Introduction to steel profiles

Enveloppe Métallique du Bâtiment
David Izabel

Informative document in any case the eurocode EN 1993-1-3 and EN 1993-1-5 apply
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Introduction

The present material complies with the current version of the EN 1993-1-3 and EN 1993-1-5.

The amendments proposed by GRISPE+ are not taken into account (see the other presentations of GRISPE+).

This training is an initiation to the design of cold formed profiles. Some simplifications are provided to help the learner.

Refer to the original Eurocode to have all the clauses that have to be applied.

Take into account the national annex of each Eurocode.

The material does not cover assemblies that also have to be checked (see EN 1993-1-3 and EN 1993-1-8).
Principles of cold formed elements
Principles of the cold formed elements

The principles are as follows:

- Optimizing the material with thin metal sheet
- Providing inertia to the geometric shape of the profiles as in the case of the shell
- Adding stiffeners to avoid local instability in the compressed area (flanges, webs)
- Adding embossments to facilitate the liaison concrete and steel

Source: EN 1993-1-3
Source: EMB
Source: GRISPE project
Different types of cold formed elements
The two main families of profiles

- The sheetings:
  (cladding, roofing, covering, decking)

- The members:
  (purlin column, cladding rail)

Source: EN 1993-1-3
Manufacturing process of cold formed elements
Manufacturing process of cold formed elements

Profiling machine

Source: EMB

Profiling rollers

Source: EMB
Using cold formed elements in construction
Using cold formed elements in construction (sheetings)

CLADDING

- Single skin system
- Facade cladding
- Double skin system

*Source: BIM Enveloppe métallique du bâtiment*
Using cold formed elements in construction (sheetings)

COVERING

Single skin covering

Double skin covering

Source: BIM Enveloppe métallique du bâtiment
Using cold formed elements in construction (sheetings)

ROOFING

Source: BIM Enveloppe métallique du bâtiment
Using cold formed elements in construction (sheeting)

DECKING – COMPOSITE FLOOR

Source: BIM Enveloppe métallique du bâtiment
Using cold formed elements in construction (members)

PORTAL FRAMES

Source: EMB
Using cold formed elements in construction (members)

PORTAL FRAME

- Purlin
- Cladding rail

Source: EN 1993-1-3
European standards for cold formed elements
European standards for raw materials

- EN 10143: tolerances on the metal core $t_{\text{nom}}$
- EN 10346 (Metallic coating): protection against corrosion
- EN 10169+A1 (Organic Coating): protection against corrosion
CE marking of the product - CPR

For non structural products

- Self supporting EN 14782
- Fully supported EN 14783
  - Class III (Non structural use)
  - EN 508-1 (measurements in the production phase)

For structural products

- EN 1090-1
  - Class I (diaphragm use)
  - Class II (collaboration member/sheeting)
Designing tests and calculations:

- EN 1993-1-3 + corrigendum + National annex (general design)
- EN 1993-1-5 + corrigendum + National annex (effective width)
- EN 1993-1-8 + corrigendum + National annex (assemblies)

Building erection:

- EN 1090-4 (steel products)
Profiled steel sheetings covered by the GRISPE⁺ project
Profiles covered by the GRISPE+ project

- **Decking with embossments and/or indentations**

  ![Diagram](image1)

  Source: Draft amendment Eurocode

- **Decking with outside stiffeners**

  ![Diagram](image2)

  Source: GRISPE WP1
Profiles covered by the GRISPE project

The liner tray with $s_1 > 1$ m distance

Source: EC3 1.3

Source: GRISPE WP2

Source: GRISPE WP2
Profiles covered by the GRISPE + project

Corrugated profiles

Fig (5) - Cross section of the profile 18/76

Fig (6) - Cross section of the profile 46/150

Source: GRISPE WP2
Profiles covered by the GRISPE + project

Curved profile with and without arch effect

Key parameters for arch profiles

Mechanical model for arch profiles

Source: GRISPE WP2
Profiles covered by the GRISPE + project

- Cantilever above profile
- Overlapping joints
- Cantilever underneath
- Continuous profiles with local reinforcement

Source: GRISPE WP2
The tested assembled profiles are:

- Continuous profiles (C)
- Two-sided overlapping (OL)
- DIN 18807 (DIN) overlapping
- Continuous profiles with reinforcement (CR)

Source: GRISPE WP2
Profiles covered by the GRISPE project

Perforated profiles

Triangular pattern (covered by the EN 1993-1-3)

Square pattern (not covered by the EN 1993-1-3)

Source: GRISPE WP3
Profiles covered by the GRISPE + project

Holed profiles

Source: GRISPE WP3
Profiles covered by the GRISPE + project

Plank profiles

Clip joint

Chevron-shaped joint

Profiles requested by architects that want to have façades without visible fasteners

Specific failure in the assembling: dislocation

Source: GRISPE WP4
Methods to design a cold formed element
The logigram to study cold formed profiles

FEM designing

Strength capacity of a Cold formed profile

Design by calculation

Checking the application criteria of the formula

Design by testing

Definition of the test program

Test report

Test interpretation

Design formula

Application of the formula

Excel software

Geometry of the profile, n end support tests, n bending tests, n interaction M/R tests + n coupon tests

Statistical approach: M_{Rd}, V_{Rd}, R_{wRd} proposal, Interaction curve M/R.

f_y, f_u, t_{obs}, curve load/ displacement /type of collapse

YES /NO

Background document

To interpolate between test results and check calculation methods at the limit of the field of application
Tests to study the cold formed sheetings
The different tests to study the cold formed profiles:

VACUUM CHAMBER:

The vacuum chamber test:

The objectives of this test:
⇒ Effective inertia of the profile: \( I_{\text{eff}} \)
⇒ Bending capacity: \( M_{c,Rd} \)

Source: GRISPE WP4

Test set-up:

Source: GRISPE WP4
Vacuum chamber test results

Typical associated collapses: local buckling/dislocation

Curve load displacement

Typical failure: dislocation

Source: GRISPE validation deliverable D 4.7
An example of test interpretation

Main collapses:

- Downward load (pressure): buckling of the compressed facing.
- Upward load (suction): dislocation of the profile assembling.
The different tests to study the cold formed profiles:

SINGLE SPAN BENDING TEST

The objectives of this test:

⇒ Effective inertia of the profile: $I_{\text{eff}}$
⇒ Bending capacity: $M_{c,Rd}$
Typical single span bending test set up

Source: GRISPE WP2
Typical single span bending test set up

Source: GRISPE WP1

Source: GRISPE validation deliverable D 1.8
Test results (case bending in single span tests)

Typical curve load displacement

Source: GRISPE validation deliverable D 1.8

Ex: Decking profile without embossments

Source: GRISPE validation deliverable D 1.8

Ex: Decking profile with embossments
An example of test interpretation

The WP1 example (embossment effects)

<table>
<thead>
<tr>
<th>Bending resistance</th>
<th>Inertia Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5% - 10%</td>
<td>1.5% - 11%</td>
</tr>
</tbody>
</table>

Source: GRISPE WP1
The different tests to study the cold formed profiles:

**INTERMEDIATE SUPPORT TEST**

The objectives of this test:

⇒ Interaction between the bending Moment $M_{c,Rd}$ and $R_{w,Rd}$
⇒ Reaction on the support $R_{w,Rd}$
Typical intermediate support test set up

To calculate the rotation on the support

To simulate the central support

Eg. Total perforation trapezoidal profile

A corner to simulate the profile lateral continuity

Source: GRISPE WP3
Test results (intermediate support case)

Eg. Total perforation decking profile

Source: GRISPE validation deliverable D 3.7

Source: GRISPE WP3
An example of test interpretation

The WP3 example (square pattern perforation effect)

<table>
<thead>
<tr>
<th></th>
<th>Moment – Reaction Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange perforation</td>
<td>0% - 5%</td>
</tr>
<tr>
<td>Web perforation</td>
<td>11% - 19%</td>
</tr>
<tr>
<td>Total perforation</td>
<td>35% - 42%</td>
</tr>
</tbody>
</table>

Source: GRISPE WP3
The different tests to study the cold formed profiles:

END SUPPORT TEST

The objectives of this test:

⇒ Capacity of the end support reaction $R_{w,Rd}$
Typical end support test set up

Modified set up to ensure the accurate position of the load

Source: EN 1993-1-3

Block of wood to avoid any web crippling in this specific part

Source: GRISPE WP2
Typical end support test set up

Source: GRISPE validation deliverable D 1.8

Source: GRISPE validation deliverable D 1.8
Test results

Not used in the design, because it is a bending collapse

Source: GRISPE validation deliverable D 1.8

Source: GRISPE validation deliverable D 1.8
An example of test interpretation

The WP1 example (embossment effects)

<table>
<thead>
<tr>
<th>End support reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5% - 20%</td>
</tr>
</tbody>
</table>

*Source: GRISPE WP1*
Collapses and instabilities of cold formed elements
Different instabilities under compression stresses

Local buckling

Eg: Corrugated sheet local buckling

Eg: Plank profile local buckling

Source: GRISPE WP2

Source: GRISPE WP4
Different instabilities under compression stresses

Local buckling

Eg: cassette/ liner tray lateral buckling

Source: GRISPE WP2

Source: GRISPE WP2
Different instabilities under compression stresses

Local buckling and local impression at an intermediate support

Eg: Continuous trapezoidal profile

Local impression of the web top + web crippling area

Source: GRISPE WP2

Source: GRISPE WP2
Collapse at an intermediate support

Local buckling and impression of the support

Eg: Corrugated sheet

Source: GRISPE WP2

Web crippling in the compression area

Source: GRISPE WP2
Collapse by plastification

Yielding

Eg: Corrugated sheet

Source: GRISPE WP2
Different instabilities under shear stresses

Shear collapse

Eg: Corrugated sheet

Source: GRISPE WP2

Web crippling in the shear area

Source: GRISPE WP2
Different instabilities under shear stresses

Local web crushing/ web crippling
Eg: assembling continuity on a support => DIN overlapping

Source: GRISPE WP2

Web crippling at the overlapping area

Source: GRISPE WP2

Source: GRISPE WP2
Collapse at end support

Web crippling

Eg: Corrugated sheet

Source: GRISPE WP2

Source: GRISPE WP2

Web crippling in the compression area
Collapse at end support

**Web crippling**

Eg: Plank profiles

Chevron shaped joint (plank 300 reinforced)

Web plank crippling

*Source: GRISPE WP4*

Eg: trapezoidal profiles with different perforation types

*Source: GRISPE WP2*
Collapse under upward load

Fasteners in the valley

Eg: Corrugated sheets

Source: GRISPE WP2

Local buckling

Source: GRISPE WP2
Collapse under upward load

Fasteners in the crest

Eg: Corrugated sheets

Source: GRISPE WP2

Local buckling at the fastening point
Collapse under upward load

Eg: Liner trays

Source: GRISPE WP2
Liner tray and plank profile specific collapses

Assembling dislocation

Eg: Plank profiles

Source: GRISPE WP2

Source: GRISPE WP4

Liner tray free flange lateral instability
Mechanical model to take the local flange instability into account
Notations used

Source: EN 1993-1-3
**Required conditions to use the EN 1993-1-3**

<table>
<thead>
<tr>
<th>Element of the cross section</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td>( b/t \leq 50 )</td>
</tr>
<tr>
<td><img src="image2.png" alt="Image 2" /></td>
<td>( b/t \leq 80 ) ( c/t \leq 50 )</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image 3" /></td>
<td>( b/t \leq 90 ) ( c/t \leq 80 ) ( d/t \leq 50 )</td>
</tr>
<tr>
<td><img src="image4.png" alt="Image 4" /></td>
<td>( b/t \leq 500 )</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image 5" /></td>
<td>( 45^\circ \leq \phi \leq 90^\circ ) ( h/t \leq 500 \sin \phi )</td>
</tr>
</tbody>
</table>

- For sheeting and members \( 0,45 \text{ mm} \leq t_{cor} \leq 15 \text{ mm} \)
- For connections \( 0,45 \text{ mm} \leq t_{cor} \leq 4 \text{ mm} \)
  \( 0,2 \leq c/b \leq 0,6 \)
  \( 0,1 \leq d/b \leq 0,3 \)

If \( r/t < 5 \) (clause 5.1 1993 1.3 ) and \( r < 0.10 \text{ b}_{p} \)

Then it is possible to ignore the profile’s corners.

*Source: table 5.1 of the EN 1993-1-3*
Plate buckling critical stress determination

According to the plate theory, the deflection \( w(x,y) \) follows the fourth order differential equation:

\[
\frac{\partial^4 w(x,y)}{\partial x^4} + 2 \frac{\partial^4 w(x,y)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y)}{\partial y^4} = -\frac{1}{D} \left( N_{xx} \frac{\partial^2 w(x,y)}{\partial x^2} \right)
\]

The corresponding solution is as follows:

\[
w(x,y) = A_{mn} \sin \left( \frac{m\pi x}{a} \right) \sin \left( \frac{n\pi y}{b} \right)
\]

\( a \) and \( b \) dimensions in plane of the plate

\( m, n : 1, 2, 3 \ldots \)
Plate buckling critical stress determination

If we put the expression of $w(x,y)$ in the fourth order differential equation, the result is:

$$\left[ \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 \right]^2 = \frac{N_{xx}}{D} \left( \frac{m\pi}{a} \right)^2$$

In addition we have this equation of the normal effort $N_{xx}$:

$$N_{xx} = \frac{D a^2}{m^2 \pi^2} \left[ \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 \right]^2 = \sigma_{xx} t$$

$N_{xx}$ must be at its minimum value (use the derivative/m):

$$n = 1$$

$$\frac{\partial N_{xx}}{\partial m} = \frac{\partial N_{cr}}{\partial m} = 2D \frac{\pi}{b^2} \left( m \frac{b}{a} + \frac{a}{mb} \right) \left( \frac{b}{a} - \frac{a}{m^2 b} \right) = 0 \quad \rightarrow \quad m = \frac{a}{b}$$
After simplification (replace $m$ by $a/b$), we obtain the following equation:

$$N_{cr} = 4 \frac{D\pi^2}{b^2} = 4 \frac{\pi^2 Et^3}{12(1 - v^2)b^2}$$

In addition we also have:

$$\sigma_{cr} = \frac{N_{cr}}{t} = 4 \frac{D\pi^2}{b^2t} = 4 \frac{\pi^2 Et^3}{12(1 - v^2)b^2t} = 4 \frac{\pi^2 E}{12(1 - v^2)b^2} \left(\frac{t}{b}\right)^2$$

For uniform compression stresses on the plate

$$\sigma_{cr} = k_\sigma \frac{\pi^2 E}{12(1 - v^2)} \left(\frac{t}{b}\right)^2$$

Buckling critical stress
Effective width notion – Determination of \( \rho \)

Top flange in compression – stress distribution

**Effective section**

\[ \sigma_{cr}(b) \]

Source: EMB

\[ b_{eff} = \rho b \]

\[ \rho = \frac{b_{eff}}{b_p} = \sqrt{\frac{\sigma_{cr}}{f_y}} \quad (v. \text{Karman}) \]

\[ \rho = \frac{b_{eff}}{b_p} = \sqrt{\frac{\sigma_{cr}}{f_y}} \quad (1\text{,}0 \pm 0\text{.}22 \sqrt{\frac{\sigma_{cr}}{f_y}}) \quad (\text{Winter}) \]

Source: EMB

Fictive hole in the compressed flange

\[ b_{eff} = \rho b \]

Effective Section AA
From the following equation we are looking for $b_{\text{eff}}$:

$$\sigma_{cr}(beff) = f_y = k_\sigma \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{b_{\text{eff}}} \right)^2$$

A proportionality exists between the critical stress and the $(t/b_{\text{eff}})^2$ ratio:

$$\sigma_{cr}(beff) = f_y = K \times \left( \frac{t}{b_{\text{eff}}} \right)^2$$
How to determine $b_{\text{eff}}$?

By dividing the critical stress by $f_y$ we obtain:

$$\frac{\sigma_{cr}(b)}{f_y} = k_{\sigma} \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{b} \right)^2 \left( \frac{1}{f_y} \right)$$

By calculating the square root the above equation becomes:

$$\sqrt{\frac{\sigma_{cr}(b)}{f_y}} = \left( k_{\sigma} \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{b} \right)^2 \left( \frac{1}{f_y} \right) \right)^{1/2}$$

By multiplying by $b$ the result is:

$$b \sqrt{\frac{\sigma_{cr}(b)}{f_y}} = b \left( k_{\sigma} \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{b} \right)^2 \left( \frac{1}{f_y} \right) \right)^{1/2}$$
How to determine $b_{\text{eff}}$?

The ratio between the critical stresses calculated for $b_{\text{eff}}$ and $b$ is:

$$\frac{\sigma_{cr(b_{\text{eff})}}}{\sigma_{cr(b)}} = \left(\frac{t}{b_{\text{eff}}}\right)^2 = \left(\frac{b}{b_{\text{eff}}}\right)^2$$

With $\sigma_{cr(b_{\text{eff})}} = f_y$ and some mathematics, we obtain:

$$\sigma_{cr(b_{\text{eff})}} = \sigma_{cr(b)} \left(\frac{b}{b_{\text{eff}}}\right)^2 \Rightarrow \sigma_{cr(b)} = f_y \left(\frac{b_{\text{eff}}}{b}\right)^2 \Rightarrow b_{\text{eff}} = b \left[ \frac{\sigma_{cr(b)}}{f_y} \right]^{1/2}$$

The reverse equation gives:

$$\frac{1}{b_{\text{eff}}} = \frac{1}{b} \left[ \frac{f_y}{\sigma_{cr(b)}} \right]^{1/2} = \frac{1}{b} \left[ \frac{12(1-\nu^2)}{k_\sigma \pi^2 E} \right] \left(\frac{b}{t}\right)^2 \left(\frac{f_y}{t}\right)^{1/2}$$

By multiplying by $b$ we obtain the ratio $b/b_{\text{eff}}$:

$$\frac{b}{b_{\text{eff}}} = \left[ \frac{f_y}{\sigma_{cr(b)}} \right]^{1/2} = \left[ \frac{12(1-\nu^2)}{k_\sigma \pi^2 E} \right] \left(\frac{b}{t}\right)^2 \left(\frac{f_y}{t}\right)^{1/2}$$

$$\frac{b}{b_{\text{eff}}} = \left[ \frac{f_y}{\sigma_{cr(b)}} \right]^{1/2} = \frac{b}{t} \left[ \frac{12(1-\nu^2)}{k_\sigma \pi^2 E} f_y \right]^{1/2}$$
How to determine the critical slenderness

From the ratio \( b / b_{\text{eff}} \), we are looking for \( b_{\text{eff}} \):

\[
b_{\text{eff}} = b \sqrt{\frac{\sigma_{cr(b)}}{f_y}} = b \sqrt{k_\sigma \frac{\pi^2 E}{12(1 - \nu^2)}} \left( \frac{t}{b_{\text{eff}}} \right)^2 \left( \frac{1}{f_y} \right)
\]

With: \( \sigma_{cr} = k_\sigma \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{b} \right)^2 \)

We obtain the Eurocode formula of the critical slenderness:

\[
\bar{\lambda}_p = \frac{b}{b_{\text{eff}}} = \left[ \frac{f_y}{\sigma_{cr(b)}} \right]^{1/2} = \frac{b}{t} \left[ \frac{12(1 - \nu^2)}{k_\sigma \pi^2 E} f_y \right]^{1/2} = 1.051868492 \left( \frac{b}{t} \right) \sqrt{\frac{f_y}{E k_\sigma}}
\]

With \( E = 210,000 \) MPa and \( \nu = 0.3 \).
**Critical slenderness**

We define:

\[ \varepsilon = \sqrt{\frac{235}{f_y}} \]

\[ f_y \times \varepsilon^2 = 235 \quad \Rightarrow \quad f_y = \frac{235}{\varepsilon^2} \]

We introduce this result in the slenderness ratio calculated at the previous step:

\[ \bar{\lambda}_p = \frac{b}{b_{eff}} = \left[ \frac{f_y}{\sigma_{cr(b)}} \right]^{1/2} = \frac{b}{t} \left[ \frac{12(1-v^2)}{k_\sigma \pi^2 E} f_y \right]^{1/2} = 1.051868492 \left( \frac{b}{t} \right) \sqrt{\frac{f_y}{E k_\sigma}} \]

We obtain:

\[ \bar{\lambda}_p = \frac{b}{b_{eff}} = 1.051868492 \left( \frac{b}{t} \right) \sqrt{\frac{235}{ \varepsilon^2 E k_\sigma}} \]

\[ \bar{\lambda}_p = \frac{b}{b_{eff}} = 1.051868492 \left( \frac{b}{t} \right) \times 0.033452169 \sqrt{\frac{1}{k_\sigma}} \]

With \( E = 210000 \), MPa and \( v = 0.3 \)

\[ \bar{\lambda}_p = \frac{b}{b_{eff}} = \frac{\left( \frac{b}{t} \right)}{28.41935846 \varepsilon \sqrt{k_\sigma}} \]

The final Eurocode formula of the critical slenderness
How to determine the reduction factor ($\rho$) ?

According to Von Karman (1910),
The reduction factor $\rho$ may be taken as follows:

When $\lambda_p \leq 1$ : $\rho = 1$

When $\lambda_p > 1$ : $\rho = \frac{1}{\lambda_p}$

According to Winter (1947),
The reduction factor $\rho$ may be taken as follows:

$$\frac{b_{eff}}{b} = \frac{\sigma_{L(b)}}{f_y} = \left(1 - \frac{0.22}{\lambda_p}\right) \frac{1}{\lambda_p} \leq 1$$
Finally after several testing calibrations we obtain, at the end, the following formula:

\[(\sigma_{cr})_{eff} = \sigma_{cr} \left( \frac{\bar{b}}{b_{eff}} \right)^2 = f_y \quad \frac{\bar{b}}{b_{eff}} = \rho = \sqrt{\frac{\sigma_{cr}}{f_y}}\]

where \(\rho\) is the reduction factor for plate buckling.
The effective width for internal compression elements

At the end, the following table has to be applied in compliance with the EN 1993-1-5

<table>
<thead>
<tr>
<th>Stress distribution (compression positive)</th>
<th>Effective width $b_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$</td>
<td>$\psi = 1$: $b_{\text{eff}} = \rho b_{e1}$ $b_{e1} = 0.5$ $b_{\text{eff}}$ $b_{e2} = 0.5$ $b_{\text{eff}}$</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>$1 &gt; \psi \geq 0$: $b_{\text{eff}} = \rho b$ $b_{e1} = 0.2$ $b_{\text{eff}}$ $b_{e2} = b_{\text{eff}} - b_{e1}$</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>$\psi &lt; 0$: $b_{\text{eff}} = \rho b_{c} = \rho b / (1-\psi)$ $b_{e1} = 0.4$ $b_{\text{eff}}$ $b_{e2} = 0.6$ $b_{\text{eff}}$</td>
</tr>
</tbody>
</table>

Wrinkler formula if $\psi = 1$

$$\rho = \frac{\lambda_p - 0.055(3 + \psi)}{\lambda_p^2} \leq 1$$

$$\lambda_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{b/t}{28.4\varepsilon\sqrt{k_{\sigma}}}$$

$\psi$ is the stress ratio determined in accordance with 4.4(3) and 4.4(4)

$b$ is the appropriate width as follows (for definitions, see Table 5.2 of EN 1993-1-1)

- $b_w$ for webs;
- $b$ for internal flange elements (except RHS);
- $b - 3t$ for flanges of RHS;
- $c$ for outstand flanges;
- $h$ for equal-leg angles;
- $h$ for unequal-leg angles;

$k_{\sigma}$ is the buckling factor corresponding to the stress ratio $\psi$ and boundary conditions. For long plates $k_{\sigma}$ is given in Table 4.1 or Table 4.2 as appropriate;

$t$ is the thickness;

$\sigma_{cr}$ is the elastic critical plate buckling stress see Annex A.1(2).

Uniform compression of the considered flange

Source: EN 1993-1-5
Procedure to calculate $b_{eff}$ (Internal compression elements)

$$b_p = b - 2g_r$$

$$g_r = \bar{r}_m \left( \tan \left( \frac{\phi}{2} \right) - \sin \left( \frac{\phi}{2} \right) \right)$$

$$\bar{b} = b_p$$

$$\varepsilon = \frac{\sqrt{235}}{f_y}$$

$$\psi = \frac{\sigma_2}{\sigma_1}$$

<table>
<thead>
<tr>
<th>$\psi$</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling coefficient $k_\sigma$</td>
<td>4.0</td>
</tr>
</tbody>
</table>

$$\tilde{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}}{t}$$

$$\tilde{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}}{t}$$

$$\rho = 1 \quad \text{for} \quad \tilde{\lambda}_p \leq 0.5 + \sqrt{0.085 - 0.055\psi}$$

$$\rho = \frac{\tilde{\lambda}_p - 0.055(3 + \psi)}{\tilde{\lambda}_p^2} \leq 1 \quad \text{for} \quad \tilde{\lambda}_p > 0.5 + \sqrt{0.085 - 0.055\psi}$$

$$A_{eff} = b_{eff} t \quad A_c = b \cdot t$$

$$A_{c,eff} = \rho A_c$$
### The effective width for outstand compression elements

**Oustand compression elements**

<table>
<thead>
<tr>
<th>Stress distribution (compression positive)</th>
<th>Effective width $b_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_2$ $\sigma_1$ $c$</td>
<td>$b_{\text{eff}} = \rho \ c$</td>
</tr>
<tr>
<td>$\psi &lt; 0$: $b_{\text{eff}} = \rho \ b_c = \rho \ c / (1 - \psi)$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\psi = \sigma_2 / \sigma_1$</th>
<th>1</th>
<th>0</th>
<th>-1</th>
<th>$1 \geq \psi \geq -3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling factor $k_\sigma$</td>
<td>0.43</td>
<td>0.57</td>
<td>0.85</td>
<td>0.57 - 0.21 $\psi$ + 0.07$\psi^2$</td>
</tr>
</tbody>
</table>

| $\sigma_1$ $\sigma_2$ $c$ | $b_{\text{eff}} = \rho \ c$ |
| $\psi < 0$: $b_{\text{eff}} = \rho \ b_c = \rho \ c / (1 - \psi)$ |

<table>
<thead>
<tr>
<th>$\psi = \sigma_2 / \sigma_1$</th>
<th>1</th>
<th>$1 &gt; \psi &gt; 0$</th>
<th>0</th>
<th>$0 &gt; \psi &gt; -1$</th>
<th>-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling factor $k_\sigma$</td>
<td>0.43</td>
<td>$0.578 / (\psi + 0.34)$</td>
<td>1.70</td>
<td>$1.7 - 5\psi + 17.1\psi^2$</td>
<td>23.8</td>
</tr>
</tbody>
</table>

$$\rho = \frac{\overline{\lambda}_p - 0.188}{\overline{\lambda}_p^2} \leq 1$$

$$\overline{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{b/t}{28.4\varepsilon \sqrt{k_\sigma}}$$

- $\psi$ is the stress ratio determined in accordance with 4.4(3) and 4.4(4)
- $b$ is the appropriate width as follows (for definitions, see Table 5.2 of EN 1993-1-1)
  - $b_w$ for webs;
  - $b$ for internal flange elements (except RHS);
  - $b - 3 \ t$ for flanges of RHS;
  - $c$ for outstand flanges;
  - $h$ for equal-leg angles;
  - $h$ for unequal-leg angles;
- $k_\sigma$ is the buckling factor corresponding to the stress ratio $\psi$ and boundary conditions. For long plates $k_\sigma$ is:
  - given in Table 4.1 or Table 4.2 as appropriate;
  - $t$ is the thickness;
- $\sigma_{cr}$ is the elastic critical plate buckling stress see Annex A.1(2).

**Source:** EN 1993-1-5
Procedure to calculate $b_{\text{eff}}$ (outstand compression elements)

$$b_p = b - 2g_r$$

$$g_r = r_m \left( \tan \left( \frac{\phi}{2} \right) - \sin \left( \frac{\phi}{2} \right) \right)$$

$$b = b_p$$

$$\varepsilon = \frac{\sqrt{235}}{f_Y}$$

$$\psi = \frac{\sigma_2}{\sigma_1}$$

Buckling coefficient $k_\sigma = 0.43$

$$\lambda_p = \frac{f_Y}{\sqrt{\sigma_{cr}}} = \frac{b/t}{28.4\varepsilon \sqrt{k_\sigma}}$$

$$\rho = 1.0 \quad \text{if} \quad \lambda_p \leq 0.748$$

$$\rho = \frac{\lambda_p^{0.188}}{\lambda_p^2} \leq 1.0 \quad \text{if} \quad \lambda_p > 0.748$$

$$A_{\text{eff}} = b_{\text{eff}} t \quad A_c = b \ t$$

$$A_{c,\text{eff}} = \rho A_c$$
The following method is used:

Source: EN 1993-1-3
Mechanical model to take the local web instability into account
Effective cross-sections of webs of trapezoidal profiled sheets

The Eurocode provides the following method according to the number of stiffeners along the web:

Source: EN 1993-1-3
Web effective width

In the case of a web without any stiffener:

- $e_c$ is the distance from the effective centroidal axis to the system line of the compression flange

$$s_{eff,0} = 0.76 \cdot t \cdot \sqrt{E / (\gamma_M \sigma_{com,Ed})}$$

$$s_{eff1} = s_{eff0}$$

$$s_{effn} = 1.5 \cdot s_{eff0}$$

Source: EN 1993-1-3
Analysis of the web effective width

**Method:**

1. Determine the position of $e_c$ with the effective flange in which the web is supposed to be fully effective

2. Compare $e_c / \sin \phi$ with $seff_1 + seff_n$

3. Determine whether the web is effective or not:
   - If $e_c / \sin \phi > seff_1 + seff_n$ Then the web is not fully effective
   - If $e_c / \sin \phi < seff_1 + seff_n$ Then the web is fully effective

4. If the web is not fully effective, a part of it has to be removed according to the following formulas:
   - $(e_c / \sin \phi - (seff_1 + seff_n)) \times t$ of the web (cross section)
   - $(seff_1 + (e_c / \sin \phi - (seff_1 + seff_n))/2) \times \sin \phi$ (distance from the flange in compression)

Source: EN 1993-1-3
Formula to determine the span bending resistance of the sheeting profile
Determination of the effective section modulus $W_{\text{eff}}$

<table>
<thead>
<tr>
<th></th>
<th>$l$ (mm) width</th>
<th>$y$ (mm) / top flange</th>
<th>$l x y$ (mm$^2$)</th>
<th>$l x y^2$ (mm$^4$)</th>
<th>$h$ (mm) vertically</th>
<th>$lh^2/12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sem sup eff plate</td>
<td>$b_{\text{eff}}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Radius top</td>
<td>$r_m \phi$ (rad)</td>
<td>$r_m \left(1 - \sin \phi / \phi \right)$</td>
<td>..................</td>
<td>..................</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Web totally effective</td>
<td>$s_w$</td>
<td>$h_w / 2$</td>
<td>..................</td>
<td>..................</td>
<td>$S_w \times \sin \phi$</td>
<td>..................</td>
</tr>
<tr>
<td>Radius inf</td>
<td>$r_m \phi$ (rad)</td>
<td>$h_w - r_m \left(1 - \sin \phi / \phi \right)$</td>
<td>..................</td>
<td>..................</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flange in tension</td>
<td>$b_b / 2 - g_r - f$</td>
<td>$h_w$</td>
<td>..................</td>
<td>..................</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ \Sigma \]

\[ \ldots \text{L11...} \]

\[ \ldots \text{LY11...} \]

\[ \text{R11} \]

\[ \ldots \text{l11...} \]

Position of ec from the top flange

\[ e_{c}/y = \Sigma (l x y) / \Sigma l \]

Along the web \((s_c = s_n) = \)

\[ (e_c / \sin(\phi)) - g_r \]
Determination of the effective section modulus $W_{\text{eff}}$

Correction if the web is not fully effective:

$$\Delta = \left( \frac{e_c}{\sin \phi} - g_r \right) - 2.5 S_{\text{eff,0}}$$

$$y_\Delta = \left( \frac{\Delta}{2} + s_{\text{eff,1}} + g_r \right) \times \sin \phi$$

| $I$ (mm width) | $y$ (mm) | $I \times y$ (mm$^3$) | $I \times y^2$ (mm$^3$) | $h$ (mm) | $Ih^2/12$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>sect 1/2 gross</td>
<td>L11</td>
<td>LY11</td>
<td>R11</td>
<td></td>
<td>I11</td>
</tr>
</tbody>
</table>
| $\Delta$       | $-\Delta$| $-y_\Delta$            | $-\ldots$              | $-\ldots$| $-\Delta \sin \phi$
| $\Sigma$       | $L22$    | $LY22$                 | $R22$                  |          | $I22$                  |

Position of $e_c$ from the top flange:

$$y_{\text{eff}} = \Sigma I y / \Sigma y$$

Effective Inertia / t:

$$ly^2 + lh^2/12 - Sd^2$$

$2 \times I_{\text{eff}}/t$

By half ribs:

$$\ldots \times y_{\text{eff}}$$

By wave:

$$= y_{\text{eff}}$$

Effective Inertia / wave:

$$2 \times I_{\text{eff}}/t \times t$$

$$I_{\text{xx eff}}$$
Determination of the effective section modulus $W_{\text{eff}}$

For the trapezoidal profile we have:

$$I_{\text{eff}} = \frac{I_{\text{eff,rib}}}{b_R}$$

With $b_r$ the pitch of the profile:

$$W_{\text{eff}} = \text{Min} \left( \frac{I_{\text{eff}}}{z_c}; \frac{I_{\text{eff}}}{(h_w - z_c)} \right)$$
Bending capacity

The bending resistance determined as follows:

\[ M_{c,Rd} = W_{eff} \cdot \frac{f_{yb}}{\gamma_{M0}} \]

Effective section modulus

\[ W_{eff} = \text{Min} \left( \frac{I_{eff}}{z_c} ; \frac{I_{eff}}{(h_w - z_c)} \right) \]

Source: EN 1993-1-3
Formula to determine the end support reaction and intermediate support reaction
The clear distance \( c \) from the beating length for the support reaction or local load to a free end, see figure 6.9 (EN 1993-1-3), is at least 40 mm; the cross-section satisfies the following criteria:

- \( r/t \leq 10 \ldots (6.17 \text{a}) \)
- \( h_w/t \leq 200\sin\phi \ldots (6.17\text{b}) \)
- \( 45^\circ \leq \phi \leq 90^\circ \ldots (6.17\text{c}) \)

**Where:**

- \( h_w \) is the web height between the midlines of the flanges;
- \( r \) is the internal radius of the corners;
- \( \phi \) is the angle of the web relative to the flanges [degrees].
The local transverse resistance is:

\[
R_{w,Rd} = \alpha t^2 \sqrt{f_{yb}E} \left( 1 - 0.1 \sqrt{\frac{r}{t}} \right) \left[ 0.5 + \sqrt{0.02 l_a/t} \right] (2.4 + (\phi/90)^2) / \gamma_{M1}
\]

- \( l_a \) is the effective bearing length for the relevant category, see (3);
- \( \alpha \) is the coefficient for the relevant category, see

(3) The values of \( l_a \) and \( \alpha \) should be obtained from (4) and (5) respectively. The maximum value for \( l_a = 200 \) mm. When the support is a cold-formed section with one web or round tube, for \( S_s \) should be taken a value of 10 mm. The relevant category (1 or 2) should be based on the clear distance \( e \) between the local load and the nearest support, or the clear distance \( c \) from the support reaction or local load to a free end, see figure 6.9.

(4) The value of the effective bearing length \( l_a \) should be obtained from the following:

a) For category 1:
   \[ l_a = 10 \text{mm} \] (6.19a)

b) For category 2:
   \[
   \begin{align*}
   \beta_v &\leq 0.2 && l_a = S_s \quad (6.19b) \\
   \beta_v &> 0.3 && l_a = 10 \text{mm} \quad (6.19c)
   \end{align*}
   \]

- \( 0.2 < \beta_v < 0.3 \) Interpolate linearly the value of \( l_a \) for 0.2 and 0.3

- The following formula issued of tests apply : (5) The value of the coefficient \( \alpha \) should be obtained from the following:
  
  a) for Category 1:
  - for sheeting profiles: \( \alpha = 0.075 \ldots \) (6.20a)
  - for liner trays and hat sections: \( \alpha = 0.057 \ldots \) (6.20b)

  b) for Category 2:
  - for sheeting profiles: \( \alpha = 0.15 \ldots \) (6.20c)
  - for liner trays and hat sections: \( \alpha = 0.115 \ldots \) (6.20d)
<table>
<thead>
<tr>
<th>Category 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>- reaction at end support with $c \leq 1.5 \ h_w$ clear from a free end.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>- reaction at end support with $c &gt; 1.5 \ h_w$ clear from a free end;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>- reaction at internal support.</td>
</tr>
</tbody>
</table>

Source: EN 1993-1-3
Formula to determine the interaction between support bending and support reaction
Combined bending moment and local load or support reaction

The following formula applies:

\[ \frac{M_{Ed}}{M_{c,Rd}} \leq 1 \]
\[ \frac{F_{Ed}}{R_{w,Rd}} \leq 1 \]
\[ \frac{M_{Ed}}{M_{c,Rd}} + \frac{F_{Ed}}{R_{w,Rd}} \leq 1.25 \]
Formula to determine the shear resistance of a sheeting
The design shear resistance

It should be determined from:

\[ V_{b,Rd} = \frac{h_w}{\sin \phi} \frac{t f_{bv}}{\gamma_M} \]

\[ \bar{\lambda}_w = 0.346 \frac{s_w}{t} \sqrt{\frac{f_{yb}}{E}} \]

where:
- \( f_{bv} \) is the shear strength considering buckling according to Table 6.1;
- \( h_w \) is the web height between the midlines of the flanges, see figure 5.1 (c);
- \( \phi \) is the slope of the web relative to the flanges, see figure 6.5.

<table>
<thead>
<tr>
<th>Relative web slenderness</th>
<th>Web without stiffening at the support</th>
<th>Web with stiffening at the support (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\lambda}_w \leq 0.83 )</td>
<td>0.58( f_{yb} )</td>
<td>0.58( f_{yb} )</td>
</tr>
<tr>
<td>( 0.83 &lt; \bar{\lambda}_w &lt; 1.40 )</td>
<td>0.48( f_{yb}/\bar{\lambda}_w )</td>
<td>0.48( f_{yb}/\bar{\lambda}_w )</td>
</tr>
<tr>
<td>( \bar{\lambda}_w \geq 1.40 )</td>
<td>0.67( f_{yb}/\bar{\lambda}_w^2 )</td>
<td>0.48( f_{yb}/\bar{\lambda}_w )</td>
</tr>
</tbody>
</table>

(1) Stiffening at the support, such as cleats, arranged to prevent distortion of the web and designed to resist the support reaction.

Source: EN 1993-1-3
Designing a liner tray
Conditions required by the EN 1993-1-3 to design a liner tray

\[ 0.75 \text{ mm} \leq t_{\text{nom}} \leq 1.5 \text{ mm} \]
\[ 30 \text{ mm} \leq b_f \leq 60 \text{ mm} \]
\[ 60 \text{ mm} \leq h \leq 200 \text{ mm} \]
\[ 300 \text{ mm} \leq b_u \leq 600 \text{ mm} \]
\[ l_a/b_u \leq 10 \text{ mm}^4/\text{mm} \]
\[ s_1 \leq 1000 \text{ mm} \]

Source: EN 1993-1-3
Wide flange in compression

\[ M_{C,Rd} = 0.8W_{eff,min} \times f_{yb}/\gamma_{M0} \]

\[ W_{eff,min} = I_{y,eff}/z_c \]

But:

\[ W_{eff,min} \leq I_{y,eff}/z_t \]

Source: EN 1993-1-3
Wide flange in tension

\[ b_{u,eff} = \frac{53.3 \times 10^{10} e_0^2 t^3 t_{eq}}{h L b_0^3} \]

- \( b_{u,eff} \): the overall width of the wide flange;
- \( e_0 \): the distance from the centroidal axis of the gross cross-section to the centroidal axis of the narrow flanges;
- \( h \): the overall depth of the liner tray;
- \( L \): the span of the liner tray;
- \( t_{eq} \): the equivalent thickness of the wide flange, given by:

\[ l_a \text{ the second moment of area of the wide flange, about its own centroid, see figure 10.9} \]

\[ M_{b,Rd} = 0.8 \beta_b W_{eff,com} \times f_y / \gamma_{M0} \]

But:

\[ M_{b,Rd} \leq 0.8 \beta_b W_{eff,t} \times f_y / \gamma_{M0} \] (10.21)

with:

\[ W_{eff,\text{min}} = I_{y,eff} / z_c \]

\[ W_{eff,\text{min}} \leq I_{y,eff} / z_t \]

**Limitation**

If \( s_1 \leq 300\text{mm} \)

\[ \beta_b = 1.0 \]

If \( 300\text{mm} \leq s_1 \leq 1000\text{mm} \)

\[ \beta_b = 1.15 s_1 / 2000 \]

\( S_t \): is the longitudinal spacing of fasteners supplying lateral restraint to the narrow flanges, see figure 10.9

*Source: EN 1993-1-3*
Designing a perforated sheet
The principle is to use a reduced thickness on the perforated area

(1) Perforated sheeting with the holes 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.

\[ t_{a,\text{eff}} = 1.18t \left(1 - 0.9 \frac{d}{a}\right) \]  \hspace{1cm} (10.25)

where:
\[ d \] is the diameter of the perforations;
\[ a \] is the spacing between the centres of the perforations.

\textit{NOTE:} These calculation rules tend to rather conservative values. More economical solutions might be obtained from design assisted by testing, see Section 9.
(3) Provided that \(0,2 \leq d/a \leq 0,9\) effective section properties may be calculated using Section 5, but replacing \(t\) by \(t_{\text{beff}}\) obtained from:

\[
t_{\text{beff}} = t^3 \sqrt{1,18(1 - d/a)} \quad \ldots (10.26)
\]

The resistance of a single web to local transverse forces may be calculated using 6.1.7], but replacing \(t\) by obtained from:

\[
t_{c,\text{eff}} = t \left[1 - \left(\frac{d}{a}\right)^2 \frac{s_{\text{per}}}{s_w}\right]^{3/2} \quad \ldots (10.27)
\]

where:
- \(s_{\text{per}}\) is the slant height of the perforated portion of the web;
- \(s_w\) is the total slant height of the web.
Deflection
How to take deflection into account:

In all the cases, the maximum deflection of the profile calculated with the effective inertia must stay below the maximum accepted deflection as defined by the Eurocode.

It is possible to make calculations with several sections characterized by different effective inertia.
Other cases not covered by the Eurocode EN 1993-1-3
Topics not covered by the current version of the eurocode 1993-1-3

- Decking embossment
- Outward stiffeners
- Curved profiles with and without arch effect
- Assembled profiles on support
- Corrugated profiles
- Liner trays with $s_1 > 1m$
- Perforated profiles with a square patent perforation
- Flange holed profiles
- Plank profiles

Covered by the GRISPE PROJECT

<table>
<thead>
<tr>
<th>Steel decks with embossments or stiffeners</th>
<th>Curved profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner trays</td>
<td>Assembled profiles</td>
</tr>
<tr>
<td>Corrugated sheetings</td>
<td>Perforated or holed profiles</td>
</tr>
<tr>
<td>Cladding systems</td>
<td></td>
</tr>
</tbody>
</table>

Source: All WP GRISPE
Bibliography
• See state deliverable of the art of GRISPE Project
• EN 1993-1-3 (design cold formed elements)
• EN 1993-1-5 (Design effective width of cold formed elements)
• EN 1090-1 (CE marking of structural cold formed elements)
• EN 14782 (CE marking of non structural cold formed elements)
• EN 508-1 (Tolerance of the non structural cold formed element)
• EN 1090-4 (Tolerance of the structural cold formed element)
• EN 10143 (Tolerance of the raw material, coil)
• EN 10346 (metallic coating)
• EN 10169 (organic coating)
• Review: L’enveloppe du bâtiment en acier réalisée à partir de plaques nervurées ou ondulées SNPPA
• APK - ESDEP WG 9THIN-WALLED CONSTRUCTION Lecture 9.1: Thin-Walled Members and Sheeting Figure 7 manufacturing by cold rolling
• BIM of l’Enveloppe Métallique du Bâtiment
• All Deliverables WP1 WP2 WP3 WP4 GRISPE
• Slide workshop PPA Europe 22 23 October 2015
• Slide workshop GRISPE 26 July 2016