GRISPE PLUS

VALORISATION OF KNOWLEDGE FOR SPECIFIC PROFILED STEEL SHEETS

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DESIGN MANUAL FOR LINER TRAYS

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FINAL VERSION

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SYMMARY

The purpose of this design manual is to present an extended new method of design by calculation for liner trays, as developed in the European project GRISPE PLUS basing on previous results achieved in the positively concluded research project GRISPE.

The manual is based on the Eurocode principles in general and more specifically on the EN 1993-1-3 and EN 1993-1-5 Eurocodes.

This new method of design by calculation for liner trays is based on tests carried out within the European GRISPE project (2013-2016).

The background of this method is described in Annex.

More in details:

Chapter 1 details the type of profiles concerned, the state of the art, the main research results of GRISPE and the general design requirements and rules.

Chapter 2 outlines the preliminary considerations that must be taken into account during the predesign phases, including in particular the verification of the field of application of the extended new design method.

Chapter 3 states the technological requirements that have to be respected including support frame, profiles characteristics and assemblies.

Chapter 4 lists the materials properties of the profiles.

Chapter 5 specifies the determination of actions and combinations.

Chapter 6 gives the basis of the design.

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

Chapter 8 explains in detail the software developed for perforated profiles.

Chapter 9 gives an example of the extended new design method.

A bibliography is included.

IMPORTANT REMARK

The experimental data, the new design method and the software have been obtained and provided by Rainer Holz, IFL –ING LEICHTBAU and by Daniel Ruff and Christian Fauth, KIT –KARLSRUHE INSTITUTE OF TECHNOLOGY

PREFACE

This Design manual have been carried out with the support of RFCS funding n°754092

This new design method has been presented at the evolution group of EN 1993-1-3 in 2016-2017 and is being considered for inclusion into the Eurocodes.

This Design manual has been written by Lisa Kramer and Dominik Pyschny basing on experimental data and considerations already performed in the positively concluded research project GRISPE; the design manual has been discussed in a GRISPE PLUS working group composed by the following members:

Mickael BLANC	France
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Thibault RENAUX	France
Walter SALVATORE	Italy
Léopold SOKOL	France
Daniel SPAGNI	France

FIGURES

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Figure 1.3.2	Karlsruher Institut für Technologie (KIT) – GRISPE project
Figure 1.3.3	Karlsruher Institut für Technologie (KIT) – GRISPE project
Figure 1.3.4	Karlsruher Institut für Technologie (KIT) – GRISPE project
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Figure 6.3.3	Karlsruher Institut für Technologie (KIT) – GRISPE project
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CONTENT

SCOPE OF PUBLICATION

The aim of this publication is to present the new design method for liner trays that has been proposed for inclusion in Eurocode EN 1993-1-3.

This design manual deals with currently occurring situations.

For exceptional situations (seismic, fire, etc.) it is necessary to follow the relevant clauses of the Eurocodes and/or EN 1090-4.

NOTATIONS

The following symbols are used :

h: overall depth

t: design thickness

b_f: width of a narrow flange

b_u: width of the wide flange

c: width of the lip of a narrow flange

$b_{u,eff}$: effective width of the wide flange

e_0: distance of the centroidal axis of the gross-section to the centroidal axis of the narrow flange

L: span of the liner tray

t_{eq}: equivalent thickness of the narrow flange

I_a: second moment of area of the wide flange

$I_{y,eff}$: effective moment of area

W_{eff}: effective section modulus

f_{yb}: basic yield strength

γ_{M0}: partial factor

$M_{b,Rd}$: buckling resistance moment of liner trays

β_b: correlation factor

s_1: longitudinal spacing of fasteners supplying lateral restraint to the narrow flange

y_{sf}: position of the neutral axis of lateral bending

A_{sf}: effective area of the compressed flange

J_{sf}: effective moment of inertia for bending about z-z-axis

1. INTRODUCTION

1.1. Type of profiled steel sheets concerned

This design manual deals with liner trays. The method presents the improvement of the reduction coefficient β_b and the extension of the application range of the fixing distance s_1 between the outer shell and the narrow flange.

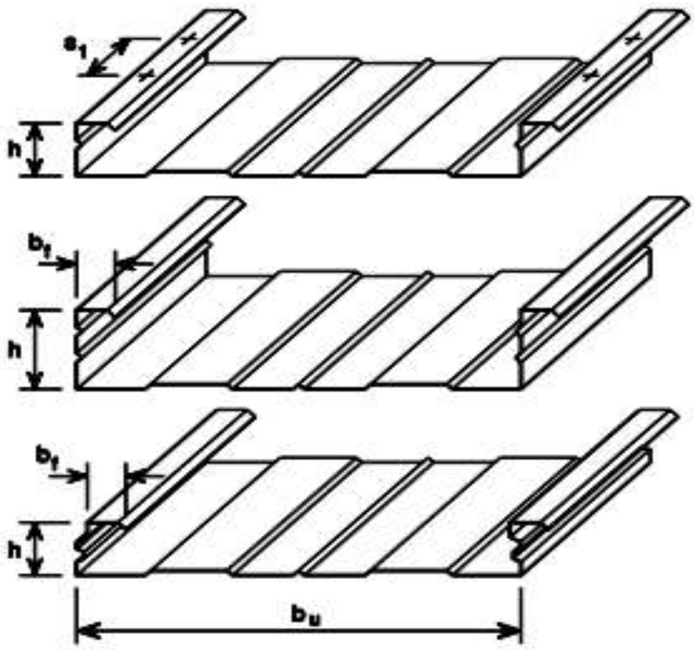


Figure 1.1.1 *- Explanation of the fixing distance s_1*

0,75 mm	$\leq$	t_{nom}	$\leq$	1,5 mm
30 mm	$\leq$	b_f	$\leq$	60 mm
60 mm	$\leq$	h	$\leq$	200 mm
300 mm	$\leq$	b_u	$\leq$	600 mm
		I_a / b_u	$\leq$	10 mm^4 / mm
		s_1	$\leq$	1000 mm

Figure 1.1.2 *- Application range of liner trays*

1.2. State of the art

Liner trays are thin-walled components of lightweight metal and used as the inner shell of a double shell wall system, shown in Figure 1.2.1.

Trapezoidal profiles or corrugated sheets are used as the outer shell. They are connected directly or via a spacer construction to the narrow flanges of the liner trays. When using spacer constructions, the distance of the fixing can be chosen larger, because of the independency of profile geometry.

Figure 1.2.1 *- Liner tray wall systems*

While the outer shell serves as weather protection, the liner tray has a supporting function. In addition, the narrow flanges are stabilized by the shear stiffness of the outer shell.

In the European standard EN 1993-1-3 the design method is given for liner trays in clause 10.2. The design procedure distinguishes between pressure and tension in the wide flange. When tension is applied to the wide flange, the ultimate bending moment

$$M_{b,Rd} = 0.8 \cdot \beta_b \cdot W_{eff,com} \cdot f_{yb}/\gamma_{M0}$$

is reduced by a reduction coefficient

$$\beta_b = 1.15 - s_1/2000$$

that takes into account the effect of the fixing distance s_1 over 300mm. If the fixing distance is less than 300mm, the bending moment does not have to be reduced.

The actual design rule of the fixing distance is rather conservative, and furthermore limited to a maximum fixing distance s_1 = 1000mm, which is no longer sufficient due to the increasing architectural and thermal requirements.

The problem with an increased fixing distance s_1 is the reduction of the shear stiffening via the outer shell. Investigating the effect of reduced shear stiffness in more detail is part of this research work.

1.3. Main results of GRISPE

To determine and compare the load-bearing capacity of liner tray wall systems with larger fixing distances, an extensive program by testing according to EN 1993-1-3 Annex A was carried out with different fixing distance s_1:

- s_1 = 621mm
- s_1 = 1242mm
- s_1 = 1863mm
- without fixing and outer shell

The following tests were done to determine of the resistance values for bending and web crippling of liner trays with varying fixing distance in totally 71 tests:

- Single span tests
- Internal support tests
- Double span tests

The specimens for the single span tests and the internal support tests consists of a full and two half liner trays which are fixed in the webs and a trapezoidal sheet perpendicular to the liner trays which is fixed with the upper flange in the distance s_1.

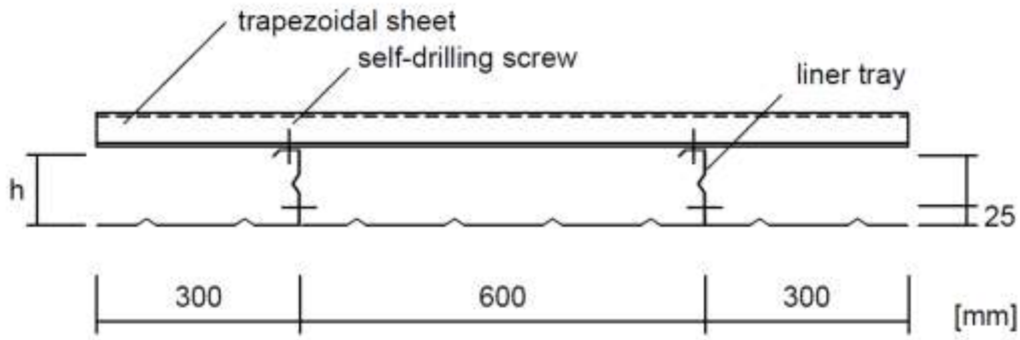


Figure 1.3.1 *– Test setup of single span tests and internal support tests*

The specimens for the double span tests consists of a full and two half liner trays which are fixed in the webs and a distance profile perpendicular to the liner trays which is fixed with the upper flange. A trapezoidal sheet parallel to the liner trays which is fixed with the distance profile builds the outer cladding.

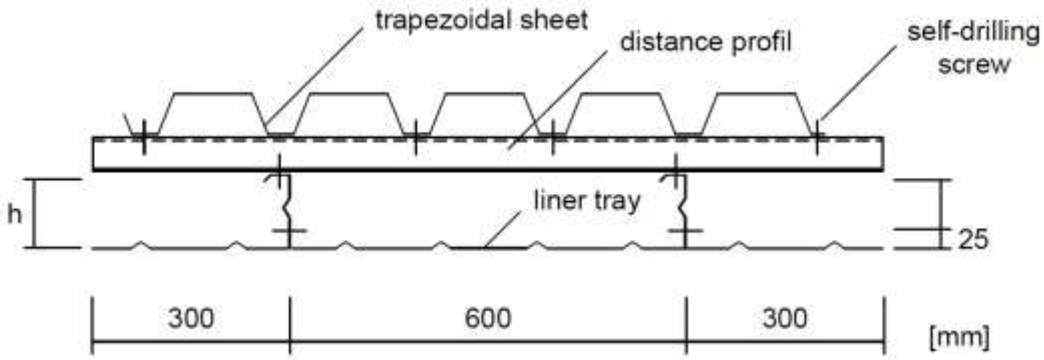


Figure 1.3.2 *– Test setup of double span tests*

The tests on the single-span beam have shown that, in addition to the failure mode, a further type of failure occurs with the test specimens without outer shell. While the test specimens with sufficient shear strength fail due to local buckling, the test specimen fails without stiffening due to lateral buckling.

Figure 1.3.3 *– Failure by lateral buckling of the compressed flanges*

Figure 1.3.4 *– Failure by lateral buckling of the compressed flanges*

1.4. General design requirements and rules

The extended design of liner trays should comply with the general rules of [1] and connected to the design method of [2].

2. PRELIMINAY CONSIDERATIONS

2.1. Field of application of the new design method

In accordance with EN 1993-1-3 this manual presents a new design method for the fixing distance s_1 of liner trays up to a fixing distance of 2000mm.

This manual does not cover load arrangement for loads during execution and maintenance.

The calculation methods specified in these design rules are only valid if the tolerances of the cold-formed profiles comply with EN 1993-1-3.

2.2. Technological dispositions

The cross-sections may either be unreinforced or contain longitudinal stiffeners in their webs or flanges. The profiled sheets have a constant nominal sheet thickness over their entire length within the permissible tolerances and may have either a uniform or a corrugated cross-section. A typical cross section is shown in the Figure 1.1.1.

The cross-sectional dimensions should comply with the general requirements of EN 1993-1-3, section 1.5.3. The design method should not be applied to cross-sections outside the range of width/thickness ratios b/t, h/t, c/t and d/t (see Figure 2.2.1). Unless otherwise specified, the design thickness t is the measured steel core thickness minus tolerance in accordance with Section 3.2.4 of EN 1993-1-3.

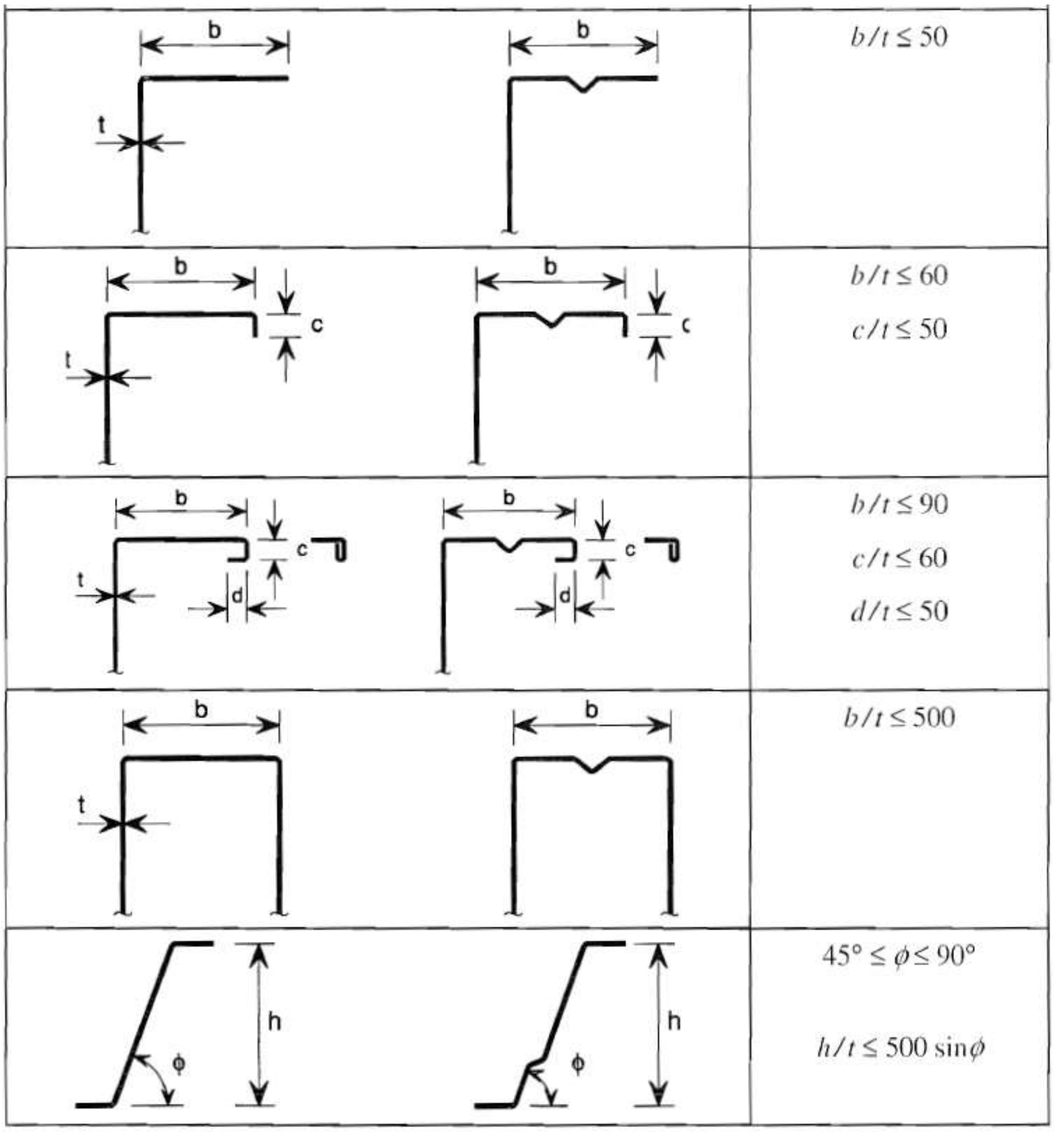


Figure 2.2.1 *– Geometric application range*

3. BASIC TECHNOLOGICAL REQUIREMENTS

Liner trays are CE marked according to the standard EN 1090-1 [3] if structural and EN 14782 [4] if not structural.

4. MATERIAL PROPERTIES

The material properties, if not further specified, used in calculation have to satisfy requirements defined within clause 3 of EN 1993-1-3.

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

5. ACTION LOADS AND COMBINATIONS

The actions and combinations which should be taken into account must be determined according to [5], [1], [6] and [7].

6. BASIS OF THE DESIGN

6.1. Principles

The ultimate positive bending moment of the liner trays (wide flange in tension) is generally limited by the ultimate compression forces of the small flanges. The compressed flanges are stabilized against lateral buckling by the connections between liner tray and outer cladding.

The fixing distance s1 determines the buckling length of the compressed flange and therefore the ultimate compression forces of the small flanges and in consequence also the ultimate bending moment. The ultimate bending moment is approximately proportional to the compression resistance of the small flanges.

The new design procedure begins with the fourth step of the current calculation method of EN 1993-1-3 "10.2.2.2 Wide flange in tension". The amendments in the design method concerns the reduction coefficient β_b for the bending moment capacity of liner trays.

6.2. Field of application of the new design method

The following design method follows the procedure according to EN 1993-1-3 and extends the maximum fixing distance s_1 of the application range given in Figure 1.1.2.

The new application range is given below:

$$\begin{array}{rcccl} 0.75\,mm & \leq & t_{nom} & \leq & 1.5\,mm \\ 30\,mm & \leq & b_f & \leq & 60\,mm \\ 60\,mm & \leq & h & \leq & 200\,mm \\ 300\,mm & \leq & b_u & \leq & 600\,mm \\ & & I_a/b_u & \leq & 10\,\mathrm{mm}^4/\mathrm{mm} \\ & & \mathrm{s}_1 & \leq & 2000\,mm \end{array}$$

6.3. Design procedure

The reduction coefficient β_b to respect the fixing distance s_1, corresponds approximately to the reduction of the compression resistance of the small flanges.

Ultimate bending moment :

$$M_{c,Rk,2} = M_{c,Rk,1} \cdot \frac{N_{Rk,2}}{N_{Rk,1}} = M_{c,Rk,1} \cdot \beta_b$$

with:

- $M_{c,Rk,1}$ (already known) ultimate positive bending moment of liner trays for a fixing distance $s_{1,1}$
- $M_{c,Rk,2}$ (unknown) ultimate positive bending moment of liner trays for a fixing distance $s_{1,2}$
- $N_{Rk,1}$ characteristic compression force of the small flanges of the liner trays, calculated with the buckling length $l=s_{1,1}$
- $N_{Rk,2}$ characteristic compression force of the small flanges of the liner trays, calculated with the buckling length $l=s_{1,2}$

The calculation of the characteristic compression force of the small flanges of the liner trays should respect the following principles:

Step 1: Gross cross section of flanges:

The gross cross section of the compressed flange consists of the small flange, the edge stiffener and 1/5 of the web. Separate calculations should be executed for the small flanges on both sides of the liner tray, because the cross sections of both flanges are different.

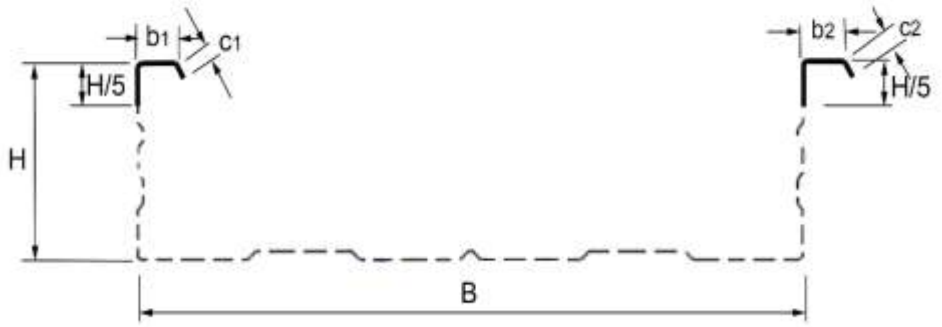


Figure 6.3.1 *– Liner tray, definition of the gross cross sections of the compressed flange*

Step 2: Effective cross section of flanges

The effective cross section should consider local buckling of flange (b_{ef1}, b_{ef2}) and the stiffener (c_{ef}) as well as buckling of the stiffener (t_{red}). The calculation is done for a chosen stress σ_{com} for both flanges of the liner tray.

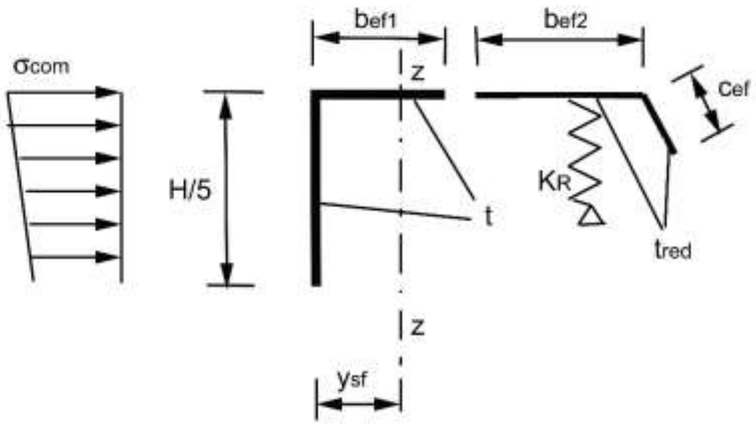


Figure 6.3.2 *– Effective cross section of the compressed flange for a chosen stress σ_{com}*

Cross section values

- y_{sf} position of the neutral axis for lateral bending
- A_{fz} effective area of the compressed flange
- J_{fz} effective moment of inertia for bending about z-z-axis

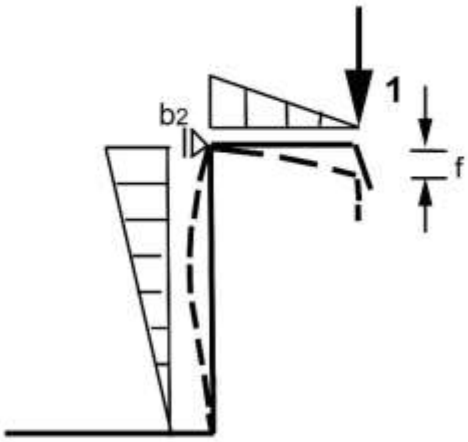


Figure 6.3.3 *– Spring stiffness of the edge stiffener*

Springs stiffness:

$$K_R = \frac{E \cdot t^3}{12 \cdot (1 - \nu^2)} \cdot \frac{3}{b_2 \cdot (b_2^2 + b_2 \cdot h)}$$

Step 3: Ultimate compression force of the small flange with respect to lateral buckling

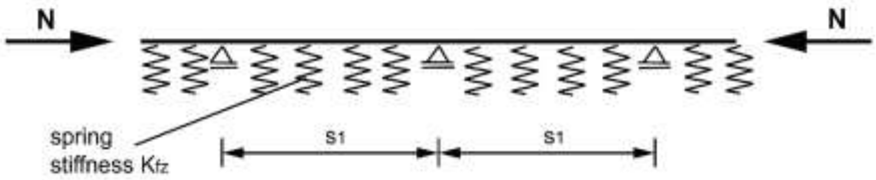


Figure 6.3.4 *– Statically system of the compressed small flange of the liner tray*

When considering lateral buckling of the compressed flange, the elastic foundation of the compressed flange in the lateral direction may be taken into account:

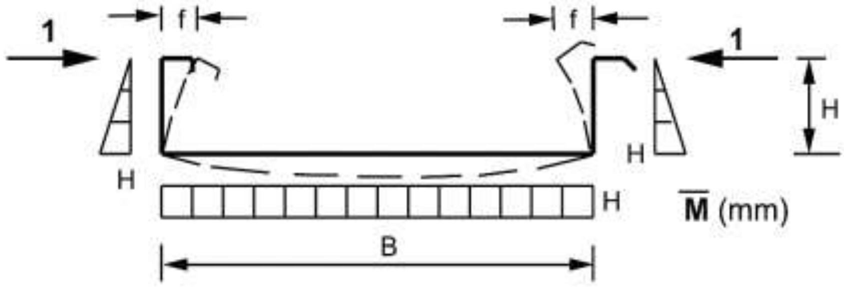


Figure 6.3.5 *– Moment distribution to calculate the spring K_{fz}*

Spring stiffness:

$$K_{fz} = \frac{E \cdot t^3}{12 \cdot (1 - \nu^2)} \cdot \frac{6}{2 \cdot h^3 + 3 \cdot b \cdot h^2}$$

Critical axial force:

$$N_{cr} = \frac{n^2 \cdot \pi^2 \cdot E \cdot J_{fz}}{s_1^2} + \frac{K_{fz} \cdot s_1^2}{n^2 \cdot \pi^2}$$

Normally, the axial force is a minimum for n = 1 (n = number of buckling waves between neighboured fixings). The ultimate axial compression force N_{Rk} is calculated according to EN 1993-1-1 clause 6.3.1.1. Hereby, buckling curve a0 may be used.

Ultimate axial force:

$$N_{Rk} = \chi(a_0) \cdot A_{fz} \cdot f_{yb}$$

Ultimate compressive stress:

$$\sigma_k = \chi(a_0) \cdot f_{yb}$$

If σ_k is different from the initially chosen stress σ_{com}, the calculation should be repeated from step 2 using $\sigma_{com} = \sigma_k$ until the stress σ_{com}, which is the basis for the effective cross section, and the buckling stress of the compressed flange σ_k have converged.

Analogue calculations should be executed for both flanges of the liner tray.

Step 4: Reduction coefficient β_b

The calculation according step 2 and step 3 is done for both flanges and for both fixing distances $s_{1,1}$ and $s_{1,2}$.

The reduction coefficient for the fixing distance $s_{1,2}$

$$\beta_b = \frac{\sum N_{Rk,1}}{\sum N_{Rk,2}}$$

7. SPECIFIC DESIGN CONSIDERATION

The subsequent issues are not covered by the present manual:

- Fire design
- Seismic design
- Environmental aspects
- Thermal aspects
- Acoustic aspects
- Every other subject not clearly identified higher or lower.

8. EXPLANATION OF THE CALCULATION SOFTWARE

8.1. General approach

The existing excel software supports the new design method. All steps of the calculation are included in the software. The ultimate axial force of the small flanges is calculated directly using the profile data. The new reduction coefficient can be calculated with very little effort.

The right way for using this iterative software is explained in the following.

8.2. DATA

Firstly, the excel software needs the profile data of the liner trays. All red cells have to be filled with profile dimensions: steel core thickness t_c, small flange underneath b_{f1}, edge stiffener c_1, small flange above b_{f2}, edge stiffener c_2, fixing distance s_1, height of liner tray H, width of liner tray B, yield stress f_{yb} and slope of edge stiffener a.

steel core thickness t_c		[mm]	fixing distance s_1		[mm]
small flange underneath b_{f1}		[mm]	Height of liner tray H		[mm]
Edge stiffener c_1		[mm]	Width of liner tray B		[mm]
small flange above b_{f2}		[mm]	yield strength f_{yb}		[N/mm²]
Edge stiffener c_2		[mm]	Slope of edge stiffener a		[rad]
			(against reference plane parallel to liner tray's bottom)		

Figure 8.2.1 *– Excel cells to be filled with the profile dimensions*

8.3. Explanation of the iterative calculation

After the excel cells have been filled with profile dimensions, the excel software compute the results automatically.

Firstly, the cross section values are calculated for the left and the right flange.

Cross section values of the small flanges (effective cross section)

flange underneath			stiffener
I_fz	A_fz	y_sf	z_sR
mm⁴	mm²	mm	mm

flange above			stiffener
I_fz	A_fz	y_sf	z_sR
mm⁴	mm²	mm	mm

Figure 8.3.1 *– Calculation of the local buckling of the small flanges*

As second Step, the local buckling of the small flanges is computed.

Local buckling of the small flanges

small flange underneath b_{f1} =				36	mm			Edge stiffener c_1 =			14	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm

small flange above b_{f2} =				38	mm			Edge stiffener c_2 =			13	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm

Figure 8.3.2 *– Calculation of the local buckling of the small flanges*

Each flange is considered separately, as they are not symmetrical. The red cells have to be filled in an iterative way, which will be explained later.

The third step is to calculate the ultimate axial force for each flange.

small flange underneath

	t_c	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm^4	mm^2	mm	N/mm^2	N	-	-	-	N/mm^2	N

small flange above

	t_k	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm^4	mm^2	mm	N/mm^2	N	-	-	-	N/mm^2	N

***Figure 8.3.3** – Calculation of the ultimate axial force for each small flanges*

To get the right results, the stress σ_u has to be iterated. For the compressive strength, σ_d (the red cells in Figure 8.3.2) is entered by the user in the course of iteration. The iteration is done as long as these values comply with σ_u (the green cells in Figure 8.3.3).

8.4. RESULTS

When the iteration is done the excel software outputs the ultimate axial load in summary for both small flanges and an average compressive stress σ_u.

both small flanges together

	t_k	s_1	n	I_fz	A_fz	N_uD	sigma_u
	mm	mm	-	mm^4	mm^2	N	N/mm^2

***Figure 8.4.1** – Calculation of the ultimate axial force in summery*

9. DESIGN EXAMPLE

9.1. Description of the building and static system

9.1.1. Disposition

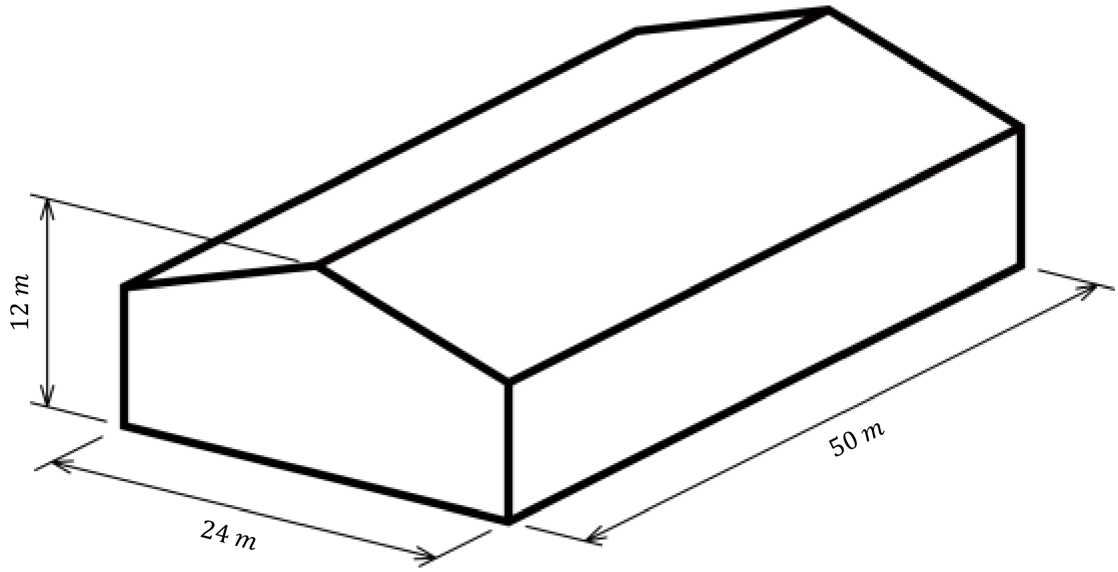


Figure 9.1.1 *- Dimensions of the building*

The span L of the liner trays at the bearing structure:

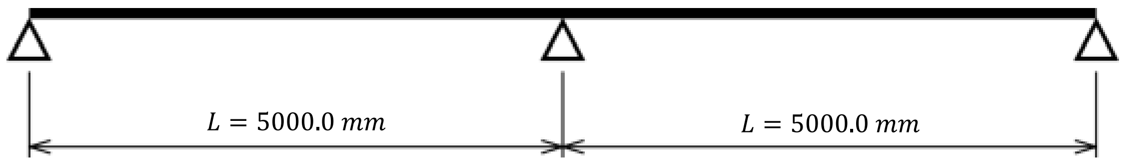


Figure 9.1.2 *- Static scheme of the liner trays disposition*

A trapezoidal sheet is used via a spacer construction as the outer cladding. A z-profile is used as the distance profile.

The calculation of the outer cladding and the z-profile is not part of this design manual.

Figure 9.1.3 *– Liner tray wall system*

The distance profile is fixed every 1250 mm, which corresponds to the buckling length $s_{1,2}$ of the small compressed flange.

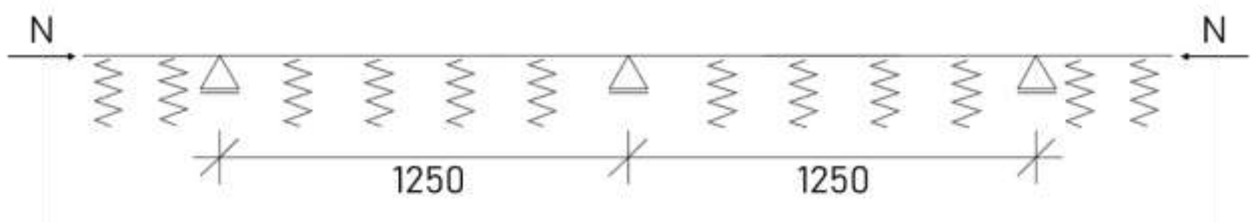


Figure 9.1.4 *- Static scheme of the compressed flange with the buckling length*

9.1.2. Geometry of the profile

The profile designed accordingly is the following:

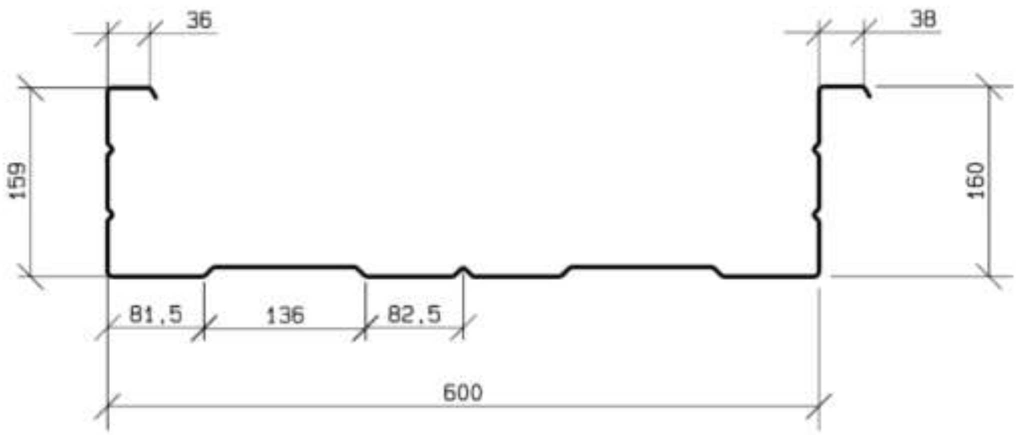


Figure 9.1.5 *- Geometry of the profile designed*

Notation:

$t_{nom} = 0.75\ mm$
$b_{f1} = 36.0\ mm$
$c_1 = 10.0\ mm$
$b_{f2} = 38.0\ mm$
$c_2 = 10.0\ mm$
$h = 160.0\ mm$
$b = 600.0\ mm$
$M_{c,Rk,1} = 5.57\ kNm/m$ (span)

9.1.3. Material properties

General:

$E = 210000\ N/mm^2$
$\nu = 0{,}3$

Steel used:

Grade of steel: S320
$f_{yb} = 320\ N/mm^2$
$t_{nom} = 0{,}75\ mm$
$t_{cor} = 0.71\ mm$

9.2. Calculation of the profile resistances

9.2.1. Validity of the geometry of the profile

$0.75\ mm \leq t_{nom} = 0.75\ mm < 1.5\ mm$
$30\ mm \leq b_f = 37.0\ mm \leq 60\ mm$
$60\ mm < h = 160.0\ mm \leq 200\ mm$
$300\ mm\ \leq b_u = 600.0\ mm \leq 600\ mm$
$I_a/b_u = 0.522\ mm^4/mm \leq 10\ mm^4/mm$
$s_1 = 1250\ mm \leq 2000\ mm$

The geometry of the profile is within the range of validity of the design procedure.

9.2.2. Moment resistance – wide flange in compression

Wide flange in compression is not part of the new design procedure and must be verified in accordance with EN 1991-1-3 "10.2.2.1 Wide flange in compression".

9.2.3. Moment resistance – wide flange in tension in span under pression load

To calculate the moment resistance under suction load according to the new design method, first the ultimate axial force for the known length and then for the unknown length is calculated. Because of that, the reduction coefficient can be calculated with

$$\beta_b = \frac{\sum N_{Rk,1}}{\sum N_{Rk,2}}.$$

Due to the different flanges, both are calculated separately and then added up.

Ultimate axial force of the known fixing distance $s_{1,1}$

The known fixing distance $s_{1,1}$ is 732 mm, which would correspond to a connecting element in every third flange of the trapezoidal. The corresponding ultimate bending moment in span $M_{c,Rk,1}$ must be calculated according to EN 1993-1-3 or taken from the manufacturer's specifications.

At the beginning the red cells have to be filled with the DATA.

steel core thickness t_c	0.71	[mm]	fixing distance s_1	732	[mm]
small flange underneath b_{f1}	36	[mm]	Height of liner tray H	160	[mm]
Edge stiffener c_1	10	[mm]	Width of liner tray B	600	[mm]
small flange above b_{f2}	38	[mm]	yield strength f_{yb}	320	[N/mm²]
Edge stiffener c_2	10	[mm]	Slope of edge stiffener a	1.047	[rad]
			(against reference plane parallel to liner tray's bottom)		

***Figure 9.2.1** – The profile dimensions and the known fixing distance $s_{1,1}$*

As first step, the gross cross sections of the compressed flanges is to calculate separately for both flanges. The flange and the edge stiffener are fully applied. In contrast, only one-fifth of the web is taken into account (see Figure 6.3.1).

Flange underneath:

$$b_{f1} = 36.0\ mm$$
$$c_1 = 10.0\ mm$$
$$h_1 = 1/5 * 159 = 31.8\ mm$$

Flange above:

$$b_{f2} = 38.0\ mm$$
$$c_2 = 10.0\ mm$$
$$h_2 = 1/5 * 160 = 32\ mm$$

Cross section values of the small flanges (effective cross section)

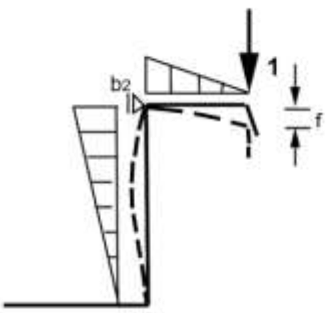
flange underneath			stiffener
I_fz	A_fz	y_sf	z_sR
mm⁴	mm²	mm	mm
6855	42.03	8.47	1.320

flange above			stiffener
I_fz	A_fz	y_sf	z_sR
mm⁴	mm²	mm	mm
7434	41.88	8.70	1.278

***Figure 9.2.2** – The computed cross section of the known fixing distance $s_{1,1}$*

As second step, the effective cross section should consider local buckling of flange and the stiffener as well as distortional buckling of the stiffener (see Figure 6.3.2). The procedure is the same like EN 1993-1-3 respects local buckling and distortional buckling in "5.5.3.2 Plane elements with edge stiffeners".

The spring stiffness of the edge stiffener has to be calculated as shown in Figure 9.2.3 and the computed results of the excel software are shown in Figure 9.2.4



spring stiffness

$$K_R = \frac{E * t^3}{12 * (1 - \mu^2)} * \frac{3}{b_2 * (b_2^2 + b_2 * H)}$$

***Figure 9.2.3** – The spring stiffness of the edge stiffener K_R*

Flange underneath:

with

$b_2 = b_{f1} = 36$ mm

$h = h_w = 160$ mm

$$K_{R,1} = \frac{210000 \cdot 0.71^3}{12 \cdot (1 - 0.3^2)} \cdot \frac{3}{b_2 \cdot (b_2^2 + b_2 \cdot h)} = 0.0813\ N/mm^2$$

Flange above:

with

$b_2 = b_{f2} = 38$ mm

$h = h_w = 160$ mm

$$K_{R,2} = \frac{210000 \cdot 0.71^3}{12 \cdot (1 - 0.3^2)} \cdot \frac{3}{b_2 \cdot (b_2^2 + b_2 \cdot h)} = 0.0722\ N/mm^2$$

In this case, the width of a narrow flange is used for b_2.

To calculate the reduction factor ρ, [8] and [9] are necessary.

When using the excel software, the stress should first be assumed at the basic yield stress and iteratively improved.

Local buckling of the small flanges

small flange underneath b_{f1} =				36	mm			Edge stiffener c_1 =			10	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm
0.71	285.4	0.9832	0.7895	14.21	0.6826	0.9928	17.87	0.7725	0.9062	9.06	19.12	98.7	0.0813	135.8	1.5352	0.4299	0.342

small flange above b_{f2} =				38	mm			Edge stiffener c_2 =			10	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm
0.71	288.07	1.0427	0.7567	14.38	0.7055	0.9754	18.53	0.7761	0.9020	9.02	19.56	98.2	0.0722	124.8	1.6013	0.4122	0.325

***Figure 9.2.4** – Consideration of the effective values of local buckling and distortional buckling of the known fixing distance $s_{1,1}$*

As third step, the ultimate compression force of the small flange with respect to lateral buckling must be calculated (see Figure 6.3.4).

For this purpose, the spring stiffness K_{fz} must be calculated only once, as it is independent of the flanges (see Figure 6.3.5).

$$K_{fz} = \frac{E \cdot t^3}{12 \cdot (1 - \nu^2)} \cdot \frac{6}{2 \cdot h^3 + 3 \cdot b \cdot h^2}$$

with

$b = 600$ mm

$h = h_w = 160$ mm

$$K_{fz} = \frac{210000 \cdot 0.71^3}{12 \cdot (1 - 0.3^2)} \cdot \frac{6}{2 \cdot h^3 + 3 \cdot b \cdot h^2} = 0.00076\ N/mm^2$$

The width of the wide flange b_u is used here as the width b.

After calculating the spring stiffness, the critical axial load can be calculated separately once more for both flanges.

$$N_{cr} = \frac{n^2 \cdot \pi^2 \cdot E \cdot J_{fz}}{s_1^2} + \frac{K_{fz} \cdot s_1^2}{n^2 \cdot \pi^2}$$

Flange underneath:

$$N_{cr,1,1} = \frac{1^2 \cdot \pi^2 \cdot 210000 \cdot 6855}{732^2} + \frac{0.00076 \cdot 732^2}{1^2 \cdot \pi^2} = 26556\,N$$

Flange above:

$$N_{cr,1,2} = \frac{1^2 \cdot \pi^2 \cdot 210000 \cdot 7434}{732^2} + \frac{0.00076 \cdot 732^2}{1^2 \cdot \pi^2} = 28796\,N$$

The reduction coefficient χ can be calculated with the corresponding critical axial load and a buckling curve, so that the ultimate axial force can be determined. Hereby, buckling curve a_0 may be used of [10] and [11].

Flange underneath:

$$N_{Rk,1,1} = \chi(a_0) \cdot A_{fz} \cdot f_{yb} = 11994\,N$$

Flange above

$$N_{Rk,1,1} = \chi(a_0) \cdot A_{fz} \cdot f_{yb} = 12096\,N$$

Because this is an iterative process, the calculation must be repeated until the ultimate compression force and the buckling stress of the compressed flange have converged.

small flange underneath	t_c	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm⁴	mm²	mm	N/mm²	N	-	-	-	N/mm²	N
	0.71	732	1	6855	42.03	12.77	0.00076	26556	0.7116	0.7865	0.8918	285.4	11994
small flange above	t_k	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm⁴	mm²	mm	N/mm²	N	-	-	-	N/mm²	N
	0.71	732	1	7434	41.88	13.32	0.00076	28796	0.6822	0.7641	0.9024	288.8	12096

Figure 9.2.5 *– The computed ultimate axial compression force of the known fixing distance $s_{1,1}$*

In use of the excel software, the red cells in Figure 9.2.4 must be iterated until they are equal to the green cells in Figure 9.2.5.

The total ultimate axial compression force for the known fixing distance, as the sum of the right and left flange, is:

$$\sum N_{Rk,1} = 11994 + 12096 = 24089\,N$$

both small flanges together	t_k	s_1	n	I_fz	A_fz	N_uD	sigma_u
	mm	mm	-	mm⁴	mm²	N	N/mm²
	0.71	732	1	14289	83.91	**24089**	287.1

Figure 9.2.6 *– The computed total ultimate axial force of the known fixing distance $s_{1,1}$*

Before the new reduction coefficient β_b can be calculated, the same calculation from step 1 until step 3 must be repeated for the unknown fixing distance $s_{1,2}$.

Ultimate axial force of the known fixing distance $s_{1,2}$

The calculation of the unknown fixing distance $s_{1,2}$ is analogue, so only the results of the excel software are displayed.

All parameters are the same except the fixing distance which changes to 1250 mm.

steel core thickness t_c	0.71	[mm]	fixing distance s_1	1250	[mm]
small flange underneath b_{f1}	36	[mm]	Height of liner tray H	160	[mm]
Edge stiffener c_1	10	[mm]	Width of liner tray B	600	[mm]
small flange above b_{f2}	38	[mm]	yield strength f_{yb}	320	[N/mm²]
Edge stiffener c_2	10	[mm]	Slope of edge stiffener a	1.047	[rad]
			(against reference plane parallel to liner tray's bottom)		

***Figure 9.2.7** – The profile dimensions and the known fixing distance $s_{1,2}$*

STEP 1:

Cross section values of the small flanges (effective cross section)

flange underneath			stiffener	flange above			stiffener
I_fz	A_fz	y_sf	z_sR	I_fz	A_fz	y_sf	z_sR
mm⁴	mm²	mm	mm	mm⁴	mm²	mm	mm
9399	47.73	10.89	1.568	9972	46.90	10.99	1.533

***Figure 9.2.8** – The computed cross section of the known fixing distance $s_{1,2}$*

STEP 2:

Local buckling of the small flanges

small flange underneath b_{f1} =				36	mm			Edge stiffener c_1 =			10	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm
0.71	207.06	0.8375	0.8804	15.85	0.7016	0.9783	17.61	0.6580	1.0639	10.00	19.60	129.3	0.0813	151.5	1.4531	0.4542	0.498

small flange above b_{f2} =				38	mm			Edge stiffener c_2 =			10	mm					
t_c	sigma_d	lam_p	rho	b_ef1	lam_p	rho	b_ef2	lam_p	rho	c_ef	A_R	I_R	c_R	sigm_kiR	lam_MR	chi_d	t_red
mm	N/mm²	-			-			-		mm	mm²	mm⁴	N/mm²	N/mm²	-	-	mm
0.71	217.3	0.9056	0.8360	15.88	0.7264	0.9597	18.23	0.6741	1.0385	10.00	20.05	130.3	0.0722	140.3	1.5104	0.4370	0.457

***Figure 9.2.9** – Consideration of the effective values of local buckling and distortional buckling of the known fixing distance $s_{1,2}$*

STEP 3:

small flange underneath

	t_c	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm⁴	mm²	mm	N/mm²	N	-	-	-	N/mm²	N
	0.71	1250	1	9399	47.73	14.03	0.00076	12588	1.1016	1.1653	0.6470	207.1	9883

small flange above

	t_k	s_1	n	I_fz	A_fz	i_fz	c_fz	N_ki,z	lam_k	Phi	Chi-a0	sigma_u	N_uD
	mm	mm	-	mm⁴	mm²	mm	N/mm²	N	-	-	-	N/mm²	N
	0.71	1250	1	9972	46.90	14.58	0.00076	13348	1.0603	1.1180	0.6790	217.3	10190

***Figure 9.2.10** – The computed ultimate axial compression force of the known fixing distance $s_{1,2}$*

both small flanges together

	t_k	s_1	n	I_fz	A_fz	N_uD	sigma_u
	mm	mm	-	mm⁴	mm²	N	N/mm²
	0.71	1250	1	19371	94.63	**20073**	212.1

***Figure 9.2.11** – The computed total ultimate axial force of the known fixing distance $s_{1,2}$*

The total ultimate axial compression force for the unknown fixing distance, as the sum of the right and left flange, is:

$$\sum N_{Rk,2} = 9883 + 10190 = 20073\ N$$

If both ultimate axial forces are calculated, the new reduction coefficient can be calculated.

Calculation of the moment resistance with the new reduction coefficient

The reduction coefficient results from the quotient of the ultimate forces.

$$\beta_b = \frac{\sum N_{Rk,2}}{\sum N_{Rk,1}} = 0.833$$

Finally, the moment resistance can be calculated with the known moment resistance, which can be assumed by manufacturer with 5.57 kNm/m.

$$M_{c,Rk,2} = M_{c,Rk,1} \cdot \beta_b = 4.64\ kNm/m$$

TABLE OF FIGURES

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[11] CEN, EN 1993-1-1:2005/A1:2014 – Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings – Amendment A1, Brussels, 2014.

ANNEX:

D2.1	GRISPE WP2 Background document	Christian FAUTH (KIT)
D2.2	GRISPE WP2 Test programme definition	Rainer HOLZ (IFL)
D2.3	GRISPE Test report	Christian FAUTH (KIT)
D2.4	GRISPE WP2 Test analysis and interpretation	Rainer HOLZ (IFL)
D2.5	GRISPE WP2 Background and draft annex for EN 1993-1-3 for liner trays	Christian FAUTH (KIT)