Fill the red cell of the following table with the number of upper flanges without a hole.

Number of upper flanges without a hole	

***Table 8.1.3** - Excel cell to be filled with the number of upper flanges without a hole*

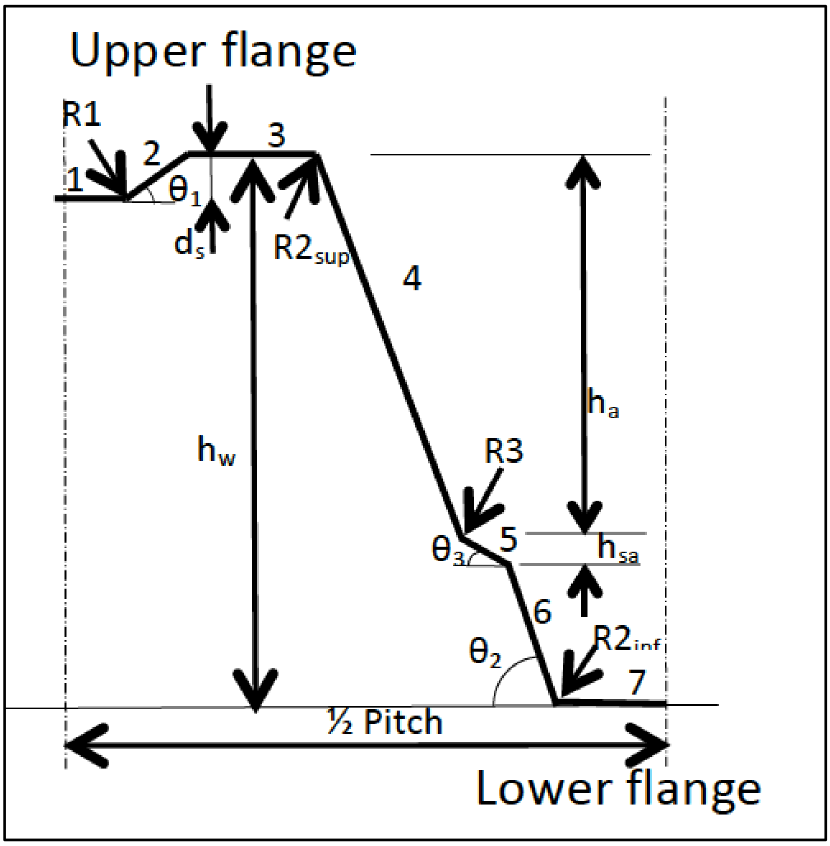


Figure 8.1.2 *- Element numbers and data (1/2 rib without a hole)*

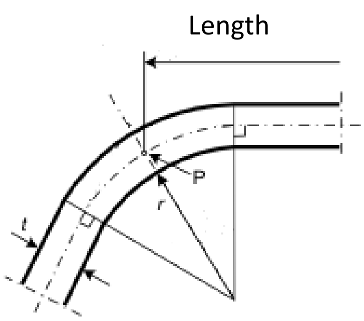


Figure 8.1.3 *- Length of the elements measured from the midpoints « P »*

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 <	$0{,}04\ t\ E\ /\ f_y$	

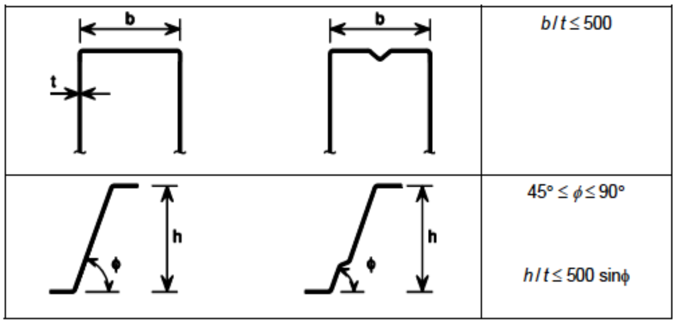


Table 8.2.1 *- Automatic checking of geometrical proportions*

8.3. RESULTS

The software automatically displays the result:

⇨ span moment resistance M_{span}= xxx kNm/m

9. DESIGN EXAMPLE

This example shows how to deal with steel profiles with a square or a circular hole in a flange, when determining the bending capacity of a sheeting with one stiffener in the others upper flanges and one stiffener in the webs.

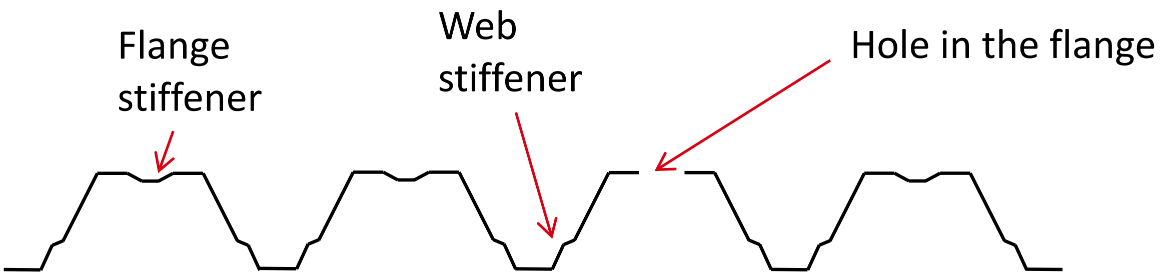


Figure 9.1 *- Steel sheeting with a hole in the flange, one stiffener in the other flanges and one stiffener in the webs.*

9.1. Sheeting cross section

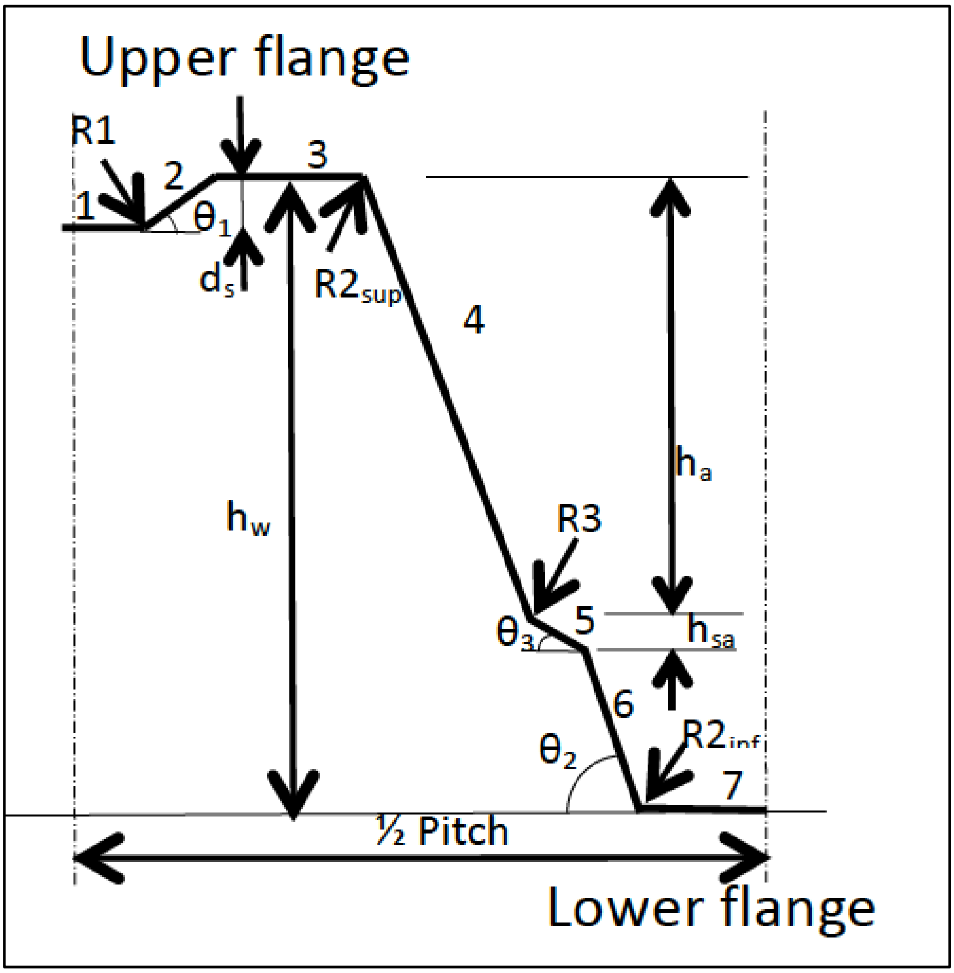


Figure 9.1.1 *- Sheeting cross section (1/2 rib <u>without</u> a hole)*

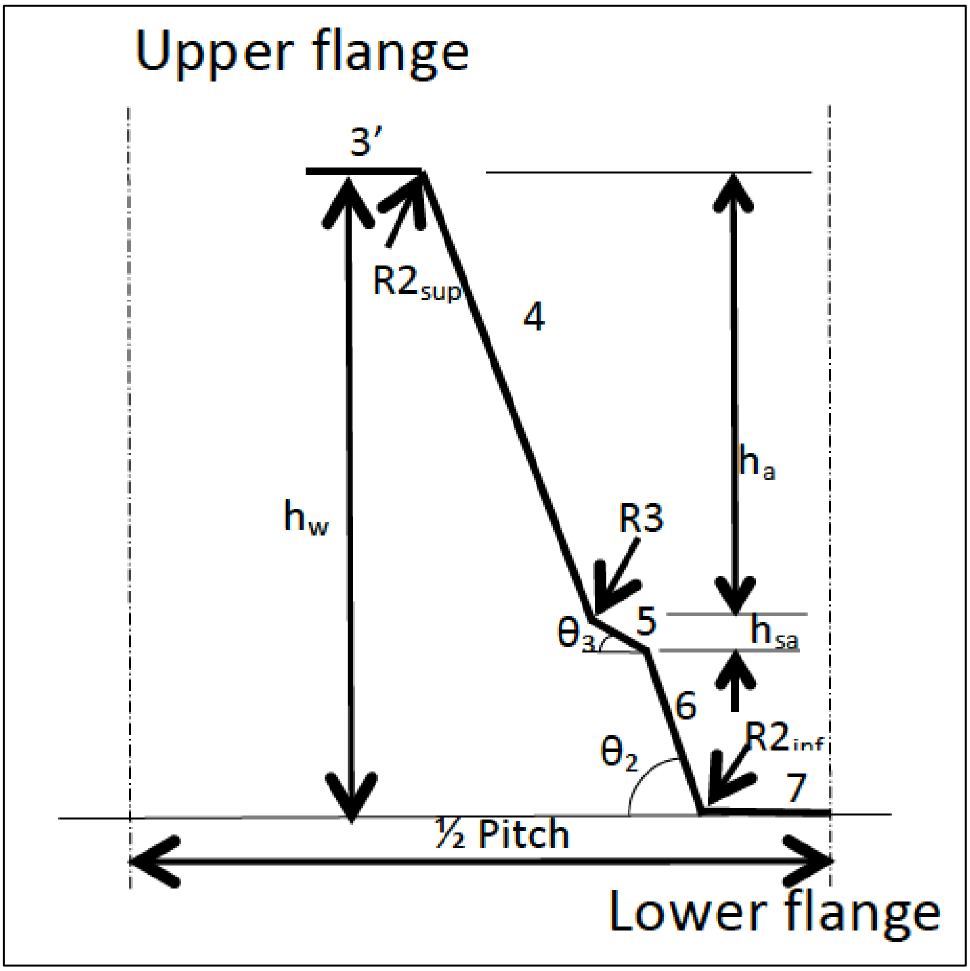


Figure 9.1.2 *- Sheeting cross section (1/2 rib with a hole)*

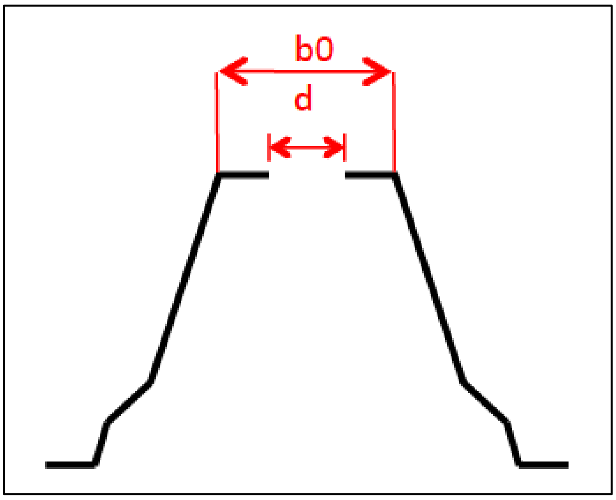


Figure 9.1.3 *– Hole dimension (rib with a hole)*

9.1.1. Data values

The example of span moment resistance calculation is performed with the following data:

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

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}	b0 (mm)	d (mm)
320.00	210000.00	1.00	125	90.00

Table 9.1.1.1 - *Sheeting data*

Element	b_{pi} (mm)
1	0.00
2	15.30
3	47.50
4	45.44
5	10.38
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 N/mm^2

	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

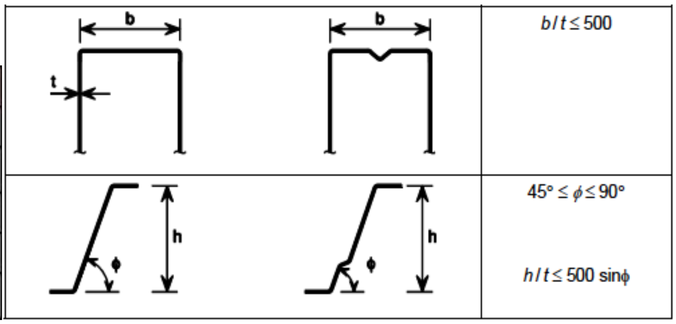
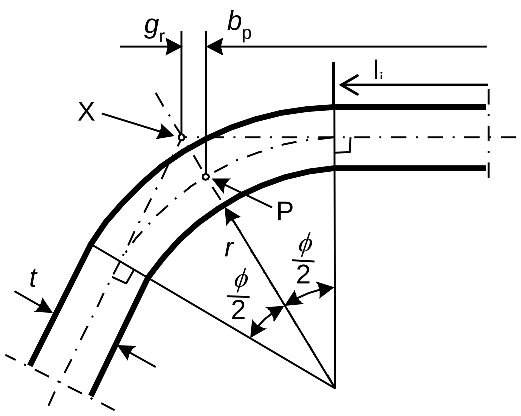


Table 9.1.2.1 - *Checking of geometrical proportions*

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

A_g is the sum of the areas of each element of the cross section (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*

9.2.1. Calculation of A_g the area of the gross-section <u>without</u> a hole

Element	l_i (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
1	0.0	0.0	70.0	0.00	-21.2
Corner 1_{inf}	0.0	0.0	70.0	0.00	-21.2
2	15.3	10.9	71.5	776.56	-22.7
Corner 1_{sup}	0.0	0.0	73.0	0.00	-24.2
3	43.8	31.1	73.0	2272.61	-24.2
Corner 2_{sup}	7.9	5.6	71.4	398.30	-22.6
4	40.4	28.7	50.5	1447.25	-1.7
Corner 3_{sup}	3.0	2.1	28.0	59.04	20.8
5	7.5	5.3	23.5	125.58	25.3
Corner 3_{inf}	3.0	2.1	19.0	40.07	29.8
6	13.4	9.5	9.5	90.70	39.3
Corner 2_{inf}	7.9	5.6	1.6	8.77	47.3
7	8.3	5.9	0.0	0.00	48.8
TOTAL		106.8		5218.9	48.8

Table 9.2.1.1 *- Elements dimensions*

A_g = 106.8 mm²

Position of the neutral axis: $z_G = S / A_g$ = 48.8 mm

9.2.2. Calculation of A_g the area of the gross-section <u>with</u> a hole

Element	l_i (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
3'	13.8	9.8	73.0	717.71	-24.2
Corner 2_{sup}	7.9	5.6	71.4	398.30	-22.6
4	40.4	28.7	50.5	1447.25	-1.7
Corner 3_{sup}	3.0	2.1	28.0	59.04	20.8
5	7.5	5.3	23.5	125.58	25.3
Corner 3_{inf}	3.0	2.1	19.0	40.07	29.8
6	13.4	9.5	9.5	90.70	39.3
Corner 2_{inf}	7.9	5.6	1.6	8.77	47.3
7	8.3	5.9	0.0	0.00	48.8
TOTAL		74.7		2887.4	38.7

Table 9.2.2.1 *- Elements dimensions*

A_g = 74.7 mm²

Position of the neutral axis: $z_G = S / A_g$ = 38.7 mm

9.3. Calculation of the effective area A_{eff} of the section Step1 of iteration

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

9.3.1. Calculation of the effective area A_{eff} of the section <u>without</u> a hole

The upper flange is with a 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".

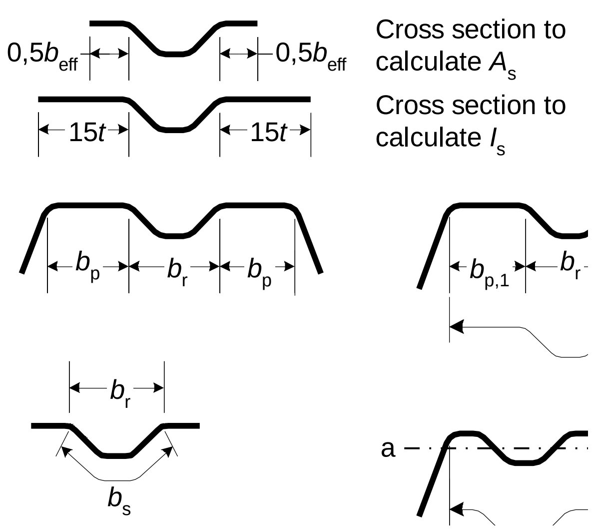


Figure 9.3.1.1 *- Flange with two stiffeners*

stress in the upper flange is $\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G$ = 158 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 $k_\sigma=4$

$\lambda_p=1.374$

$\lambda_{pred}= \lambda_p \times \sqrt{\frac{\sigma\ com}{fy/\gamma M0}}$ ➔ $\lambda_{pred1}= 0.966$

$\lambda_{pred} > 0.673$ ➔ $\rho = \frac{1-0{,}055(3+\psi)/\bar{\lambda}_{p,red}}{\bar{\lambda}_{p,red}} + 0{,}18\frac{(\bar{\lambda}_p-\bar{\lambda}_{p,red})}{(\bar{\lambda}_p-0{,}6)}$ ➔ ρ = 0.894

$b_{eff}= \rho * b_p$ = 42.5 ➔ 0,5 b_{eff} = 21.2 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	21.23	15.08
Corner 1_{sup}	0.00	0.00
2	15.30	10.86
Corner 1_{inf}	0.00	0.00
2	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	21.23	15.08
TOTAL		51.9

Table 9.3.1.1 *- Elements lengths and areas*

A_s = 51.9 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 ≥ 2 ➔ $k_w = k_{wo}$

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

k_{wo} = 1.54

critical buckling stress $\sigma_{cr,s}$ = 76.8 N/mm²

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

$\bar{\lambda}_d$ = 2.04

$$\bar{\lambda}_d \geq 1{,}38 \rightarrow \chi_d = \frac{0{,}66}{\bar{\lambda}_d}$$

reduction factor for the distortional buckling resistance χ_d = 0,323

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

Reduced thickness t_{red} = 0.46 mm

<u>Web Effective area</u>

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

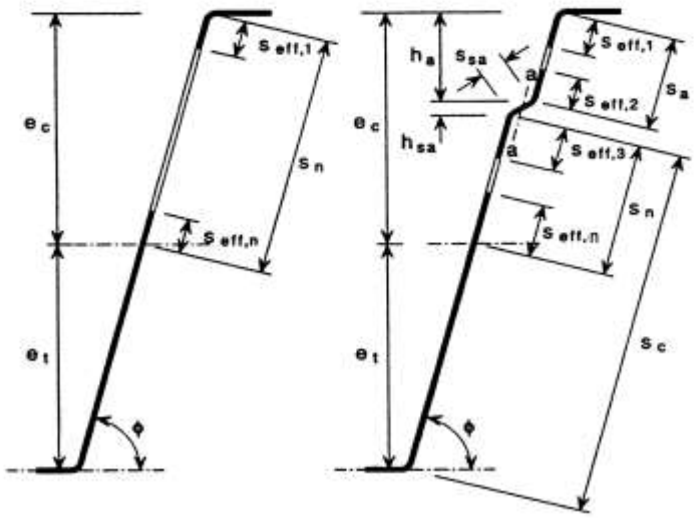


Figure 9.3.1.2 - *Web effective area*

As z_g = 48.8 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.

$e_c = h_w - z_G$=24,2 mm ➔ s_n = 24,1 mm

$\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G$ = 158 N / mm²

effective section properties refined iteratively ➔

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

➔ $s_{\text{eff},0}$ = 24,6 mm

$s_{\text{eff},1} = s_{\text{eff},0}$ ➔ $s_{\text{eff},1}$ = 24.6 mm

$s_{\text{eff},n} = 1.5\ s_{\text{eff},0}$ ➔ $s_{\text{eff},n}$ = 36.9 mm ➔ $s_{\text{eff},1} + s_{\text{eff},n} \geq s_n$ the entire web is effective

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

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

<u>Lower flange effective area</u>

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

<u>Total effective area</u>

Calculation of A_{eff}

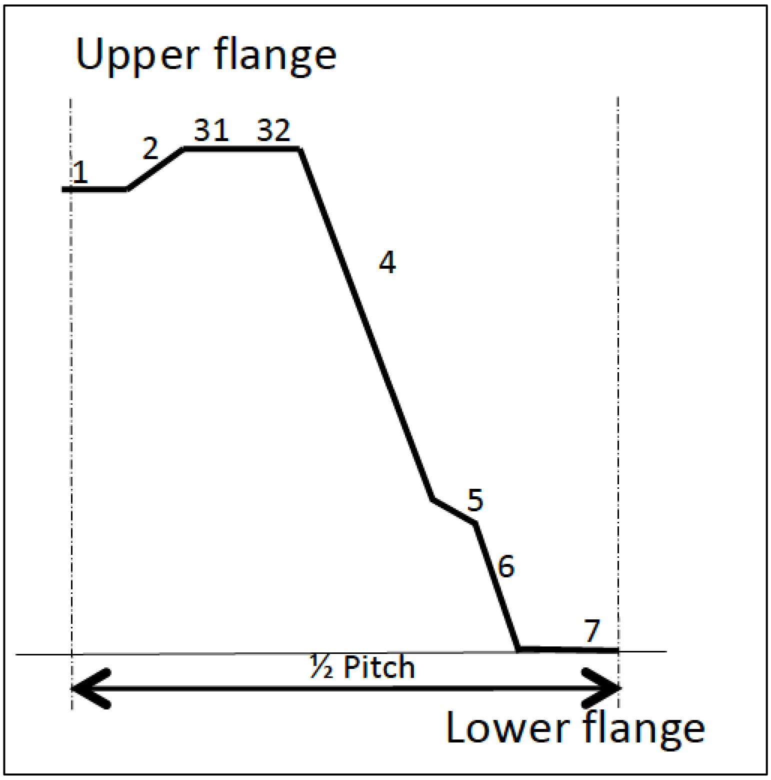


Figure 9.3.1.3 *- Elements numbers*

Element	l_i (mm)	t_{eff} (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
1	0.0	0.46	0.0	70.00	0.00	-23.97
Corner 1_{inf}	0.0	0.46	0.0	70.00	0.00	-23.97
2	15.3	0.46	7.1	71.50	507.80	-25.47
Corner 1_{sup}	0.0	0.46	0.0	73.00	0.00	-26.97
31	23.8	0.46	11.0	73.00	804.94	-26.97
32	17.6	0.71	12.5	73.00	911.17	-26.97
Corner 2_{sup}	7.9	0.71	5.6	71.43	398.30	-25.40
4	40.4	0.71	28.7	50.50	1447.25	-4.47
Corner 3_{sup}	3.0	0.71	2.1	28.00	59.04	18.03
5	7.5	0.71	5.3	23.50	125.58	22.53
Corner 3_{inf}	3.0	0.71	2.1	19.00	40.07	27.03
6	13.4	0.71	9.5	9.50	90.70	36.53
Corner 2_{inf}	7.9	0.71	5.6	1.57	8.77	44.45
7	8.3	0.71	5.9	0.00	0.00	46.03
TOTAL			95.5		4393.6	46.0

Table 9.3.1.3 *- Elements lengths and areas*

A_{eff} = 95.5 mm²

Position of the neutral axis of the effective section: z_G = 46.0 mm

9.3.2. Calculation of the effective area A_{eff} of the section with a hole

Effective area Upper flange with a hole

The effective flange area is calculated according to EN 1993-1-5 with the gross cross-sectional area Ac: Ac,eff = ρ Ac where ρ is the reduction factor for plate buckling

Both parts of the flange of rib with a hole are considered as outstand compression elements, the reduction factor ρ is :

$$\rho = \frac{\bar{\lambda}_p - 0{,}188}{\bar{\lambda}_p^{\ 2}} \leq 1{,}0$$

and effective width b is determined according to Table 4.2: Outstand compression elements of EN 1993-1-5

stress in the upper flange is $\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G$ = 284 N / mm²

b_p = 17.5 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 $k_\sigma=0.43$

$\lambda_p=1.544$

$\lambda_{pred} = \lambda_p \times \sqrt{\frac{\sigma\ com}{fy/\gamma M0}}$ ➔ $\lambda_{pred1} = 1.455$

$\lambda_{pred} > 0.748$ and as σ_{com} = 284 N / mm² < 320 N / mm² < 320

➔ $$\rho = \frac{1 - 0{,}188/\bar{\lambda}_{p,red}}{\bar{\lambda}_{p,red}} + 0{,}18\ \frac{(\bar{\lambda}_p - \bar{\lambda}_{p,red})}{(\bar{\lambda}_p - 0{,}6)}$$ ➔ ρ = 0.615

$b_{eff} = \rho * b_p$ = 10.8 ➔ 0,5 b_{eff} = 5.4 m

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-

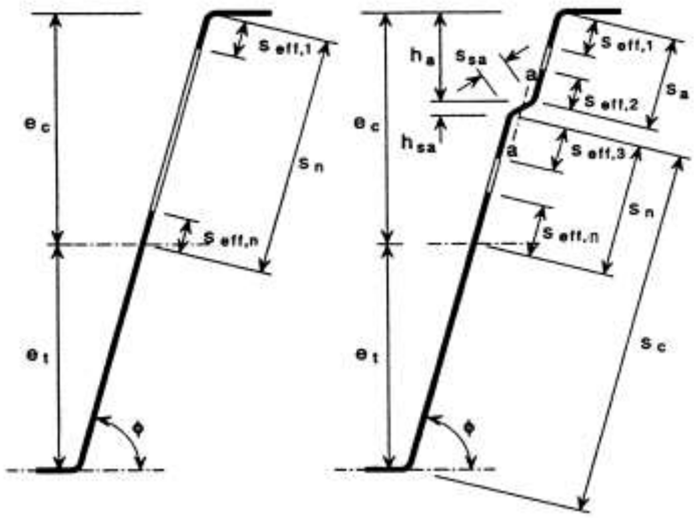


Figure 9.3.2.1 *- Web effective area*

As z_g = 38.7 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.

$e_c = h_w - z_G$=34,3 mm ➔ s_n = 34.6 mm

$\sigma_{com} = f_{yb} \times (h_w - z_G)/ z_G$ = 284 N / mm²

effective section properties refined iteratively ➔

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

➔ $s_{\text{eff},0}$ = 18.3 mm

$s_{\text{eff},1} = s_{\text{eff},0}$ ➔ $s_{\text{eff},1}$ = 18.3 mm

$s_{\text{eff},n} = 1.5\ s_{\text{eff},0}$ ➔ $s_{\text{eff},n}$ = 27.5 mm ➔ $s_{\text{eff},1} + s_{\text{eff},n} \geq s_n$ the entire web is effective

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

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

<u>Lower flange effective area</u>

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

<u>Total effective area</u>

Calculation of A_{eff}

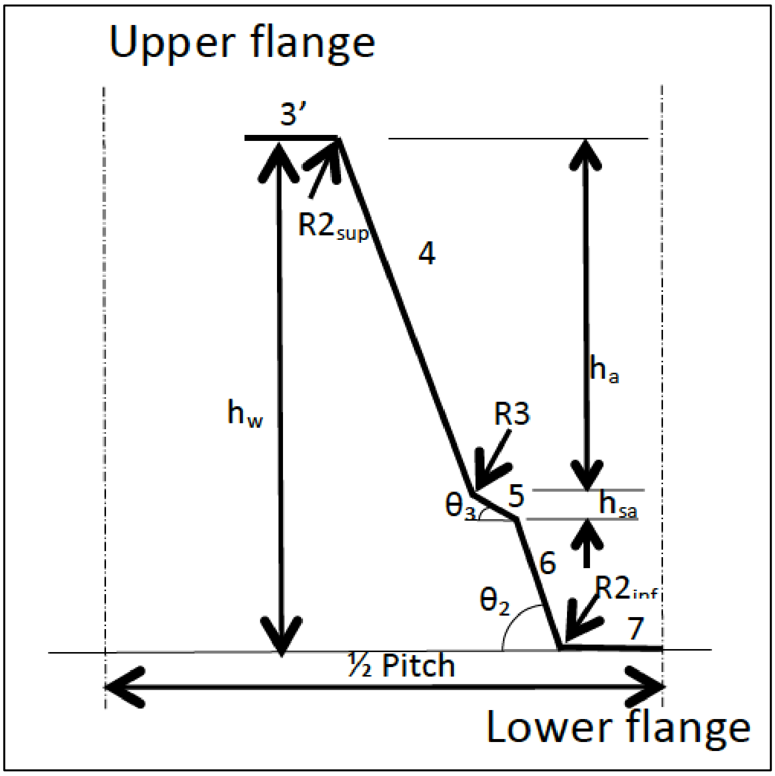


Figure 9.3.2.2 *- Elements numbers*

Element	l_i (mm)	t_{eff} (mm)	A_i(mm²)	z(mm)	S_i(mm³)	z0(mm)
3'	1.7	0.7	1.2	73.0	89.7	-38.8
Corner 2_{sup}	7.9	0.7	5.6	71.4	398.3	-37.2
4	40.4	0.7	28.7	50.5	1447.3	-16.3
Corner 3_{sup}	3.0	0.7	2.1	28.0	59.0	6.2
5	7.5	0.7	5.3	23.5	125.6	10.7
Corner 3_{inf}	3.0	0.7	2.1	19.0	40.1	15.2
6	13.4	0.7	9.5	9.5	90.7	24.7
Corner 2_{inf}	7.9	0.7	5.6	1.6	8.8	32.6
7	8.3	0.7	5.9	0.0	0.0	34.2
TOTAL			66.1		2259.4	34.2

Table 9.3.2.1 *- Elements lengths and areas*

A_{eff} = 66.1 mm²

Position of the neutral axis of the effective section: z_G = 34.2 mm

9.4. Calculation of the effective area A_{eff} of the section Next steps of iteration

9.4.1. Calculation of the effective area A_{eff} of the section with a hole

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

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

Web Effective area 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} .

Lower flange effective area

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 4are 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}	188	195	197
	ρ	0.827	0.810	0.806
	0,5 $b_{1,eff}$	19.63	19.24	19.15
Upper flange stiffener	$\sigma_{cr,s}$	80.31	81.22	81.43
	χ_d	0.33	0.33	0.33
	t_{red}	0.40	0.39	0.38
Web	e_c	27.0	27.7	27.8
	s_n	27.0	27.7	27.9
	$s_{eff,0}$	22.6	22.1	22.0
	$s_{eff,1}$	22.6	22.1	22.0
	$s_{eff,n}$	33.9	33.2	33.0
	$s_{eff,1} + s_{eff,n}$	56.4	55.3	55.0
		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}	93.0	92.4	92.3
Position of neutral axis	z_c	45.3	45.2	45.1

Table 9.4.1.1 *– Steps 2, 3, 4 values*

9.4.2. Calculation of the effective area A_{eff} of the section with a hole

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 and 3 are indicated in following table. The convergence is considered satisfactory at step 3, the iteration stops at step 3.

		2nd step	3rd step
Upper flange	σ_{com}	320	320
	ρ	0.569	0.569
	$0,5\ b_{1,eff}$	4.98	4.98
Web	e_c	38.8	39.0
	s_n	39.2	39.4
	$s_{eff,0}$	17.3	17.3
	$s_{eff,1}$	17.3	17.3
	$s_{eff,n}$	25.9	25.9
	$s_{eff,1} + S_{eff,n}$	43.2	43.2
		entire web is effective	entire web is effective
	$s_{eff,1}$	0,4sn	0,4sn
	$s_{eff,n}$	0,6sn	0,6sn
Total effective Area	A_{eff}	65.8	65.8
Position of neutral axis	z_c	34.0	34.0

Table 9.4.2.1 *– Steps 2 and 3 values*

9.5. Calculation of span moment resistance

9.5.1. Calculation of the moment resistance of the section <u>without</u> a hole

The 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	0.38	0.0	70.00	0.00	-24.87	0.71	0.00
Corner 1_{inf}	0.0	0.38	0.0	70.00	0.00	-24.87	0.00	0.00
2	15.3	0.38	5.9	71.50	419.41	-26.37	3.30	4085.73
Corner 1_{sup}	0.0	0.38	0.0	73.00	0.00	-27.87	0.00	0.00
31	23.8	0.38	9.1	73.00	664.83	-27.87	0.71	7076.68
32	17.6	0.71	12.5	73.00	911.17	-27.87	0.71	9698.82
Corner 2_{sup}	7.9	0.71	5.6	71.43	398.30	-26.30	0.00	3867.93
4	40.4	0.71	28.7	50.50	1447.25	-5.37	38.99	4458.17
Corner 3_{sup}	3.0	0.71	2.1	28.00	59.04	17.13	0.00	618.79
5	7.5	0.71	5.3	23.50	125.58	21.63	6.29	2516.63
Corner 3_{inf}	3.0	0.71	2.1	19.00	40.07	26.13	0.00	1439.62
6	13.4	0.71	9.5	9.50	90.70	35.63	12.99	12251.28
Corner 2_{inf}	7.9	0.71	5.6	1.57	8.77	43.55	0.00	10587.71
7	8.3	0.71	5.9	0.00	0.00	45.13	0.71	12068.76
TOTAL			92.3		4165.1	45.1		68670.1

***Table 9.5.1.1**– Step 4 data*

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

For ½ pitch I_{eff} =68670 mm^4

For 1 m I_{eff} = 704 mm^3

v = max (45.1;27.9)=45.1 mm

W_{eff} = I_{eff} / v = 15.6 mm^3

Moment resistance without a hole

M = 4,99 kNm/m

9.5.2. Calculation of the moment resistance$_f$ of the section <u>with</u> a hole

The 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)
3	1,3	0,7	0,9	73,0	68,6	-39,0	0,7	1427,3
Corner 2_{sup}	7,9	0,7	5,6	71,4	398,3	-37,4	0,0	7811,6
4	40,4	0,7	28,7	50,5	1447,3	-16,5	39,0	11409,9
Corner 3_{sup}	3,0	0,7	2,1	28,0	59,0	6,0	0,0	76,9
5	7,5	0,7	5,3	23,5	125,6	10,5	6,3	609,5
Corner 3_{inf}	3,0	0,7	2,1	19,0	40,1	15,0	0,0	476,3
6	13,4	0,7	9,5	9,5	90,7	24,5	13,0	5876,2
Corner 2_{inf}	7,9	0,7	5,6	1,6	8,8	32,5	0,0	5882,7
7	8,3	0,7	5,9	0,0	0,0	34,0	0,7	6861,2
TOTAL			65,8		2238,3	34,0		40431,5

***Table 9.5.2.1**– Step 4 data*

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

For ½ pitch I_{eff} =40431.5 mm^4

For 1 m I_{eff} = 415 mm^3

v = max (34.0; 39.0)=39 mm

W_{eff} = I_{eff} / v = 10.6 mm^3

Moment resistance with a hole:

M_{hole} = 3.4 kNm/m

9.5.3. Calculation of the span moment resistance of the profile

The moment resistance of the profile is the mean value of the moment resistance of ribs without a hole and of the moment resistance of the rib with a hole. The profile has 3 ribs without a hole and 1 rib with a hole, total n_{ribs} = 4

The span moment resistance is:

M_{span} = (3*M + M_{hole})/n_{ribs} =(3 x 4,99 + 3.4)/4

M_{span} = 4.6 kNm/m

10. AUTO-CONTROL OF THE SOFTWARE

The auto control is based on the previous example.

Calculation of span moment resistance:

The calculated span moment resistance in the previous example is

M_{span} = 4.6 kNm/m

The result of the software is M_{span}= 4.6 kNm/m

The results are the same

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[6] Narayan R., Chow F.Y, Strength of biaxially compressed perforated plates, 1984.

[7] Paik J.K, Ultimate strength of perforated steel plates under edge sheer loading,Thin-Walled Structures 45, 2007.

[8] Shanmugan N.E, Design formula for axially compressed perforated plates, Thin-Walled Structures, 34, 1999.

Annex 1

Background of the new design method for steel decks with a hole

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)