GRISPE PLUS

VALORISATION OF KNOWLEDGE FOR SPECIFIC PROFILED STEEL SHEETS

# 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*

# Contents

# 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 :

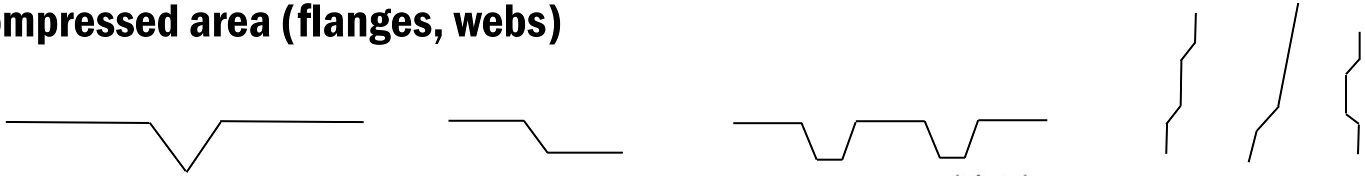
- Optimizing the material with thin metal sheet

*Source: EMB*

- Providing inertia to the geometric shape of the profiles as in the case of the shell

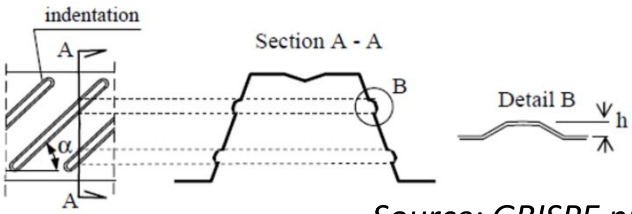
*Source: EMB*

- Adding stiffeners to avoid local instability in the compressed area (flanges, webs)



*Source: EN 1993-1-3*

- Adding embossments to facilitate the liaison concrete and steel

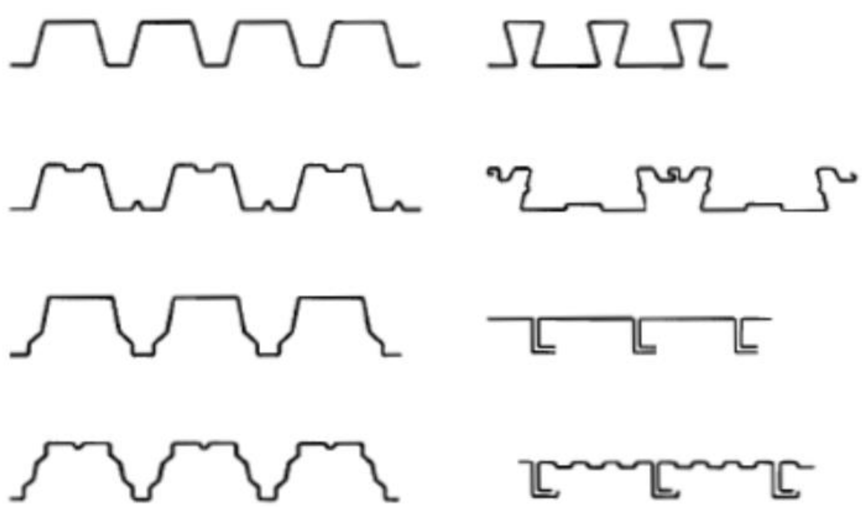



*Source: GRISPE project*

# Different types of cold formed elements

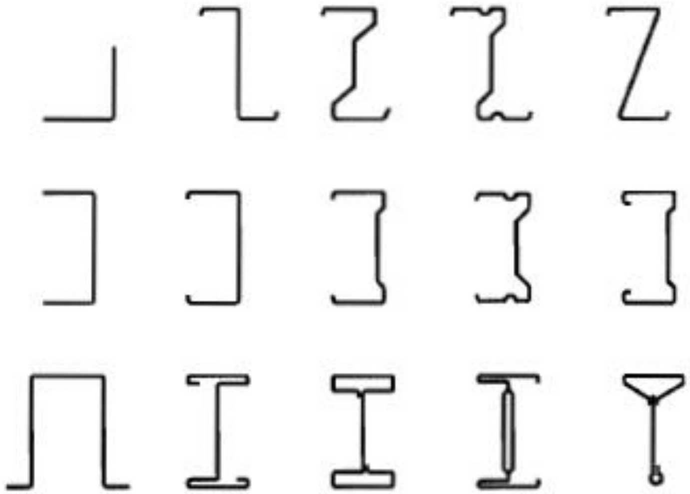
# The two main families of profiles

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



*Source: EN 1993-1-3*

- **The members :**
  **(purlin column, cladding rail)**



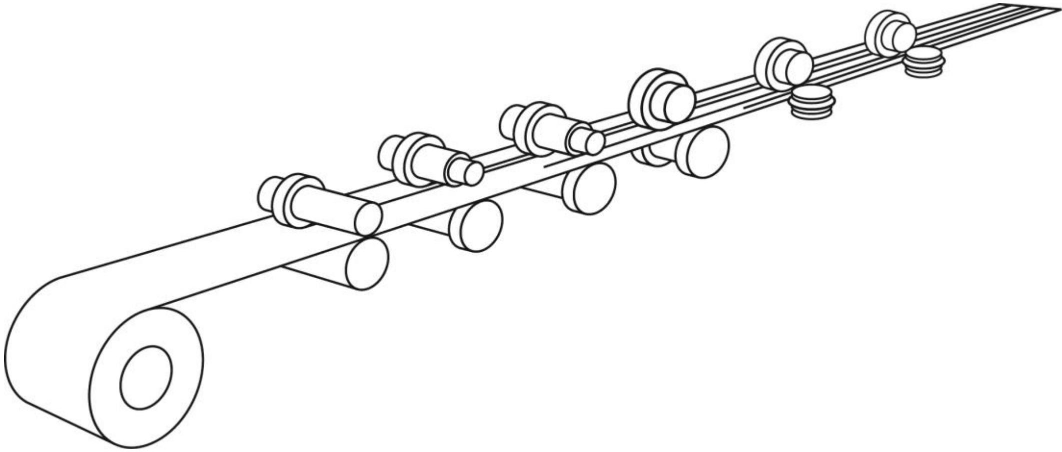
*Source: EN 1993-1-3*

# Manufacturing process of cold formed elements

# Manufacturing process of cold formed elements

- **Profiling machine**

*Source: EMB*



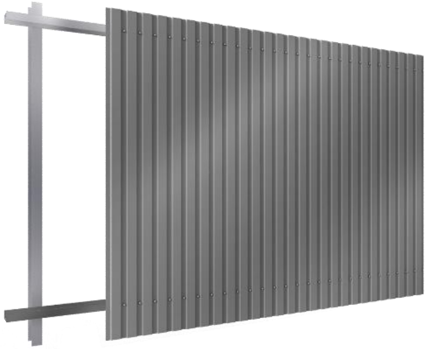
*Source: EMB*

- **Profiling rollers**

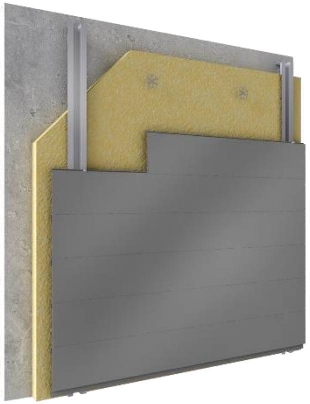
# Using cold formed elements in construction

# Using cold formed elements in construction (sheetings)

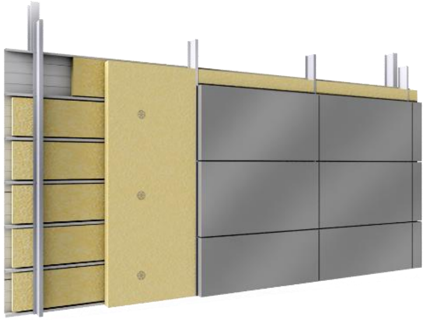
## CLADDING



Single skin system



Facade cladding

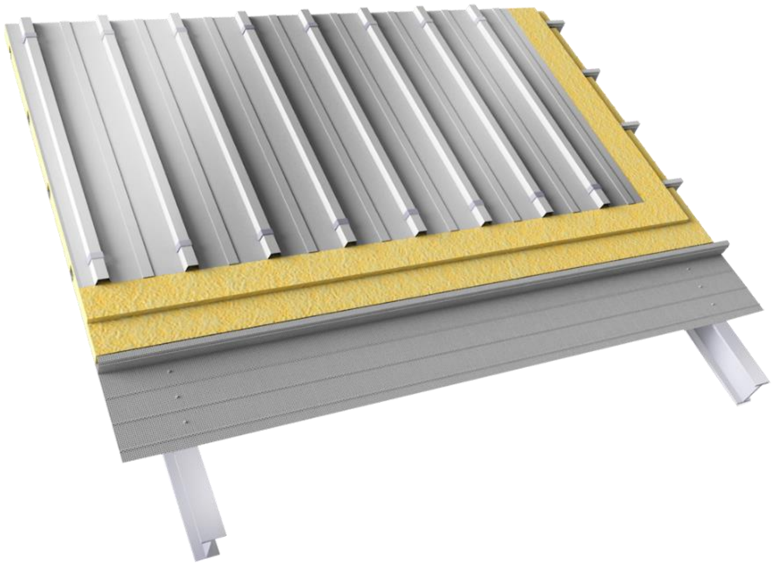


Double skin system

*Source: BIM Enveloppe métallique du bâtiment*

# Using cold formed elements in construction (sheetings)

## COVERING

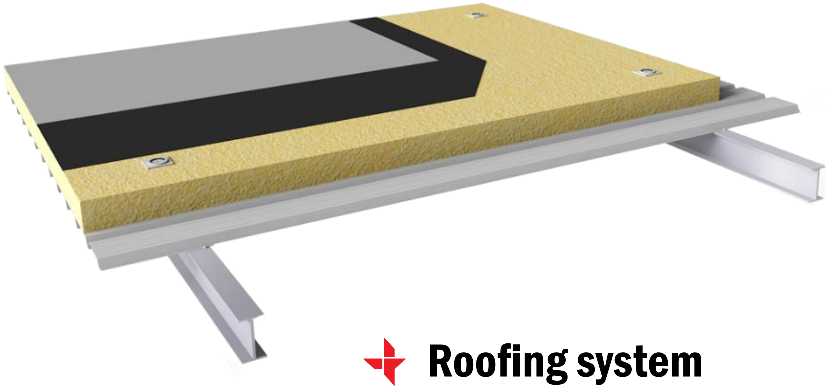


Single skin covering

Double skin covering

*Source: BIM Enveloppe métallique du bâtiment*

## ROOFING

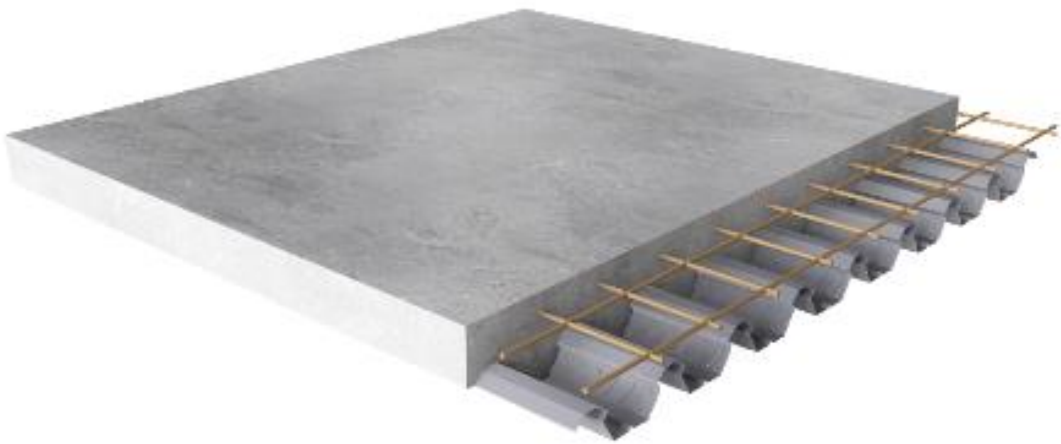


Roofing system

*Source: BIM Enveloppe métallique du bâtiment*

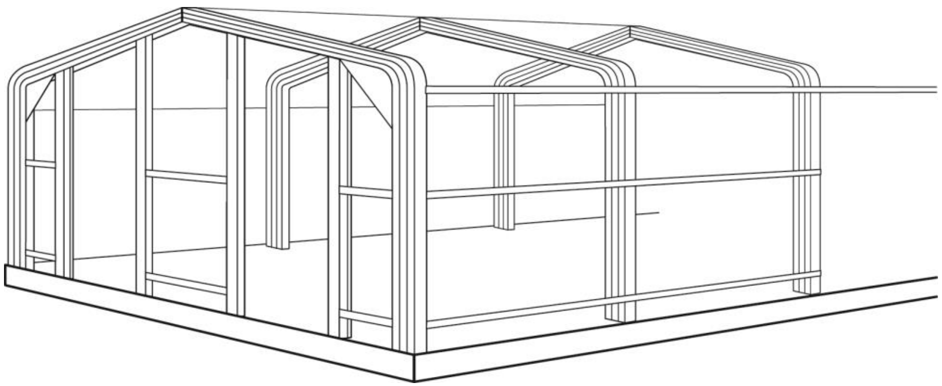
# Using cold formed elements in construction (sheeting)

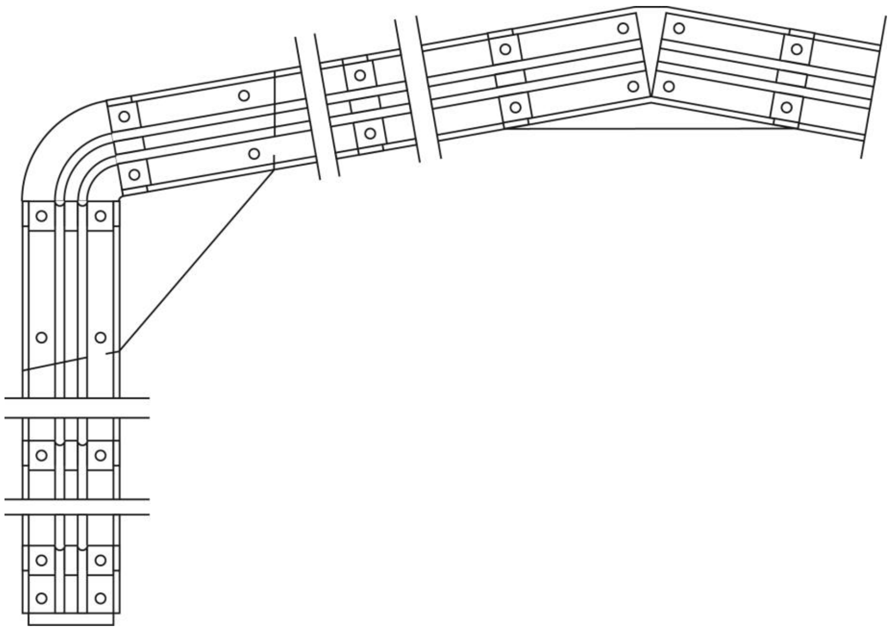
## DECKING – COMPOSITE FLOOR



*Source: BIM Enveloppe métallique du bâtiment*

## PORTAL FRAMES



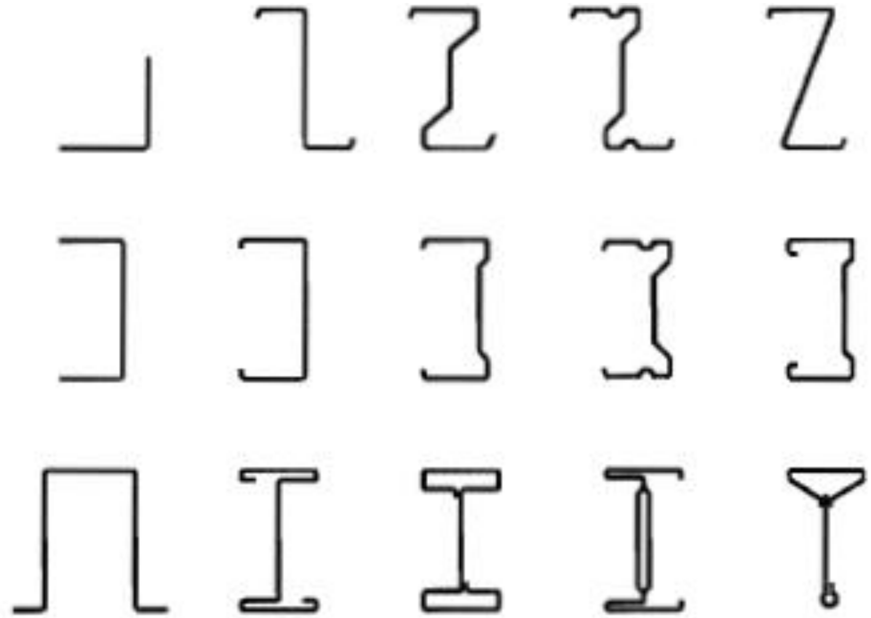


*Source: EMB*

# 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 $t_{nom}$
- EN 10346 (Metallic coating) → protection against corosion
- EN 10169+A1 (Organic Coating) → protection against corosion

# 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 (measurments in  the production phase)

For structural products → EN 1090-1

- Class I (diaphragm use)
- Class II (collaboration member/sheeting)

# Design and erection of the systems and buildings

## Designing tests and calculations :

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

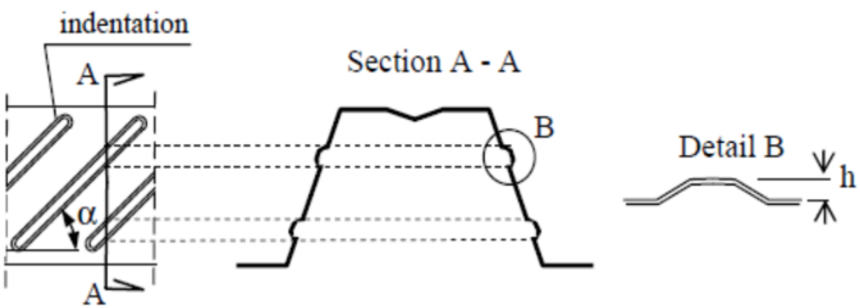
## Building erection :

- EN 1090-4 (steel products)

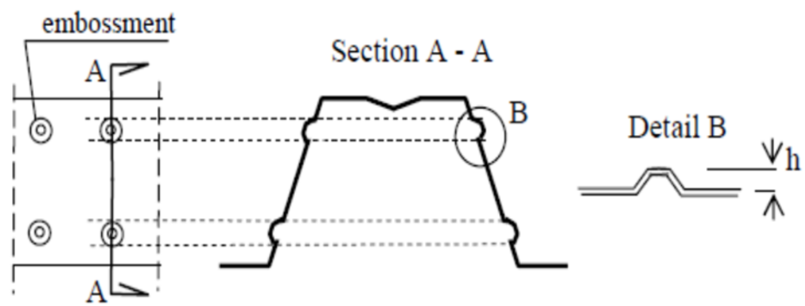
# Profiled steel sheetings covered by the GRISPE$^+$ project

# Profiles covered by the GRISPE + project

## Decking with embossments and / or indentations

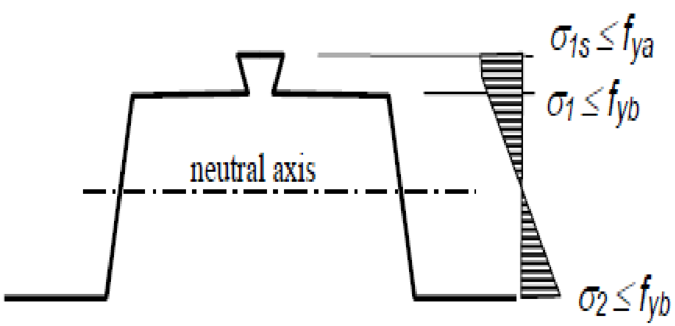



*Source: Draft amendement Eurocode*




*Source : Draft amendement Eurocode*

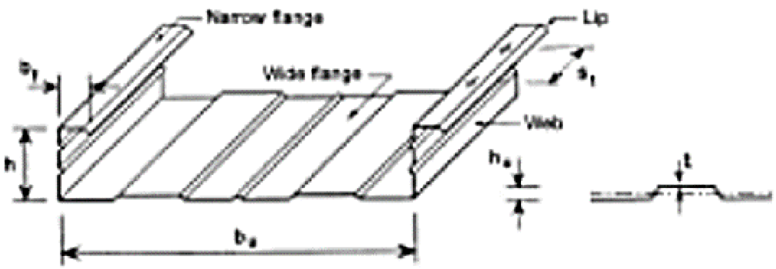
## Decking with outside stiffeners



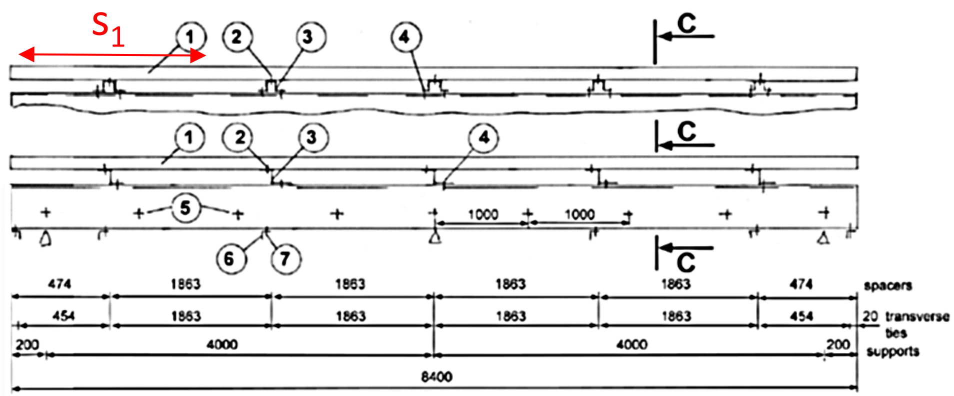

*Source: GRISPE WP1*

# Profiles covered by the GRISPE +project

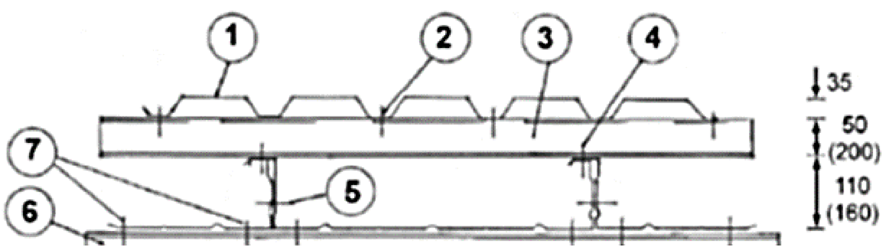
## The liner tray with $s_1$> 1m distance




*Source: EC3 1.3*



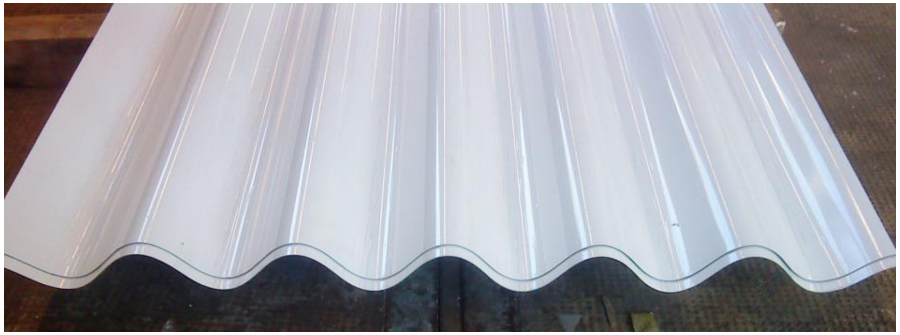

*Source: GRISPE WP2*




*Source: GRISPE WP2*

# Profiles covered by the GRISPE + project

**Corrugated profiles**



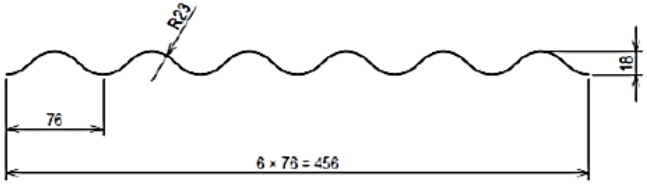



Fig (5) - Cross section of the profile 18/76

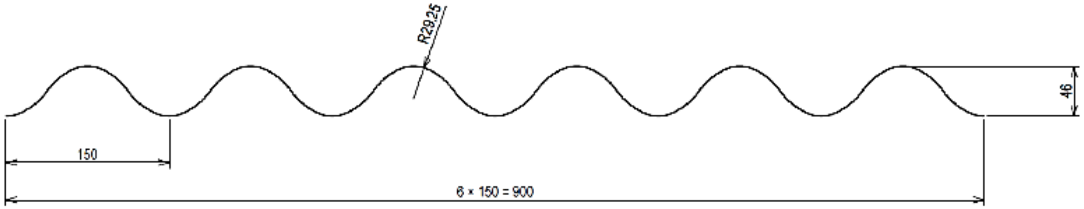
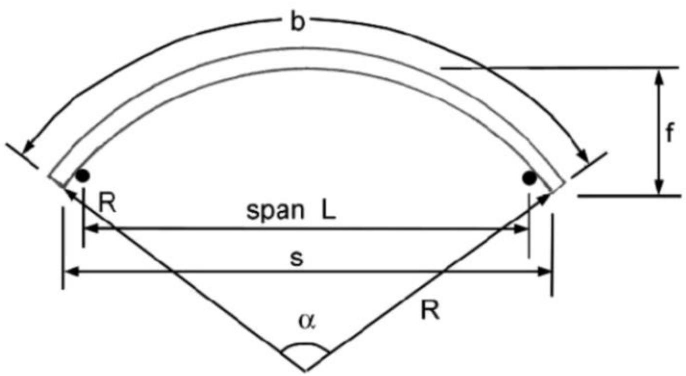



Fig (6) - Cross section of the profile 46/150

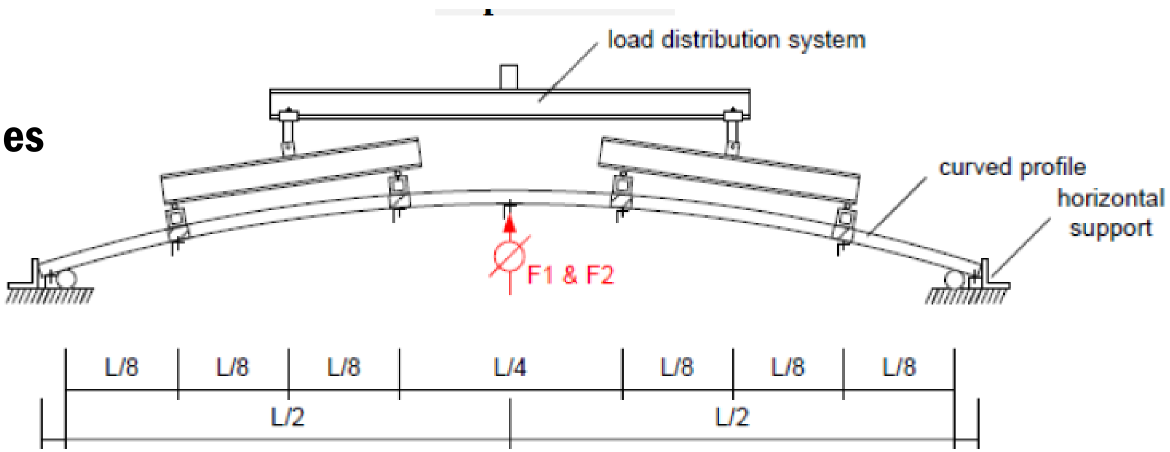
*Source: GRISPE WP2*

# Profiles covered by the GRISPE + project

**Curved profile with and without arch effect**




**Key parameters for arch profiles**

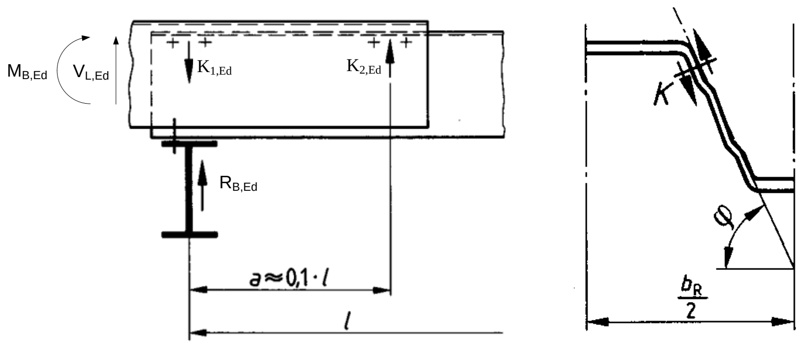



**Mechanical model for arch profiles**

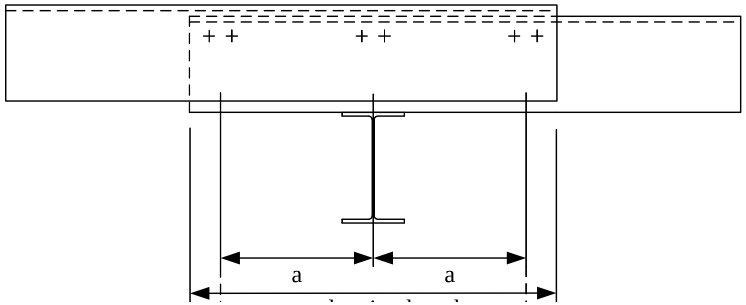
*Source: GRISPE WP2*

# Profiles covered by the GRISPE + project

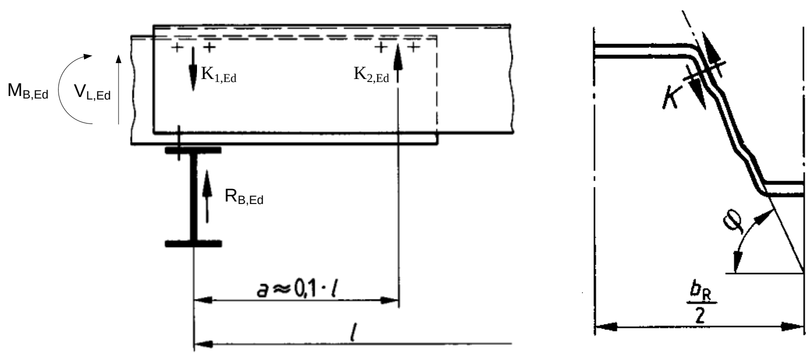
## Cantilever above profile



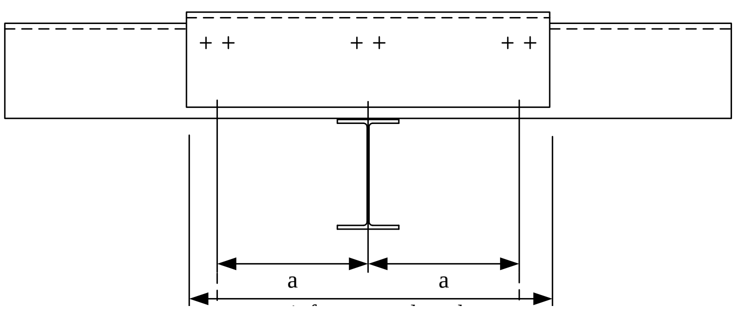

## Overlapping joints




## Cantilever underneath



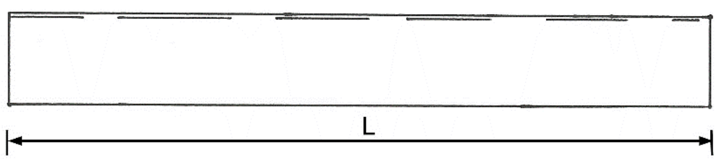

## Continuous profiles with local reinforcement



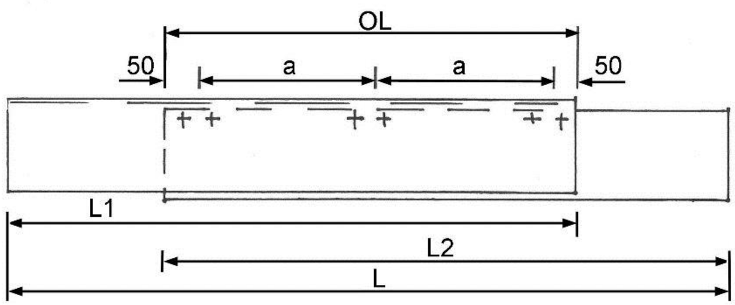

*Source: GRISPE WP2*

# Assembled profiles

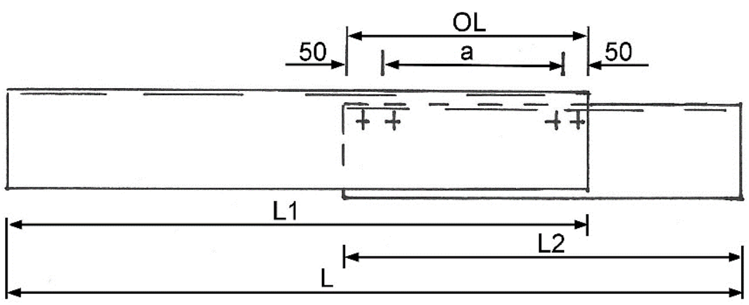
**THE TESTED ASSEMBLED PROFILES ARE:**



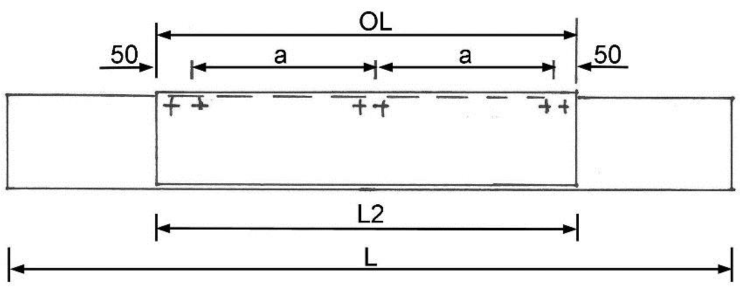

- **Continuous profiles (C)**




- **Two-sided overlapping (OL)**




- **DIN 18807 (DIN) overlapping**

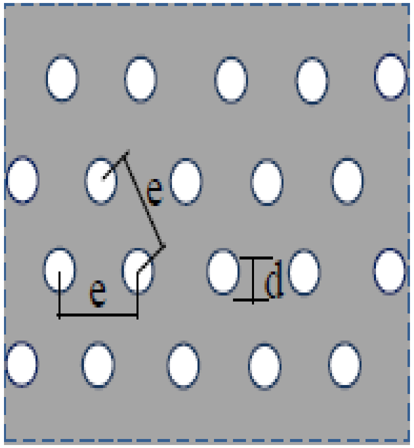



- **Continuous profiles with reinforcement (CR )**

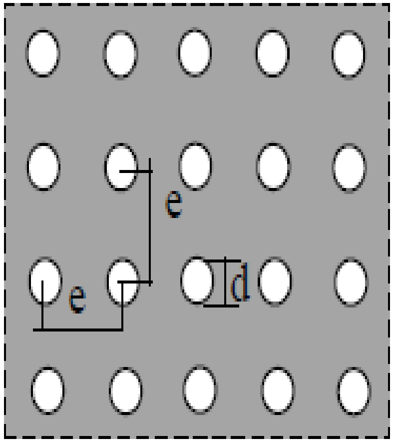
*Source: GRISPE WP2*

# Profiles covered by the GRISPE + project

**Perforated profiles**




(a)




(b)

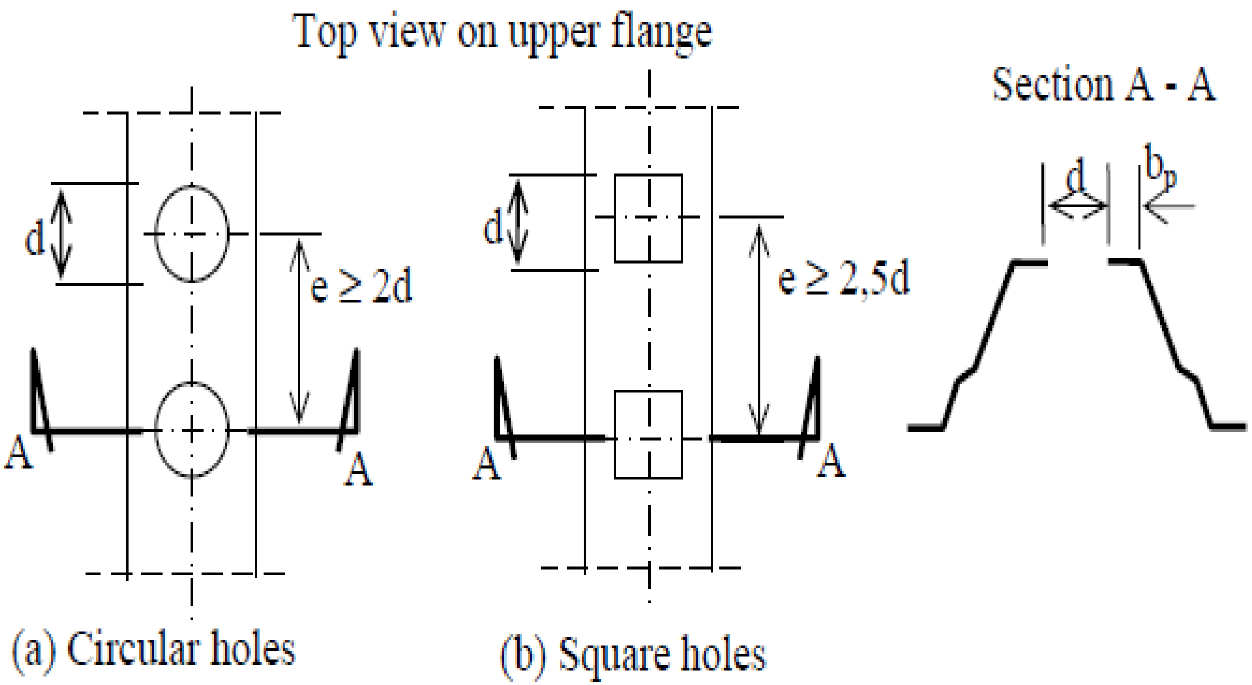
Triangular pattern (covered by the EN 1993-1-3)

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

*Source: GRISPE WP3*

# Profiles covered by the GRISPE + project

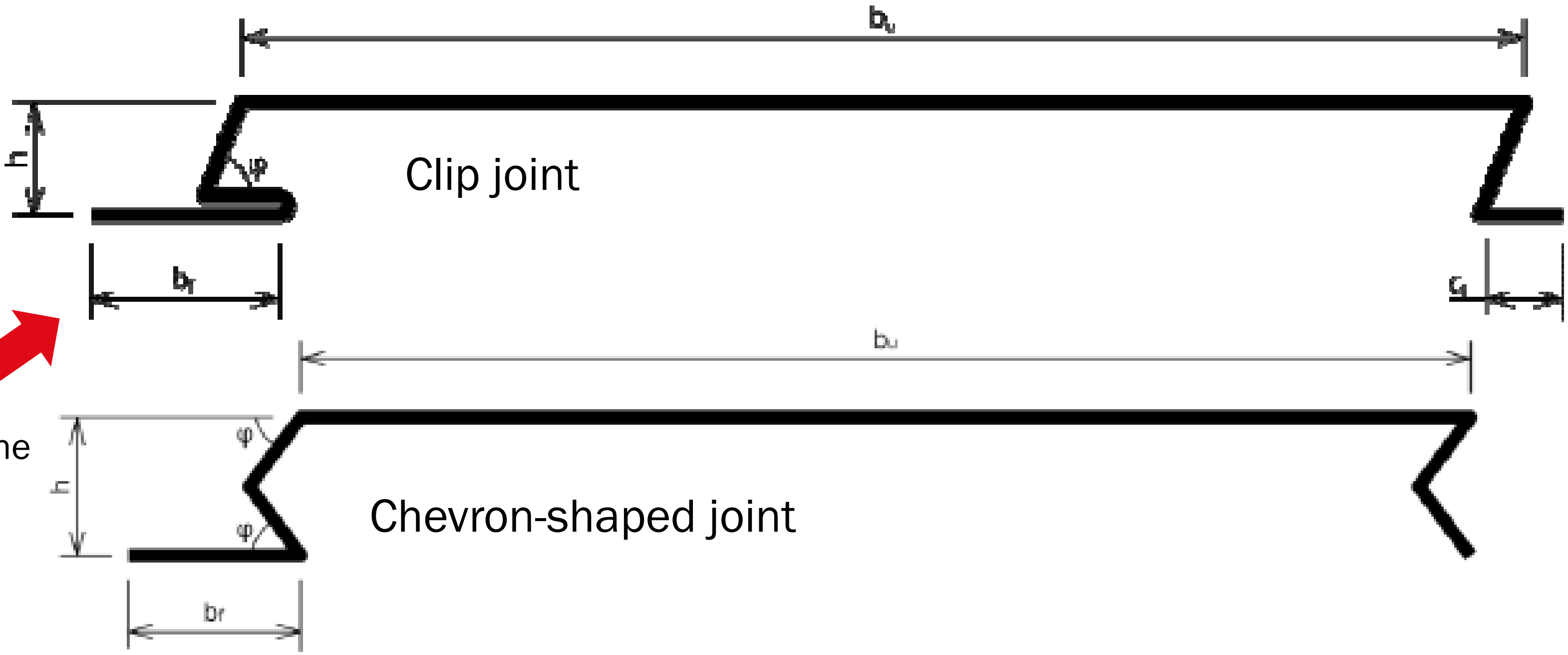
**Holed profiles**




*Source: GRISPE WP3*

# Profiles covered by the GRISPE + project

## Plank profiles



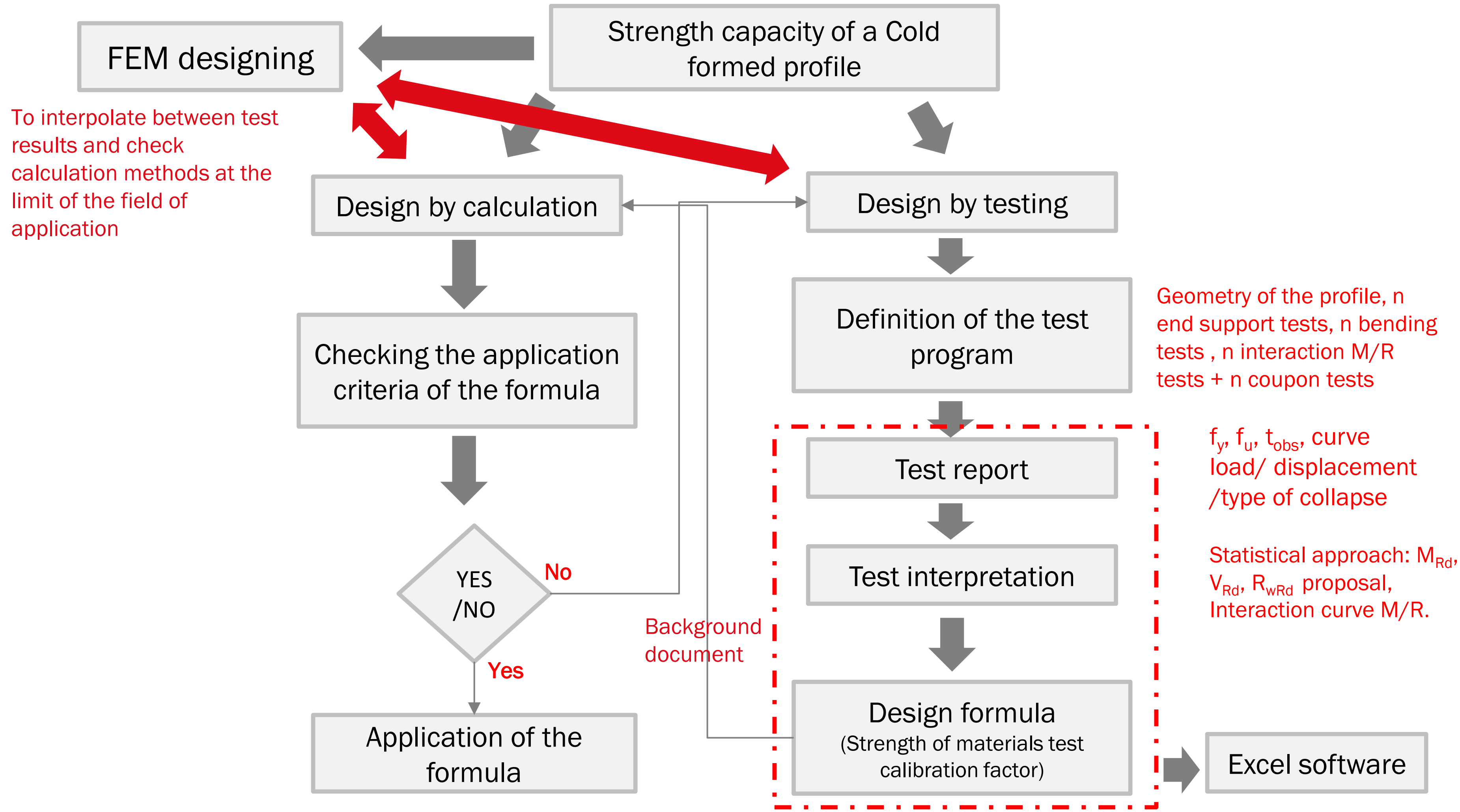

Specific failure in the assembling : dislocation

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

*Source: GRISPE WP4*

# Methods to design a cold formed element

# The logigram to study cold formed profiles

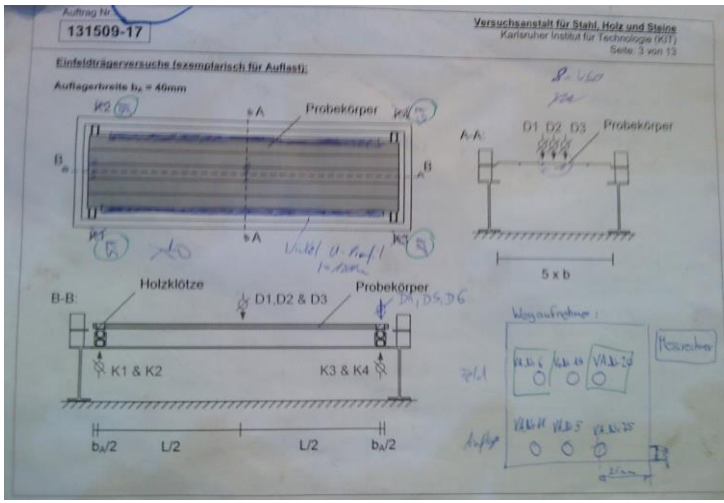


# Tests to study the cold formed sheetings

# The different tests to study the cold formed profiles:

## VACUUM CHAMBER:

### The vacuum chamber test:




Source: GRISPE WP4

### Test set-up:

Source: GRISPE WP4

The objectives of this test :

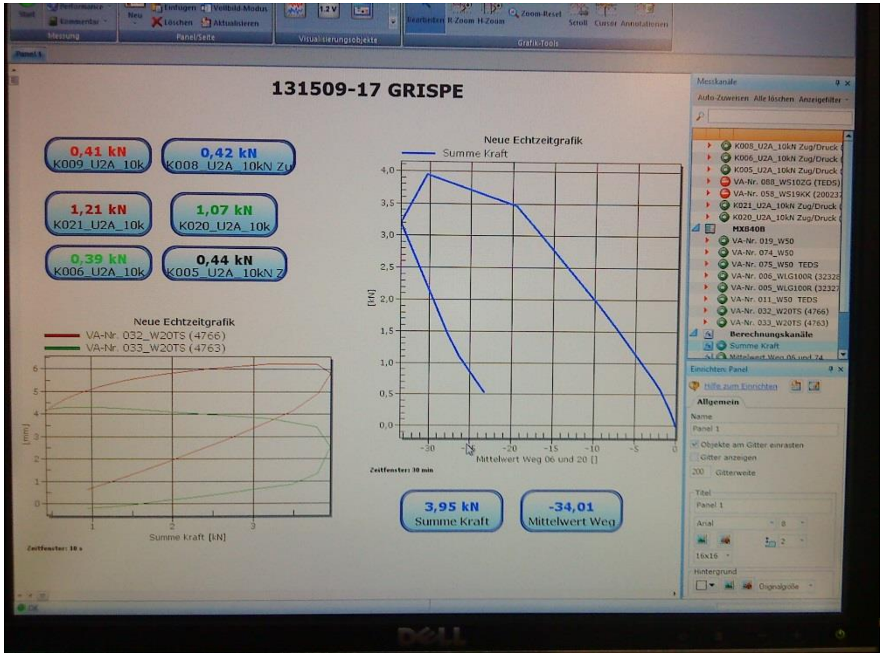
$\Rightarrow$ Effective inertia of the profile : $I_{eff}$

$\Rightarrow$ Bending capacity : $M_{c,Rd}$

# Vacuum chamber test results

## Typical associated collapses: local buckling/dislocation

### Curve load displacement




*Source: GRISPE validation deliverable D 4.7*

### 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:

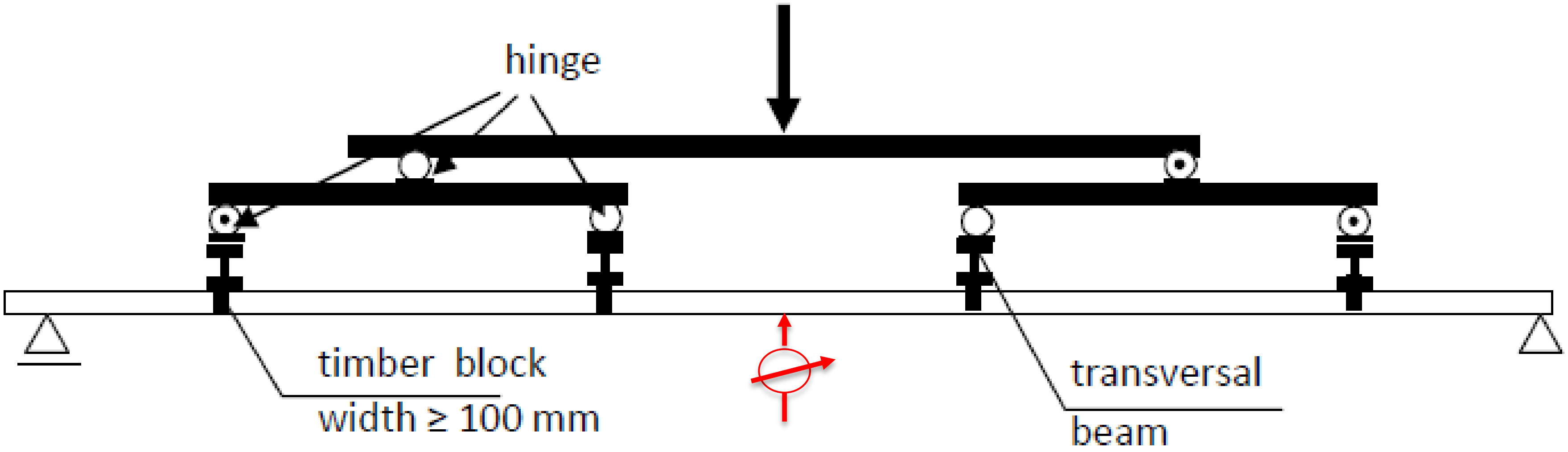
## SINGLE SPAN BENDING TEST

**The objectives of this test:**

$\Rightarrow$ Effective inertia of the profile : $I_{eff}$

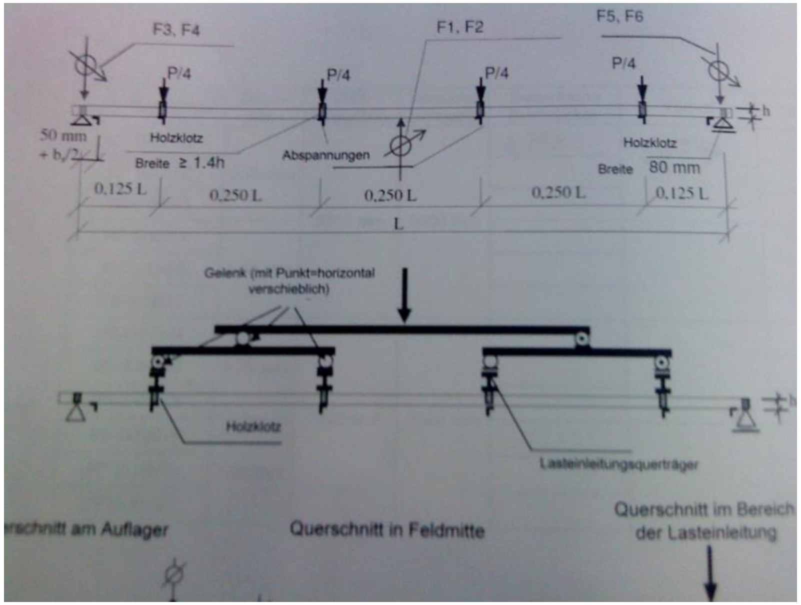
$\Rightarrow$ Bending capacity : $M_{c,Rd}$

# Typical single span bending test set up

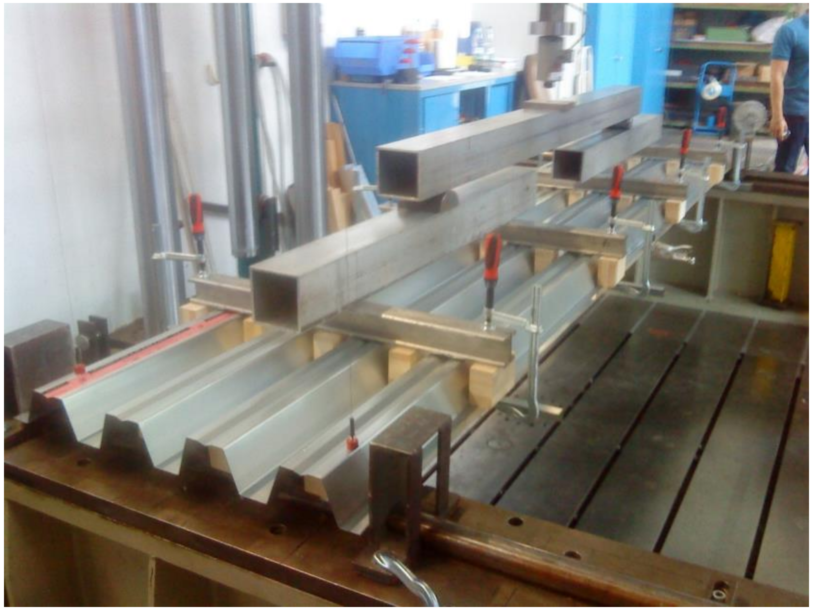



*Source: GRISPE WP2*

# Typical single span bending test set up

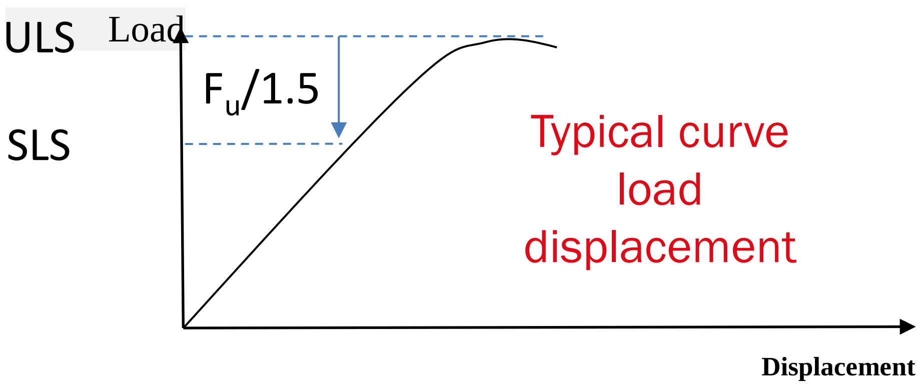



*Source: GRISPE WP1*



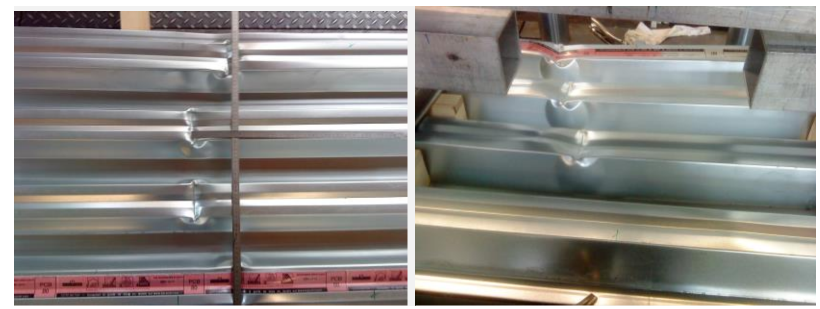
*Source: GRISPE validation deliverable D 1.8*

# Test results (case bending in single span tests)




*Source: GRISPE validation deliverable D 1.8*

- **Ex: Decking profile without embossments**



- **Ex: Decking profile with embossments**

*Source: GRISPE validation deliverable D 1.8*

# An example of test interpretation

## The WP1 example (embossment effects)

| Bending resistance | Inertia Moment |
|---|---|
| ↘ | ↘ |
| 3.5% - 10% | 1.5% -11% |

*Source: GRISPE WP1*

# The different tests to study the cold formed profiles:

## INTERMEDIATE SUPPORT TEST

**The objectives of this test:**

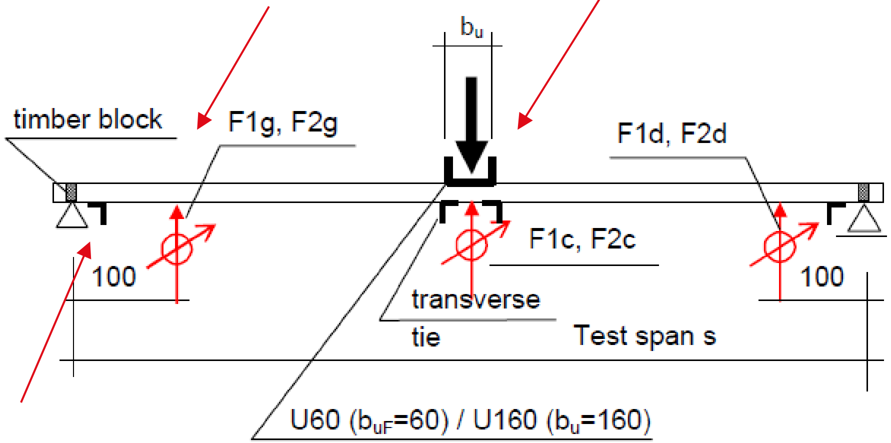
$\Rightarrow$Interaction between the bending Moment $M_{c,Rd}$ and $R_{w,Rd}$

$\Rightarrow$Reaction on the support $R_{w,Rd}$

# Typical intermediate support test set up

To calculate the rotation on the support

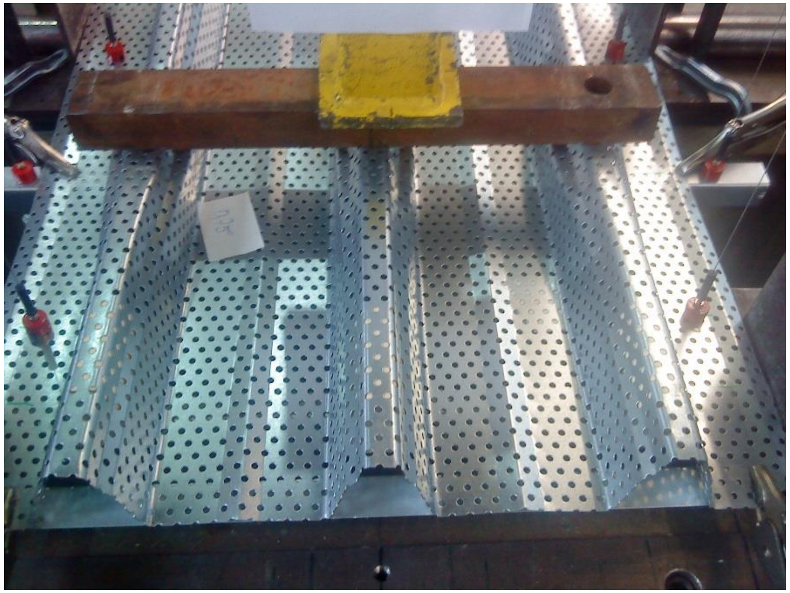
To simulate the central support




A corner to simulate the profile lateral continuity

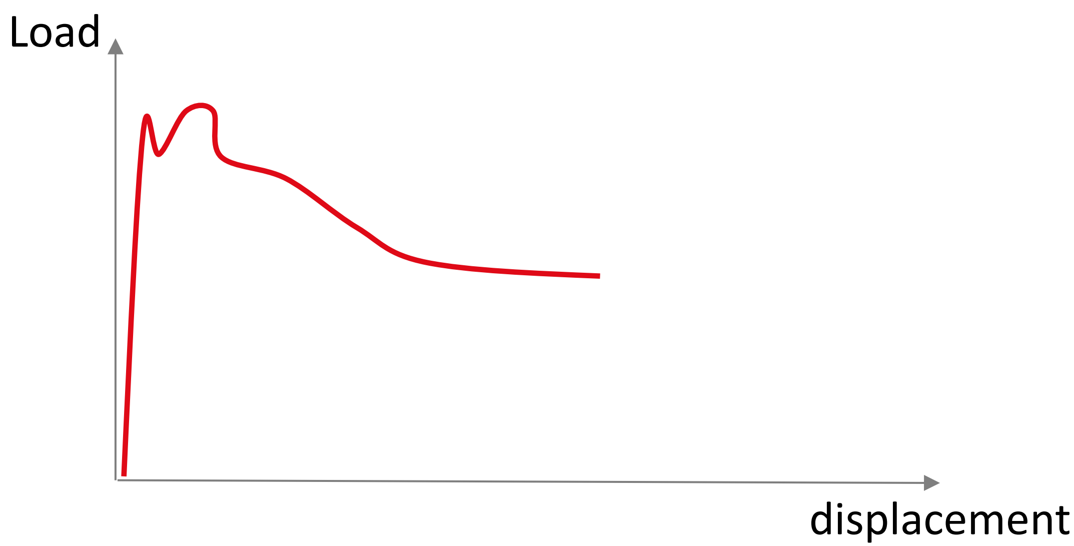
*Source: GRISPE WP3*

Eg. Total perforation trapezoidal profile



*Source: GRISPE WP3*

# Test results (intermediate support case)




*Source: GRISPE validation deliverable D 3.7*

Eg. Total perforation decking profile

*Source: GRISPE WP3*

# An example of test interpretation

## The WP3 example (square pattern perforation effect)

| | Moment – Reaction Interaction |
|---|---|
| Flange perforation | 0% - 5% |
| Web perforation | 11% - 19% |
| Total perforation | 35% - 42 % |

*Source: GRISPE WP3*

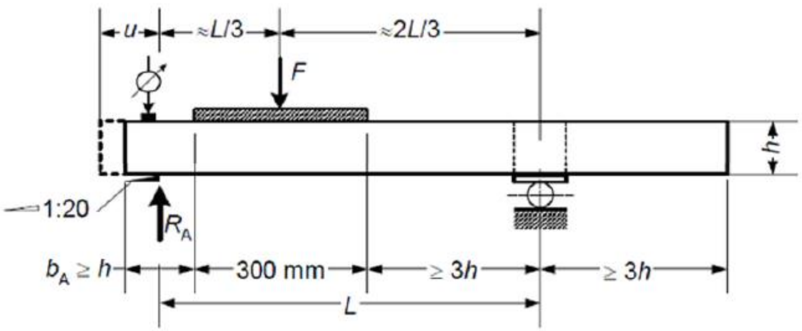
# The different tests to study the cold formed profiles:

## END SUPPORT TEST

**The objectives of this test:**

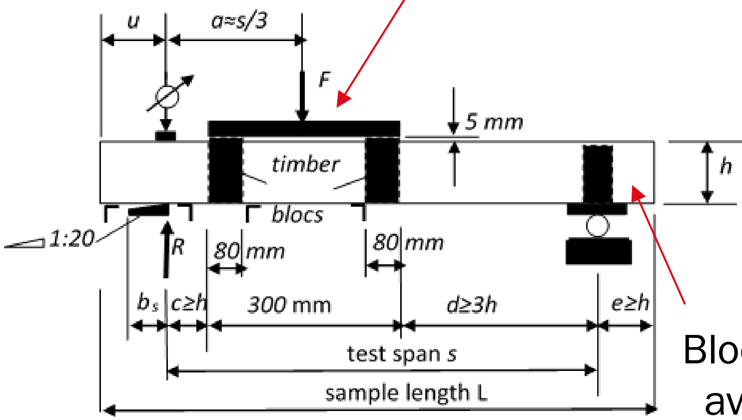
$\Rightarrow$ Capacity of the end support reaction $R_{w,Rd}$

# Typical end support test set up




*Source: EN 1993-1-3*

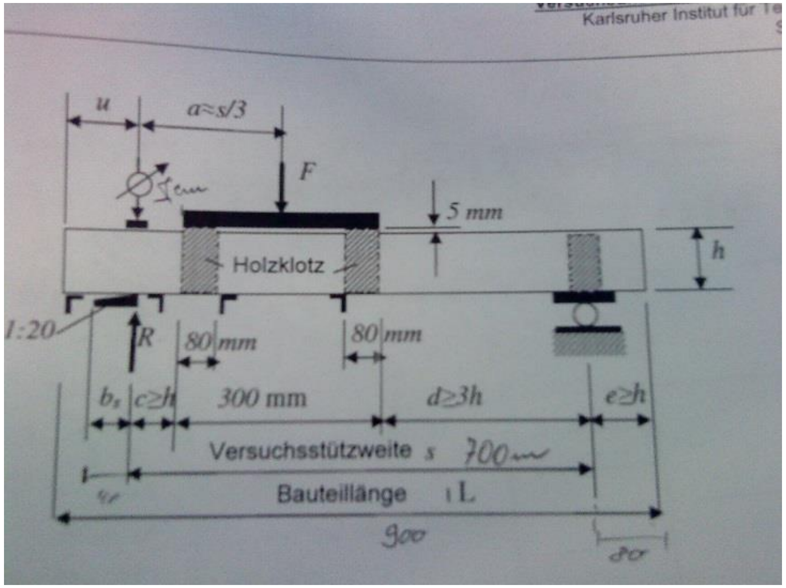
Modified set up to ensure the accurate position of the load



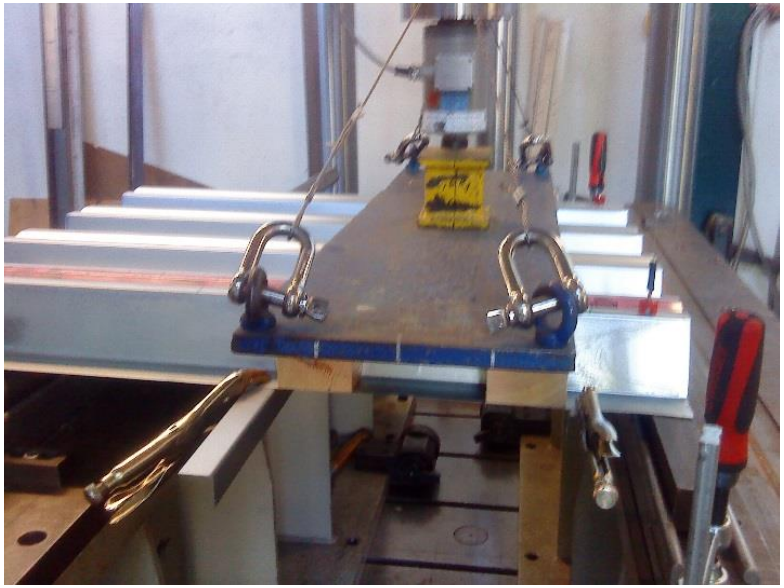

*Source: GRISPE WP2*

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

# Typical end support test set up



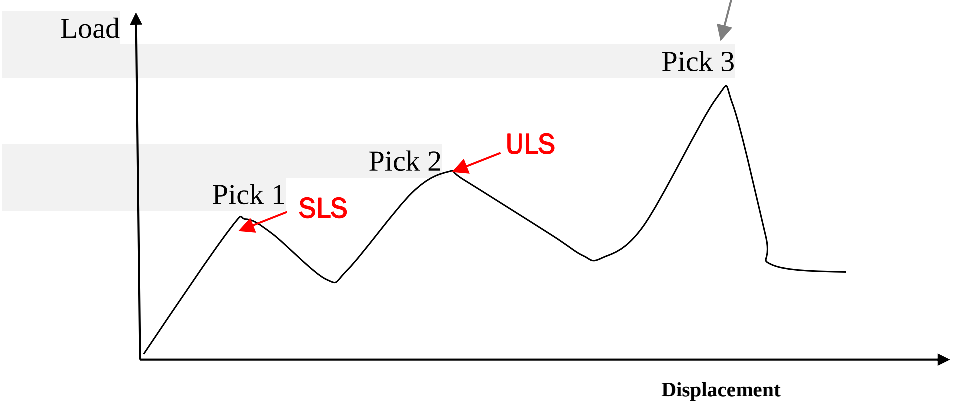

Source: GRISPE validation deliverable D 1.8

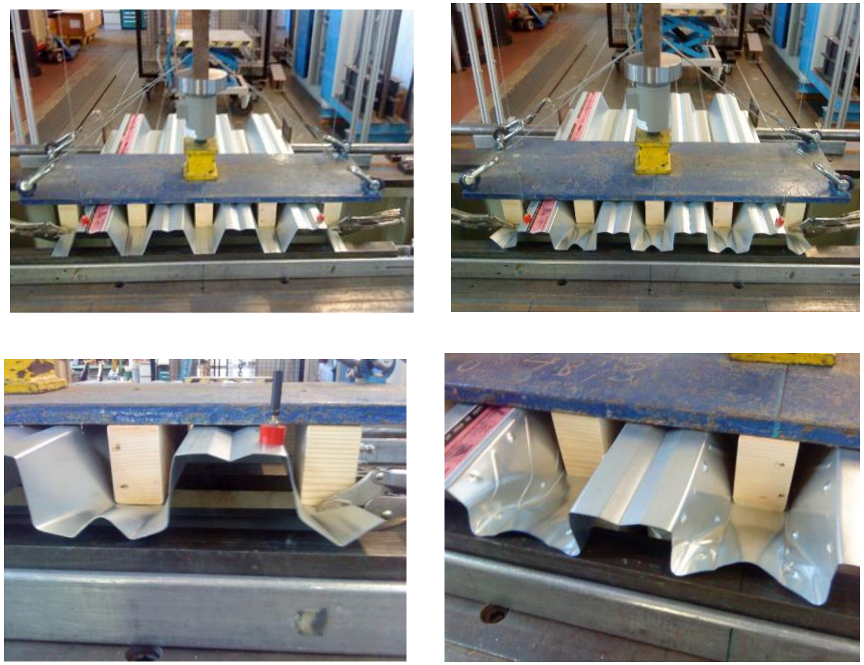


Source: GRISPE validation deliverable D 1.8

# Test results

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



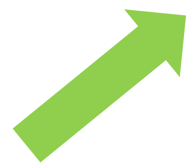



*Source: GRISPE validation deliverable D 1.8*

*Source: GRISPE validation deliverable D 1.8*

# An example of test interpretation

## The WP1 example (embossment effects)

| End support reaction |
| --- |
|  |
| 5.5% - 20 % |

*Source: GRISPE WP1*

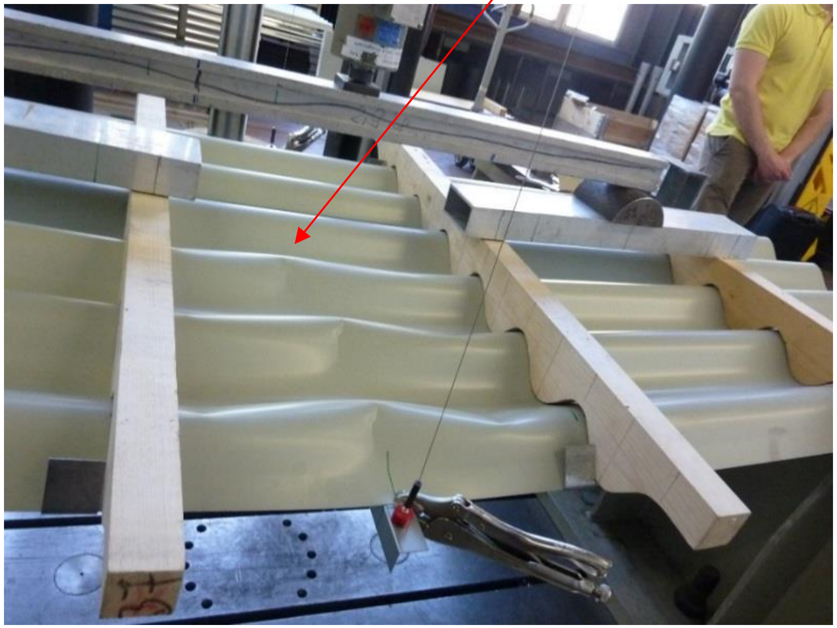
# Collapses and instabilities of cold formed elements

# Different instabilities under compression stresses

## Local buckling

Eg : Corrugated sheet
local buckling

Eg : Plank profile
local buckling



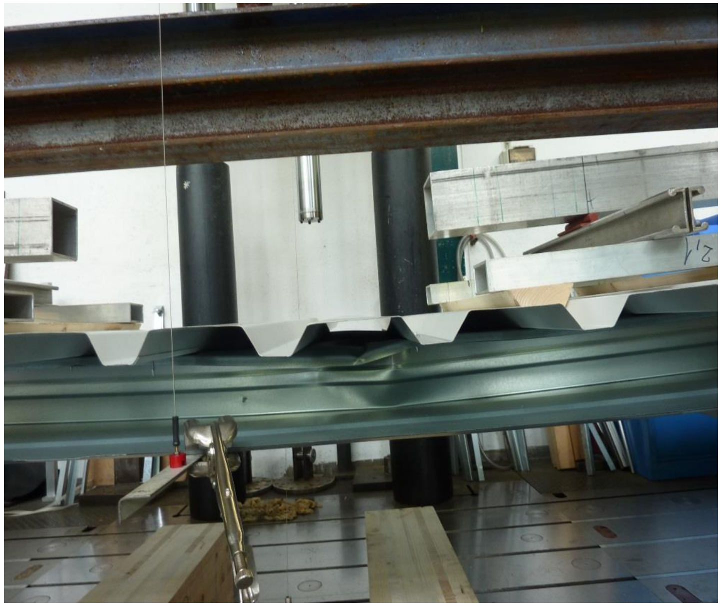
*Source: GRISPE WP2*

*Source: GRISPE WP4*

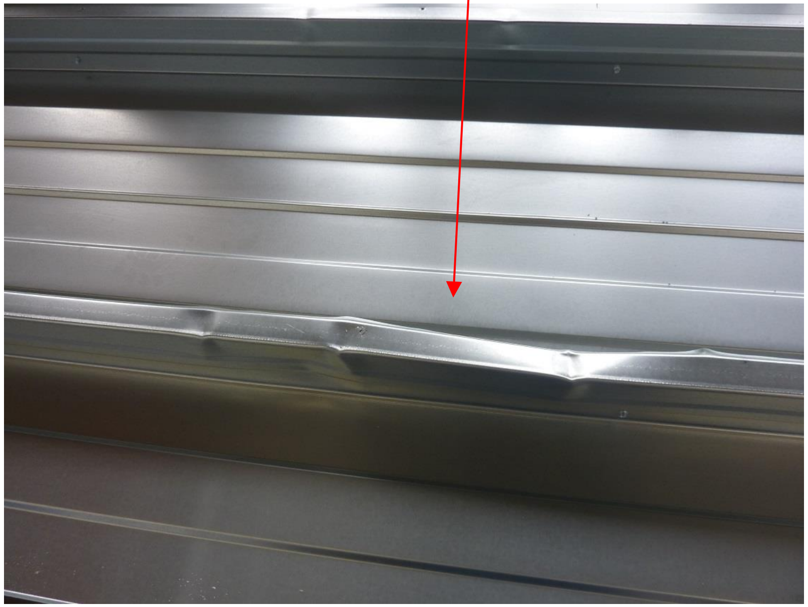
# Different instabilities under compression stresses

## Local buckling

Eg : cassette/ liner tray lateral buckling



*Source: GRISPE WP2*



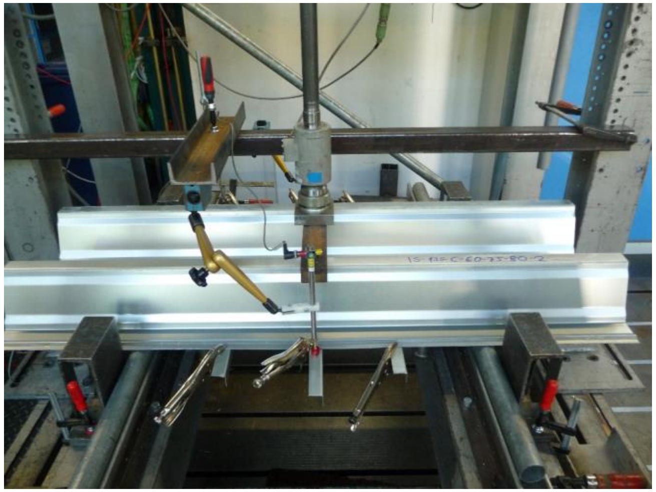
*Source: GRISPE WP2*

# Different instabilities under compression stresses

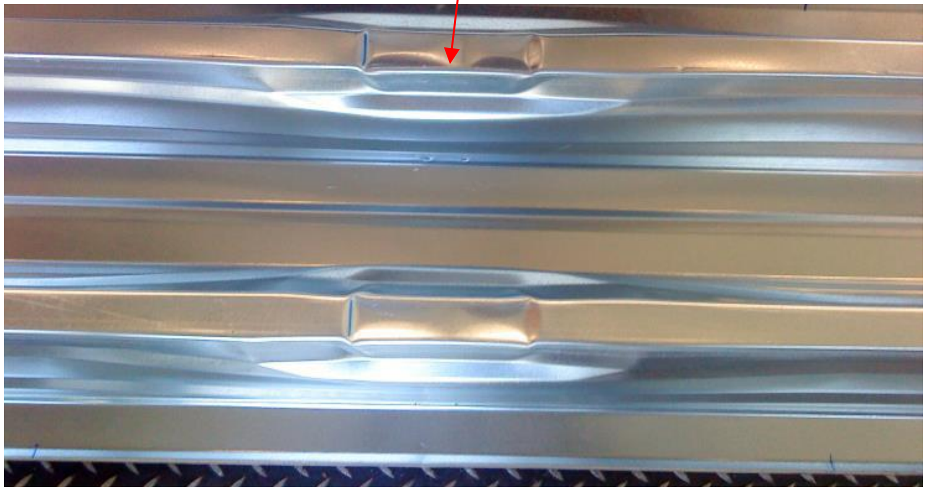
## Local buckling and local impression at an intermediate support

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

Web crippling in the compression area

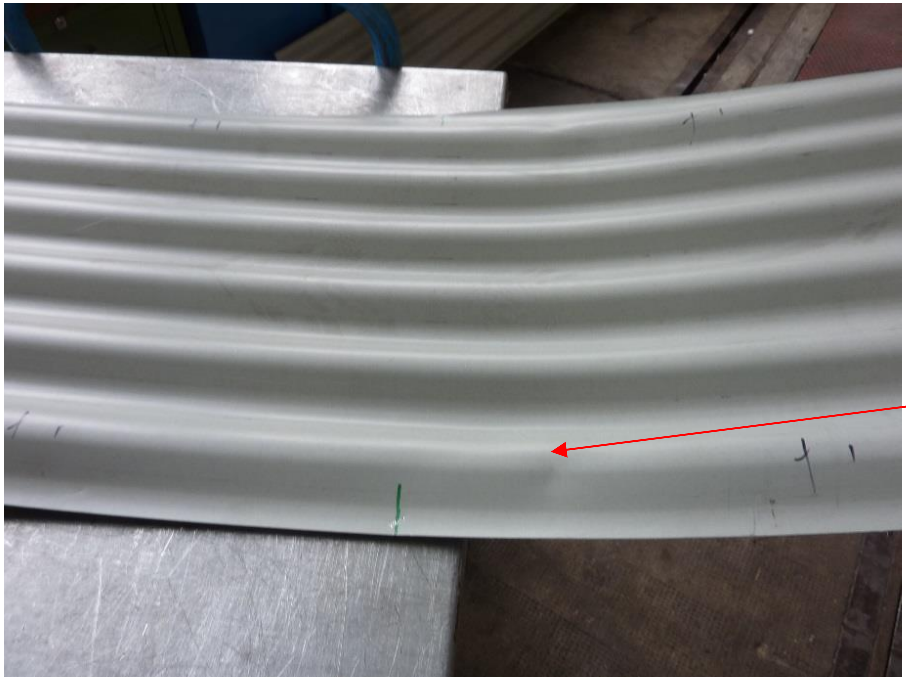
*Source: GRISPE WP2*

*Source: GRISPE WP2*

# Collapse by plastification

## Yielding

Eg : Corrugated sheet




*Source: GRISPE WP2*

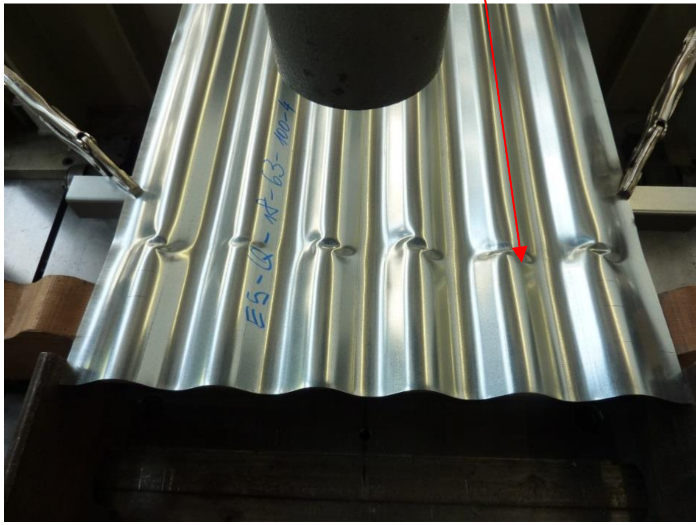
# Different instabilities under shear stresses

## Shear collapse

Eg : Corrugated sheet

*Source: GRISPE WP2*

Web crippling in the shear area

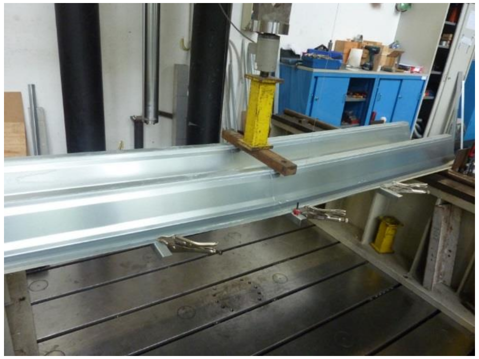


*Source: GRISPE WP2*

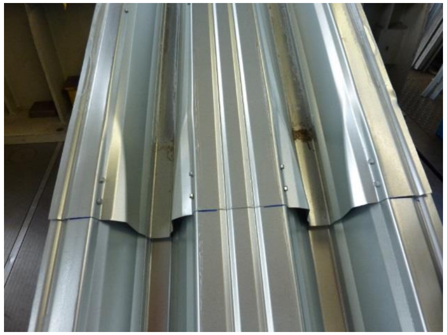
# Different instabilities under shear stresses

## Local web crushing/ web crippling

Eg : assembling continuity on a support => DIN overlapping

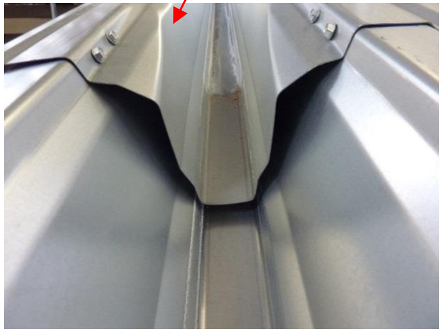


*Source: GRISPE WP2*



*Source: GRISPE WP2*

Web crippling at the overlapping area

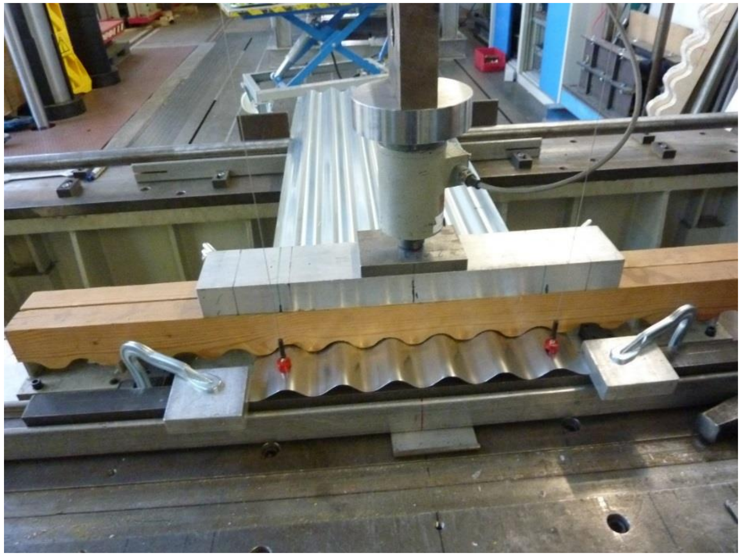


*Source: GRISPE WP2*

# Collapse at end support

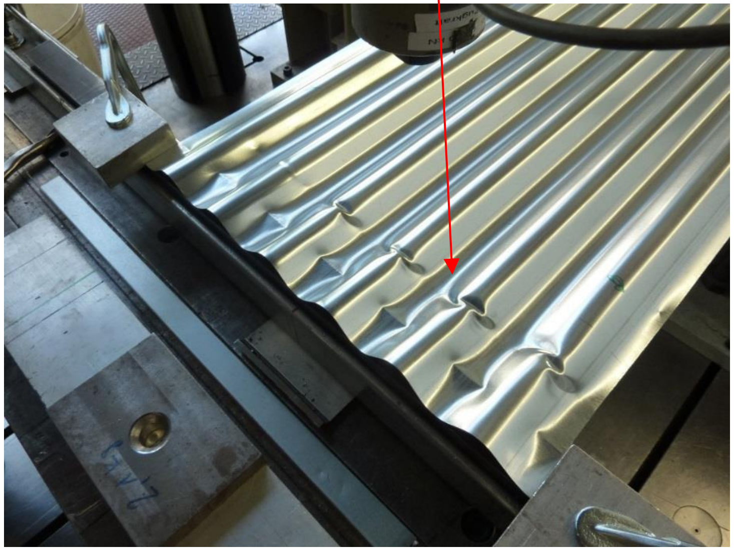
## Web crippling

Eg : Corrugated sheet



Source: GRISPE WP2

Web crippling in
the compression area



Source: GRISPE WP2

# 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

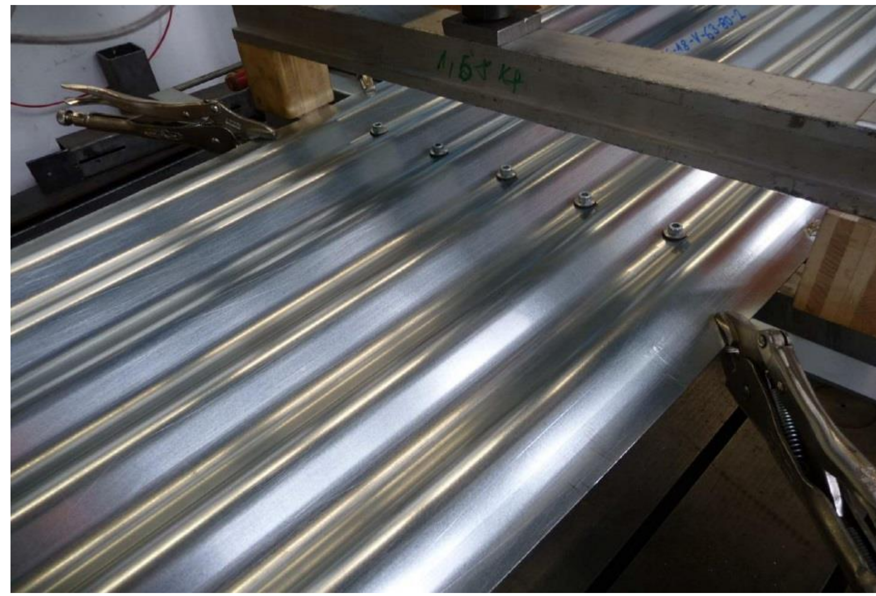
## Fasteners in the valley

Eg : Corrugated sheets

Fasteners in the valley

*Source: GRISPE WP2*

Fasteners in the valley



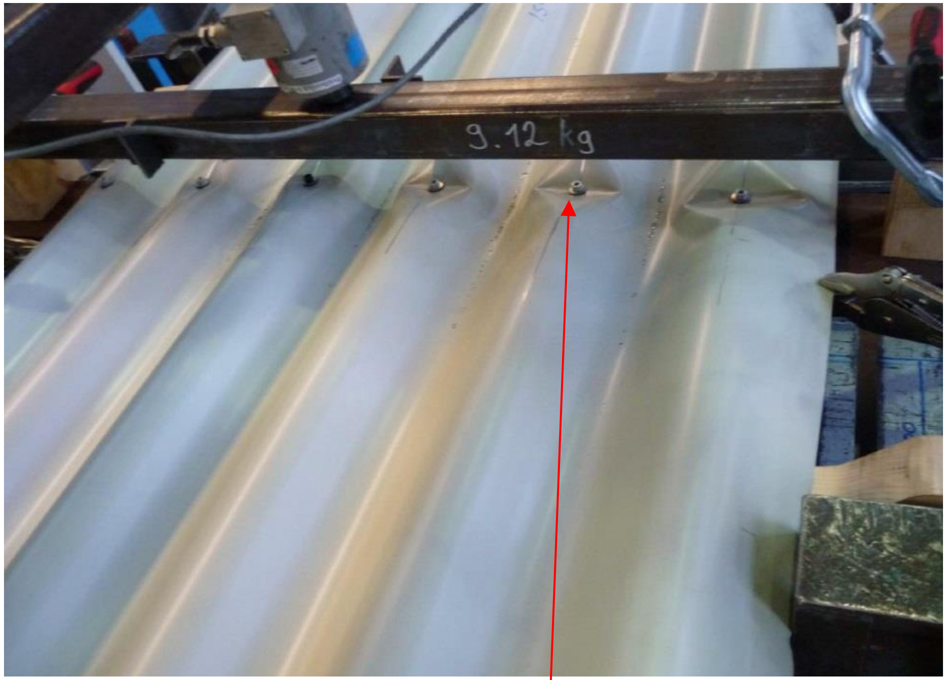
*Source: GRISPE WP2*

Local buckling

# Collapse under upward load

## Fasteners in the crest

Eg : Corrugated sheets



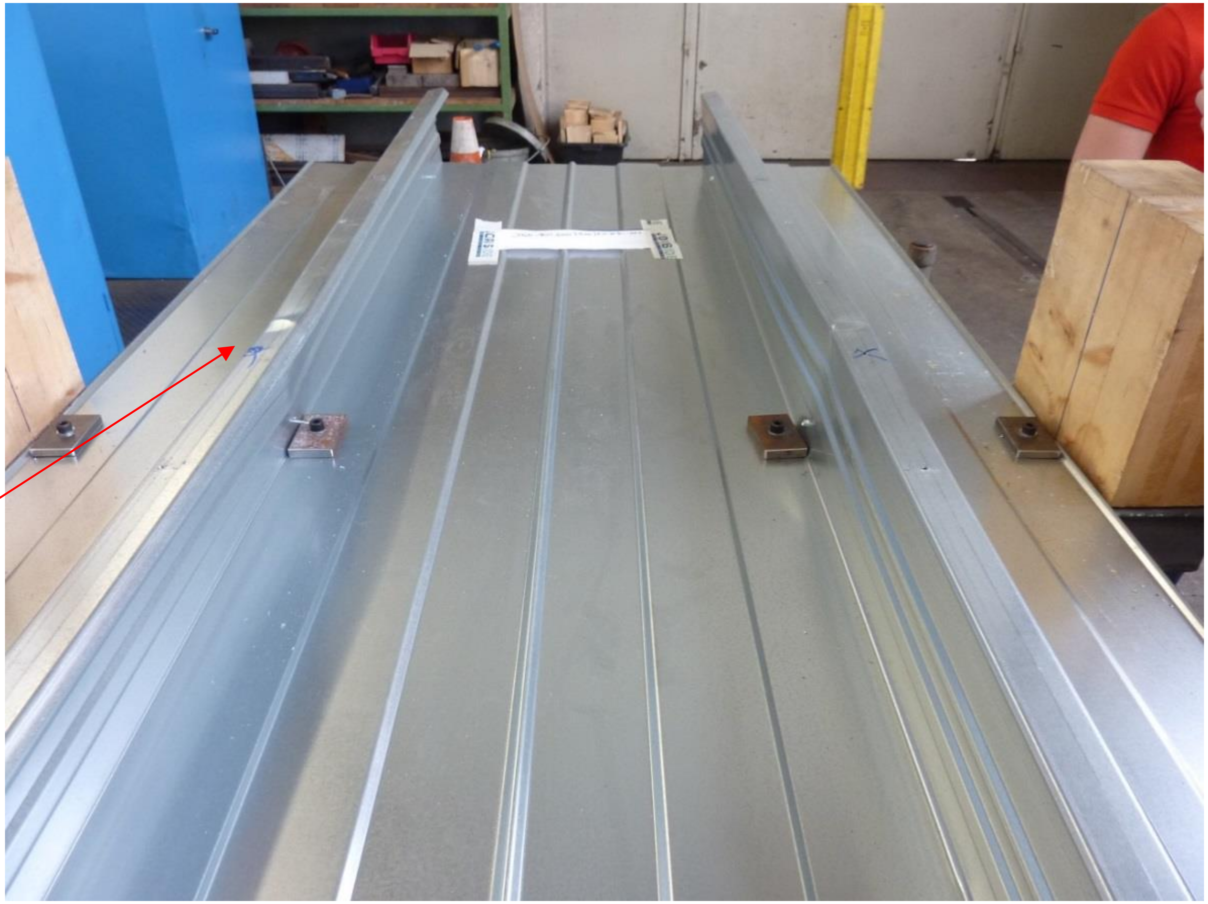

*Source: GRISPE WP2*

Local buckling at the fastening point

# Collapse under upward load

Eg : Liner trays

Free flange buckling



*Source: GRISPE WP2*

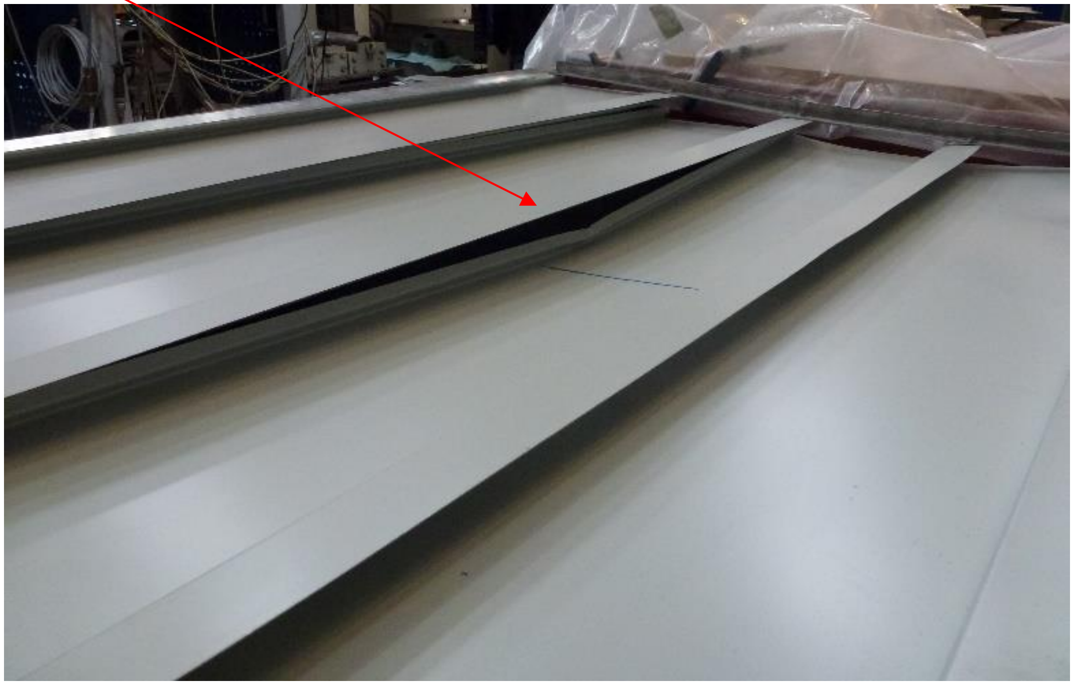
# Liner tray and plank profile specific collapses

## Assembling dislocation

Eg : Plank profiles

Figure B.10: Deformation of the upper flange and the web of the liner tray (liner tray without outer cladding, load distribution in the lower flange)

*Source: GRISPE WP2*

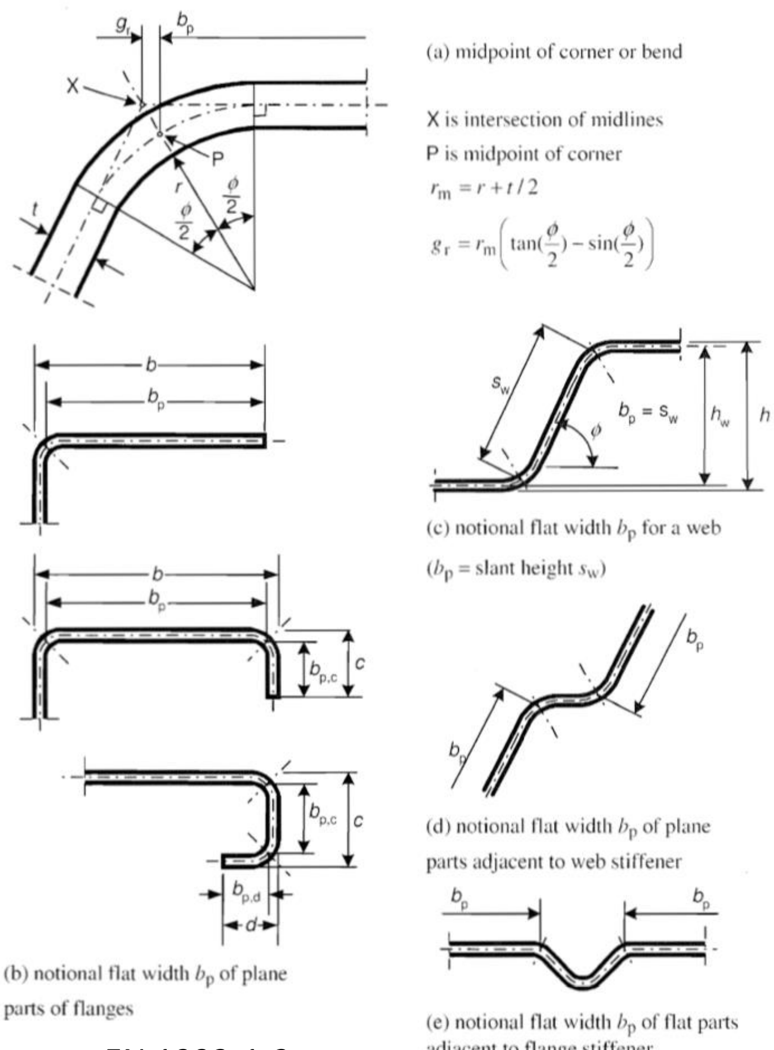


*Source: GRISPE WP4*

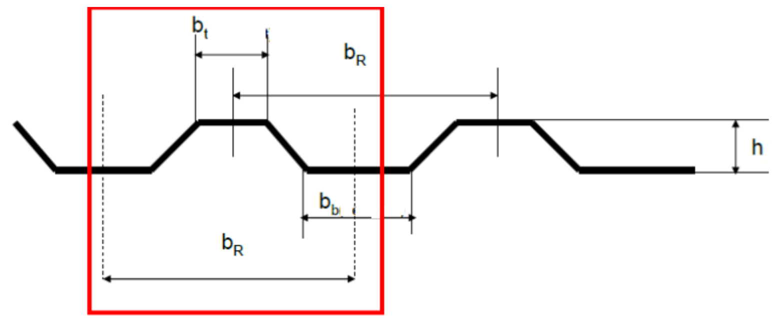
## Liner tray free flange lateral instability

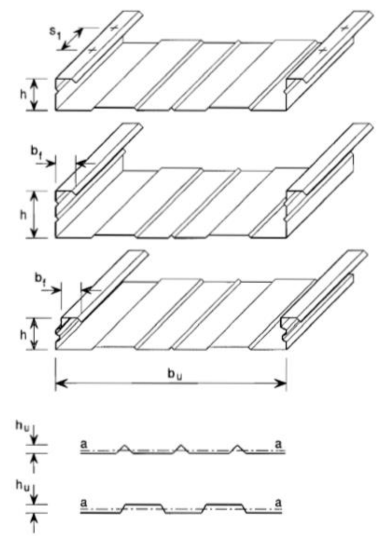
# Mechanical model to take the local flange instability into account

# Notations used



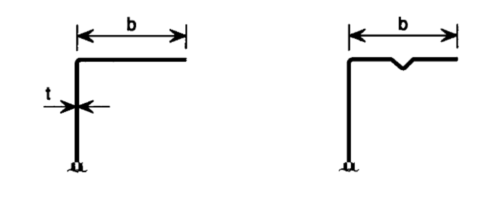
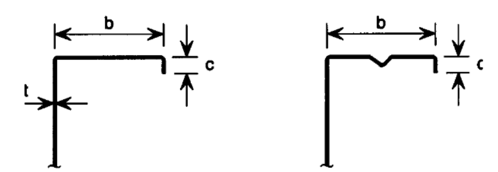
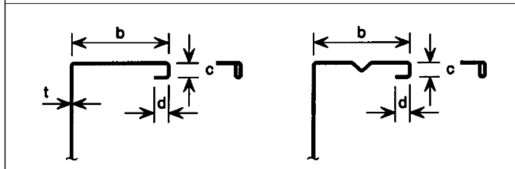
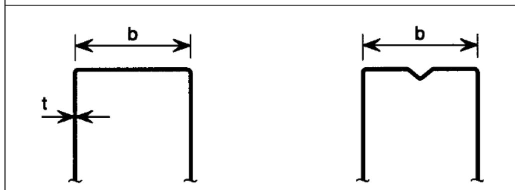
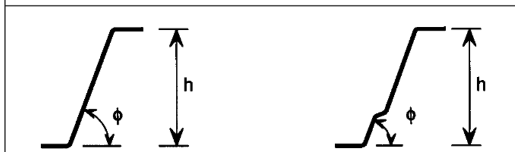

Source: EN 1993-1-3




Source: EN 1993-1-3

# Required conditions to use the EN 1993-1-3

| Element of the cross section | Maximum value |
|---|---|
|  | $b/t \le 50$ |
|  | $b/t \le 60$<br>$c/t \le 50$ |
|  | $b/t \le 90$<br>$c/t \le 60$<br>$d/t \le 50$ |
|  | $b/t \le 500$ |
|  | $45° \le \phi \le 90°$<br>$h/t \le 500 \sin \phi$ |

*Source: table 5.1 of the EN 1993-1-3*

- For sheeting and members $0{,}45\ \text{mm} \le t_{cor} \le 15mm$
- For connections $0{,}45\ \text{mm} \le t_{cor} \le 4mm$

$$0{,}2 \le c/b \le 0{,}6$$

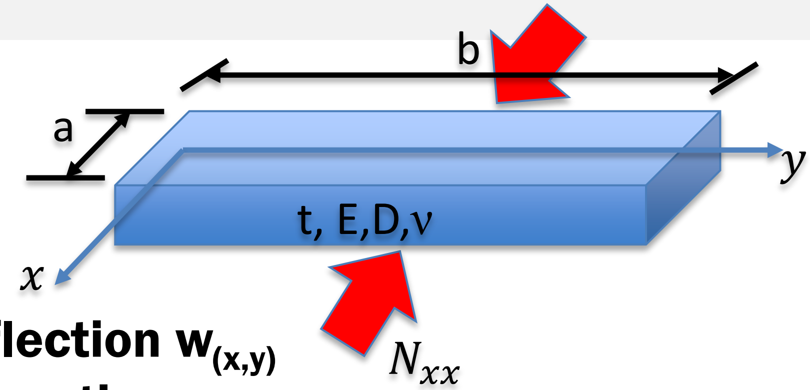
$$0{,}1 \le d/b \le 0{,}3$$

If r/t < 5 (clause 5.1 1993 1.3 )
and r < 0.10 $b_p$

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

# Plate buckling critical stress determination

$$D = \frac{Et^3}{12(1-\nu^2)}$$




**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 …*

# 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 $N_{xx}$:**

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

- **$N_{xx}$ must be at its minimum value (use the derivative/m):** $n=1$

$$\frac{\partial N_{xx}}{\partial m}=\frac{\partial N_{cr}}{\partial m}=2D\frac{\pi}{b^2}\left(m\frac{b}{a}+\frac{a}{mb}\right)\left(\frac{b}{a}-\frac{a}{m^2b}\right)=0 \quad \Rightarrow \quad m=\frac{a}{b}$$

# Plate buckling critical stress determination

- **After simplification (replace m by  a/b) , we obtain the following equation :**

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

- **In addition we also have :**

For uniform compression stresses on the plate

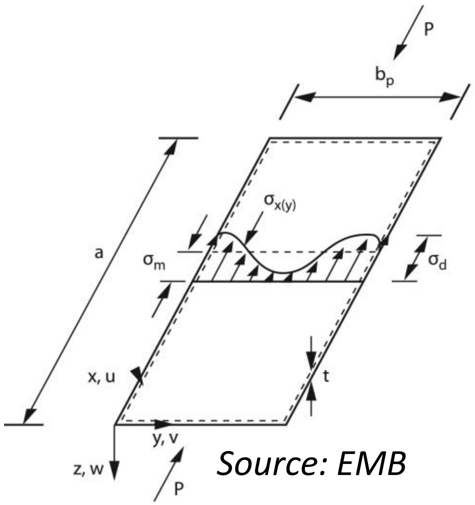
$$\sigma_{cr} = \frac{N_{cr}}{t} = 4\frac{D\pi^2}{b^2 t} = 4\frac{\pi^2 E t^3}{12(1-v^2)b^2 t} = 4\frac{\pi^2 E}{12(1-v^2)b^2}\left(\frac{t}{b}\right)^2$$

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

Buckling critical stress

# Effective width notion – Determination of ρ

- Top flange in compression – stress distribution

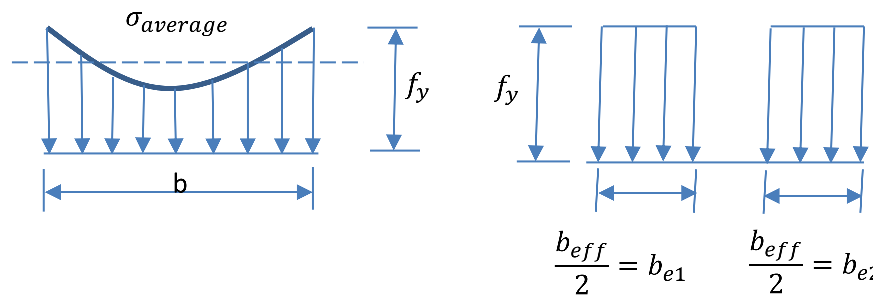



Source: EMB

$\sigma_{cr(b)}$

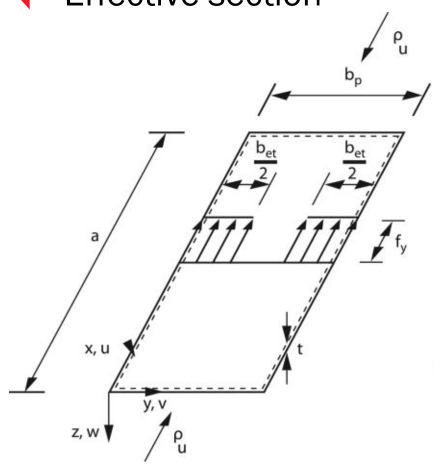
$P = \int_a^{b_a} \sigma_{x(y)} . t . dy$

$= \sigma_m . b_p$


$$\sigma_{average} \times b = 2\left(\sigma_{max}\frac{b_{eff}}{2}\right) = f_y \times b_{eff}$$

- Effective section




$\sigma_{cr(beff)}$

$P_u = f_y . b_{ef} . t$

$b_{ef} = f(\sigma_{cr}, f_y)$

$\frac{b_{ef}}{b_p} = \sqrt{\frac{\sigma_{cr}}{f_y}}$ (v.Karman)

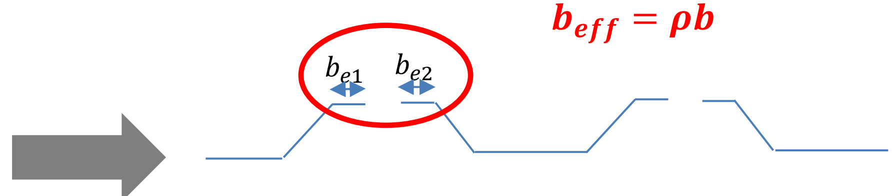
$\rho = \frac{b_{ef}}{b_p} = \sqrt{\frac{\sigma_{cr}}{f_y}}\ (1-0,22\sqrt{\frac{\sigma_{cr}}{f_y}})$

(Winter)

Source: EMB

Fictive hole in the compressed flange

$b_{eff} = \rho\bar{b}$




Effective Section AA

# Plate buckling critical stress determination

- **From the following equation we are looking for $b_{eff}$ :**

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

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

$$\boxed{\sigma_{cr(beff)} = f_y = K \times \left(\frac{t}{b_{eff}}\right)^2}$$

# How to determine $b_{eff}$ ?

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

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

- **By calculating the square root the above equation becomes :**

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

- **By multiplying by b the result is:**

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

# How to determine $b_{eff}$ ?

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

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

- With $\sigma_{cr(beff)} = f_y$ and some mathematics, we obtain:

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

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

- The reverse equation gives:

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

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

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

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

# How to determine the critical slenderness

- **From the ratio b/b$_{eff}$, we are looking for b$_{eff}$ :**

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

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 :

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

With E = 210 000 MPa and v = 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 :

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

We obtain :

$$\bar{\lambda}_p = \frac{b}{b_{eff}} = 1.051868492\left(\frac{b}{t}\right)\sqrt{\frac{235}{\varepsilon^2 Ek_\sigma}}$$

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

With E =210 000, MPa and ν = 0.3

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

The final Eurocode formula of the critical slenderness

# How to determine the reduction factor (ρ ) ?

**According to Von Karman (1910),**
**The reduction factor ρ may be taken as follows :**

When $\bar{\lambda}_p \leq 1 : \rho = 1$

When $\bar{\lambda}_p > 1 : \rho = \frac{1}{\bar{\lambda}_p}$

$$\boxed{b_{eff} = \rho \bar{b}}$$

**According to Winter (1947),**
**The reduction factor ρ may be taken as follows :**

$$\frac{b_{eff}}{b} = \frac{\sigma_{L(b)}}{f_y} = \left(1 - \frac{0{,}22}{\bar{\lambda}_p}\right)\frac{1}{\bar{\lambda}_p} \leq 1$$

# Effective area of the section in compression

- **Finally after several testing calibrations we obtain, at the end, the following formula :**

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

where ρ is the reduction factor for plate buckling

# The effective width for internal compression elements

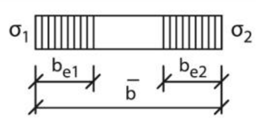
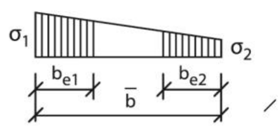
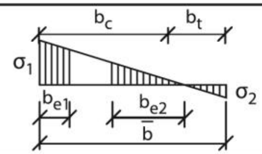
- **At the end, the following table has to be applied in compliance with the EN 1993-1-5**

Wrinkler formula if ψ = 1

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

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}}$$

Internal compression elements

| Stress distribution (compression positive) | Effective width $b_{eff}$ |
|---|---|
|   | $\underline{\psi = 1:}$<br>$\boxed{b_{eff} = \rho\,\bar{b}}$<br>$b_{e1} = 0{,}5\ b_{eff}$ $\quad b_{e2} = 0{,}5\ b_{eff}$ |
|   | $\underline{1 > \psi \geq 0:}$<br>$b_{eff} = \rho\,\bar{b}$<br>$b_{e1} = \frac{2}{5-\psi} b_{eff}$ $\quad b_{e2} = b_{eff} - b_{e1}$ |
|   | $\underline{\psi < 0:}$<br>$b_{eff} = \rho\, b_c = \rho\,\bar{b} / (1-\psi)$<br>$b_{e1} = 0{,}4\ b_{eff}$ $\quad b_{e2} = 0{,}6\ b_{eff}$ |

| $\psi = \sigma_2/\sigma_1$ | 1 | $1 > \psi > 0$ | 0 | $0 > \psi > -1$ | -1 | $-1 > \psi > -3$ |
|---|---|---|---|---|---|---|
| Buckling factor $k_\sigma$ | 4,0 | $8{,}2 / (1{,}05 + \psi)$ | 7,81 | $7{,}81 - 6{,}29\psi + 9{,}78\psi^2$ | 23,9 | $5{,}98\,(1-\psi)^2$ |

Uniform compression of the considered flange

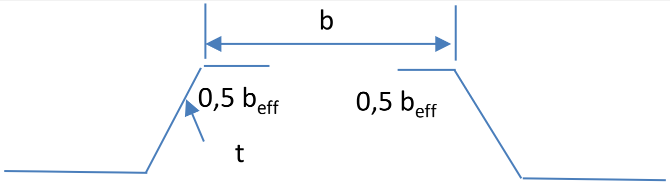
*Source: EN 1993-1-5*

ψ 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 ψ 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).

# Procedure to calculate $b_{eff}$ (Internal compression elements)

$$b_p = b - 2g_r$$

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




$$\bar{b} = b_p$$

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

| $\psi = \sigma_2/\sigma_1$ | **1** |
|---|---|
| Buckling coefficient $k_\sigma$ | 4,0 |

$$A_{eff} = b_{eff}t \qquad A_c = b\ t$$

$$A_{c,eff} = \rho A_c$$

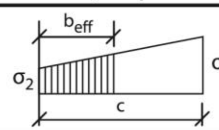
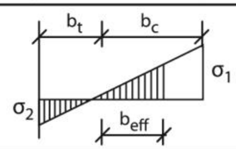
$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}}$$

$$\rho = 1 \quad for \quad \bar{\lambda}_p \le 0{,}5 + \sqrt{0{,}085 - 0{,}055\psi}$$

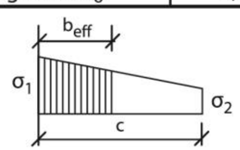
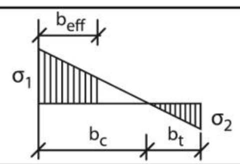
$$\rho = \frac{\bar{\lambda}_p - 0{,}055(3+\psi)}{\bar{\lambda}_p^2} \le 1 \quad for \quad \bar{\lambda}_p > 0{,}5 + \sqrt{0{,}085 - 0{,}055\psi}$$

# The effective width for outstand compression elements

## Oustand compression elements

<table>
<tr><th>Stress distribution (compression positive)</th><th>Effective width $b_{eff}$</th></tr>
<tr><td>
</td><td>$1 > \psi \geq 0$:<br>$b_{eff} = \rho c$</td></tr>
<tr><td>
</td><td>$\psi < 0$:<br>$b_{eff} = \rho b_c = \rho c / (1-\psi)$</td></tr>
</table>

| $\psi = \sigma_2/\sigma_1$ | 1 | 0 | -1 | $1 \geq \psi \geq -3$ |
|---|---|---|---|---|
| Buckling factor $k_\sigma$ | 0,43 | 0,57 | 0,85 | $0,57 - 0,21\,\psi + 0,07\psi^2$ |

<table>
<tr><td>
</td><td>$1 > \psi \geq 0$:<br>$b_{eff} = \rho c$</td></tr>
<tr><td>
</td><td>$\psi < 0$:<br>$b_{eff} = \rho b_c = \rho c / (1-\psi)$</td></tr>
</table>

| $\psi = \sigma_2/\sigma_1$ | 1 | $1 > \psi > 0$ | 0 | $0 > \psi > -1$ | -1 |
|---|---|---|---|---|---|
| Buckling factor $k_\sigma$ | 0,43 | $0,578 / (\psi + 0,34)$ | 1,70 | $1,7 - 5\psi + 17,1\psi^2$ | 23,8 |

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

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28,4\varepsilon\sqrt{k_\sigma}}$$

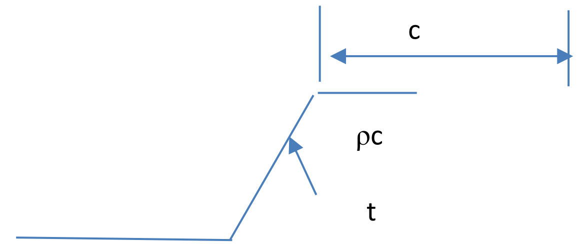
- $\psi$ is the stress ratio determined in accordance with 4.4(3) and 4.4(4)
- b is the appropriate width as follows (for definitions, see Table 5.2 of EN 1993-1-1)
- $b_w$ for webs;
- b for internal flange elements (except RHS);
- b - 3 t for flanges of RHS;
- c for outstand flanges;
- h for equal-leg 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 $b_{eff}$ (outstand compression elements)

$$b_p = b - 2g_r$$

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




$$\bar{b} = b_p$$

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

| $\psi = \sigma_2/\sigma_1$ | **1** |
|---|---|
| Buckling coefficient $k_\sigma$ | 0.43 |

$$A_{eff} = b_{eff}t \qquad A_c = b \ \ t$$

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}}$$

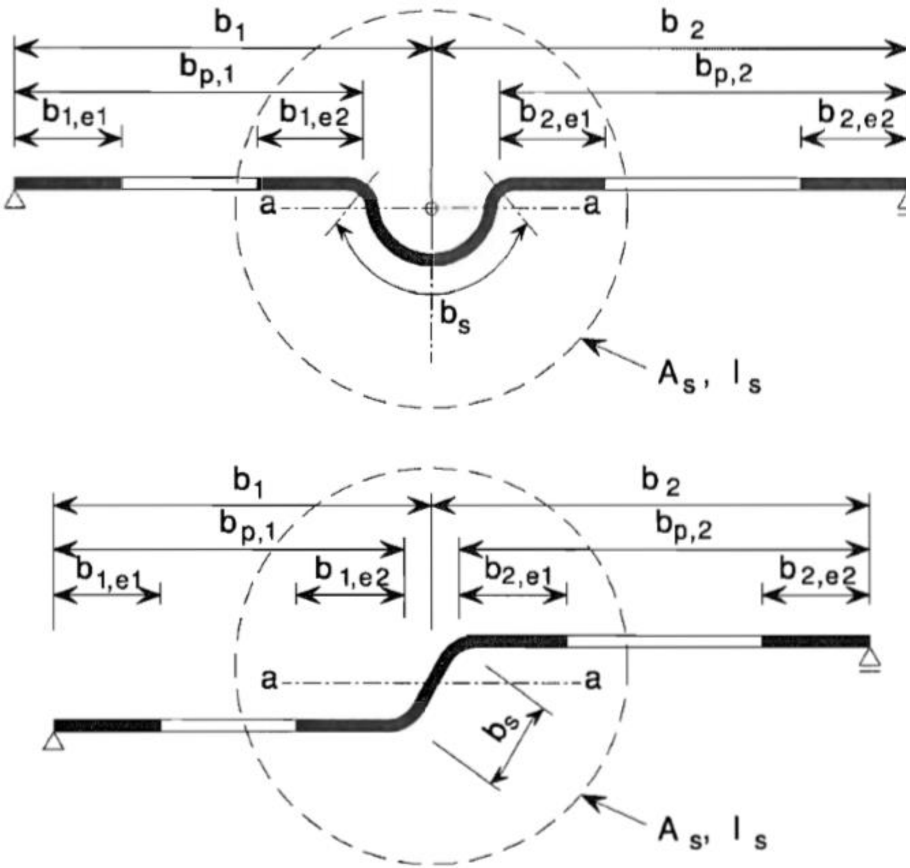
$$A_{c,eff} = \rho A_c$$

$$\rho = 1{,}0 \qquad \text{if} \quad \bar{\lambda}_p \leq 0{,}748$$

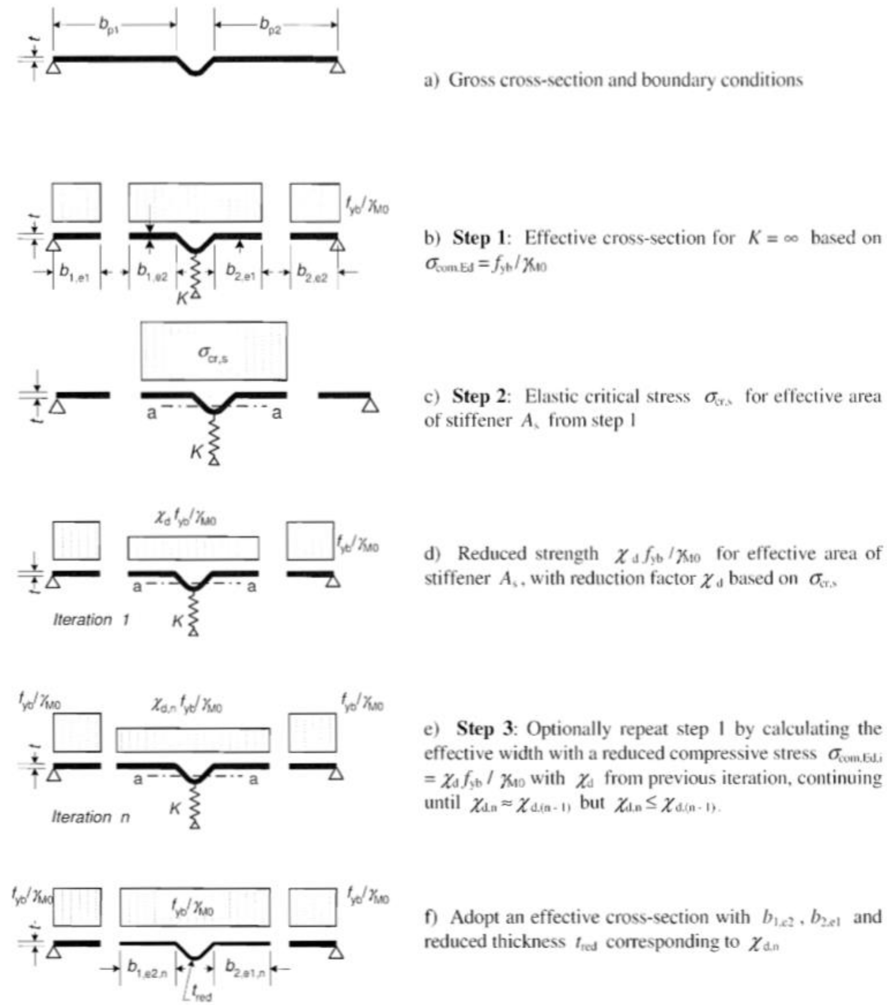
$$\rho = \frac{\bar{\lambda}_p - 0{,}188}{\bar{\lambda}_p^{\,2}} \leq 1.0 \qquad \text{if} \quad \bar{\lambda}_p > 0{,}748$$

# Plane elements with intermediate stiffeners

## The following method is used:




Source: EN 1993-1-3

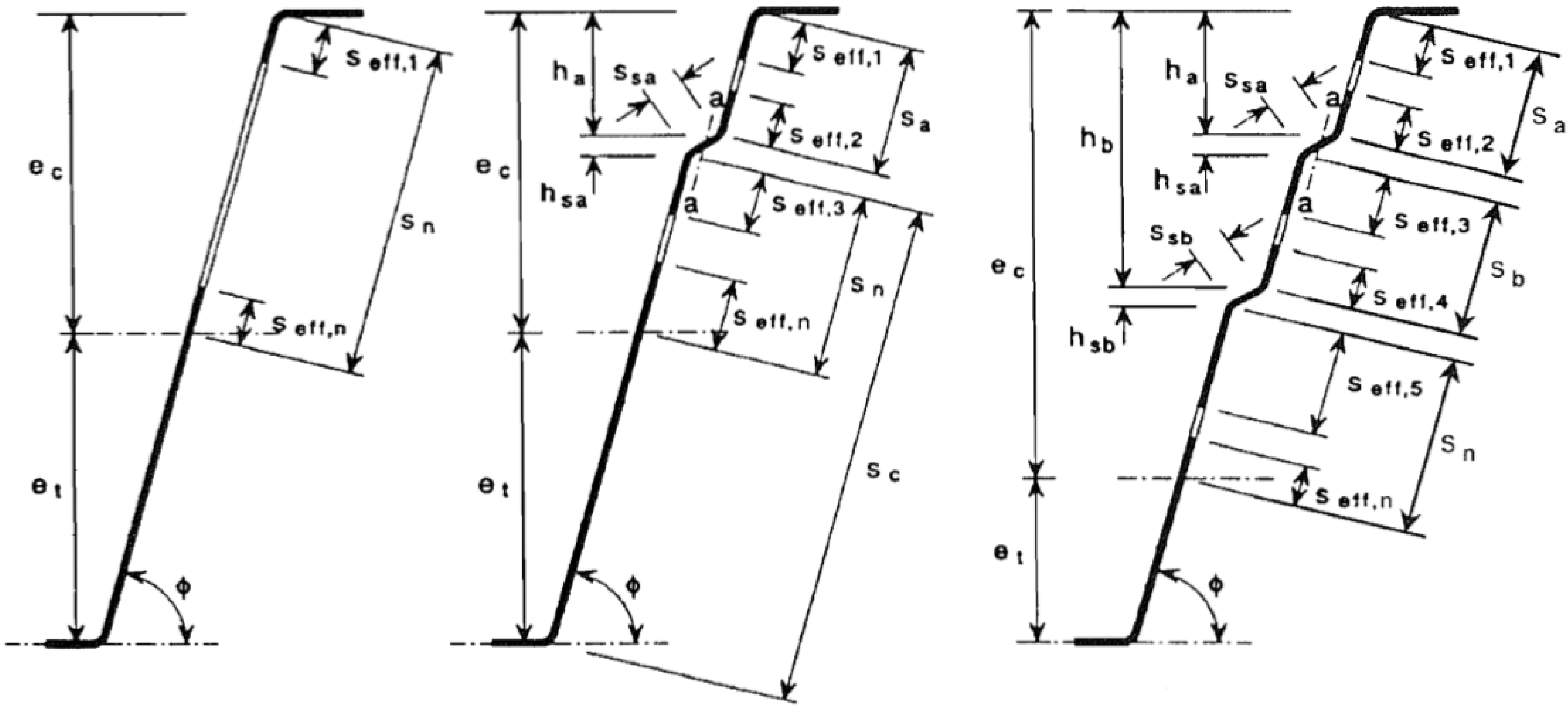



Source: EN 1993-1-3

# 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

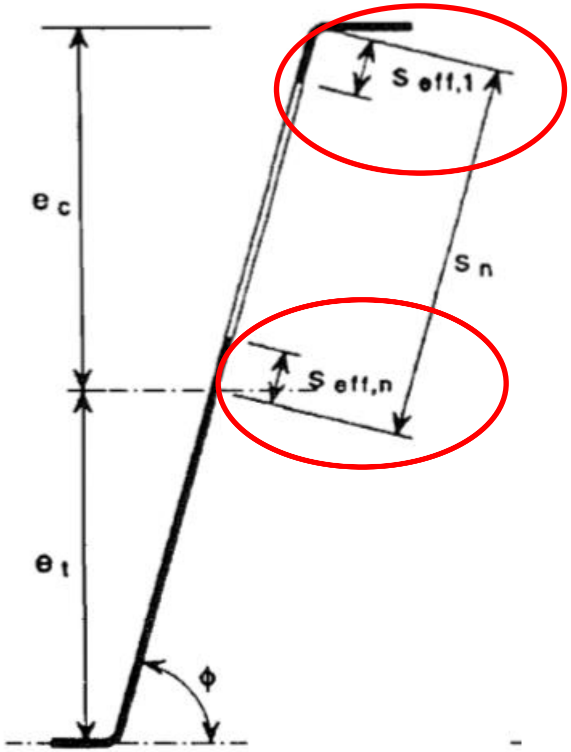
- **In the case of a web without any stiffener:**

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

$$s_{eff,0} = 0{,}76\, t \sqrt{E/(\gamma_{M0}\sigma_{com,Ed}}$$

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

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




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

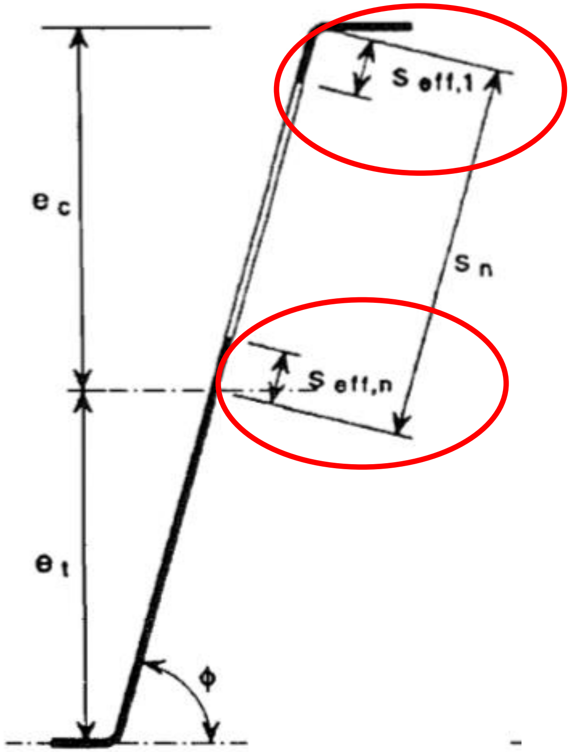
2. Compare $e_c$ /sinϕ with $seff_1$+$seff_n$

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

   ($e_c$ /sinϕ – ( $seff_1$+ $seff_n$)) x t of the web (cross section)

   ($s_{eff1}$ + ($e_c$ /sinϕ – ( $seff_1$+ $seff_n$))/2)*sinϕ (distance from the flange in compression)

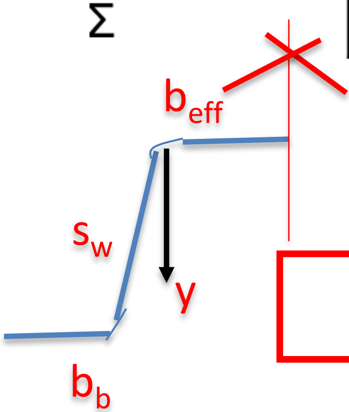



*Source: EN 1993-1-3*

# Formula to determine the span bending resistance of the sheeting profile

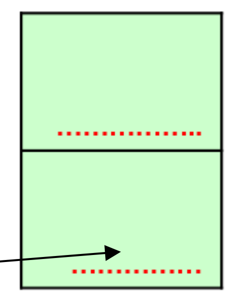
# Determination of the effective section modulus $W_{eff}$

| | l (mm) width | y (mm) / top flange | l x y (mm²) | l x y² ($mm_3$) | h (mm) vertically | lh²/12 |
|---|---|---|---|---|---|---|
| Sem sup eff plate | $b_{eff}$ | 0 | 0 | 0 | 0 | 0 |
| Radius top | $r_m\phi_{(rad)}$ | $r_m$ (1-sin$\phi/\phi$) | ................ | ................ | 0 | 0 |
| Web totally effective | $s_w$ | $h_w/2$ | ................. | ................. | $S_w$ x sin$\phi$ | ................. |
| Radius inf | $r_m\phi_{(rad)}$ | $h_w$-$r_m$ (1-sin$\phi/\phi$) | .................. | .................. | 0 | 0 |
| Flange in tension | $b_b/2$-$g_r$-f | $h_w$ | .................. | .................. | 0 | 0 |
| Σ | ...L11... ... | | ...LY11... | R11 | | ......I11... ....... |




Position of ec from the top flage

$$e_c//y = \Sigma\ (\ l \times y)\ \ /\ \Sigma\ l$$



.................. mm

Along the web $(s_c = s_n)$ = $(e_c\ /\ \sin(\varnothing))$-$g_r$ .............. mm

# Determination of the effective section modulus $W_{eff}$

## Correction if the web is not fully effective :

| | l (mm) width | y (mm) | l x y (mm²) | l x y² (mm³) | h (mm) | lh²/12 |
|---|---|---|---|---|---|---|
| sect 1/2 gross | L11 | | LY11 | R11 | | I11 |
| delta | $-\Delta$ | $-y_{\Delta}$ | -................ | -............... | $-\Delta \sin\phi$ | - ... ... ... ... ... ... . |
| Σ | L22 | | LY22 | R22 | | I22 |

$$\Delta = ( e_c / \sin\phi - g_r ) - 2.5\, S_{eff,0}$$

$$y_{\Delta} = ( \Delta/2 + s_{eff,1} + g_r ) \times \sin\phi$$

**Position of $e_c$ from the top flange**

| | | | | |
|---|---|---|---|---|
| $y_{eff} = \Sigma\, l\, y / \Sigma\, y$ | | $y_{eff}$ | | |
| Effective Inertia / t | ly² +lh²/12-Sd² | lxxeff/t | | |

**By half ribs**

| | |
|---|---|
| ......$y_{eff}$ | mm |
| $I_{eff}/t$ | mm3 |

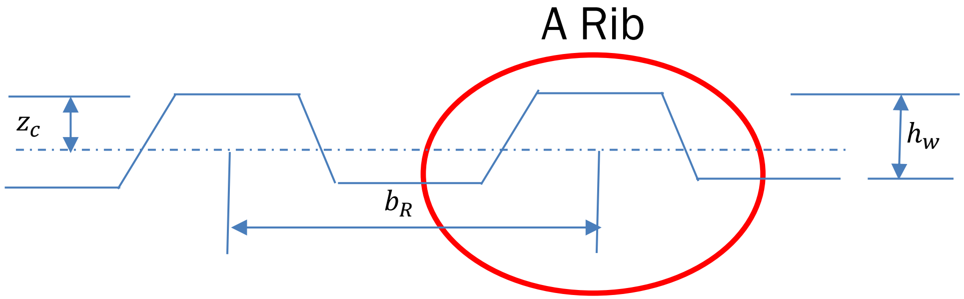
**By wave**

| | | |
|---|---|---|
| | $=y_{eff}$ | mm³ |
| | $2 \times I_{eff} /t$ | mm³ |
| lxxeff /wave | $2 \times I_{eff/t} \times t$ | mm⁴ |

# Determination of the effective section modulus $W_{eff}$

**For the trapezoidal profile we have :**

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




With $b_r$ the pitch of the profile :

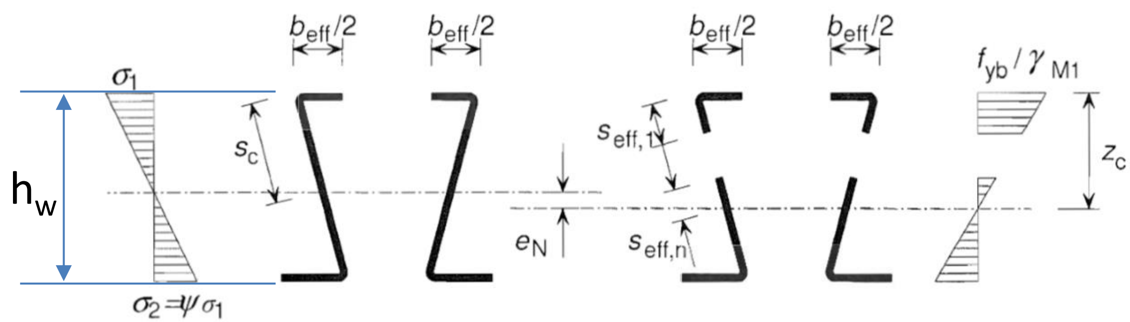
$$\boxed{W_{eff} = Min\left(\frac{I_{eff}}{z_c};\frac{I_{eff}}{(h_w - z_c)}\right)}$$

# Bending capacity

- **The bending resistance determined as follows:**

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

Effective section modulus




*Source: EN 1993-1-3*

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

# Formula to determine the end support reaction and intermediate support reaction

# Eurocode application conditions

- **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:**

  - $r/t \leq 10$… (6. 17 a)
  - $h_w/t \leq 200 sin\phi$… (6.17b)
  - $45° \leq \phi \leq 90°$… (6.17c)

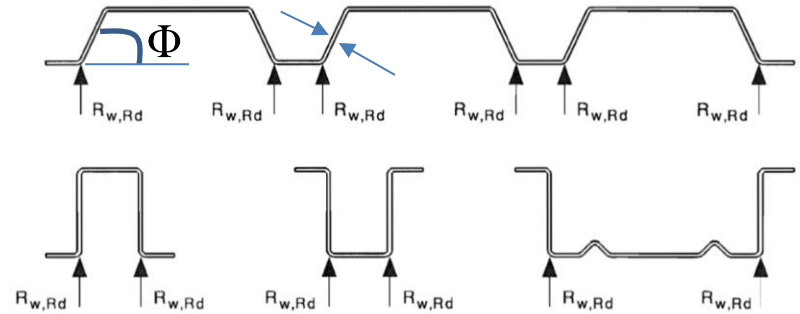
- **Where:**

  - $h_w$ 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].

# Reaction capacity

## The local transverse resistance is:

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




*Source: EN 1993-1-3*

$l_a$ 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 Ss should be taken a value of 10 mm. The relevant category (l 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 la should be obtained from the following:

a) For category 1 :

$l_a = 10mm$ (6.19a)

b) For category 2

$\beta_v \leq 0{,}2$ $l_a = S_s$ (6.19b)

$\beta_v \geq 0{,}3$ $l_a = 10mm$ (6.19c)

$0{,}2 < \beta_v < 0{,}3$ Interpolate linearly the value of la for 0,2 and 0,3

- The following formula issued of tests apply :(5) The value of the coefficient *α* should be obtained from the following:
- a) for Category 1 :

- for sheeting profiles: *α* = 0,075 ... (6.20a)

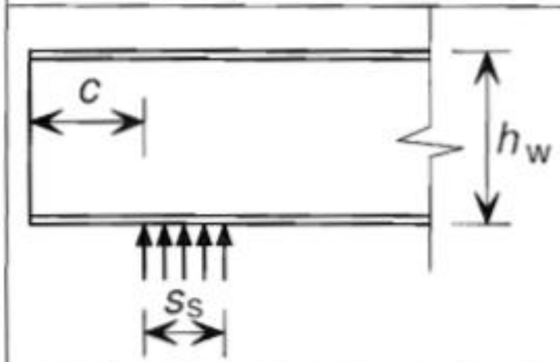
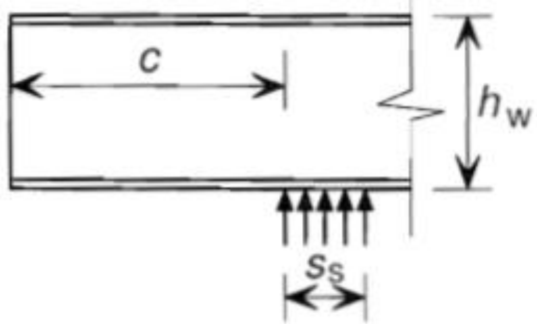
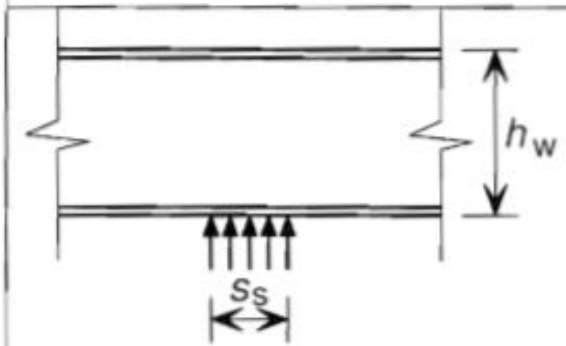
- for liner trays and hat sections*:* *α*= 0,057 ... (6.20b)

- b) for Category 2:

- for sheeting profiles: *α* = 0,15 ... (6.20c)

- for liner trays and hat sections: *α* = 0,115 ... (6.20d

# Definition of the categories 1 and 2

| | |
|---|---|
|  | Category 1<br>- reaction at end support with $c \leq 1{,}5\, h_w$ clear from a free end. |
|  | Category 2<br>- reaction at end support with $c > 1{,}5\, h_w$ clear from a free end; |
|  | Category 2<br>- reaction at internal support. |

*Source: EN 1993-1-3*

# Formula to determine the interaction between support bending and support reaction

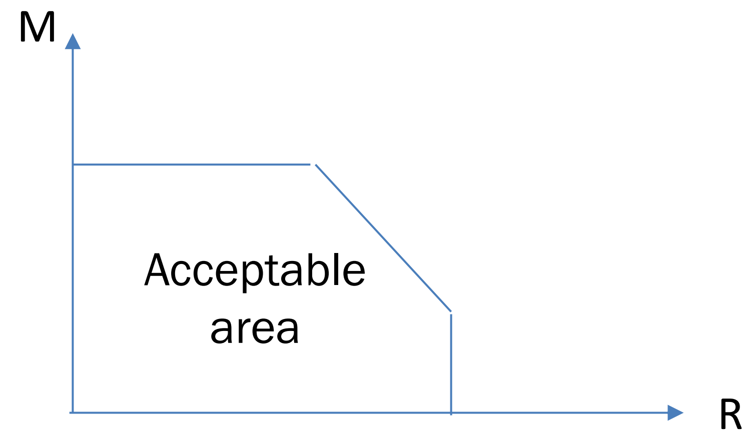
# Combined bending moment and local load or support reaction

## The following formula applies:

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

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

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




Interaction diagram

# Formula to determine the shear resistance of a sheeting

# The design shear resistance

## It should be determined from:

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

$$\overline{\lambda}_w = 0.346 \frac{s_w}{t} \sqrt{\frac{f_{yb}}{E}}$$

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

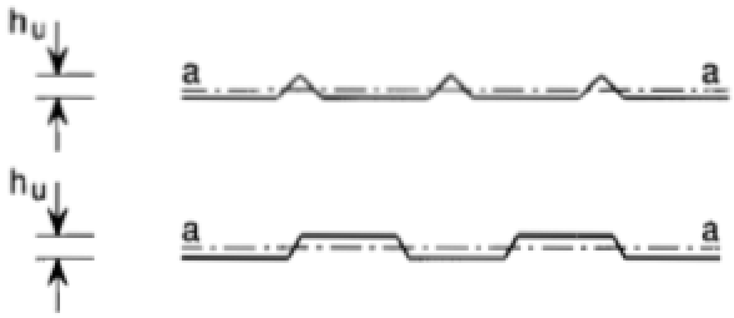
| **Relative web slenderness** | **Web without stiffening at the support** | **Web with stiffening at the support (1)** |
|---|---|---|
| $\overline{\lambda}_w \leq 0{,}83$ | $0{,}58 f_{yb}$ | $0{,}58 f_{yb}$ |
| $0{,}83 < \overline{\lambda}_w < 1{,}40$ | $0{,}48 f_{yb}/\overline{\lambda}_w$ | $0{,}48 f_{yb}/\overline{\lambda}_w$ |
| $\overline{\lambda}_w \geq 1{,}40$ | $0{,}67 f_{yb}/\overline{\lambda}_w{}^2$ | $0{,}48 f_{yb}/\overline{\lambda}_w$ |
| **(1) Stiffening at the support, such as cleats, arranged to prevent distortion of the web and designed to resist the support reaction** | | |

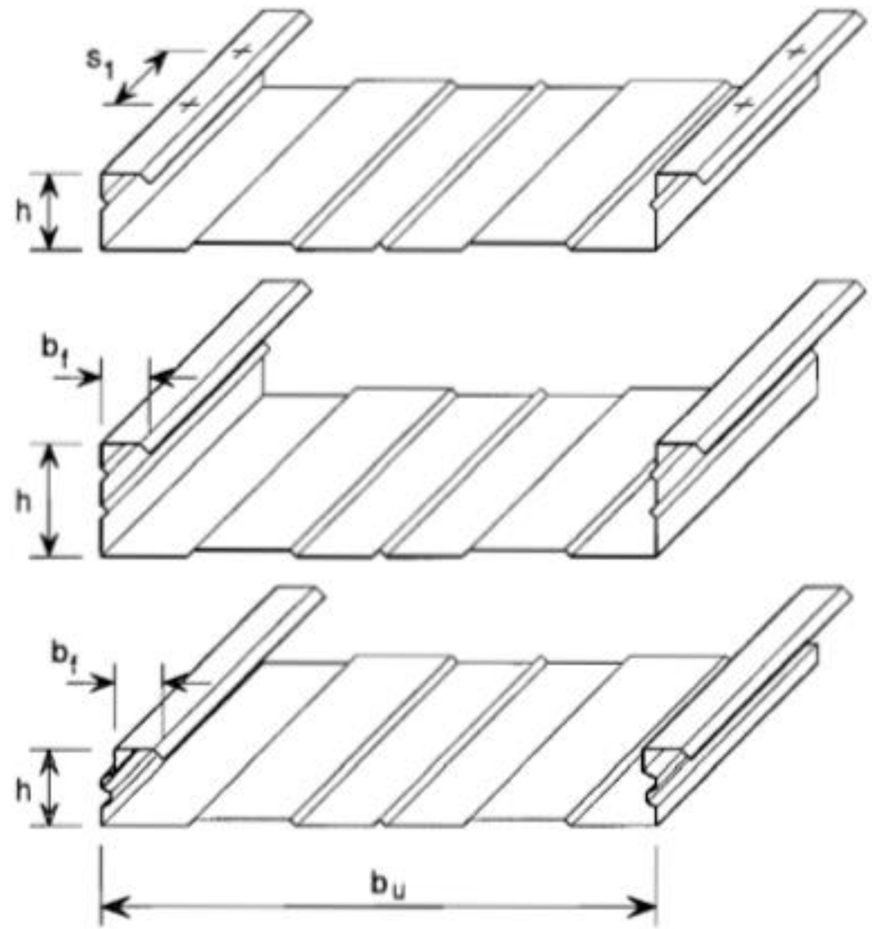
*Source: EN 1993-1-3*

# Designing a liner tray

# Conditions required by the EN 1993-1-3 to design a liner tray

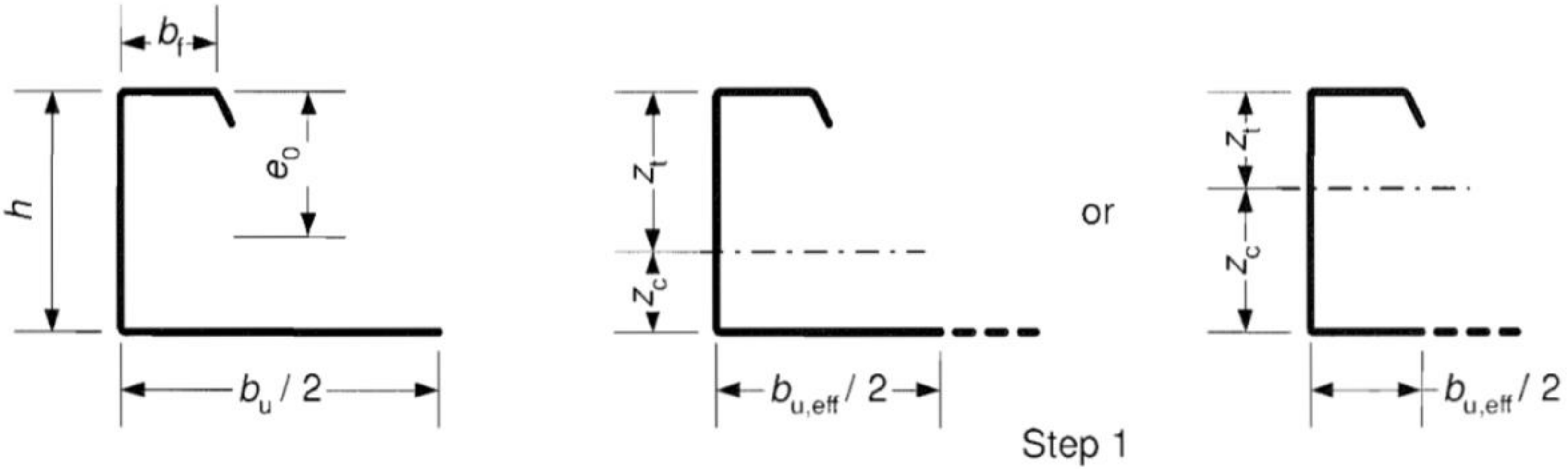
| | | | |
|---|---|---|---|
| 0,75 mm | ≤ | $t_{nom}$ | ≤ 1,5 mm |
| 30 mm | ≤ | $b_f$ | ≤ 60 mm |
| 60 mm | ≤ | $h$ | ≤ 200 mm |
| 300 mm | ≤ | $b_u$ | ≤ 600 mm |
| | | $I_a/b_u$ | ≤ 10 $mm^4/mm$ |
| | | $s_1$ | ≤ 1 000 mm |




*Source: EN 1993-1-3*

# Wide flange in compression

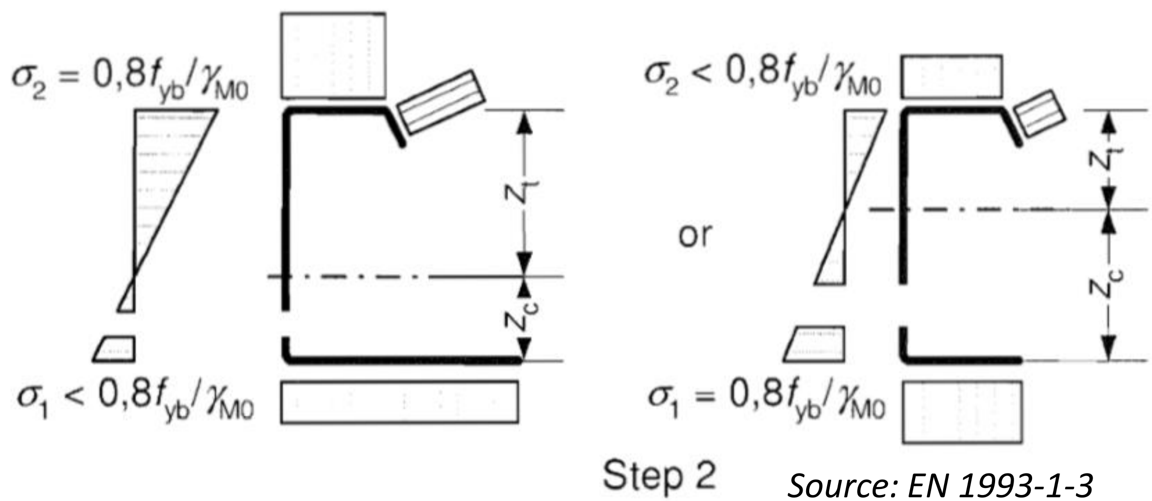



$$M_{C,Rd} = 0{,}8 W_{eff,min} \times f_{yb} / \gamma_{M0}$$

$$W_{eff,min} = I_{y,eff} / z_c$$

But :

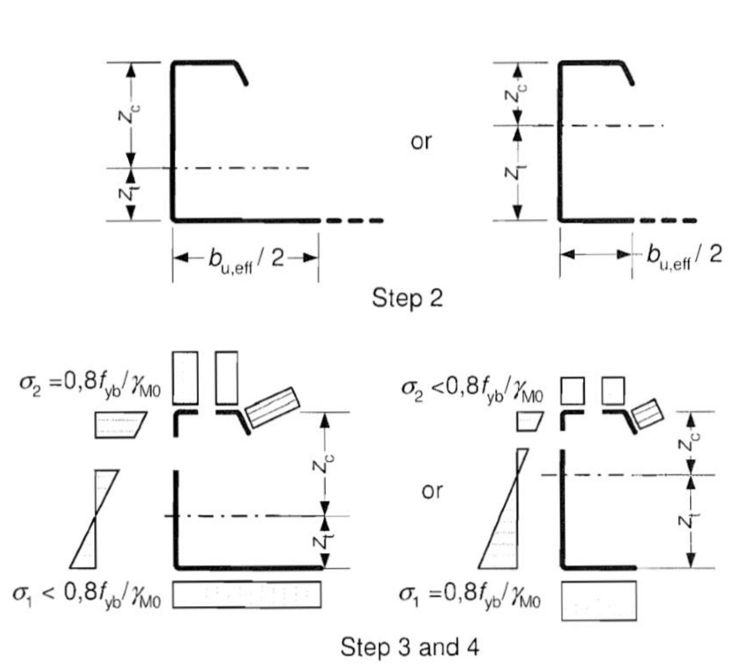
$$W_{eff,min} \leq I_{y,eff} / z_t$$




*Source: EN 1993-1-3*

# Wide flange in tension

$$\boxed{b_{u,eff} = \frac{53.3.10^{10} e_0^2 t^3 t_{eq}}{h L b_0^3}}$$




*Source: EN 1993-1-3*

$b_{u,eff}$ the overall width of the wide flange;
$e_o$ 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:
$I_a$ the second moment of area of the wide flange, about its own centroid, see figure 10.9

$$M_{b,Rd} = 0{,}8\beta_b W_{eff,com} \times f_{yb}/\gamma_{M0}$$

But :

$$M_{b,Rd} \leq 0{,}8\beta_b W_{eff,t} \times f_{yb}/\gamma_{M0} \quad (10.21)$$

with:

$$W_{eff,min} = I_{y,eff}/z_c$$

Limitation

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

*If* $s_1 \leq 300mm$

$$\beta_b = 1{,}0$$

*If* $300mm \leq s_1 \leq 1000mm$

$$\beta_b = 1{,}15 s_1/2000$$

$S_1$ is the longitudinal spacing of fasteners supplying lateral restraint to the narrow flanges, see figure 10.9

# Designing a perforated sheet

# Perforation with a triangular pattern

## The principle is to use a reduced thickness on the perforated area

(I) 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.

***NOTE:*** These calculation rules tend to rather conservative values. More economical solutions might he obtained from design assisted by testing, see Section 9.

(2) Provided that $0{,}2 \leq d/\,a \leq 0{,}9$ gross section properties may be calculated but replacing t by $t_{a.eff}$ obtained from:

$$\boxed{t_{a,eff} = 1.18t\left(1 - 0.9\frac{d}{a}\right) \qquad (10.25)}$$

where:

*d* is the diameter of the perforations;

*a* is the spacing between the centres of the perforations.

# Perforation with a triangular pattern

(3) Provided that **0,2** $\leq$ ***d* / *a*** $\leq$ 0,9 **effective section properties** may be calculated using Section 5, but replacing *t* by $t_{beff}$ obtained from:

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

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

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

where:

$s_{per}$ 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.

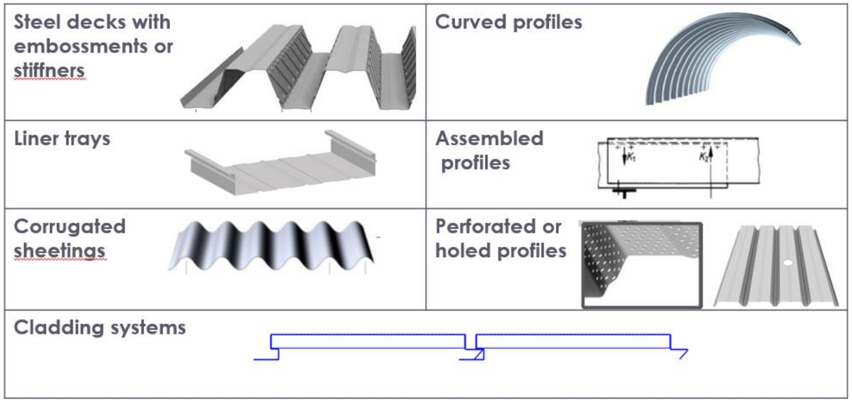
- It is possible to make calculations with several sections characterized by different effective inertia.

# 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




*Source: All WP GRISPE*

# Bibliography

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- *EN 1993-1-5 (Design effective width of cold formed elements)*
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- *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 (metalic coating)*
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