GRISPE

Guidelines and **R**ecommendations for **I**ntegrating **S**pecific **P**rofiled steel sheets in the **E**urocodes (**GRISPE**)

Working Package 3

WP3 Background guidance for EN 1993-1-3 to design of sheeting with perforations or with a hole

30th November 2015

Deliverable D 3.5

Guidelines and Recommandations for Integrating Specific Profiled Steels sheets in the Eurocodes (GRISPE)

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D 3.5 WP3 Background and guidance for EN 1993-1-3		***Due date : 30.11.2015*** ***Completion date: 30.11.2015***

1. INTRODUCTION

For architectural reasons and also in order to improve the acoustic performance perforated profiles (Fig. 1), with different types, geometries and distribution of micro-perforations on the profile web and flange, are increasingly developed and used.

Fig. 1 - Trapezoidal sheet with perforated web (Montana Bausysteme AG, Villemergen [1])

As we could see in the state of the art [2] completed within GRISPE project, European Standard EN 1993-1-3 dealing with design rules for cold-formed members and sheeting covers only the triangular distribution of such perforations while many sheeting with square distribution of perforations exist on the market. For perforated sheeting with triangular and quadratic pattern perforations, some useful information was given by Th. Misiek [3] and [4] investigations on the effective width and web crippling resistance. However, this investigation was based on numerical computer analysis that doesn't lead directly to the analytical formulation.

As far as round or square holes in the flange of sheeting are concerned, they are often required for the passage of services (Fig. 2).

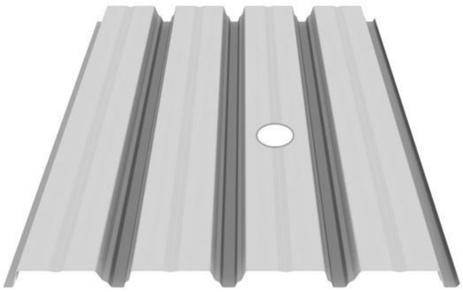


Fig. 2 - Round holes in the flange of sheeting

EN 1993-1-3 doesn’t cover profiles with a hole, it deals only with plane walls without a hole. And the studies on profiles with a hole [5] to [10] only deal with buckling and postbuckling of plates subjected to compression and shear loadings, and don't give any data about moment resistance.

This lack in the EN 1993-1-3 is even more disturbing and serious as several previous studies have shown that holes [5] to [10], and perforations [11] to [14] reduce the strength locally and globally and have an impact on its bending resistance.

Therefore the one way to design sheeting with perforations or with a hole on the upper flange is to determine resistance values by testing, which takes a long time and is expensive.

The aim of this study is to develop a calculation method for steel decks with perforations arranged in square and for steel decks with a round or a square hole in the upper flange, based on a huge testing program performed within GRISPE project [15], [16].

2. ACQUIRED DATA THROUGH GRISPE PROJECT

2.1. Steel sheeting test analysis

A huge program of 272 tests was performed on steel trapezoidal sheeting in order to determine and compare resistance values of sheeting without and with perforations in the upper flange, in the webs, in the upper flange and in the webs, and without and with a hole [15], [16]. Two different profiles PML 73 (Fig. 2.1.1) and PML 56 (Fig. 2.1.2) from JORIS IDE, were tested:

- PML 73: without and with perforations in the upper flange, in the webs, in the upper flange and in the webs, with two different thicknesses of the sheets. And without and with a square or a circular hole, with two different thicknesses of the sheets.
- PML 56: without and with a square or a circular hole, with two different thicknesses of the sheets.

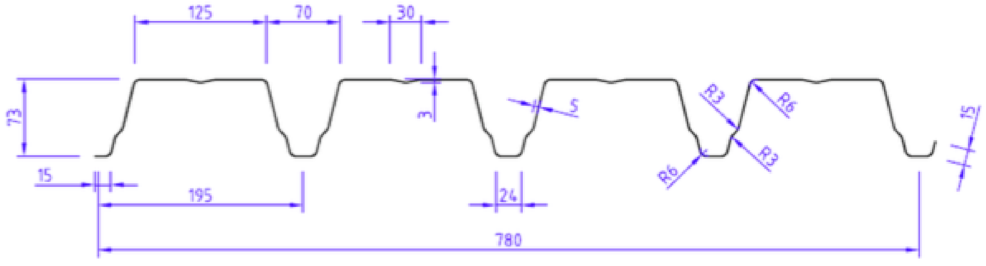


Fig. 2.1.1: PML 73 from JORIS IDE

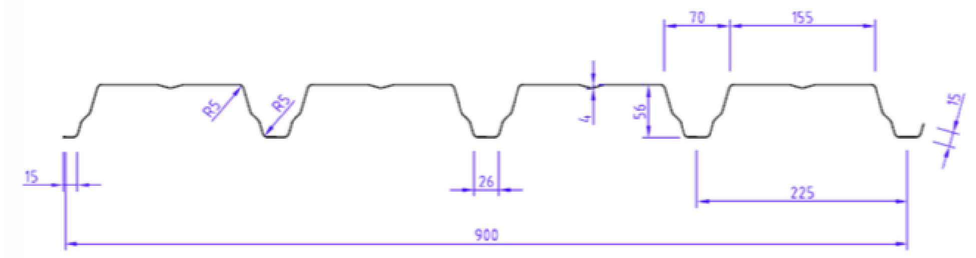
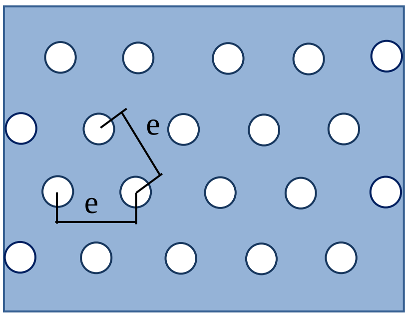


Fig. 2.1.2: PML 56 from JORIS IDE

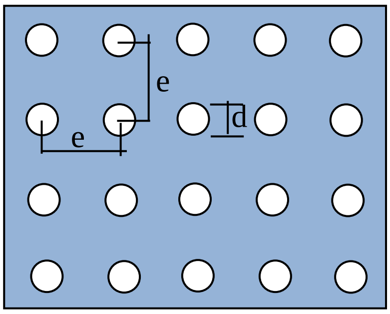
An example of perforation arranged in equilateral triangles, currently used in practice, is shown in the Fig. 2.1.3



d = 5 mm
e = 12.5 mm
perforation percentage: 15%

Fig. 2.1.3 Dimensions of existing perforation arranged in equilateral triangles

The perforation arranged in squares adopted for testing is shown in the Fig. 2.1.4



d = 5 mm
e = 11.5 mm
perforation percentage: 15%

Fig. 2.1.4 Dimensions of perforation arranged in squares

The profiles were tested according to EN 1993-1-3, Annex A:

- <u>single span tests (profiles without and with perforations or with a hole)</u>

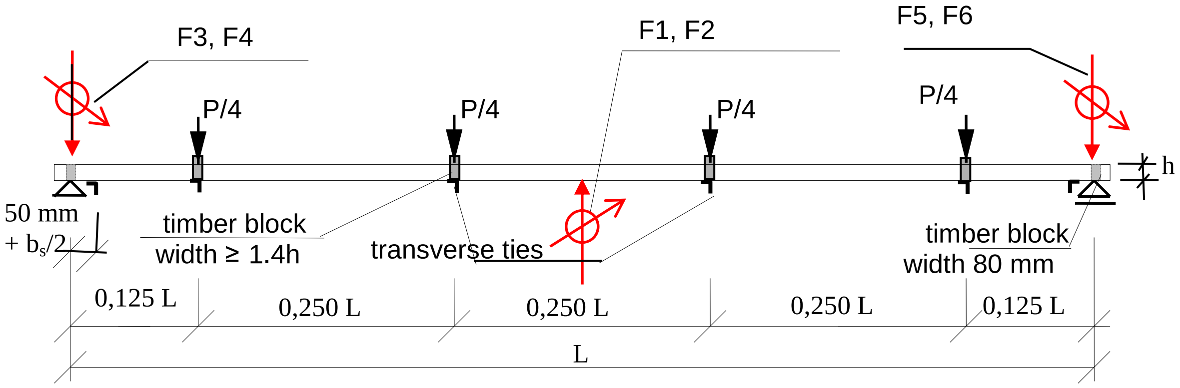


Fig. 2.1.5. – Test set-up for single span tests

- <u>end support tests (profiles without and with perforations)</u>

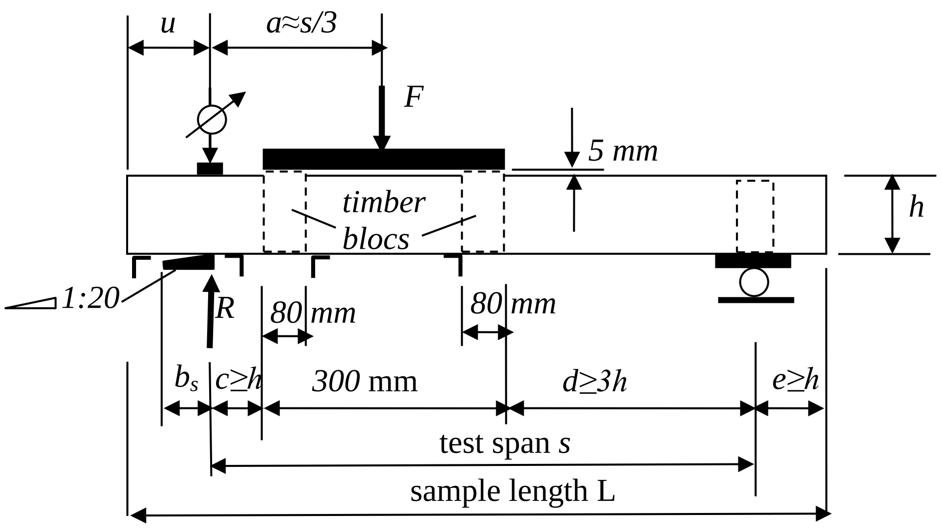


Fig. 2.1.6 – Test set-up for end support test

- <u>internal support tests (profiles without and with perforations)</u>

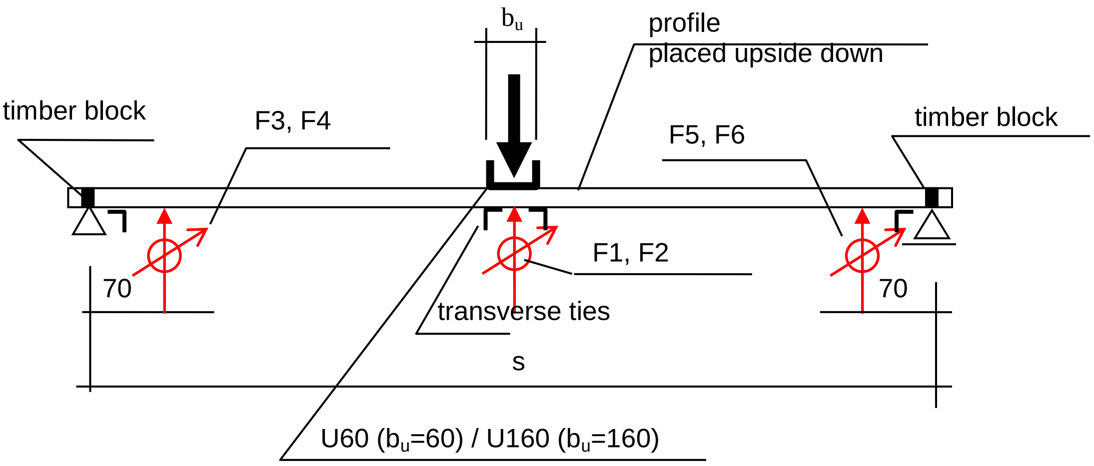


Fig. 2.1.7 – Test set-up for internal support tests

The effect of perforations on resistance and stiffness is summarized in table 2.1.1

↘	Moment Resistance	Inertia Moment	Reaction Resistance	Moment – Reaction Interaction
Flange perforation	6% - 9%	10%	1% - 4%	0% - 5%
Web perforation	6% - 9%	9% - 11%	24% - 30%	11% - 19%
Total perforation	36% - 37%	33% - 34%	37% - 40%	29% - 35%

Table 2.1.1 – Effect of perforations on resistance

The effect of a square and circular holes on resistance is similar, it is summarized in table 2.1.2

↘	Moment Resistance	Inertia Moment
Hole d=90mm	4% - 7%	0% - 4%
Hole d=105mm	6% - 11%	0% - 6%
Hole d=120mm	13% - 15%	2% - 9%

Table 2.1.2 – Effect of a hole on resistance

The analysis of those tests allowed us to conclude:

- Moment resistance:
  - Flange perforation and web perforation induce similar decrease. The resistant moment decreases from 6,2% to 8,6%, for profiles with web or flange perforation. Total perforation (flange + web) induces much more decrease: from 36,1% to 37,1% for the resistant moment.
  - Circular and square holes induce similar decrease. The bigger the hole is, the bigger the decrease of resistant moment is (-12,9% to -15,3% for d=120mm; -5,8 to -10,5%, for d=90mm; -4 to 6,9% for d=105mm).

- The end support resistance (web crippling):
  - Is slightly decreased by flange perforations (from 1% to 4%)
  - Is significantly decreased by web perforations (from 24% to 30%)
  - Is the most decreased by total perforations (from 37% to 40%)

- The moment-reaction interaction, in general tendency, is significantly decreased by web perforations (11% to 19%) and total perforations (35% to 42%)

2.2. Local tests analysis

As we pointed out in the state of the art [2] completed within GRISPE project, in section 10.4 of EN 1993-1-3 it is specified that perforated sheeting with the perforations arranged in the shape of equilateral triangles may be designed by calculation, provided that the rules for non-perforated sheeting are modified by introducing the effective thicknesses given below.

- gross section properties may be calculated using part 5.1, but replacing t by $t_{a,eff}$ obtained from:

$$t_{a,eff} = 1{,}18t\left(1-\frac{d}{0{,}9a}\right) \quad \text{(eq. 2.2.1)}$$

where:

d	is	the diameter of the perforations;
a	is	the spacing between the centers of the perforations.

- effective section properties may be calculated using Section 5, but replacing t by $t_{b,eff}$ obtained from:

$$t_{b,eff} = t\sqrt[3]{1{,}18(1-d/a)} \quad \text{(eq. 2.2.2)}$$

- the resistance of a single web to local transverse forces may be calculated using part 6.1.9, but replacing t by $t_{c,eff}$ obtained from:

$$t_{c,eff} = t\left[1-(d/a)^2 s_{per}/s_w\right]^{3/2} \quad \text{(eq. 2.2.3)}$$

where:

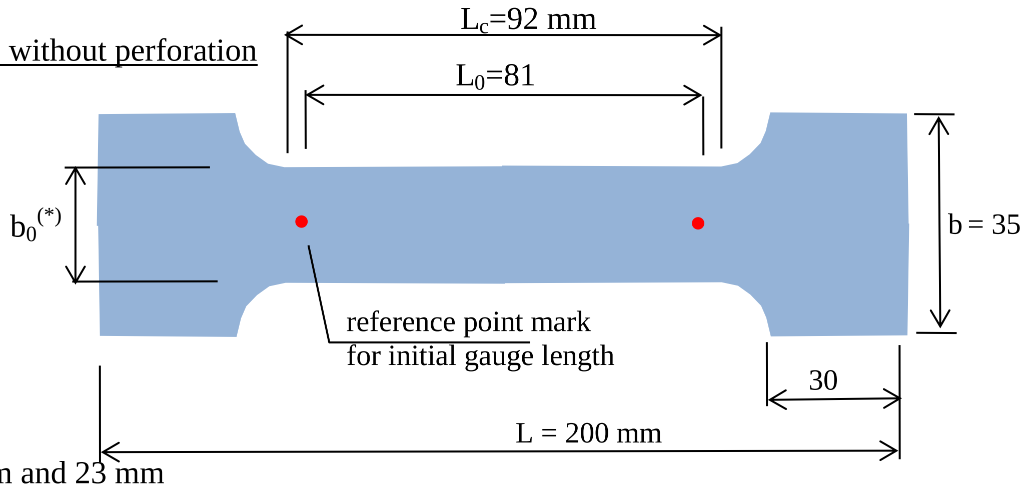
s_{per}	is	the slant height of the perforated portion of the web;
s_w	is	the total slant height of the web.

Within the present GRISPE project local testing on coupons without perforations and with perforations arranged in square and with perforations arranged in triangle was performed with two different thicknesses in order to determine the influence of perforations arranged in square and in triangle and to define effective thickness t_{eff} (s) for sheeting with perforations arranged in square as a function of effective thickness t_{eff} (t) for sheeting with perforations arranged in triangle.

2.2.1. Tensile testing

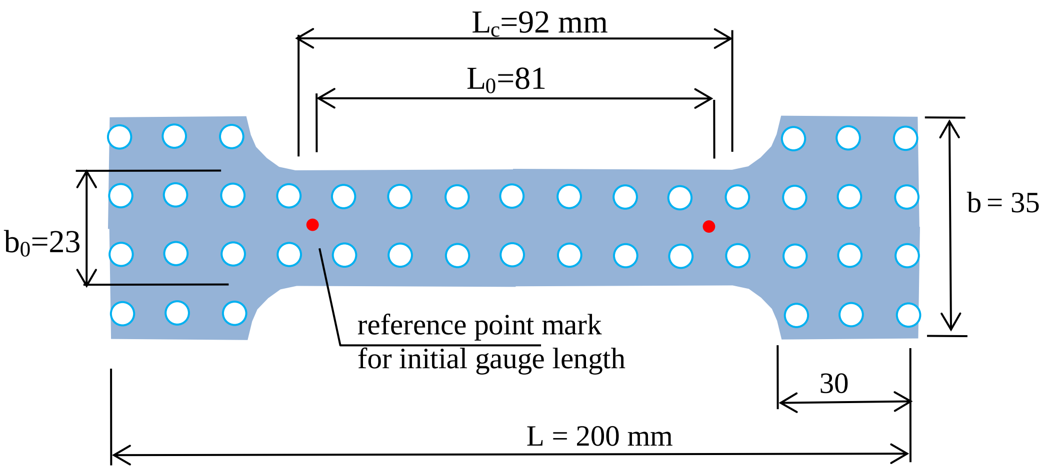
The coupons were tested according to EN ISO 6892-1.

a) coupons without perforation



(*) b_0 = 22 mm and 23 mm

b) coupons with perforation arranged in squares



c) coupons with perforation arranged in triangles

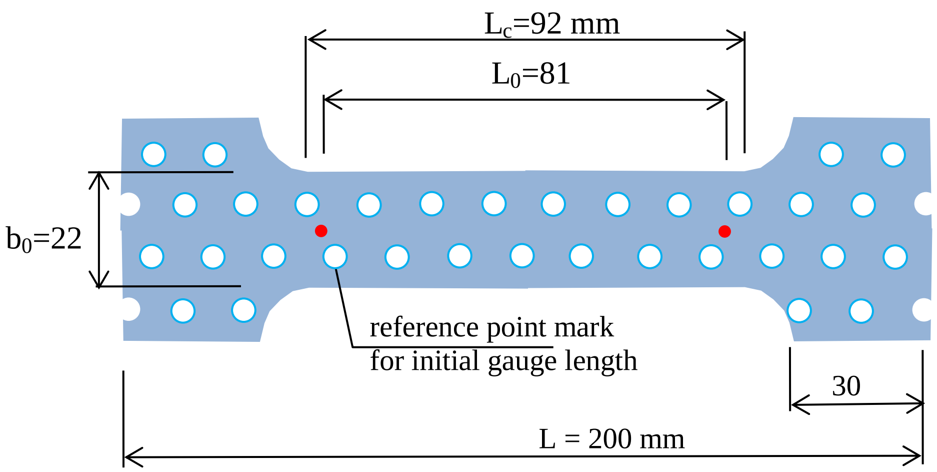


Fig. 2.2.1.1 Dimensions of coupons for tensile tests with perforated sheet

Key:

L = total length

L_c = parallel length
L_0 = initial gauge length
b_0 = width of the coupon
e = perforations space

In the Table below Yield Strength is given for all the coupons [15]

Test	Nominal thickness t_N [mm]	Width b_0 [mm]	e [mm]	d [mm]	Core thickness t_K [mm]	F_{max} [kN]	Yield strength f_y [N/mm²]	Tensile strength R_m [N/mm²]
TT-4fs-075-1		20.01			0.704	6.31	394	448
TT-4fs-075-2		20.00	-	-	0.705	6.32	399	448
TT-4fs-075-3		19.99			0.705	6.29	394	446
TT-4ft-075-1		20.01			0.706	7.09	387	502
TT-4ft-075-2		20.02	-	-	0.706	7.05	387	499
TT-4ft-075-3		20.02			0.705	7.08	388	502
TT-4s-075-1	0.75	20.03			0.703	3.42	206	243
TT-4s-075-2		20.04	11.21	4,98	0.701	3.43	207	244
TT-4s-075-3		20.04			0.701	3.40	205	242
TT-4t-075-1		20.01			0.707	4.31	233	305
TT-4t-075-2		20.02	12.49	4,98	0.706	3.97	228	281
TT-4t-075-3		20.02			0.706	3.59	229	254
TT-4t-075-4		20.03			0.706	3.59	229	254
TT-4fs-100-1		20.00			0.926	8.71	376	471
TT-4fs-100-2		20.01	-	-	0.926	8.68	375	468
TT-4fs-100-3		20.04			0.924	8.64	375	466
TT-4ft-100-1		20.01			0.925	8.57	390	463
TT-4ft-100-2		20.02	-	-	0.927	8.64	386	466
TT-4ft-100-3	1.00	20.01			0.925	8.64	390	467
TT-4s-100-1		20.03			0.917	4.61	208	251
TT-4s-100-2		20.02	11.22	4,98	0.919	4.70	208	255
TT-4s-100-3		20.03			0.920	4.71	207	256
TT-4t-100-1		20.02			0.927	4.57	227	246
TT-4t-100-2		20.02	12.50	4,99	0.925	4.60	217	249
TT-4t-100-3		20.01			0.926	3.95	217	247

Table 2.2.1.1 – Results of coupons tensile tests

Ratios between the yield stress of the coupons with perforation in triangle (t) and the yield stress of the coupons without perforation (ft) are calibrated for the same width b_0 and for the same core thickness (Table 2.2.1.2 in blue):

$$\boxed{ratio = f_y(t) / f_y(ft) * t(ft) / t(t) * b_0(ft) / b_0(t)} \qquad \text{(eq. 2.2.1.1)}$$

Ratios between the yield stress of the coupons with perforation in square (s) and the yield stress of the coupons without perforation (fs) are calibrated for the same width b_0 and for the same core thickness (Table 2.2.1.2 in red):

$$\boxed{ratio = f_y(s) / f_y(fs) * t(fs) / t(s) * b_0(fs) / b_0(s)} \qquad \text{(eq. 2.2.1.2)}$$

t_N	Coupons	Average Yied Stress	Core Thickness	b_0	Ratio With perf/Without
0,75 mm	Without perforation	387	0,706	20,02	
	With triangle perforation	229	0,706	20,02	0,590
	Without perforation	396	0,705	20,00	
	With square perforation	206	0,702	20,04	0,522
1 mm	Without perforation	389	0,926	20,01	
	With triangle perforation	220	0,926	20,02	0,567
	Without perforation	375	0,925	20,02	
	With square perforation	208	0,919	20,03	0,557

Table 2.2.1.2 – Ratios between the yield stress of the coupons with perforation and without perforation

In order to compare the influence of perforations arranged in square and in triangle, ratios between the yield stress of the coupons with perforation in square and the yield stress of the coupons with perforation in triangle are calibrated taking into account the actual perforation rate and core thickness (Table 2.2.1.3)

$\boxed{ratio = f_y(s) / f_y(t) * t(t) / t(s) * b_0(t) / b_0(s)}$ (eq. 2.2.1.3)

t_N	Coupons	Average Yied Stress	Core Thickness	Surface area	Ratio Yield stress square / triangle (eq.2.2.1.3)
0,75 mm	With triangle perforation	229	0,706	1388	0,932
	With square perforation	206	0,702	1350	
1 mm	With triangle perforation	220	0,926	1387	0,976
	With square perforation	208	0,919	1349	

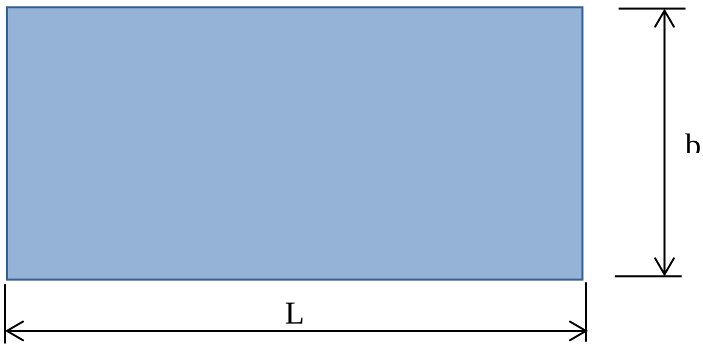
Table 2.2.1.3 – Ratios between the yield stress of the coupons with perforation arranged in square and with perforation arranged in triangle

In the Table 2.2.1.3 are presented the ratios for thicknesses t=0.75 mm and t=1.00 mm.
This leads to the effective thickness (in the meaning of the clause 10.4(2) EN 1993-1-3) for sheeting with perforations arranged in square as a function of the thickness for sheeting with perforation arranged in triangle: $t_{eff}(s) = \rho * t_{eff}(t)$ for the perforation rate where $\rho = 0,93$ is the minimum value of ratio defined above for thicknesses t=0.75 mm and t=1.00 mm for safety reason.

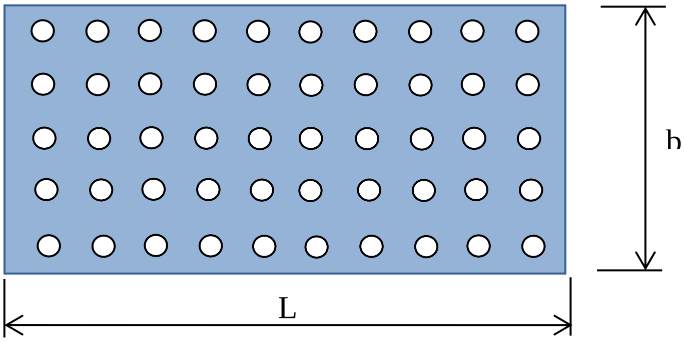
2.2.2. Flexion testing

Dimension of plates:

a) plates without perforation



b) plates with perforation arranged in squares



c) plates with perforation arranged in triangles

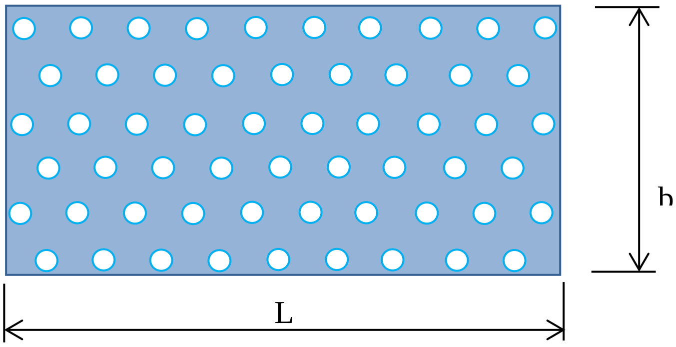


Fig. 2.2.2.1 Dimensions of coupons for plate flexion tests

The testing is performed on plates:

a) without perforation
b) with perforation arranged in triangles
c) with perforation arranged in squares

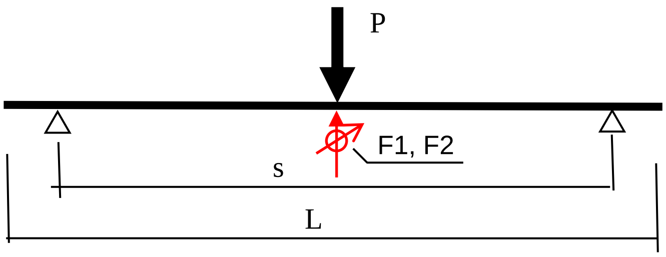


Fig. 2.2.2.2 Test set-up for plate flexion tests

Key:
e = perforations space
L = coupon length
s = test span
b = coupon width
P = applied force

Ratios between the flexural stiffness of the coupons with perforation in triangle (t) and the stiffness of the coupons without perforation (ft) are calculated taking into account the observed width b_0 and core thickness (Table 2.2.2.1, in blue):

$$\boxed{\text{ratio} = R_p(t) / R_p(ft) * t(ft) / t(t) * b_0(ft) / b_0(t)} \qquad \text{(eq. 2.2.2.1)}$$

Ratios between the stiffness of the coupons with perforation in square (s) and the stiffness of the coupons without perforation (fs) are calculated taking into account the observed width b_0 and core thickness (Table in red):

$\boxed{ratio = R_p(s) / R_p(fs) * t(fs) / t(s) * b_0(fs) / b_0(s)}$ (eq. 2.2.2.2)

t_N	Coupons	Average Stifness (N/mm)	Core Thickness	b_0	Ratio With perf/Without
0,75 mm	Without perforation	10,09	0,67	42,88	
	With triangle perforation	7,45	0,72	42,53	0,592
	Without perforation	11,24	0,69	45,88	
	With square perforation	8,06	0,69	45,70	0,731
1 mm	Without perforation	23,84	0,92	43,18	
	With triangle perforation	17,13	0,94	44,64	0,650
	Without perforation	25,81	0,91	45,87	
	With square perforation	18,21	0,90	45,88	0,717

Table 2.2.2.1 – Ratios between the stiffness of the coupons with perforation and without perforation

In order to compare the influence of perforations arranged in square and in triangle, ratios between the stiffness of the coupons with perforation in square and the stiffness of the coupons with perforation in triangle are calculated for the same surface area of perforations and for the same core thickness (Table 2.2.2.2):

$\boxed{ratio = R_p(s) / R_p(t) * t(t) / t(s) * b_0(t) / b_0(s)}$ (eq. 2.2.2.3)

t_N	Coupons	Average Stiffness (N/mm)	Core Thickness	Surface area	Ratio Stiffness square / triangle (eq.2.2.2.3)
0,75 mm	With triangle perforation	7,45	0,72	4363	1,198
	With square perforation	8,06	0,69	4627	
1 mm	With triangle perforation	17,13	0,94	4614	1,192
	With square perforation	18,21	0,90	4649	

Table 2.2.2.2 – Ratios between the Stiffness of the coupons with perforation arranged in square and with perforation arranged in triangle

Stiffness with perforation arranged in square is superior to the stiffness with perforation arranged in triangle, nevertheless the ratio $\rho = 0,93$ for t_{eff} (s) = ρ * t_{eff} (t) defined by tensile testing is adopted for safety reason.
In conclusion the ρ=0,93 is proposed to be generally adopted for the evaluation of the effective thickness for sheeting with perforations arranged in square as a function of the effective thickness for sheeting with perforations arranged in triangle: t_{eff} (s) = 0,93 * t_{eff} (t) for the same percentage of perforations. With t_{eff} (t) defined according to section 10.4 of EN 1993-1-3 and taking for "a" the spacing between the centers of the perforations arranged in triangle the distance calculated as a function of "e" the spacing between the centers of the perforations arranged in square.

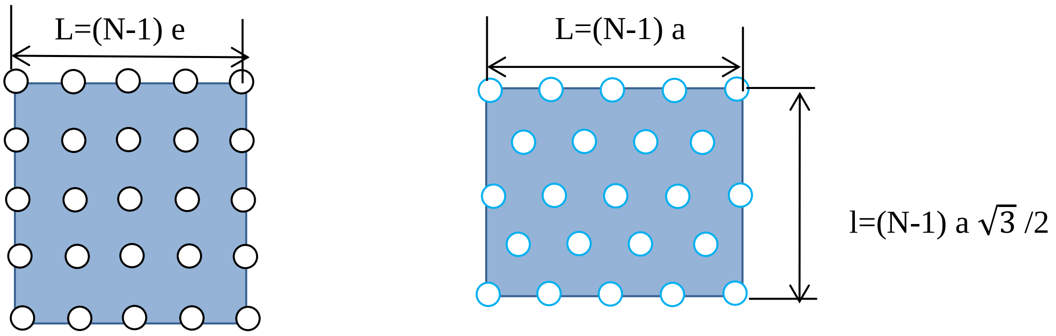


Fig. 2.2.2.5 Surface area with perforations arranged in square and perforations arranged in triangle

For the surface with perforations arranged in square the surface area is (Fig. 2.2.2.5):
$(N-1)^2 e^2$

For the surface with perforations arranged in triangle the surface area is (Fig. 2.2.2.5):
(N-1) a (N-1) ($\sqrt{3}$ /2) a = $(N-1)^2 \sqrt{3}/2\, a^2$

Therefore for the same surface area and the same percentage of perforation

$$\boxed{a = e\sqrt{\frac{2}{\sqrt{3}}}} \qquad \text{(eq. 2.2.2.4)}$$

or in the following simplified form: $\boxed{a = 1.075e}$ (eq. 2.2.2.5)

As a conclusion it is proposed that perforated sheeting with the perforations arranged in the shape of squares may be designed by calculation, provided that the rules for non-perforated sheeting are modified by introducing the effective thicknesses given below.

- gross section properties may be calculated using part 5.1, but replacing t by $t_{a,eff}$ obtained from:

$$t_{a,eff} = 0{,}93 * 1{,}18t\left(1 - \frac{d}{0{,}9e\sqrt{\frac{2}{\sqrt{3}}}}\right) \qquad \text{(eq. 2.2.2.6)}$$

or in the following simplified form:

$$\boxed{t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{e}\right)} \qquad \text{(eq. 2.2.2.7)}$$

where:

d	is	the diameter of the perforations;
e	is	the spacing between the centers of the perforations.

- effective section properties may be calculated using Section 5, but replacing t by $t_{b,eff}$ obtained from:

$$t_{b,eff} = 0{,}93t\sqrt[3]{1{,}18\left(1 - \frac{d}{e\sqrt{\frac{2}{\sqrt{3}}}}\right)} \qquad \text{(eq. 2.2.2.8)}$$

or in the following simplified form:

$$\boxed{t_{b,eff} = 0{,}98t\sqrt[3]{\left(1 - \frac{0{,}93d}{e}\right)}} \qquad \text{(eq. 2.2.2.9)}$$

- the resistance of a single web to local transverse forces may be calculated using part 6.1.9, but replacing t by $t_{c,\mathrm{eff}}$ obtained from:

$$t_{c,eff} = 0{,}93t\left[1-\left(\frac{d}{e\sqrt{\frac{2}{\sqrt{3}}}}\right)^{2}\frac{s_{per}}{s_{w}}\right]^{3/2} \qquad \text{(eq. 2.2.2.10)}$$

or in the following simplified form:

$$\boxed{t_{c,eff} = 0{,}93t\left[1 - 0{,}866\left(\frac{d}{e}\right)^{2}\frac{s_{per}}{s_{w}}\right]^{3/2}} \qquad \text{(eq. 2.2.2.11)}$$

where:

s_{per}	is	the slant height of the perforated portion of the web;
s_{w}	is	the total slant height of the web.

3. STUDY ON CALCULATION METHOD OF SHEETING WITH PERFORATIONS OR WITH A HOLE

Resistances of the profiles PML 73 and PML 56 without and with perforations or with a hole are calculated in order to be compared to the test results presented in § 2.1.
The profiles (with and without profiles or a hole) resistance is calculated according to EN 1993-1-3.
The geometrical proportions *b/t*, *h/t*, *c/t* and *d/t* are inside the range of width to thickness given in Table 3.1. (Table 5.1 of EN 1993-1-3)

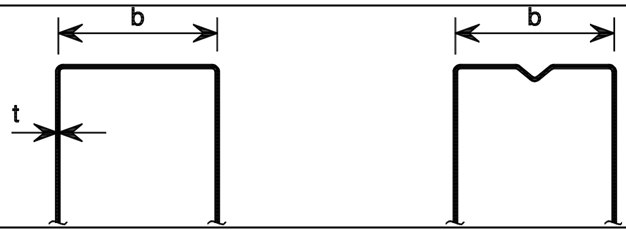
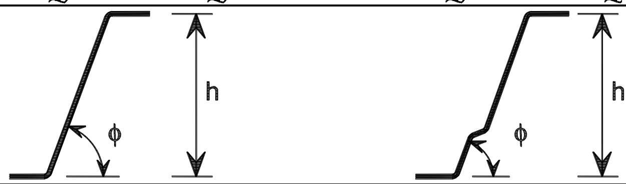
	$b/t \leq 500$
	$45° \leq \phi \leq 90°$ $h/t \leq 500\ \sin\phi$

Table 3.1 - Maximum width to thickness ratios

For the comparison the tests results are not adjusted and the calculation are made with the actual observed properties and geometry of the test specimen.

3.1. SHEETING WITH PERFORATIONS

3.1.1. Span moment resistance

3.1.1.1. Resistance values of profiles without perforation

The moment resistances of the effective section are calculated according to EN 1993-1-3 and are compared to the values defined by testing for PML 73 in Table 3.1.1.1.1

PML 73:

The tested profile properties are:
t= 0,709 mm and f_{yb} = 397 N/mm^2
t= 0,924 mm and f_{yb} = 377 N/mm^2

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation	
0,75	5,61	5,89	-5,0%
1,00	8,22	7,60	7,5%

Table 3.1.1.1.1 – Comparison between calculated and defined by testing moment resistances for PML 73

The calculated resistance moment is lower than the tested one for PML 73 t=1mm of 7,5% .

On the contrary the calculated resistance moment is higher than the tested one for PML 73 t=0,75mm of 5%. The width and the angle of the web stiffener and the angle of the web were not measured on the tested profiles therefore for these values, theoretical values were taken for the calculation. The possible differences between the theoretical and the actual geometry can explain that the calculated resistance moments are higher than the tested ones.

3.1.1.2. Resistance values of profiles with perforation arranged in square

The moment resistances of the effective section are calculated according to EN 1993-1-3, determining for the perforated section the thickness as below (§ 2.2.2)

- gross section properties may be calculated using part 5.1, but replacing t by $t_{a,eff}$ obtained from eq. 2.2.2.7:

$$\boxed{t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{e}\right)}$$

where:

d	is	the diameter of the perforations;
e	is	the spacing between the centers of the perforations.

- effective section properties may be calculated using Section 5, but replacing t by $t_{b,eff}$ obtained from eq. 2.2.2.9:

$$\boxed{t_{b,eff} = 0{,}98t\sqrt[3]{\left(1 - \frac{0{,}93d}{e}\right)}}$$

The tested profile properties are:
t= 0,709 mm and f_{yb} = 397 N/mm^2
t= 0,924 mm and f_{yb} = 377 N/mm^2

In Table 3.1.1.2.1 the calculated resistance moments and the defined by testing resistance moments are presented.

PML 73 Flange perforation				PML 73 Web perforation				PML 73 Total perforation			
t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation		mm	Test	Calculation		mm	Test	Calculation	
0,75	5,26	5,46	**-3,7%**	0,75	5,27	5,18	**1,6%**	0,75	3,53	4,60	**-30,4%**
1,00	7,51	7,00	**6,8%**	1,00	7,51	6,59	**12,2%**	1,00	5,25	5,93	**-13,0%**

Table 3.1.1.2.1 – Comparison between calculated and defined by testing resistance moment for PML 73 with perforation arranged in square

Flange perforation influence			Web perforation influence			Total perforation influence		
t_{nom}	Test	Calculation	t_{nom}	Test	Calculation	t_{nom}	Test	Calculation
0,75	-6,2%	-7,3%	0,75	-6,1%	-12,0%	0,75	-37,1%	-21,9%
1,00	-8,6%	-7,9%	1,00	-8,6%	-13,3%	1,00	-36,1%	-22,0%

Table 3.1.1.2.2 – Perforation influence on resistance moment defined by testing and calculation for PML 73

As shown in the Table 3.1.1.2.1 the difference between the calculated moment resistances and the tested ones for thickness t=0,75 mm is of -3,7% for flange perforation and of 1,6% for web perforation. This difference is coherent with the difference observed in 3.1.1.1.1 where for the profiles without perforation the calculated moment resistance was higher than the tested one of 5%. These superior values are probably due to the possible differences between the theoretical and the actual geometry.

The difference between the calculated moment resistances and the tested ones for thickness t=1 mm is of 6,8% for flange perforation and of 12,2% for web perforation. This difference is coherent with the difference observed in 3.1.1.1.1 where for the profiles without perforation the calculated moment resistance was lower than the tested one of 7,5%.

The decreases induced by a perforation in the flange and by a perforation in the web defined by calculation are coherent with the decrease defined by testing (Table 3.1.1.2.2).

However, as far as total perforation is concerned the difference between the calculated moment resistances and the tested ones for thickness t=0,75 mm is of 30,4% and for thickness t=0,75 mm of 13%. This difference is non coherent with the differences observed in 3.1.1.1.1. for the profiles without perforation.

This finding calls into question the use of the formula (10.25), EN 1993-1-3, for totally perforated sheeting.
Moreover, it makes impossible to propose a coherent equivalent formula for the totally perforated sheeting with perforation arranged in square.

3.1.2. Web crippling resistance

3.1.2.1. Web crippling resistance values of profiles without perforation

The web crippling resistances, calculated according to equation (6.18) EN 1993-1-3, are compared to the values defined by testing for PML 73 in Table 3.1.2.1.

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

The tested profile PML 73 properties are:
t= 0,709 mm and f_{yb} = 397 N/mm^2
t= 0,924 mm and f_{yb} = 377 N/mm^2

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation	
0,75	23,18	9,60	**58,6%**
1,00	39,12	16,71	**57,3%**

Table 3.1.2.1.1 – Comparison between calculated and defined by testing web crippling resistances for PML 73

The calculated web crippling resistance at the end support is much lower than the tested one: about 58%.

This confirms the observation already noticed by M. Bakker [14] and in the Work Package 1 [17] that web crippling prediction formula gives the results very different and considerable underestimated compared to the tests results.

3.1.2.2. Web crippling resistance values of profiles with perforation arranged in square

The web crippling resistances of the effective section are calculated according to EN 1993-1-3, determining for the perforated section the thickness as below (§ 2.2.2)

- the resistance of a single web to local transverse forces may be calculated using part 6.1.9, but replacing t by $t_{c,eff}$ obtained from eq. 2.2.2.11:

$$t_{c,eff} = 0{,}93t\left[1 - 0{,}866\left(\frac{d}{e}\right)^2 \frac{s_{per}}{s_w}\right]^{3/2}$$

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 Table 3.1.2.2.1 the calculated resistance moments and the defined by testing resistance moments are presented.

PML 73 Flange perforation				PML 73 Web perforation				PML 73 Total perforation			
t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation		mm	Test	Calculation		mm	Test	Calculation	
0,75	22,88	9,70	**57,6%**	0,75	17,53	5,65	**67,8%**	0,75	15,08	4,66	**69,1%**
1,00	37,68	16,36	**56,6%**	1,00	27,32	9,87	**63,9%**	1,00	23,60	8,01	**66,1%**

Table 3.1.2.2.1 – Comparison between calculated and defined by testing web crippling resistance for PML 73 with perforation arranged in square

As for the profile without perforation, the difference between the calculated web crippling resistances and the tested ones is very important, higher than 56%. The web crippling prediction formula for sheeting with perforation arranged in square gives very underestimated results from test results.

Moreover the decrease induced by web perforation and total perforation defined by calculation is much higher than the decrease defined by testing (Table 3.1.2.2.2).

Flange perforation influence			Web perforation influence			Total perforation influence		
t_{nom}	Test	Calculation	t_{nom}	Test	Calculation	t_{nom}	Test	Calculation
0,75	-1,3%	1,1%	0,75	-24,4%	-41,2%	0,75	-34,9%	-51,4%
1,00	-3,7%	-2,1%	1,00	-30,2%	-40,9%	1,00	-39,7%	-52,1%

Table 3.1.2.2.2 – Perforation influence on resistance moment defined by testing and calculation for PML 73 with perforation arranged in square

Therefore it is proposed to calculate the web crippling resistance at support for profiles with perforation arranged in square as it is specified in section 10.4 of EN 1993-1-3 for perforated sheeting with the perforations arranged in the shape of equilateral triangles: using part 6.1.9, but replacing t by $t_{\mathrm{c,eff}}$ and replacing a by $a = e\sqrt{\frac{2}{\sqrt{3}}}$:

$$t_{c,eff} = t\left[1 - \left(\frac{d}{e\sqrt{\frac{2}{\sqrt{3}}}}\right)^2 \frac{s_{per}}{s_w}\right]^{3/2} \quad \text{(eq. 3.1.2.2.1)}$$

or in the following simplified form:

$$\boxed{t_{c,eff} = t\left[1 - 0,866\left(\frac{d}{e}\right)^2 \frac{s_{per}}{s_w}\right]^{3/2}} \quad \text{(eq. 3.1.2.2.2)}$$

where:

a is the spacing between the centers of the perforations arranged in triangle

e is the spacing between the centers of the perforations arranged in square

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

s_{w} is the total slant height of the web.

PML 73 Flange perforation				PML 73 Web perforation				PML 73 Total perforation			
t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)			t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation		mm	Test	Calculation		mm	Test	Calculation	
0,75	22,88	9,70	**57,6%**	0,75	17,53	6,63	**62,2%**	0,75	15,08	5,47	**63,7%**
1,00	37,68	16,36	**56,6%**	1,00	27,32	11,50	**57,9%**	1,00	23,60	9,34	**60,4%**

Table 3.1.2.2.1 – Comparison between web crippling resistance calculated with the formula from eq. 3.1.2.2.2 and web crippling resistance of PML 73 with perforation arranged in square defined by testing

3.1.3. Moment-Reaction interaction

The web crippling resistance is calculated according to EN 1993-1-3.

For the purposes of the present study, the theoretical resistance to combined action of moment M_{Ed} and reaction R_{Ed}, (M-R theor.) used in the calculation model defined by the eq. (6.28c), EN 1993-1-3 is transformed in the following form:

$$\frac{M_E}{M_0} + \frac{R_E}{R_0} \leq 1 \qquad (1a)$$

$M_0 = 1.25M_{c,Rd}$ (1b)
$R_0 = 1.25R_{c,Rd}$ (1c)

These relations are presented in the Fig. 3.1.3.1

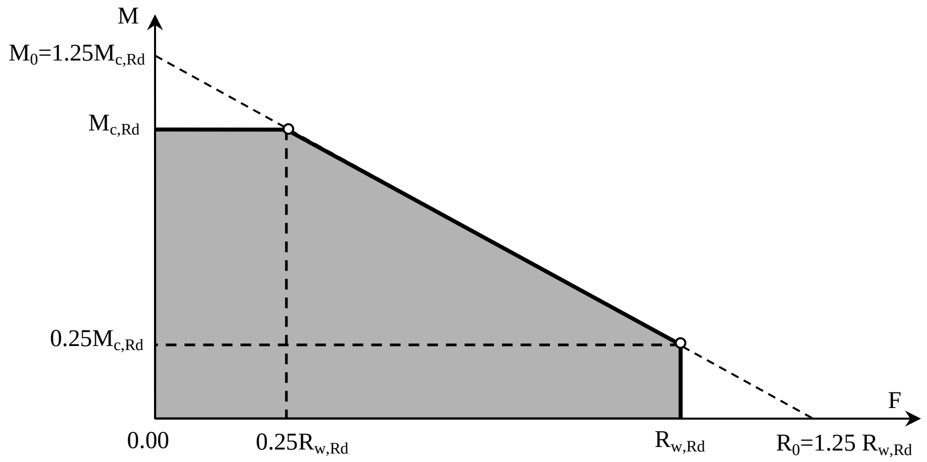


Fig. 3.1.3.1 Graphical presentation of the equation (1)

3.1.3.1. Resistance values of profiles without perforation

The theoretical values of moment resistance and the web crippling reaction are calculated using the observed values of the thickness and yield stress
The observed values of the thickness and yield stress of the tested profiles properties are:
t= 0,709 mm and f_{yb} = 397 N/mm^2
t= 0,924 mm and f_{yb} = 377 N/mm^2

In the Fig. 3.1.3.1.1 to 3.1.3.1.4 the results of theoretical calculation are compared to the results of testing.

PML 73 0.75mm, b_u=60mm

without perforation

M_{Rk_max}	R_{Rk_min}
6,01	14,11

M_{Rk_min}	R_{Rk_max}
3,59	28,74

without perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6,15	26,57	7,69	33,21

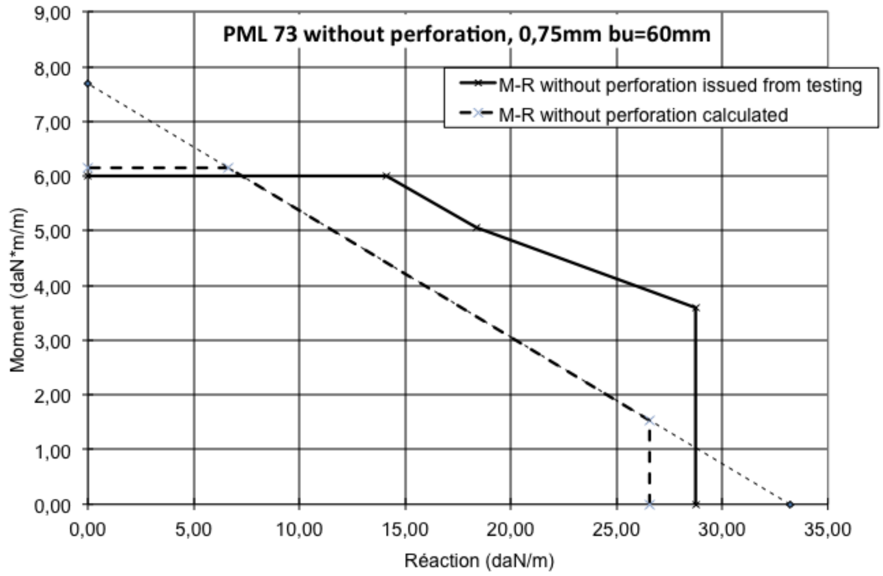


Figure 3.1.3.1.1 – Comparison between calculated and defined by testing moment-reaction interaction resistances for PML 73 without perforation, 0,75 mm and b_u= 60 mm

PML 73 0.75mm, b_u=160mm

without perforation

M_{Rk_max}	R_{Rk_min}
7,47	17,53

M_{Rk_min}	R_{Rk_max}
4,98	39,80

without perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6,15	39,30	7,69	49,12

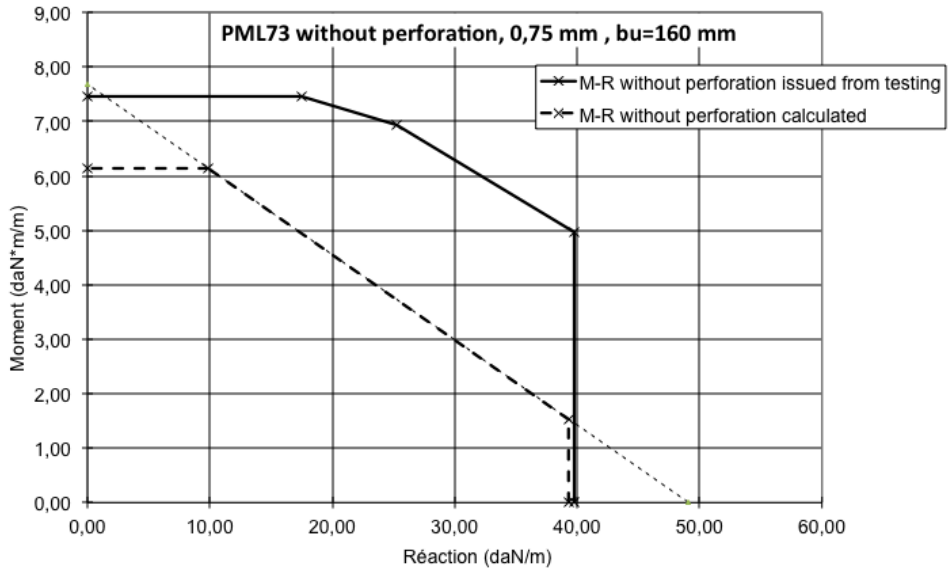


Figure 3.1.3.1.2 – Comparison between calculated and defined by testing moment-reaction interaction resistances for PML 73 without perforation, 0,75 mm and b_u= 160 mm

PML 73 1 mm, b_u=60mm
without perforation

M_{Rk_max}	R_{Rk_min}
8,70	20,40

M_{Rk_min}	R_{Rk_max}
5,81	46,47

without perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
7,81	42,94	9,76	53,67

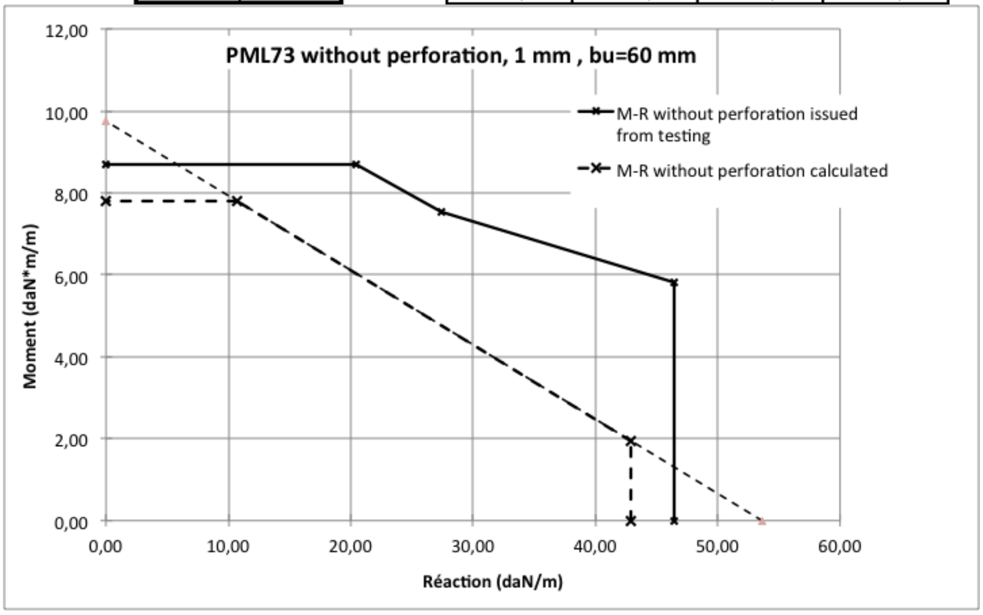


Figure 3.1.3.1.3 – Comparison between calculated and defined by testing moment-reaction interaction resistances for PML 73 without perforation, 1 mm and b_u= 60 mm

PML 73 1 mm, b_u=160mm
without perforation

M_{Rk_max}	R_{Rk_min}
10,52	24,69

M_{Rk_min}	R_{Rk_max}
7,55	60,37

without perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
7,81	61,83	9,76	77,28

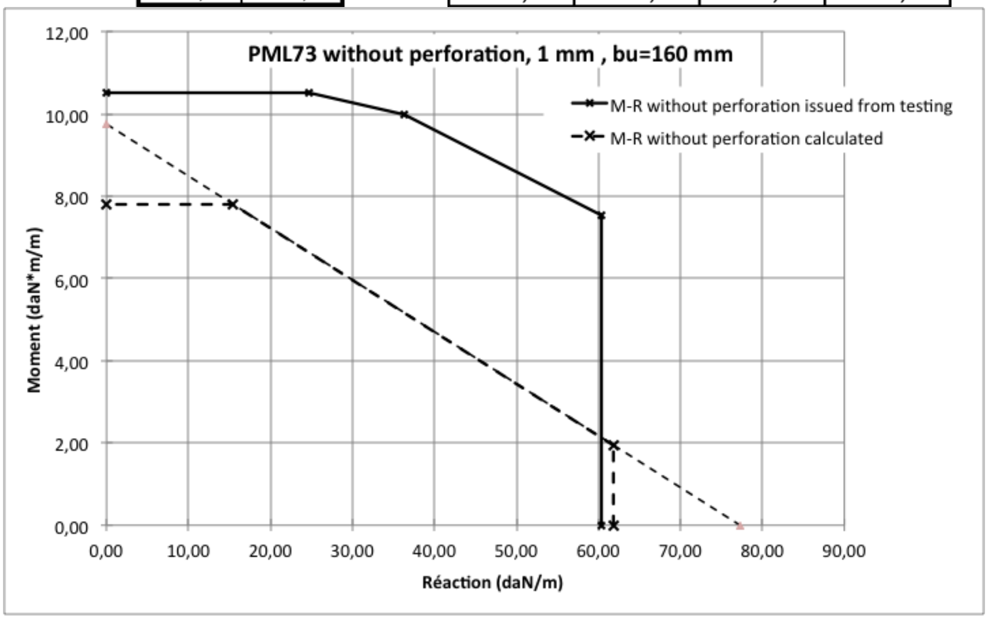


Figure 3.1.3.1.3 – Comparison between calculated and defined by testing moment-reaction interaction resistances for PML 73 without perforation, 1 mm and b_u= 160 mm

3.1.3.2 Resistance values of profiles with perforation arranged in square

The moment and web resistances of the effective section are calculated according to EN 1993-1-3, determining for the perforated section the thickness as below (§ 3.1.1.2 and 3.1.2.2)

- gross section properties may be calculated using part 5.1, but replacing t by $t_{a,eff}$ obtained from eq. 2.2.2.7:

$$\boxed{t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{e}\right)}$$

where:

d	is	the diameter of the perforations;
e	is	the spacing between the centers of the perforations.

- effective section properties may be calculated using Section 5, but replacing t by $t_{b,eff}$ obtained from eq. 2.2.2.9:

$$\boxed{t_{b,eff} = 0{,}98t\sqrt[3]{\left(1 - \frac{0{,}93d}{e}\right)}}$$

- the resistance of a single web to local transverse forces may be calculated using part 6.1.9, but replacing t by $t_{c,eff}$ obtained from eq. 3.1.2.2.2

$$\boxed{t_{c,eff} = t\left[1 - 0{,}866\left(\frac{d}{e}\right)^2 \frac{s_{per}}{s_w}\right]^{3/2}}$$

where:

e	is	the spacing between the centers of the perforations arranged in square
s_{per}	is	the slant height of the perforated portion of the web;
s_w	is	the total slant height of the web.

The tested profile properties are:
t= 0,709 mm and f_{yb} = 397 N/mm^2
t= 0,924 mm and f_{yb} = 377 N/mm^2

In the Fig. 3.1.3.2.1 to 3.1.3.2.12 the results of the proposed calculation for profiles with perforations (dotted color lines) are compared to the results of theoretical calculation without perforation (dotted black lines), and to the results of testing (with perforation color lines and without perforation black lines)

PML 73 0.75mm, b_u=60mm

flange perforation

M_{Rk_max}	R_{Rk_min}
5,91	13,86

M_{Rk_min}	R_{Rk_max}
3,52	28,14

flange perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5,88	26,77	7,35	33,47

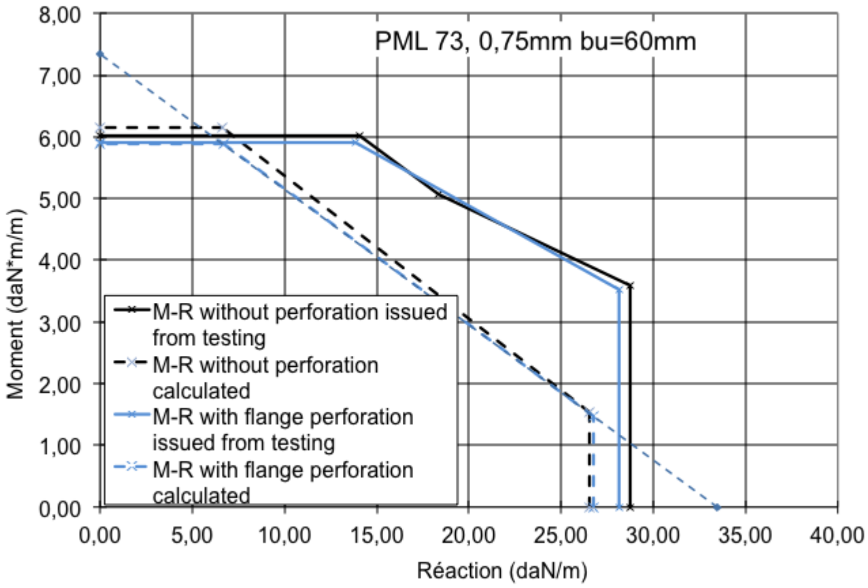


Fig. 3.1.3.2.1 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=60 mm, without and with flange perforation

PML 73 0.75mm, b_u=160mm

flange perforation

M_{Rk_max}	R_{Rk_min}
7,06	16,58

M_{Rk_min}	R_{Rk_max}
5,04	40,28

flange perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5,88	39,01	7,35	48,77

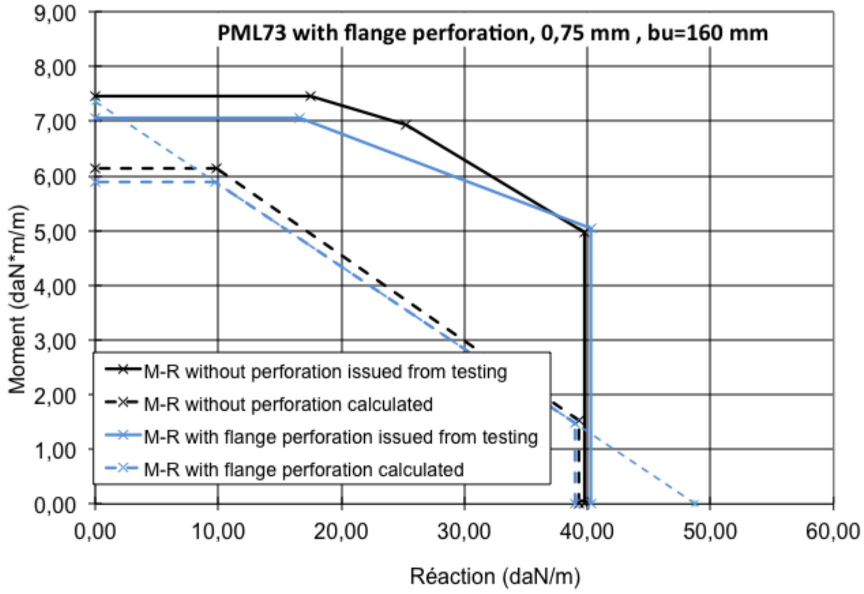


Fig. 3.1.3.2.2 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=160 mm, without and with flange perforation

PML 73 1 mm, b_u=60mm

flange perforation

M_{Rk_max}	R_{Rk_min}
8,41	19,74

M_{Rk_min}	R_{Rk_max}
5,69	45,54

flange perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
7.35	42.66	9.19	53.32

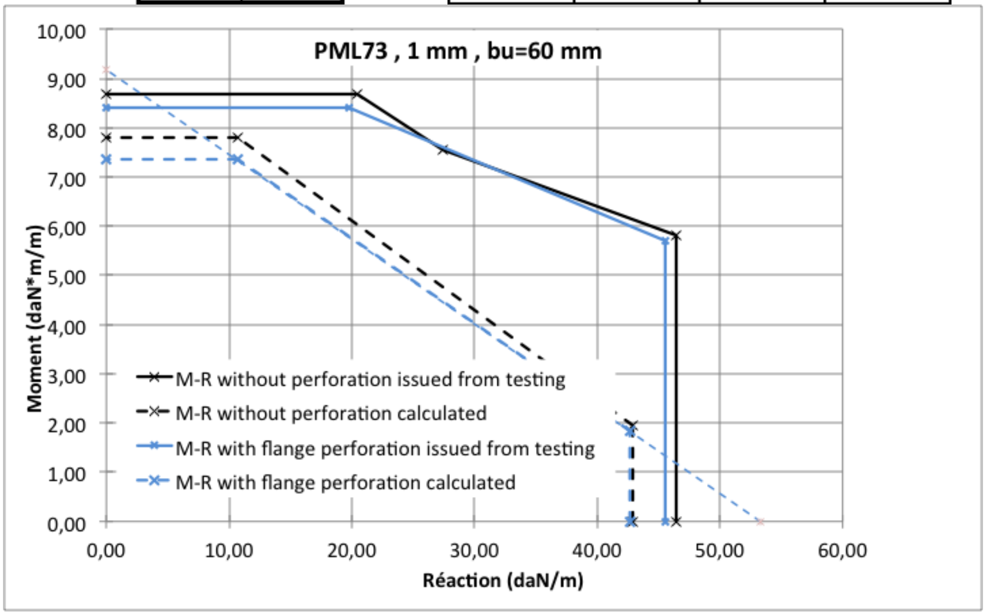


Fig. 3.1.3.2.3 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=60 mm, without and with flange perforation

PML 73 1 mm, b_u=160mm

flange perforation

M_{Rk_max}	R_{Rk_min}
10,20	23,94

M_{Rk_min}	R_{Rk_max}
7,70	61,62

flange perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
7.35	61.43	9.19	76.78

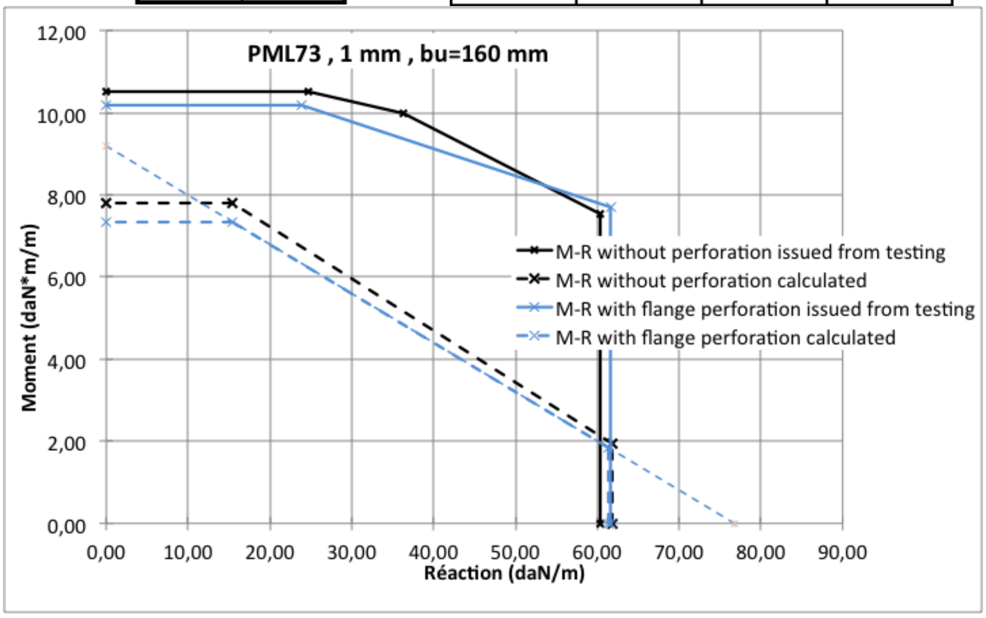


Fig. 3.1.3.2.4 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=160 mm, without and with flange perforation

PML 73 0.75mm, b_u=60mm

web perforation

M_{Rk_max}	R_{Rk_min}
5,27	12,35

M_{Rk_min}	R_{Rk_max}
2,93	23,40

web perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5,31	19,17	6,63	23,96

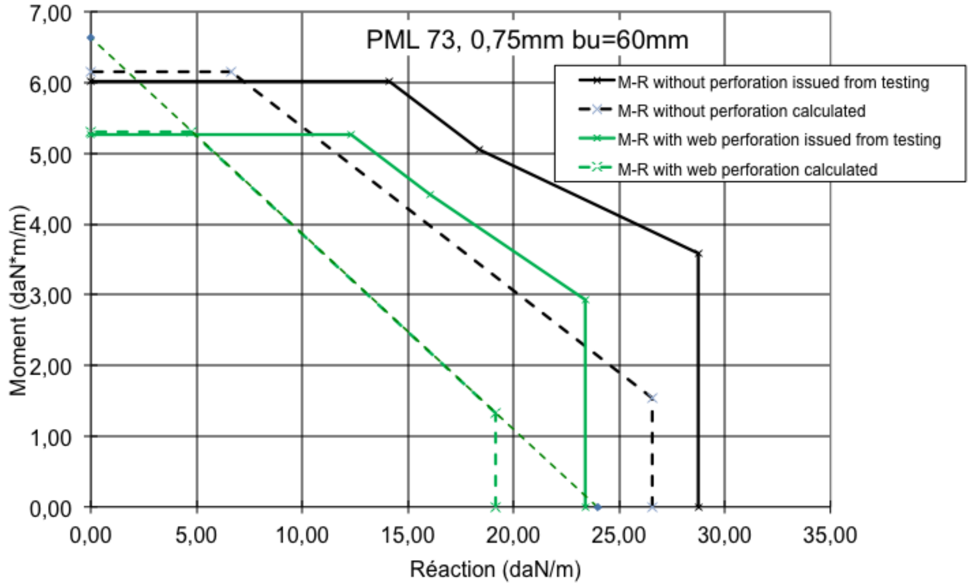


Fig. 3.1.3.2.5 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=60 mm, without and with web perforation

PML 73 0.75mm, b_u=160mm

web perforation

M_{Rk_max}	R_{Rk_min}
6,31	14,80

M_{Rk_min}	R_{Rk_max}
4,03	32,26

web perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5,31	28,14	6,63	35,18

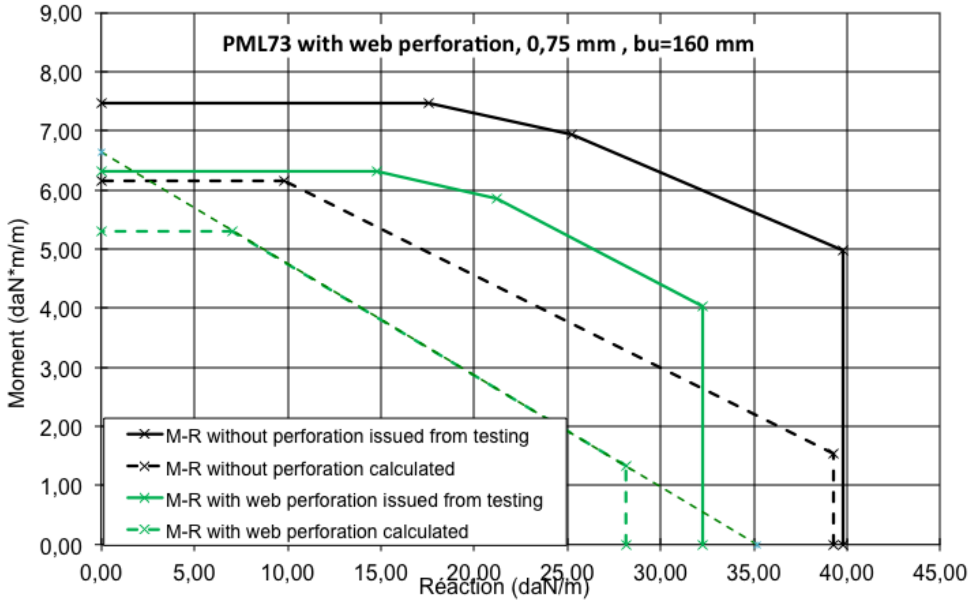


Fig. 3.1.3.2.6 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=160 mm, without and with web perforation

PML 73 1 mm, b_u=60mm

web perforation

M_{Rk_max}	R_{Rk_min}
7,55	17,72

M_{Rk_min}	R_{Rk_max}
4,70	37,60

web perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6.68	30.80	8.35	38.50

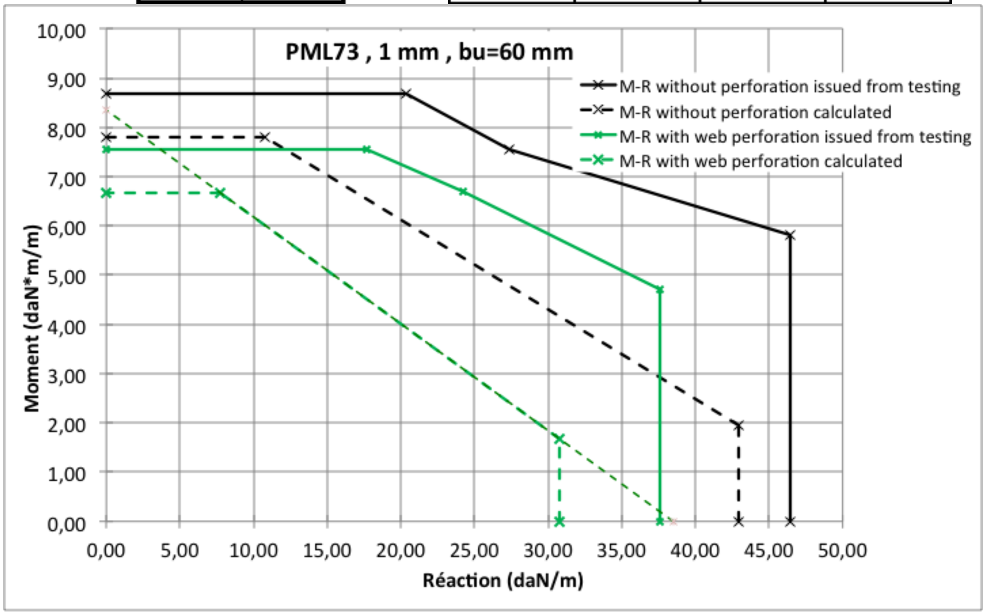


Fig. 3.1.3.2.7 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=60 mm, without and with web perforation

PML 73 1 mm, b_u=160mm

web perforation

M_{Rk_max}	R_{Rk_min}
9,00	21,12

M_{Rk_min}	R_{Rk_max}
6,37	50,93

web perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6.68	44.70	8.35	55.88

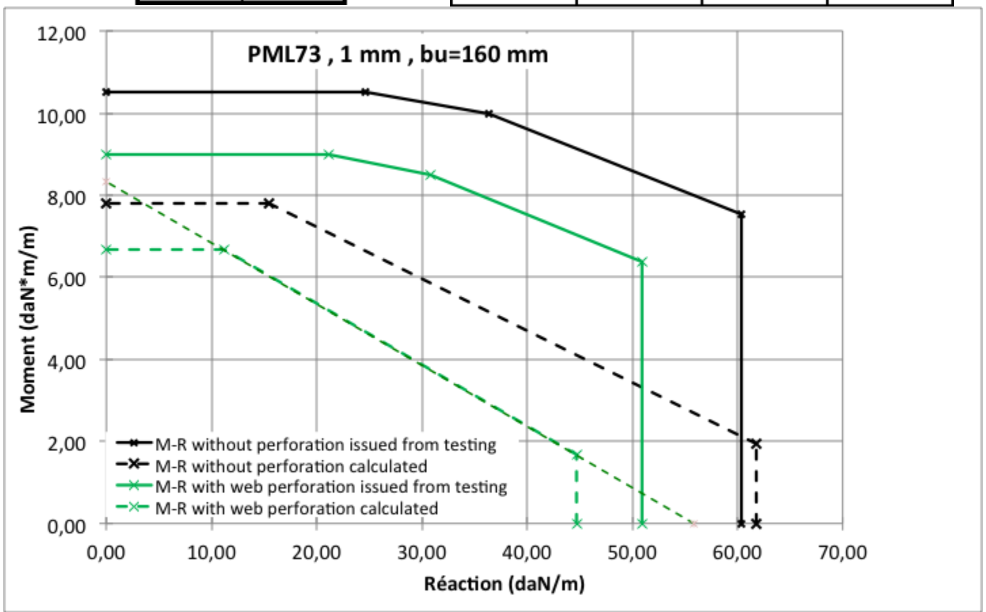


Fig. 3.1.3.2.8 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=160 mm, without and with web perforation

PML 73 0.75mm, bu=60mm
with total perforation

M_{Rk_max}	R_{Rk_min}
3,99	9,36

M_{Rk_min}	R_{Rk_max}
2,54	20,30

total perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5,04	16,02	6,30	20,02

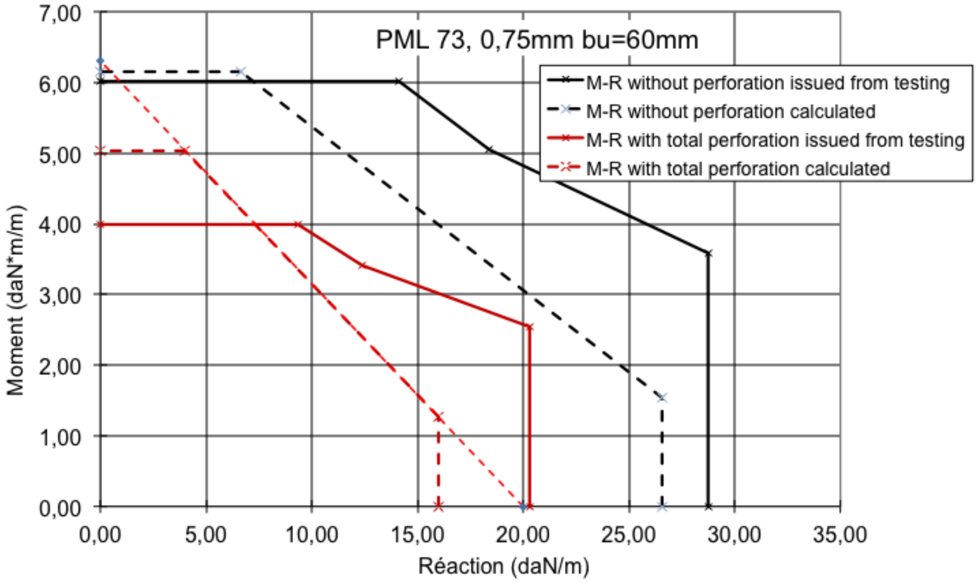


Fig. 3.1.3.2.9 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=60 mm, without and with total perforation

PML 73 0.75mm, bu=160mm
with total perforation

M_{Rk_max}	R_{Rk_min}
4,83	11,32

M_{Rk_min}	R_{Rk_max}
3,35	26,77

total perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
5.04	23.61	6.30	29.52

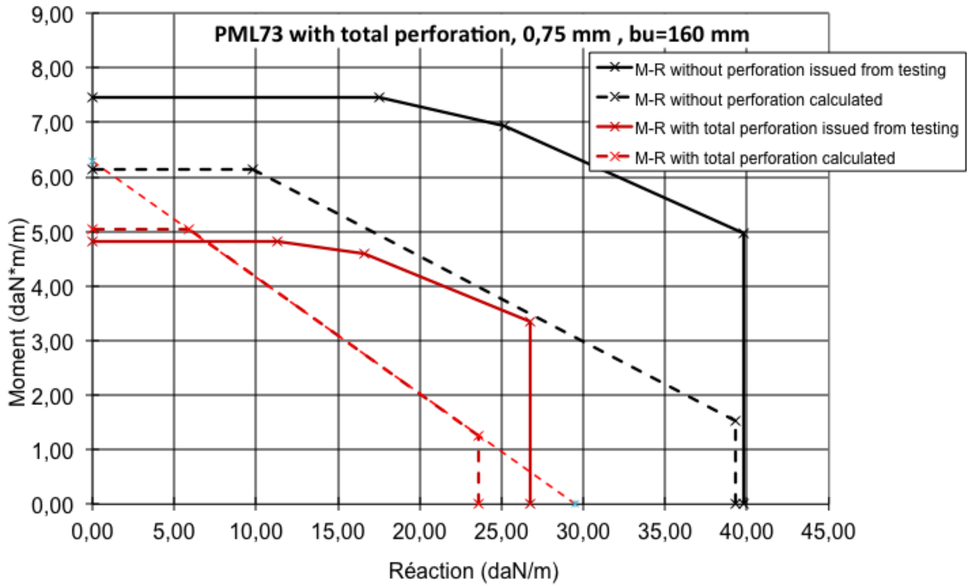


Fig. 3.1.3.2.10 Comparison between proposed calculation method and tests results for PML 73 0.75 mm at the support width bu=160 mm, without and with total perforation

PML 73 1 mm, bu=60mm
with total perforation

M_{Rk_max}	R_{Rk_min}
5,86	13,74

M_{Rk_min}	R_{Rk_max}
3,93	31,39

total perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6.26	25.46	7.83	31.82

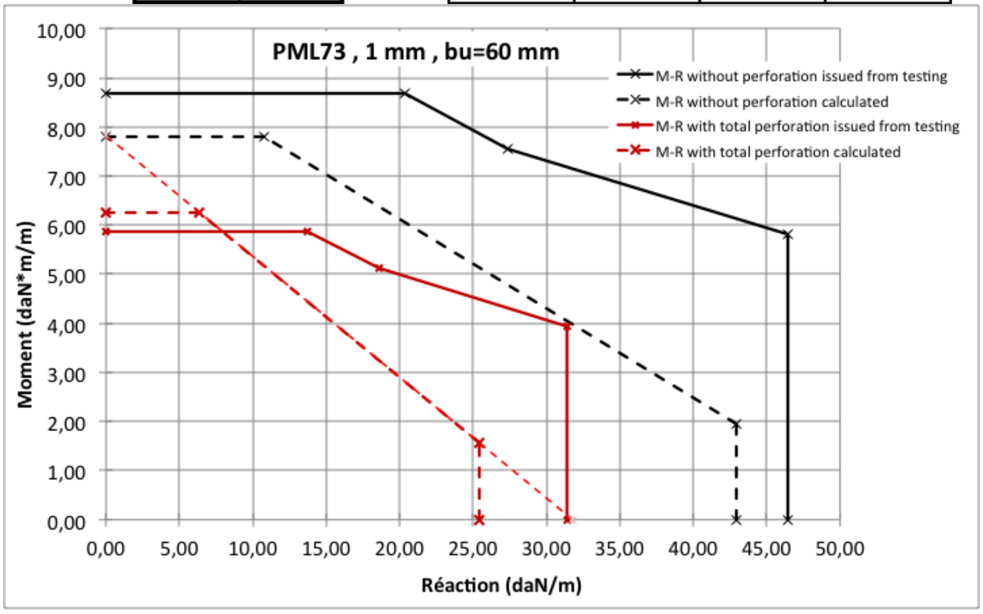


Fig. 3.1.3.2.11 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=60 mm, without and with total perforation

PML 73 1 mm, bu=160mm
with total perforation

M_{Rk_max}	R_{Rk_min}
6,95	16,30

M_{Rk_min}	R_{Rk_max}
5,13	41,05

total perforation			
$M_{calculated}$	$R_{calculated}$	M0	R0
6.26	37.12	7.83	46.40

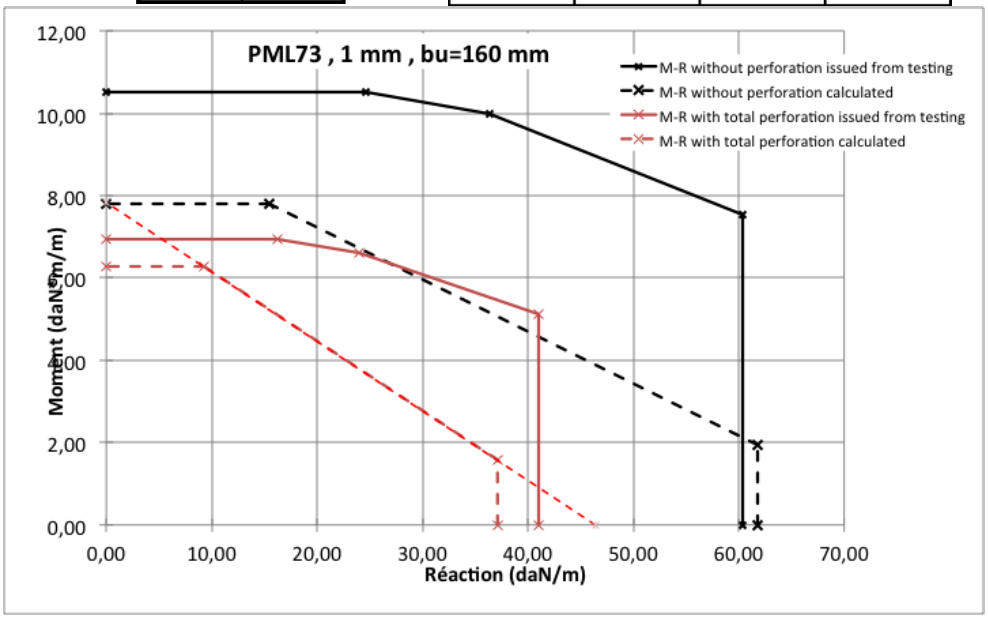


Fig. 3.1.3.2.12 Comparison between proposed calculation method and tests results for PML 73 1 mm at the support width bu=160 mm, without and with total perforation

3.2. SHEETING WITH A HOLE

3.2.2. Span moment resistance of profiles without a hole

The moment resistances of the effective section are calculated according to EN 1993-1-3 and are compared to the values defined by testing for PML 56 in Table 3.2.1.1 and for PML 73 in Table 3.2.1.2.

PML 56:
The tested profiles properties are:
t= 0,698 mm and f_{yb} = 357,67 N/mm^2
t= 0,929 mm and f_{yb} = 370 N/mm^2

PML 56			
t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation	
0,75	3,18	3,23	**-1,7%**
1,00	5,09	4,61	**9,5%**

Table 3.2.1.1 – Comparison between calculated and defined by testing moment resistances for PML 56

PML 73:
The tested profiles properties are:
t= 0,700 mm and f_{yb} = 357,33 N/mm^2
t= 0,945 mm and f_{yb} = 361,67 N/mm^2

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test	Calculation	
0,75	4,98	5,34	**-7,1%**
1,00	8,05	7,47	**7,3%**

Table 3.2.1.2 – Comparison between calculated and defined by testing moment resistances for PML 73

The calculated resistance moments are lower than the tested ones for PML 56 t=1mm and for PML 73 t=1mm, from 7,3% to 9,5%.

On the contrary the calculated resistance moments are higher than the tested ones for PML 56 t=0,75mm and for PML 73 t=0,75mm, respectively 1,7% and 7,1%. The width and the angle of the web stiffener and the angle of the web were not measured on the tested profiles therefore for these values theoretical values were taken for the calculation. The possible differences between the theoretical and the actual geometry can explain that the calculated resistance moments are higher than the tested ones.

3.2.3. Resistance values of profiles with a hole

As shown in the Deliverable D34 [16] when the diameter of the hole (d) is equal to the width of the hole (w) the influence on resistant moment is quite similar for circular and square holes. (Fig.

3.2.3.1) Therefore the same model of calculation is proposed for square holes and circular holes depending on the width of the hole in the flange section (Fig. 2.2.2.6).

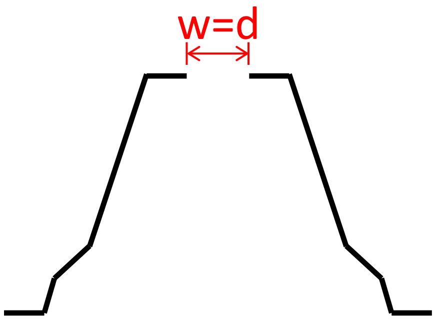


Fig. 3.2.3.1 Square (width=w) or circular (diameter=d) hole in the upper flange

The moment resistance of the profile is calculated according to EN 1993-1-3 where the global modulus W_{eff} is the sum of the effective section without a hole modulus and of the effective section with a hole modulus. The effective flange area is calculated according to EN 1993-1-5 with the gross cross-sectional area A_c: $A_{c,eff} = \rho\ A_c$ where ρ is the reduction factor for plate buckling.

- The flanges without a hole are considered as internal compression elements, the reduction factor ρ is :

$$\rho = \frac{\bar{\lambda}_p - 0{,}055\,(3+\psi)}{\bar{\lambda}_p^2} \leq 1{,}0$$

and effective width b is determined according to Table 4.1:Internal compression elements of EN 1993-1-5

- Both parts of the flange 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

PML 56:

PML 56 profile was tested with:

- circular holes of diameter d=103,15 mm; d=66,6 mm (t=0,75 mm)
- circular holes of diameter d=100,9 mm; d=65,75 mm (t=1 mm)
- square holes of width w=101,55 mm; w=66,7 mm (t=0,75 mm)
- square holes of width w=101,9 mm; w=66 mm (t=1 mm)
-

The tested profiles properties are:
t= 0,698 mm and f_{yb} = 357,67 N/mm^2
t= 0,929 mm and f_{yb} = 370 N/mm^2

In Table 3.2.2.1 and 3.2.2.2 the calculated moment resistance and the defined by testing moment resistance are presented.

PML 56			
t_{nom}	M_R (kN*m/m)		
mm	Test square hole d=100mm	Calculation	
0,75	2,97	2,94	**0,9%**
1,00	4,83	4,22	**12,6%**

PML 56			
t_{nom}	M_R (kN*m/m)		
mm	Test square hole d=65mm	Calculation	
0,75	2,97	2,95	**0,7%**
1,00	4,84	4,25	**12,2%**

Table 3.2.2.1 – Comparison between calculated and defined by testing resistance moment for PML 56 with a square hole

PML 56			
t_{nom}	M_R (kN*m/m)		
mm	Test circular hole d=100mm	Calculation	
0,75	2,93	2,94	**-0,2%**
1,00	4,87	4,22	**13,3%**

PML 56			
t_{nom}	M_R (kN*m/m)		
mm	Test circular hole d=65mm	Calculation	
0,75	3,04	2,95	**2,9%**
1,00	4,90	4,25	**13,2%**

Table 3.2.2.2 – Comparison between calculated and defined by testing resistance moment for PML 56 with a circular hole

In Table 3.2.2.3 and 3.2.2.4 the influence of square and circular hole on calculated moment resistance and on the defined by testing moment resistance is presented.

PML 56	hole influence	
t_{nom}	Test circular hole d=100mm	Calculation
0,75	-7,6%	-9,0%
1,00	-4,4%	-8,5%

PML 56	hole influence	
t_{nom}	Test square hole d=100mm	Calculation
0,75	-6,5%	-9,0%
1,00	-5,2%	-8,5%

Table 3.2.2.3 – Square Hole influence on resistance moment defined by testing and calculation for PML 56

PML 56	hole influence	
t_{nom}	Test square hole d=65mm	Calculation
0,75	-6,5%	-8,7%
1,00	-5,0%	-7,8%

PML 56	hole influence	
t_{nom}	Test circular hole d=65mm	Calculation
0,75	-4,4%	-8,7%
1,00	-3,9%	-7,8%

Table 3.2.2.4 – Circular Hole influence on resistance moment defined by testing and calculation for PML 56

As shown in the Tables 3.2.2.1 and 3.2.2.2 the difference between the calculated moment resistances and the tested ones are from -0,2% to 13,3%.
The decrease induced by a circular hole and a square hole defined by calculation for PML 56 are coherent with the decrease defined by testing for all the width and the diameters of the holes (Table 3.2.2.3 and 3.2.2.4).

PML 73:

PML 73 profile was tested with:

- circular holes of diameter d=121,45 mm; d=106,45 mm; d=91,8mm (t=0,75 mm)
- circular holes of diameter d=121,95 mm; d=106,3 mm; d=91,5mm (t=1 mm)
- square holes of width w=121,65mm; w=106,35mm; w=91,2mm (t=0,75 mm)

- square holes of width w=121,6mm; w=106,55mm; w=92,15mm (t=1 mm)

The tested profiles properties are:
t= 0,700 mm and f_{yb} = 357,33 N/mm^2
t= 0,945 mm and f_{yb} = 361,67 N/mm^2

In Tables 3.2.2.5 and 3.2.2.6 are presented calculated moment resistance and moment resistance defined by testing

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test square hole d=120mm	Calculation	
0,75	4,22	4,43	**-4,9%**
1,00	6,88	6,51	**5,4%**

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test square hole d=105mm	Calculation	
0,75	4,51	4,91	**-8,8%**
1,00	7,21	6,69	**7,2%**

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test square hole d=90mm	Calculation	
0,75	4,67	4,93	**-5,6%**
1,00	7,73	6,78	**12,3%**

Table 3.2.2.5 – Comparison between calculated and defined by testing resistance moment for PML 73 with a square hole

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test circular hole d=120mm	Calculation	
0,75	4,23	4,43	**-4,5%**
1,00	7,01	6,50	**7,3%**

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test circular hole d=105mm	Calculation	
0,75	4,59	4,91	**-6,9%**
1,00	7,59	6,68	**12,0%**

PML 73			
t_{nom}	M_R (kN*m/m)		
mm	Test circular hole d=90mm	Calculation	
0,75	4,64	4,93	**-6,4%**
1,00	7,60	6,79	**10,6%**

Table 3.2.2.6 – Comparison between calculated and defined by testing resistance moment for PML 73 with a circular hole

PML 73	hole influence	
t_{nom}	Test square hole d=120mm	Calculation
0,75	-15,3%	-17,1%
1,00	-14,5%	-12,8%

PML 73	hole influence	
t_{nom}	Test square hole d=105mm	Calculation
0,75	-9,5%	-8,1%
1,00	-10,5%	-10,4%

PML 73	hole influence	
t_{nom}	Test square hole d=90mm	Calculation
0,75	-6,2%	-7,6%
1,00	-4,0%	-9,2%

Table 3.2.2.7 – Square hole influence on moment resistance defined by testing and calculation for PML 73

PML 73	hole influence	
t_{nom}	Test circular hole d=120mm	Calculation
0,75	-15,0%	-17,1%
1,00	-12,9%	-13,0%

PML 73	hole influence	
t_{nom}	Test circular hole d=105mm	Calculation
0,75	-7,8%	-8,1%
1,00	-5,8%	-10,6%

PML 73	hole influence	
t_{nom}	Test circular hole d=90mm	Calculation
0,75	-6,9%	-7,6%
1,00	-5,7%	-9,1%

Table 3.2.2.8 – Circular hole influence on moment resistance defined by testing and calculation for PML 73

As shown in the Tables 3.2.2.5 and 3.2.2.6 the difference between the calculated moment resistances and the tested ones for thickness t=0,75 mm varies from –4,5% to -8,8%. This difference is coherent with the difference observed in 3.2.1 where for the profiles without a hole the calculated moment resistance was higher than the tested one of 7,1%. These superior values are probably due to the possible differences between the theoretical and the actual geometry.

The difference between the calculated moment resistances and the tested ones for thickness t=1 mm varies from 5,4% to 12,3%. This difference is coherent with the difference observed in 3.2.1

where for the profiles without a hole the calculated moment resistance was higher than the tested one of 7,3%.

As for PML 56, the decrease induced by a circular hole and a square hole defined by calculation for PML 73 are coherent with the decrease defined by testing for all the width and diameters of the holes (Table 3.2.2.7 and 3.2.2.8).

These comparisons confirm that the calculation method for the resistance moment of the steel sheeting with a circular or a square hole adopted in the present study gives results that are coherent and in the same time safe in relation with the testing results.

4. CONCLUSION

Based on the study of results of tests performed on coupons and on steel trapezoidal sheeting it is proposed to calculate the resistances of the effective section, with perforation arranged in square, in the flange or in the web (but not for a total perforation), according to EN 1993-1-3, determining for the perforated section the thickness as below:

- gross section properties may be calculated using part 5.1, but replacing t by $t_{a,eff}$ obtained from eq. 2.2.2.7:

$$\boxed{t_{a,eff} = 1{,}09t\left(1 - \frac{1{,}03d}{e}\right)}$$

where:

d	is	the diameter of the perforations;
e	is	the spacing between the centers of the perforations.

- effective section properties may be calculated using Section 5, but replacing t by $t_{b,eff}$ obtained from eq. 2.2.2.9:

$$\boxed{t_{b,eff} = 0{,}98t\sqrt[3]{\left(1 - \frac{0{,}93d}{e}\right)}}$$

- the resistance of a single web to local transverse forces may be calculated using part 6.1.9, but replacing t by $t_{c,eff}$ obtained from eq. 3.1.2.2.2:

$$\boxed{t_{c,eff} = t\left[1 - 0{,}866\left(\frac{d}{e}\right)^2 \frac{s_{per}}{s_w}\right]^{3/2}}$$

where:

s_{per}	is	the slant height of the perforated portion of the web;
s_w	is	the total slant height of the web.

For a totally perforated sheeting with perforation arranged in square the calculation results are much higher than the test results. This important difference makes it impossible to propose a coherent equivalent and safe formula for the totally perforated sheeting. Moreover it calls into question the use of the formula (10.25), EN 1993-1-3, for totally perforated sheeting.

As far as steel trapezoidal sheeting with a hole is concerned the same model of calculation is proposed for a square hole and circular hole depending on the width of the hole in the flange section

The moment resistance of the profile is calculated according to EN 1993-1-3 where the global modulus W_{eff} is the sum of the effective section without a hole modulus and of the effective section with a hole modulus. The effective flange area is calculated according to EN 1993-1-5 with the gross cross-sectional area A_c: $A_{c,eff} = \rho\ A_c$ where ρ is the reduction factor for plate buckling.

- The flanges without a hole are considered as internal compression elements, the reduction factor ρ is :

$$\rho = \frac{\overline{\lambda}_p - 0{,}055\,(3+\psi)}{\overline{\lambda}_p^2} \leq 1{,}0$$

and effective width b is determined according to Table 4.1:Internal compression elements of EN 1993-1-5

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

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

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

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