Version
April 2015

Program

PLATE-BUCKLING

Plate Buckling Analysis for Stiffened and Unstiffened Plates According to EN 1993-1-5 and DIN 18800-3

Program Description

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1. Introduction

1.1 About PLATE-BUCKLING

The European standard Eurocode 3 (EN 1993-1-5:2010-12 + NA 2010-12) describes design and construction of plate-like structural steel components used in the member states of the European Union. With the add-on module PLATE-BUCKLING, the DLUBAL company provides a powerful tool for designing plate-like structural components. Country-specific regulations are taken into account by National Annexes (NA). In addition to the parameters included in the program, you can define your own limit values or create new National Annexes.

PLATE-BUCKLING can be used as a stand-alone program or as an add-on module in RSTAB or RFEM. In the add-on module, you can import design-relevant input data and internal forces from the current RSTAB or RFEM model.

Finally, the design process can be documented in the global printout report, from input data to design.

PLATE-BUCKLING performs all typical stability, stress, and deformation analyses as well as the torsional buckling safety check for stiffeners. The Stability analysis is carried out according to the method of stresses reduced by the interaction criterion. Furthermore, analytical equations for calculation of critical buckling stresses from Annex A are implemented, thus allowing for a calculation using the eigenvalue solution.

We hope you will enjoy working with PLATE-BUCKLING.

Your DLUBAL-Team

1.2 PLATE-BUCKLING Team

The following people were involved in the development of PLATE-BUCKLING:

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1.3 Using the Manual

Topics like installation, graphical user interface, results evaluation, and printout are described in detail in the manual of the main program RSTAB or RFEM. The present manual focuses on typical features of the add-on module PLATE-BUCKLING.

The descriptions in this manual follow the sequence of the module's input and results windows as well as their structure. The text of the manual shows the described **buttons** in square brackets, for example [View mode]. At the same time, they are pictured on the left. **Expressions** appearing in dialog boxes, windows, and menus are set in *italics* to clarify the explanations.

At the end of the manual, you find the index. However, if you do not find what you are looking for, please check our website **www.dlubal.com** where you can go through our comprehensive *FAQ* pages by selecting particular criteria.

1.4 Opening the PLATE-BUCKLING Module

There are several possibilities to start the add-on module PLATE-BUCKLING.

Menu

To start the program in the RSTAB or RFEM menu bar, click

Add-on Modules → Design - Steel → PLATE-BUCKLING.

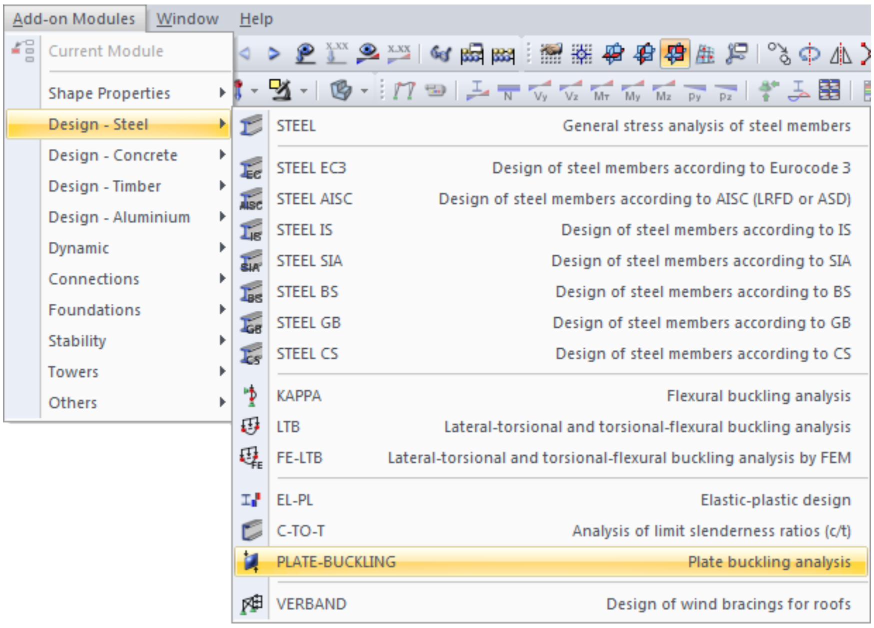


Figure 1.1: Menu: *Add-on Modules → Design - Steel → PLATE-BUCKLING*

Navigator

As an alternative, you can start the add-on module in the *Data* navigator by clicking

Add-on Modules → PLATE-BUCKLING.

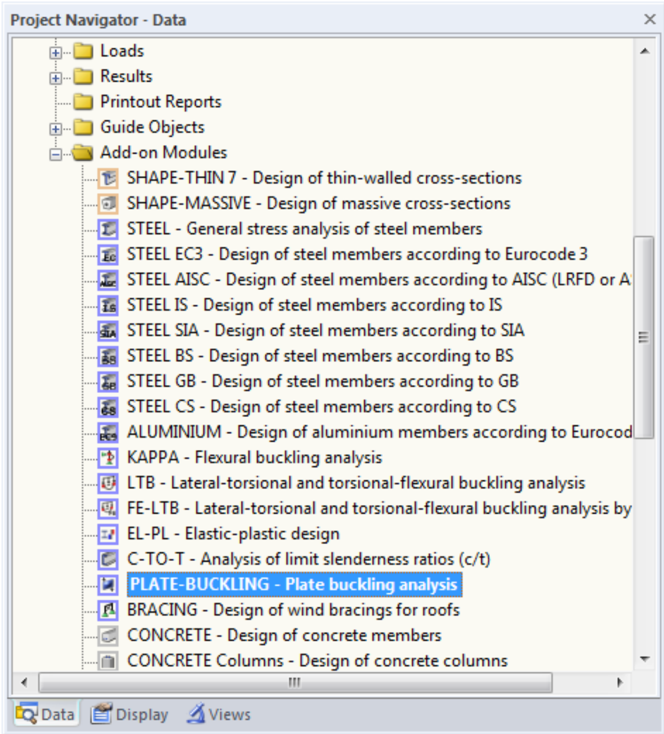
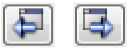


Figure 1.2: Data navigator: *Add-on Modules → PLATE-BUCKLING*

2. Input Data

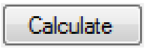
After you have opened the module, a new window appears with a navigator on the left showing all selectable windows. Above the navigator, you see a drop-down list with the possibly already available design cases.



You can select a window either by clicking the corresponding entry in the PLATE-BUCKLING navigator or by using the buttons shown on the left. You can also use the function keys to select the next [F2] or previous [F3] window.

The animated graphics in the info field help visualize your input. In addition to that, you can click [Graphics] to visualize and manage your input data.

To save your specifications and exit PLATE-BUCKLING, click [OK]. If you click [Cancel], you exit the module but without saving the data.



After you have entered all relevant data, click [Calculate] to generate the structural system defined in PLATE-BUCKLING and to calculate it with RFEM or RSTAB and RF-STABILITY/RSBUCK. Then, the results of the eigenvalue analysis are evaluated in PLATE-BUCKLING in order to carry out the relevant designs and to show them in the input windows.

2.1 General Data

In the window *General Data*, you have to enter the plates to be analyzed, their geometry, the material properties, and boundary conditions. Furthermore, you have to define the standard according to which you want to perform the plate buckling analysis.

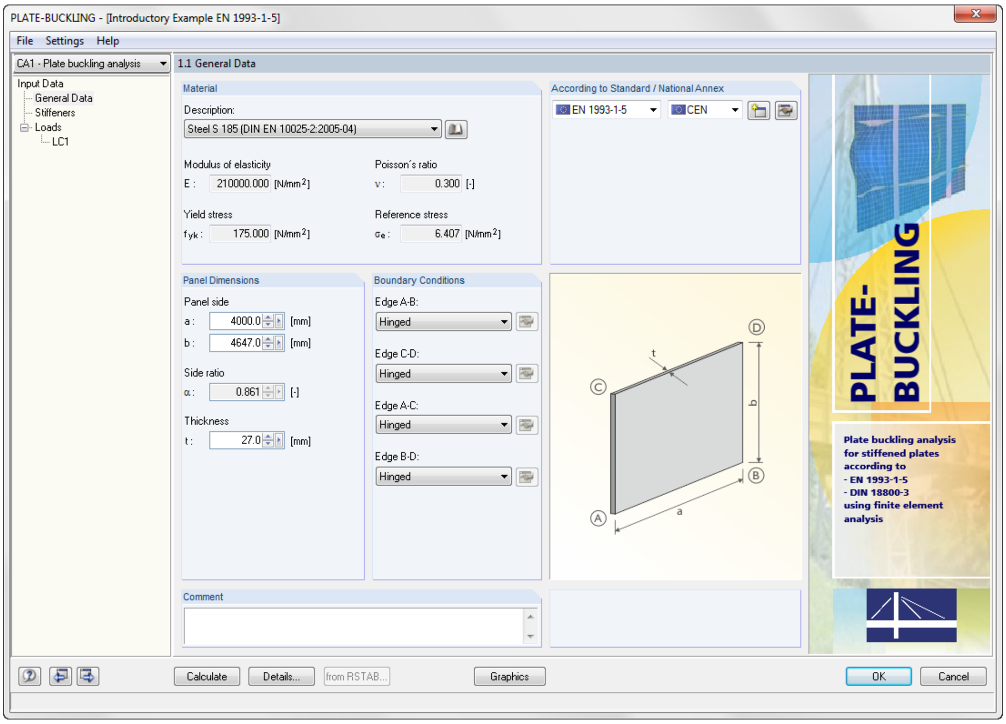


Figure 2.1: Window 1.1 *General Data*

Material

This section allows you to select one of the materials stored in the program. You can select from the steel materials that are allowed by the selected standard. The respective steel grades and their properties are stored in the program's library. To access the library containing the steel grades, click [Material Library]. To import the material to Window 1.1, select it and confirm the selection by clicking [OK].

When you have entered the panel dimensions *a*, *b*, and *t*, the Euler critical stress is computed.

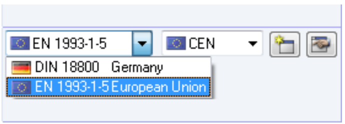
According to EN 1993-1-5:

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-\upsilon^2)} \cdot \left(\frac{t}{b}\right)^2$$

According to DIN 18800-3:

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-\mu^2)} \cdot \left(\frac{t}{b}\right)^2$$

Standard / National Annex



In the drop-down lists, you can select the standard and the National Annex (NA) for the design. Both the standards EN 1993-1-5 and DIN 18800-3 are available.

If you choose to design according to EN 1993-1-5, you can select in the list the National Annex whose parameters you want to apply for the design.

To check and, if necessary, adjust the preset parameters of the current National Annex or standard, click the [Edit] button. Those parameters are mainly partial safety factors used for the design.

To create a user-defined National Annex, click [New].

You can also delete a National Annex by clicking [Delete].

Panel Dimensions

In the dialog section *Panel Dimensions*, you can enter geometrical specifications for the respective surface. According to the sketch, you have to specify the length of *Panel side a, b,* and plate *thickness t*. The side ratio α is determined from these input parameters.

α = a/b

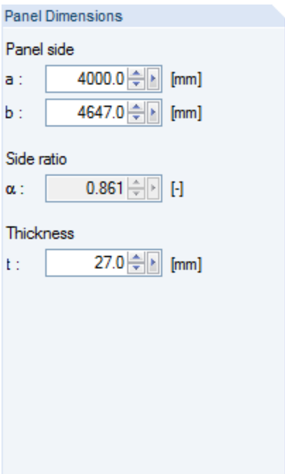


Figure 2.2: *Panel Dimensions*

Boundary Conditions

This dialog section allows you to define the support of the buckling panel. You can select *Hinged*, *Built-in*, *Unsupported*, or *Hinged - Elastic*.

The boundary conditions to be considered in this calculation depend on the characteristics of the plate edges and are influenced by the connection of adjacent parts. Fully hinged or built-in edges do not exist in practice, since the plates usually form flanges and webs of beams. Use the option *Hinged - Elastic* to consider the real support by entering spring stiffness resulting from the adjacent parts.

A common simplified assumption is that the plates have hinged supports along their edges. With this assumption you are on the save side. In PLATE-BUCKLING, you have to specify these geometric boundary conditions for displacement, rotation, and warping on the nodes of the four plate edges of the entire plate. The following is assumed:

- Built-in edge (rotation restrained)
- Hinged edge (freedom of rotation)
- Free edge (rotation and displacement are possible perpendicular to the plate plane)
- Hinged elastic edge (rotation is partially restrained)

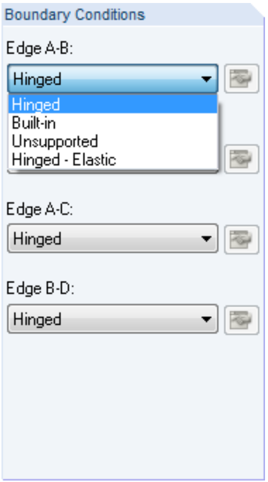


Figure 2.3: *Boundary Conditions*

In case you perform a design according to DIN 18800-3, the following option is available:

- *Uniform Edge Displacement u according to Table 1, row 5*

With this option, you decide how to calculate the reduction factor κ for buckling panels supported on three sides.

Comment

In this input field, you can enter user-defined notes.

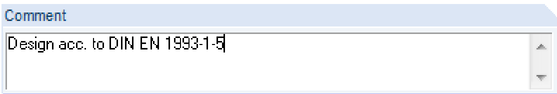


Figure 2.4: *Comment*

2.2 Stiffeners

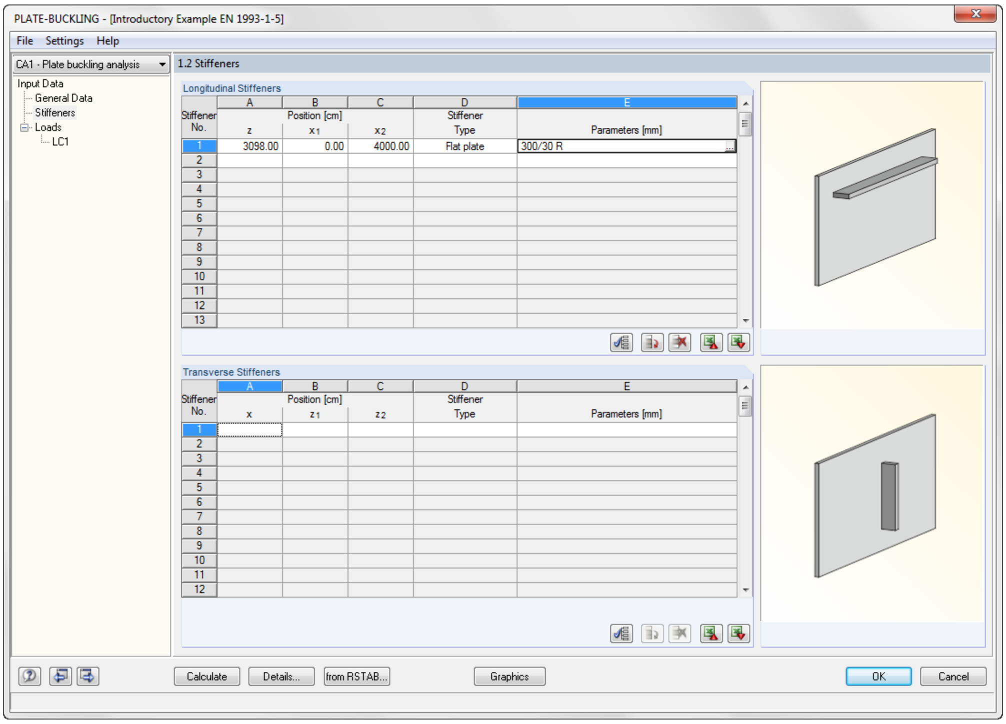


Figure 2.5: Window 1.2 *Stiffeners*

In this two-part input window, the upper part *Longitudinal Stiffeners* contains the stiffeners arranged in longitudinal direction and to be included in the calculation. The lower part offers the same input possibilities for *Transverse Stiffeners*. Both tables are identical except for the mentioned difference and will therefore be described together.

The various additional functions facilitate the work in this window. The buttons are reserved for the following functions:

Button	Description	Function
	Regular stiffener positions	Distributes the existing stiffeners over the buckling panel depth uniformly
	Copy row	Copies the currently selected row to the next row
	Delete row	Deletes the selected row
	Export to Excel	Exports the current table to MS Excel
	Import from Excel	Imports the existing input from MS Excel

Enter the *Position* of the longitudinal and transverse stiffeners in the columns A to C. According to ***EN 1993-1-5***, these are the positions *z, x1, x2* or *x, y1, y2* and according to ***DIN 18800-3***, the positions *y, x1, x2* or *x, y1, y*.

In column D *Stiffener Type*, specify the cross-section of the stiffeners. You can choose from the following stiffener types.

Figure 2.6: *Stiffener Types*

After you have selected the type, you can enter the cross-section parameters in a dialog box.

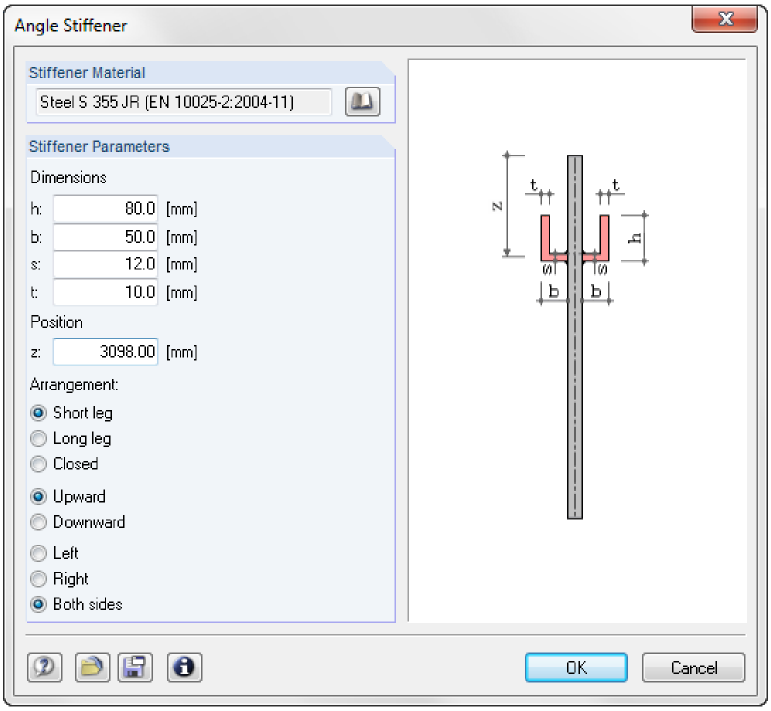


Figure 2.7: *Angle Stiffener*

In this dialog box, you can specify the type and orientation of the stiffeners. PLATE-BUCKLING allows you to define various materials for the stiffeners and buckling panel. You can select one of the materials that depend on the selected standard and are stored in the program's material list. The corresponding steel grades and their properties are stored in the library. To open the data base containing the steel grades, click [Library]. When you have selected a material, click [OK] to transfer it to Window 1.2.

To receive information on the cross-section values of the selected stiffener, click [Info].

To save the specified data in a stiffener data base, click [Save]. The data can be reimported by clicking [Load].

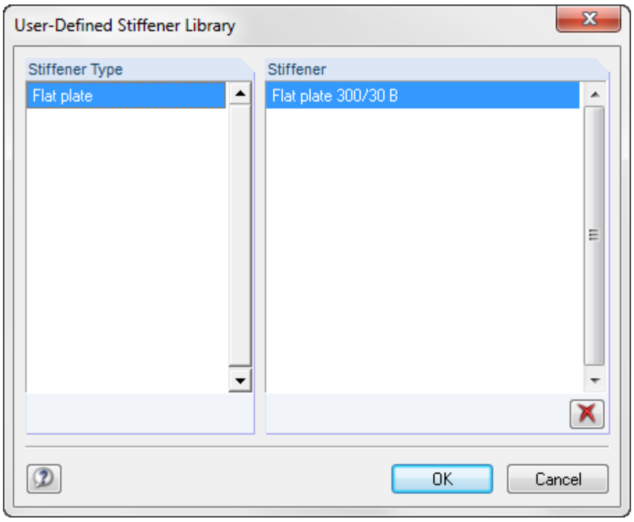


Figure 2.8: *User-Defined Stiffener Library*

To transfer a saved stiffener to the dialog box *Flat Plate Stiffener* and, if necessary, modify it, double-click the relevant stiffener in the library.

Click [OK] to exit the *Flat Plate Stiffener* dialog box and to transfer the stiffener to the PLATE-BUCKLING input Window 1.2. If you do not want to transfer the stiffener to the input table, click [Cancel].

In column E *Parameters* of Window 1.2, the properties of the specified stiffener are displayed. To edit the input data, click the button [...].

When you have defined the loads in Window 1.3 *Loads*, the layout in Window 1.2 *Stiffeners* changes as follows.

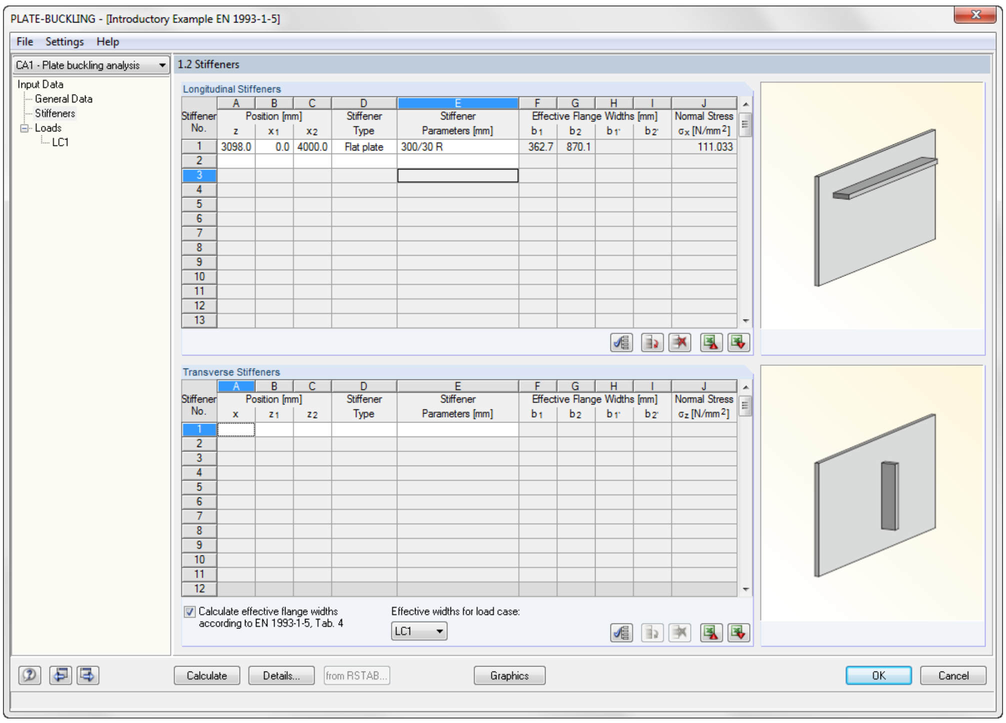


Figure 2.9: Window 1.2 *Stiffeners*

Effective flange widths

This table part is shown only after you have entered the loading in Window 1.3.

The effective flange widths of the stiffeners are used to determine the critical buckling stresses and calculate the critical buckling stress of the stiffeners.

You have to specify whether or not to calculate the effective width according to the standard (EN 1993-1-5 or DIN 18800). When you have cleared the check box, you can define the effective flange widths in columns F to I manually.

According to EN 1993-1-5, the Table 4.1 or 4.2 is used, according to DIN 18800-3, chapter (4). Note that you have to consider the *Boundary Conditions* defined in Window 1.1 *General Data*.

Moreover, the respective normal stress resulting from the provided loads is displayed for the respective stiffener under the normal stresses.

If several load cases are defined, the effective flange widths are calculated and displayed separately. Then you can use the drop-down list to choose the individual load cases.

2.3 Loads

In this window, you can specify the loads (stresses) on the buckling panel.

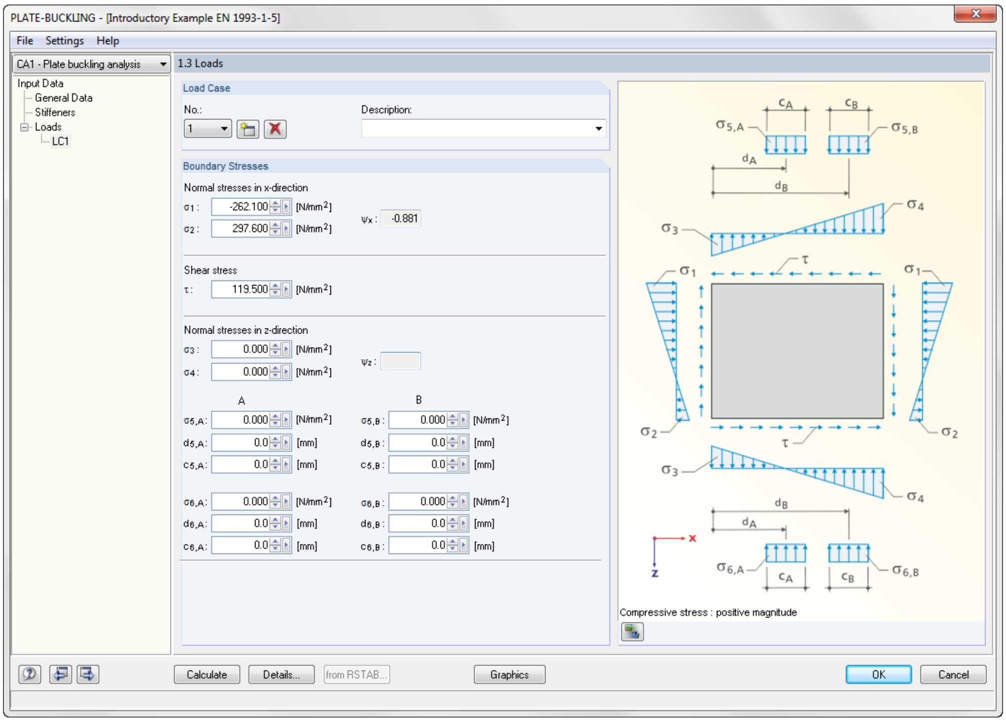


Figure 2.10: Window 1.3 *Loads*

Load Case

Assign a *No.* to the new load case and enter a *Description*. To show the descriptions already used, click [▼]. To create a new load case No., click [New]. To delete a current load case, click [Delete].

Boundary Stresses

In this dialog section you have to specify the effective normal stresses (*Normal stresses in x-direction*), shear stresses, and transverse stresses (*Normal stresses in z-direction*). Compressive stresses are specified as positive, tensile stresses as negative, and shear stresses as positive.

Note on *Normal stresses in z-direction*

In PLATE-BUCKLING, you can combine transverse stresses and local transverse stresses. The superposition principle is used here. Thus, the stress resulting from the superposition is the governing loading of the buckling panel.

Import stresses from RSTAB or RFEM

Click [from RSTAB]/[from RFEM] to import the buckling panel stresses from RSTAB resp. RFEM. A dialog box opens where you can select the *Member*, the *c/t-Part*, and the relevant *Load Cases*.

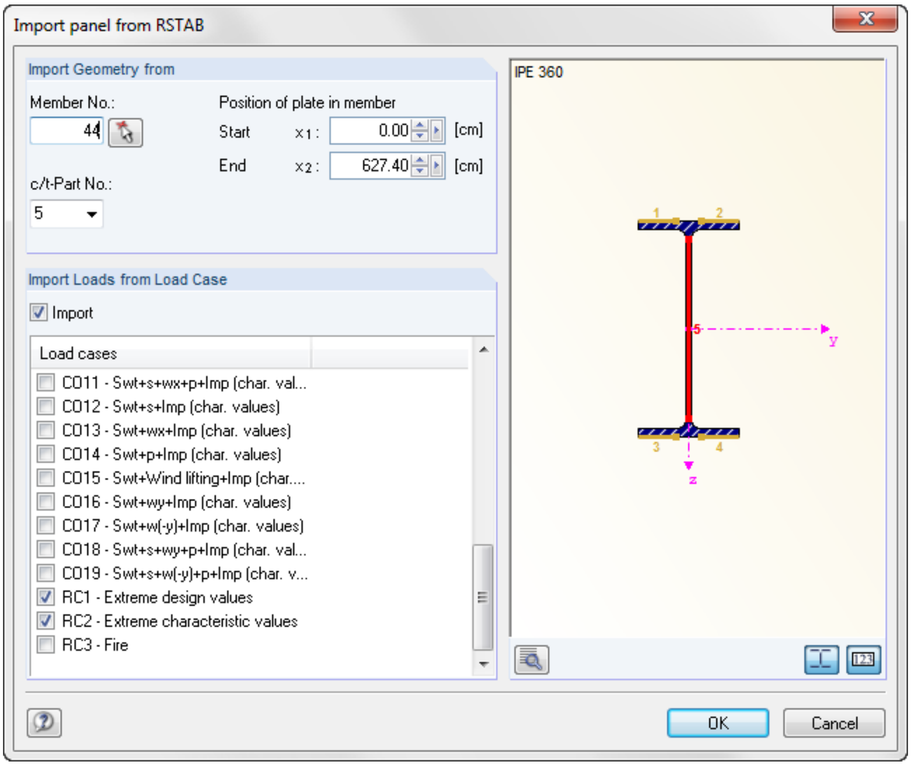


Figure 2.11: *Import panel from RSTAB*

To select a member in the work window graphically by clicking it, use the button [↖].

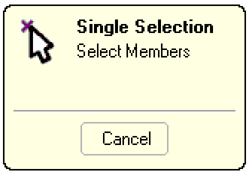
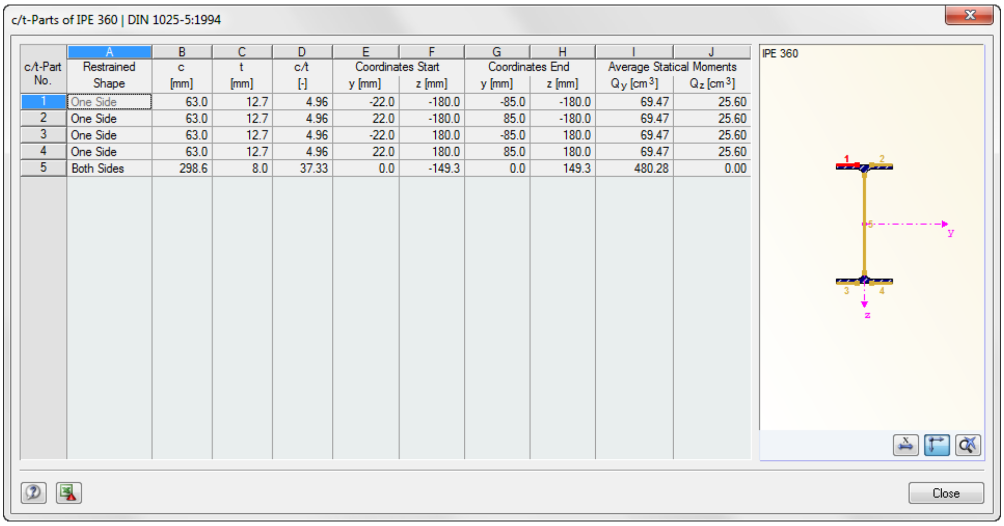


Figure 2.12: Graphical selection of members

Immediately after you have selected a member by clicking it, the number of the member is entered in the dialog box. Furthermore, when exiting the dialog box, a query appears as to whether or not you want to adjust the panel dimensions in Window 1.1 *General Data* to the geometrical conditions of the member.

The relevant panel can be selected from the list *c/t-Part No.* or in the cross-section graphic. Thus you can adjust the geometrical parameters of the panel in Window 1.1 *General Data*.

To receive further information on the buckling panel data, click [Details about c/t-parts].



c/t-Part No.	A Restrained Shape	B c [mm]	C t [mm]	D c/t [-]	E Coordinates Start y [mm]	F Coordinates Start z [mm]	G Coordinates End y [mm]	H Coordinates End z [mm]	I Average Statical Moments Q_y [cm³]	J Average Statical Moments Q_z [cm³]
1	One Side	63.0	12.7	4.96	-22.0	-180.0	-85.0	-180.0	69.47	25.60
2	One Side	63.0	12.7	4.96	22.0	-180.0	85.0	-180.0	69.47	25.60
3	One Side	63.0	12.7	4.96	-22.0	180.0	-85.0	180.0	69.47	25.60
4	One Side	63.0	12.7	4.96	22.0	180.0	85.0	180.0	69.47	25.60
5	Both Sides	298.6	8.0	37.33	0.0	-149.3	0.0	149.3	480.28	0.00

Figure 2.13: *c/t-parts*

In the dialog section *Import Loads from Load Case* in the dialog box *Import panel from RSTAB* (see Figure 2.11), you can select the loading of the panel from all RSTAB load cases.

After exiting the dialog box *Import panel from RSTAB* by clicking [OK], the RSTAB calculation of the load cases not calculated yet is started automatically. To close the dialog box without importing the data, click [Cancel].

Graphic window

To select the view mode of the graphic, click [Show figure or rendering]. In addition to the panel figure with the stress graphics, 3D rendering of the panel is possible.

You can control the rendering view of the panel selected for analysis by using the buttons shown on the left. If your pointer is in the graphic window, you can use the zoom and rotation functions. For more information, see [3], chapter 3.4.9.

3. Calculation

Before you start the [Calculation], it is recommended to check the design details. The corresponding dialog box can be accessed in all windows of PLATE-BUCKLING by clicking [Details].

3.1 Details DIN 18800

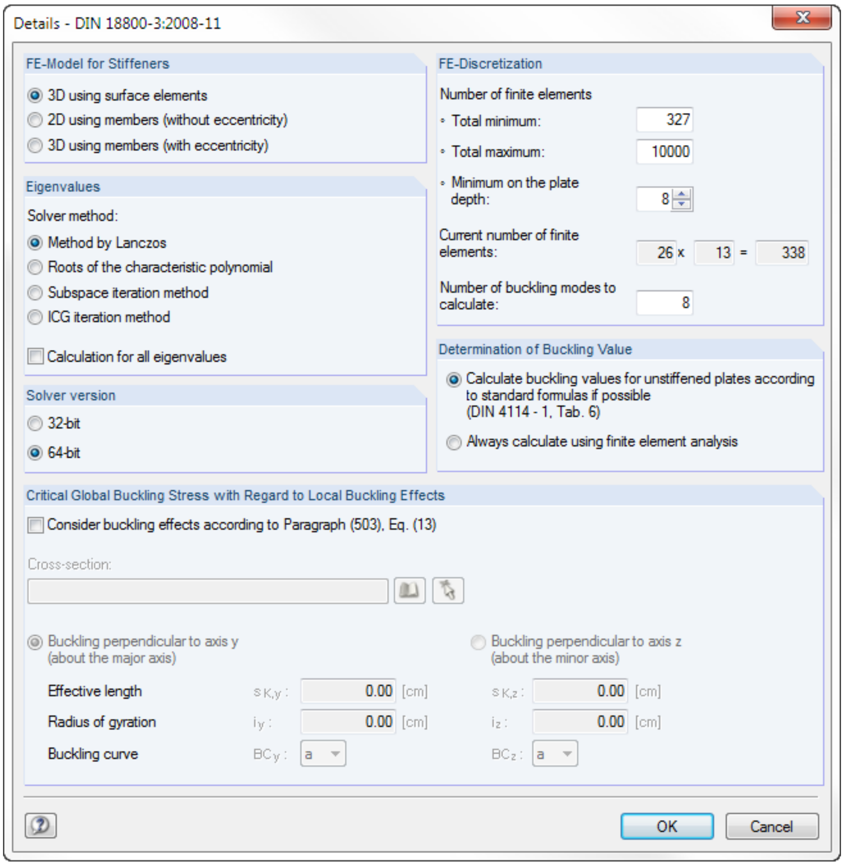


Figure 3.1: Dialog box *Details - DIN 18800-3*

FE-Model for Stiffeners

In this dialog section, you have to specify according to which conventions the stiffeners are to be considered in the calculation of the buckling shape. In the settings *3D using surface elements* and *3D using members*, the real stiffnesses of the stiffeners are included in the calculation. The option *2D using members* considers the stiffener only in relation to the centroid as a line element with increased stiffnesses in the plate plane. Thus, the advantages of the stiffener's eccentric connection are lost. Use the *3D* options in order to better consider the effectiveness of the cross-section in the design ratio. If, however, you use the *2D using members* option, the calculation time will be reduced significantly.

Eigenvalues

The determination of a buckling shape of a plate is performed as an eigenvalue calculation of the buckling panel. Here, the program calculates the ideal plate buckling values σ_x, σ_y, τ as well as the ideal buckling value for the simultaneous occurrence of all stress components. To do this, you can use one of the three direct solver methods (*Method by Lanczos*, *Roots of the characteristic polynomial*, *Subspace iteration method*) or the iterative solver (*ICG iteration method*).

The direct solver methods are recommended for small and medium-sized models. However, the RAM memory should be large enough for the files of the triangular decomposition, or else this method will result in longer computing times. The method by Lanczos is preset because it is suited for most models. For further information on that method, see http://en.wikipedia.org/wiki/Lanczos_algorithm.

The ICG iteration method should be applied if none of the direct methods is successful, or if it takes really much time to calculate large models. The advantages of that method are minimum requirements for the size of RAM memory as well as the output of accurate results in case of poorly convergent models, that is, systems that are close to instability.

To perform the plate buckling analysis for each selected eigenmode and its eigenvalues, select the option *Calculation for all eigenvalues*. If the check box is cleared, the first eigenmode is considered as governing.

Solver Version

This dialog section controls whether the *32-bit* or *64-bit* solver method is to be applied.

FE-Discretization

The fields *Number of finite elements* control the degree of refinement of the FE mesh. To obtain a good approximation solution, it might be necessary to increase the number of elements of the FE mesh. However, a large number of finite elements requires a longer computing time.

To carry out the calculation, at least four elements must be created *Minimum on the plate depth*.

PLATE-BUCKLING determines the most unfavorable buckling shapes, whereby the lowest buckling shape corresponds with the governing buckling shape. A large *Number of buckling modes to calculate* will affect the computing time.

Determination of Buckling Value

In this dialog section, you decide which method to use for the computation of buckling values: analytically according to *standard formulas* or according to the *finite element* method. If there are stiffeners in the model, FE-BEUL uses the option *Always calculate using finite element analysis* to calculate the buckling value. The applied calculation method is documented in the result window.

Critical Local Buckling Stresses with Regard to Global Buckling Effects

If a buckling analysis is required for the structural component containing the buckling panel, select the check box *Consider Buckling Effects according to Paragraph (503), Eq. (13)*. This is the case if the buckling panel is, for example, part of a compression member. Thereby, a reciprocal influence of plate buckling and local buckling is given: If single cross-section elements of the compression member buckle before the critical compressive force is reached, a reduction of stiffness will be the result for the compression member. The bearable compressive force falls to a value smaller than the critical compression force.

If you select the check box, the fields below become available for the input of the parameters.

To use the cross-section library from RSTAB or RFEM, click [Library]. To import the cross-section properties and the length of a member from the work window in RSTAB or RFEM, use the [↖] button. The parameters for *Buckling perpendicular to axis y* are then entered automatically. The cross-section's effective length, radius of gyration, and buckling curve can be defined manually, too.

3.2 Details EN 1993-1-5

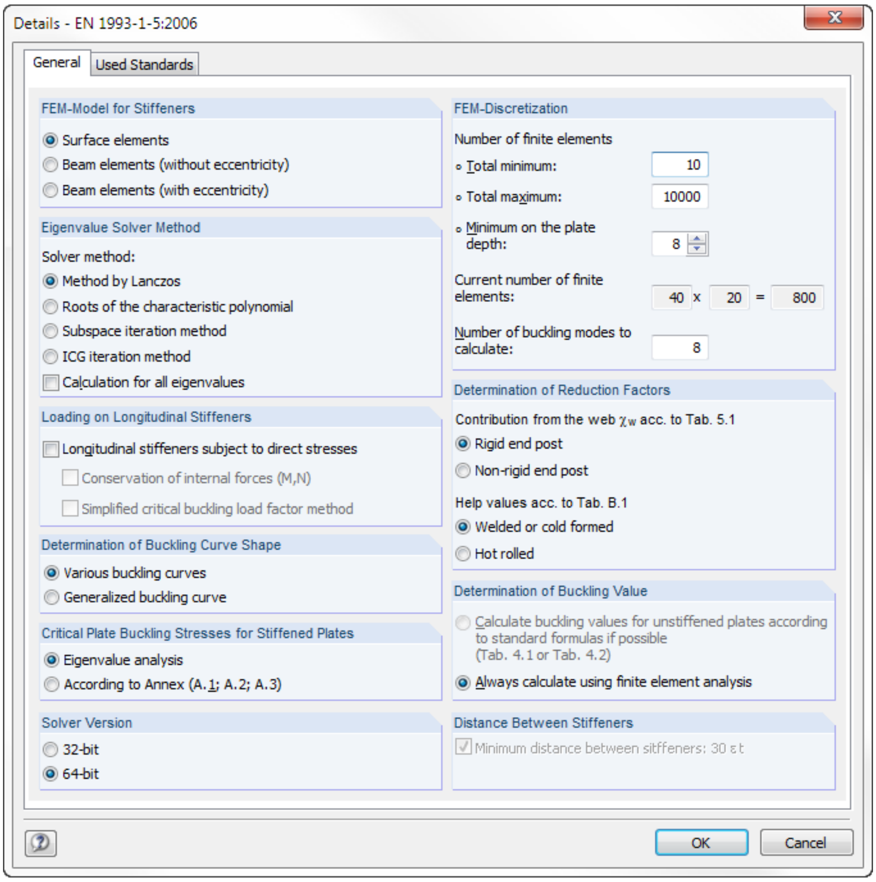


Figure 3.2: Dialog box *Details - EN 1993-1-5*

The dialog sections ***FEM-Model for Stiffeners***, ***Eigenvalue Solver Method***, ***Solver Version***, ***FEM-Discretization***, and ***Determination of Buckling Value*** are described in chapter 3.1.

Loading on Longitudinal Stiffeners

If the *Longitudinal stiffeners subject to direct stresses* box is checked, the stresses defined in the longitudinal direction are also applied to the longitudinal stiffeners and will be considered in the calculation of the eigenvalues. If not, the stresses act on the panel only.

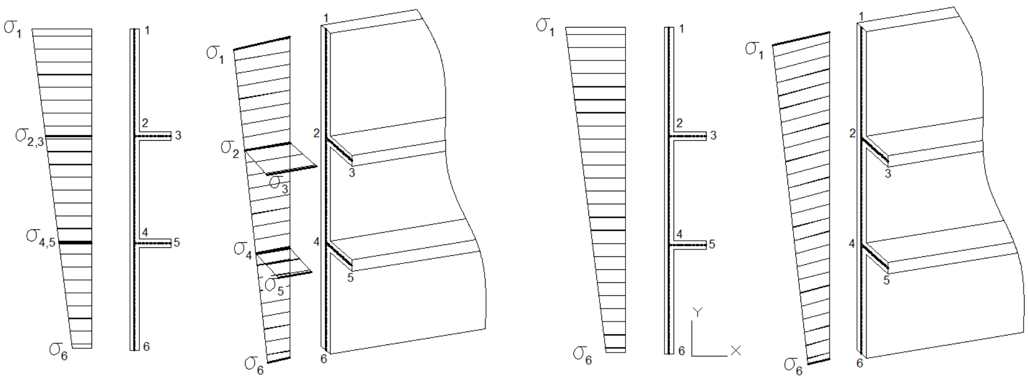
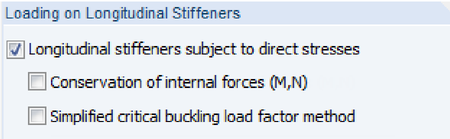


Figure 3.3: Longitudinal stresses applied to panel and stiffeners (left) or panel only (right)

Longitudinal stiffeners subject to direct stresses

If the *Longitudinal stiffeners subject to direct stresses* check box is selected, the stress is distributed along the stiffeners according to the stresses defined in Window 1.3 *Loads*.



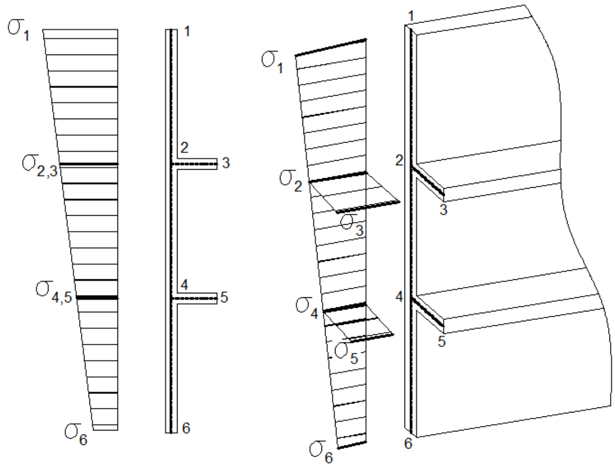
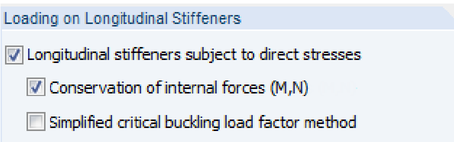


Figure 3.4: Stress distributed along the stiffeners

Loading on stiffeners with conservation of internal forces



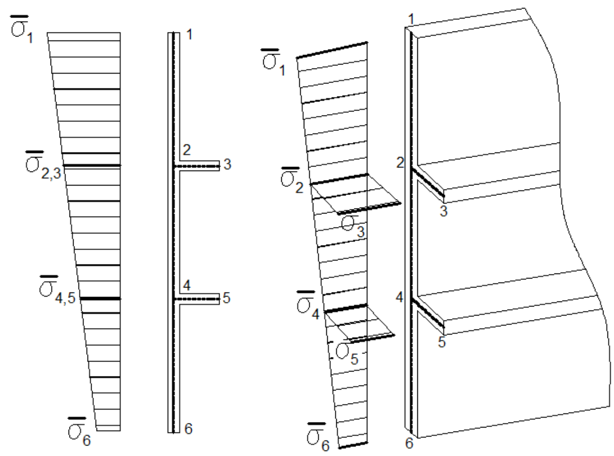


Figure 3.5: Stress distributed according to *Conservation of internal forces (M, N)*

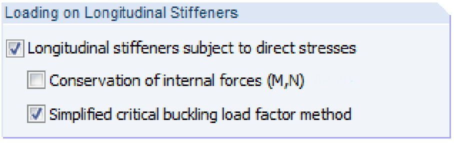
In order to maintain the original internal forces (M, N) in the cross-section, the stress must be recalculated. Only in this way is it possible to observe the relationship between external loading and internal forces of the initial model where the stiffeners have not yet been implemented. Adding stiffeners to the panel without recalculating the stress will result in an imbalance between the external loads and the internal forces.

To recalculate the stress, a linear stress distribution is considered as shown in Figure 3.5, using the following equations.

$$\oint_A \sigma(\bar{a})d\bar{a} = \oint_A \sigma(a)da = N$$

$$\oint_A \sigma(\bar{a})z\cdot d\bar{a} = \oint_A \sigma(a)da\cdot z = M$$

Loading on stiffeners with simplified critical buckling load factor method



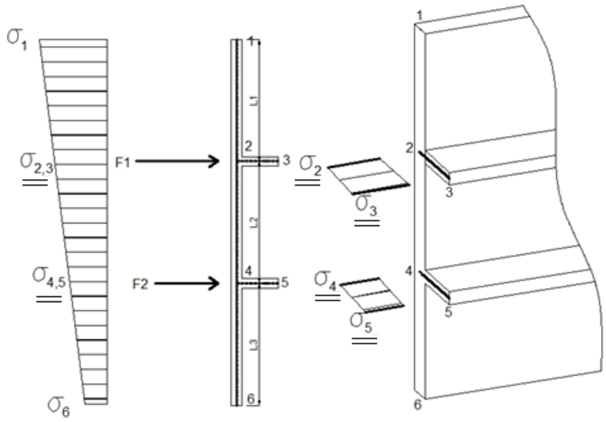


Figure 3.6: Stress distributed according to *Simplified critical buckling load factor method*

With this method, the horizontal stresses are completely concentrated in the stiffeners. An advantage of this method is that only few local extremes of the buckling modes have to be calculated. The stress in the stiffener corresponds to a proportional part of the length of the panel adjacent to the stiffener. This method is described in [18] at page 65.

$$F_1 = \int_{L_1/2}^{L_2/2} \sigma(x)tdz + A_{Stiff\_1}\sigma_{2,3}$$

$$F_2 = \int_{L_2/2}^{L_3/2} \sigma(x)tdz + A_{Stiff\_2}\sigma_{4,5}$$

$$\underline{\underline{\sigma_2}} = \underline{\underline{\sigma_3}} = F_1 / A_{Stiff\_1}$$

$$\underline{\underline{\sigma_4}} = \underline{\underline{\sigma_5}} = F_2 / A_{Stiff\_2}$$

It is possible to combine the *Simplified critical buckling load factor* and the *Conservation of internal forces* methods.

Determination of Buckling Curve Shape

For the interaction formula and the reductions factors, EN 1993-1-5 provides the possibility either to use a *Generalized buckling curve* for the entire analysis or *Various buckling curves* for each existing stress.

Critical Plate Buckling Stresses for Stiffened Plates

The *Annex* to EN 1993-1-5 provides analytical methods for the determination of critical plate buckling stresses. The following variants are included in the standard:

- one or two stiffeners in the compression area of the buckling panel
- three or more stresses in the buckling area

If the check box *According to Annex* is selected, PLATE-BUCKLING analyzes the stiffeners and load situation and calculates the critical plate buckling stress according to the governing variant. If the required restrictions are not met, the buckling values are determined according to the *Eigenvalue analysis* (FE method), thus computing the buckling stress.

Determination of Reduction Factors

According to *Table 5.1* of EN 1993-1-5, you can select a rigid end-post or non-rigid end-post to determine χ_w (web contribution). To make use of the standard's possibilities, choose between the two options.

When you determine the reduction factors for the plate buckling, the program, according to EN 1993-1-5, Annex B.1, *Table B.1*, distinguishes between welded or cold-formed and hot-rolled products. Use the check boxes to select one of these variants.

4. Results

Immediately after the calculation, the Window 2.1 *Governing Load Case* appears. The Windows 2.1 to 2.5 display the designs including the explanations for each structural component. Every window can be opened from the PLATE-BUCKLING navigator. As an alternative, you can use the function keys to select the next [F2] or previous [F3] window.

Click [OK] to save the results. Thus you exit PLATE-BUCKLING and return to the RSTAB or RFEM work window.

Chapter 4 *Results* describes the results windows one by one. Evaluating and controlling results is described in chapter 5 *Results Evaluation*, page 27 ff.

4.1 Governing Load Case

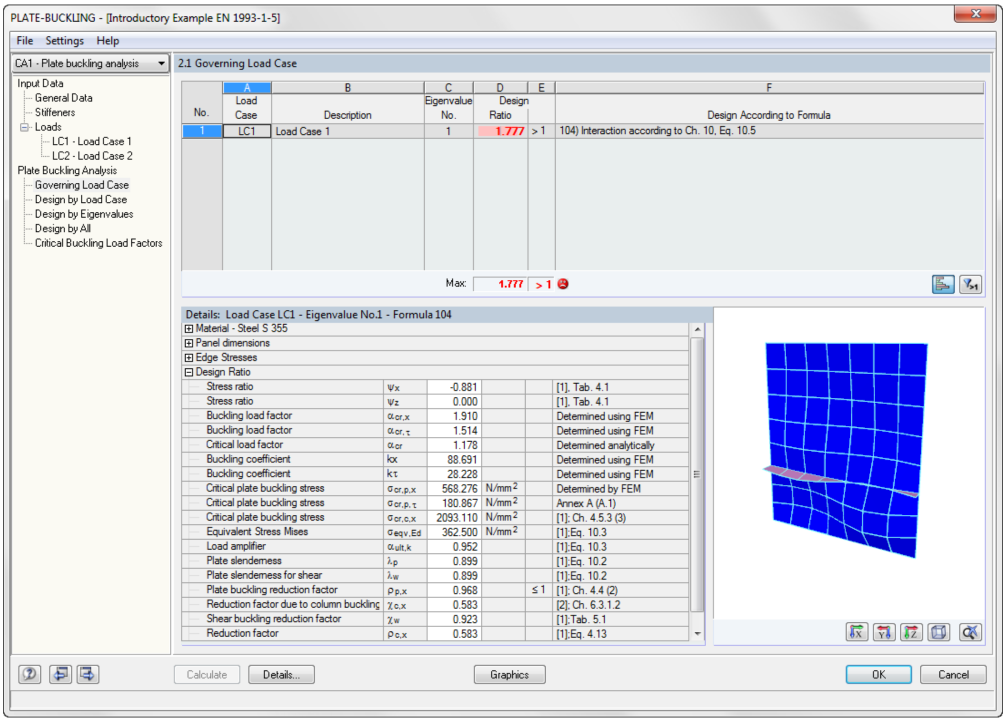


Figure 4.1: Window 2.1 *Governing Load Case*

Description

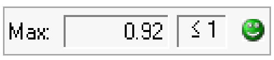
This column provides information on the description of load cases, load combinations, and result combinations governing for the respective designs.

Eigenvalue No.

For each designed load case, load combination, and result combination, the number of the eigenvalue (buckling shape) with the highest design ratio is displayed.

Design

For each type of design as well as for each load case or load combination and result combination, the design conditions are displayed according to EN 1993-1-5 or DIN 18800.



The colored scales visualize the ratios due to individual load cases.

Design According to Formula

This column lists the code's equations by which the designs have been performed.

Details

In the lower dialog section *Details*, the intermediate result for the performed designs are shown in a comprehensible form with references to the selected standard.

Graphic window

The graphic window shows the designed panel using 3D rendering. The different view modes can be controlled by using the buttons bellow the graphic window. For more information, see [3], chapter 3.4.9.

4.2 Design by Load Case

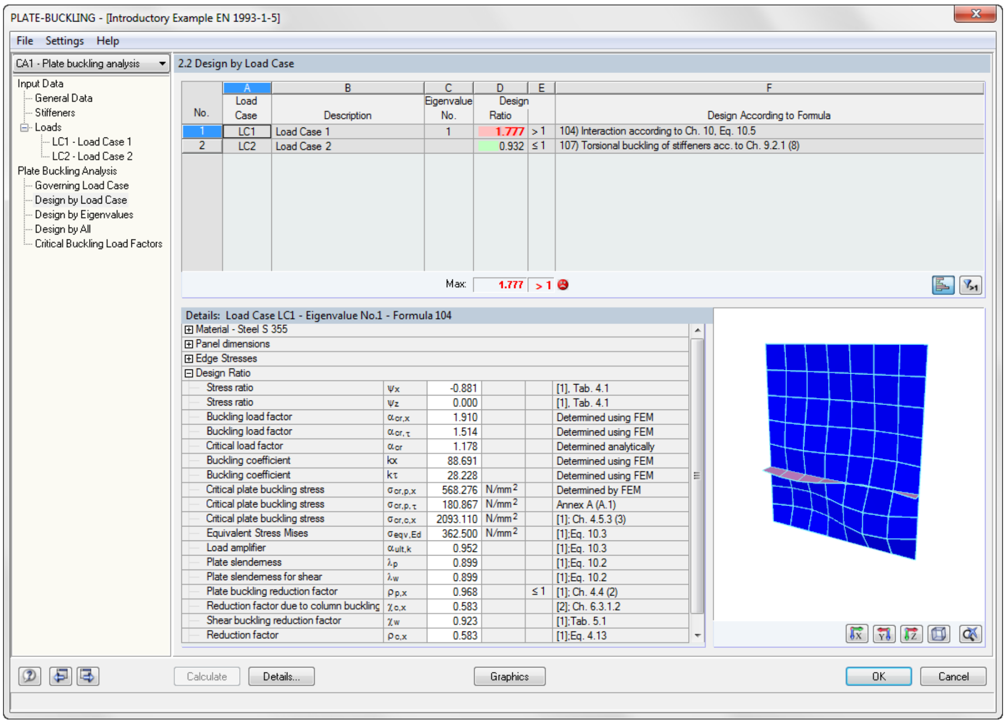


Figure 4.2: Window 2.2 *Design by Load Case*

This window lists the maximum ratios and the corresponding governing designs of all load cases, load combinations, and result combinations defined for the design.

Dlubal

4.3 Design by Eigenvalues

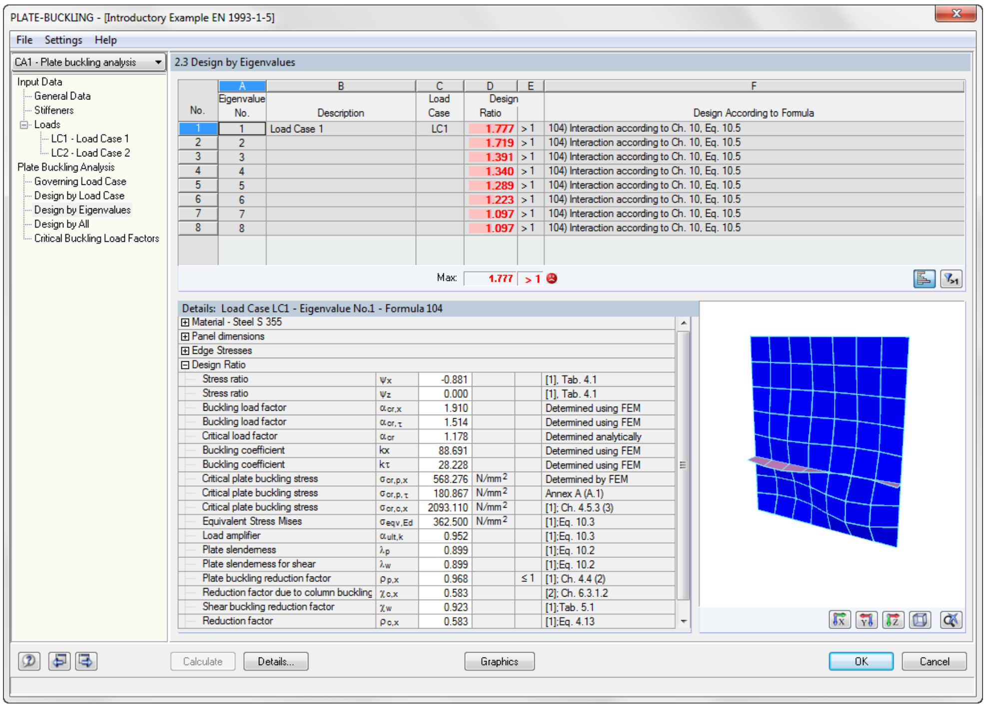


Figure 4.3: Window 2.3 *Design by Eigenvalues*

Calculation for all eigenvalues

This results window will be shown if you select the check box *Calculation for all eigenvalues* in the dialog box *Details* (see Figure 3.2, page 19). PLATE-BUCKLING calculates the designs for the selected amount of eigenmodes. Then, the governing load case with the respective design is displayed in Window 2.3.

4.4 Design by All

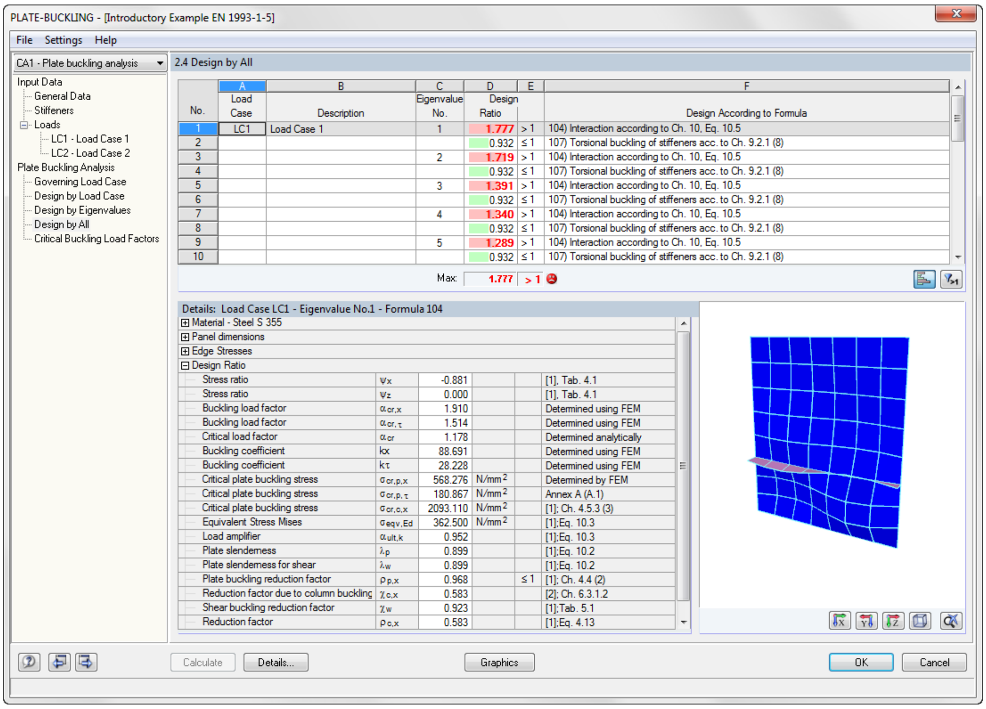


Figure 4.4: Window 2.4 *Design by All*

This window displays an overview of all results with reference to EN 1993-1-5, EN 1993-1-1 and Design of Plated Structures ISBN (ECCS Design Manual): 978-92-9147-100-3 for European Standards or DIN 18800-3 for the German Standard.

According to *DIN 18800-3*, the calculation results are displayed separately for the actions of only one edge stress and to an action due to simultaneous occurrence of all edge stresses.

The designs according to *EN 1993-1-5* include the interaction design of the buckling panel and the other designs that are required for the possibly existing stiffeners.

4.5 Critical Buckling Load Factors

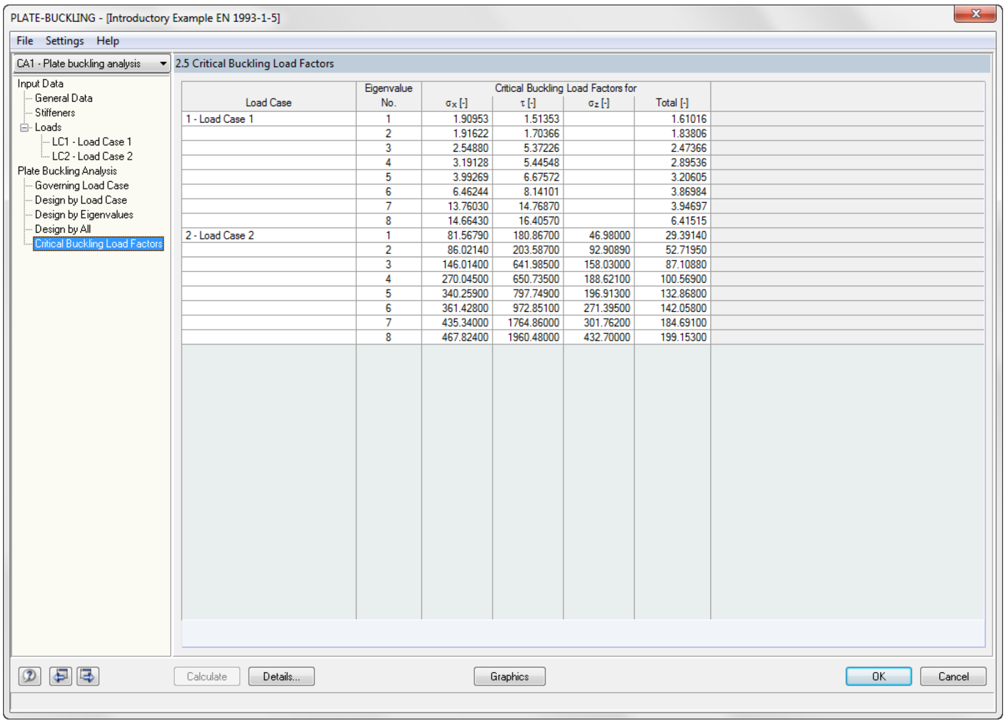


Figure 4.5: Window 2.5 *Critical Buckling Load Factors*

The last result window displays the critical buckling load factors resulting from σ_x, τ and σ_z (σ_y) for all load cases. They are listed by action for all buckling shapes.

5. Results Evaluation

You can evaluate the design results in various manners.

5.1 Results Windows

The buttons at the end of the upper table facilitate the evaluation in the results windows.

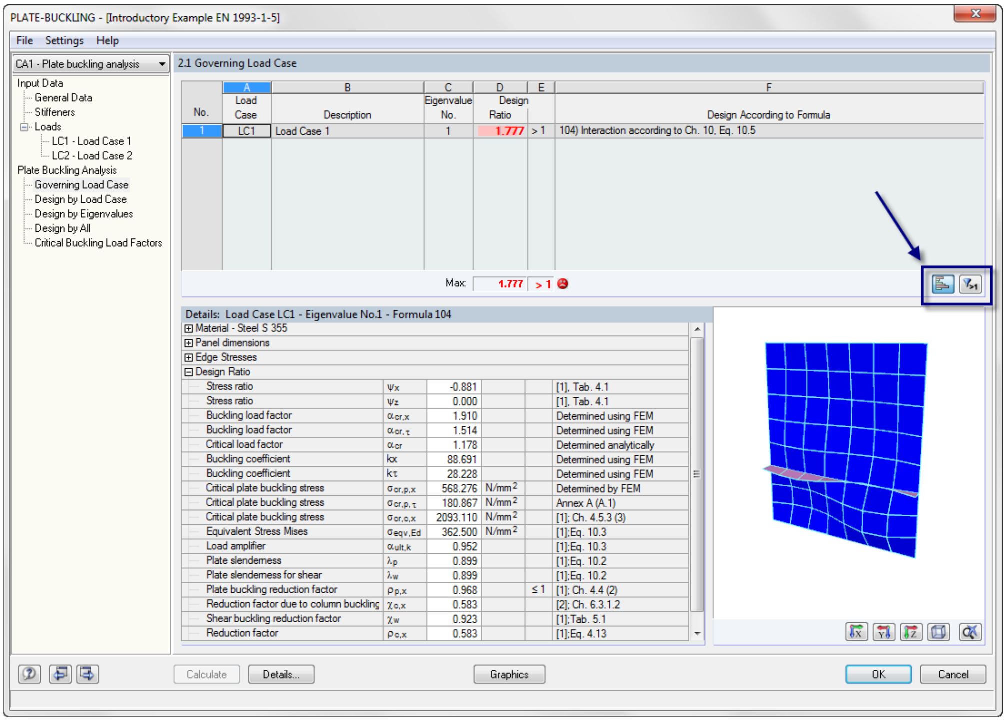


Figure 5.1: Buttons for results evaluation

The buttons are reserved for the following functions:

Button	Description	Function
	Show Color Bars	Turns on and off the colored reference scales in the results tables
	Exceeding	Displays only the rows where the ratio is greater than 1, and thus the design is failed

Table 5.1: Buttons in results windows 2.1 to 2.5

5.2 Visualization of Buckling Shapes

To display the buckling shapes graphically, click [Graphics]. To this end, a PLATE-BUCKLING window opens.

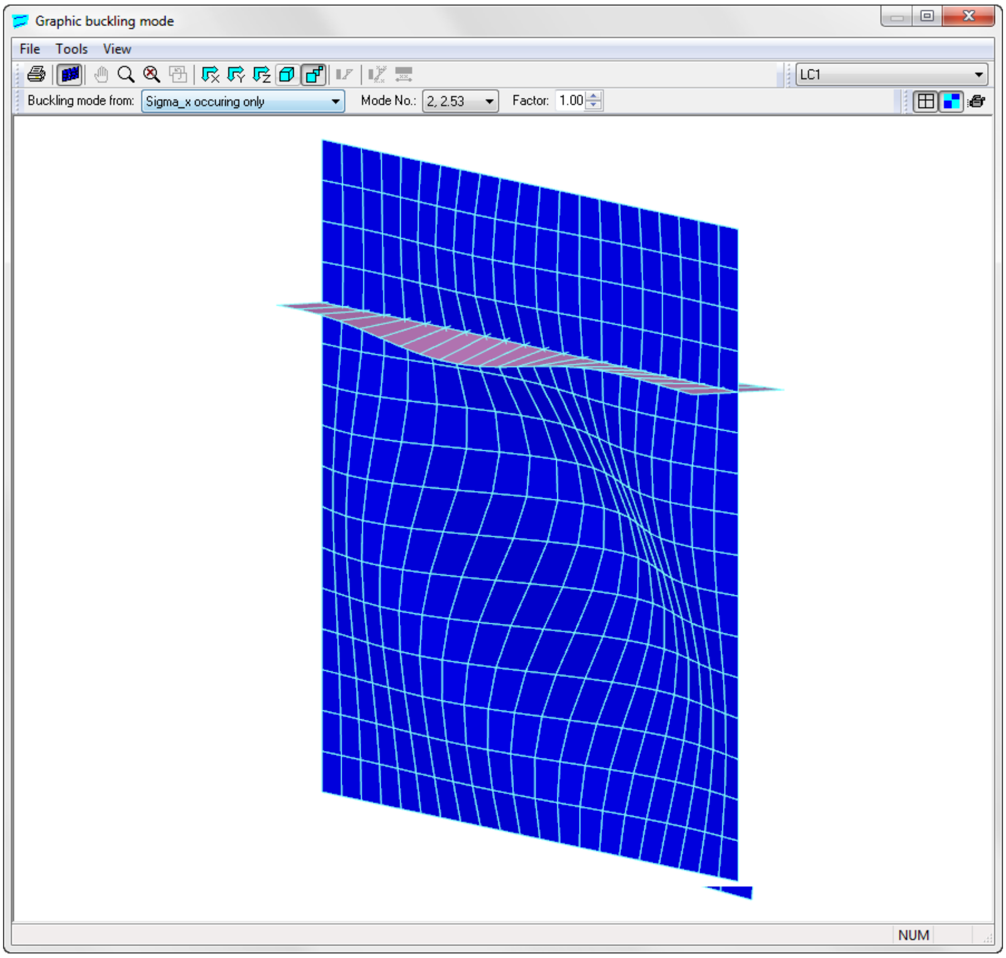
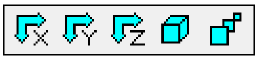


Figure 5.2: *Graphic Buckling mode*

In this window, you can visualize different actions on the panel, different load cases and buckling shapes. For load cases that are not calculated yet, the loads on the panel are shown. The graphical representation allows for a quick check of the buckling shapes and load data.



The graphic can be controlled by using the drop-down menu or the functions of the toolbar. The buttons shown on the left allow you to view the buckling panel from different angles.

The grab button is a special feature: By left-clicking and pressing the [Shift] key simultaneously while moving the mouse up or down, you can zoom the view in or out. By left-clicking and pressing the [Ctrl] key at the same time, you can rotate the view. You can "play" with this function in order to better understand how it works.

The field [Factor] allows you to show small deformations as elevated.

The [Animation] of the buckling shapes often helps to understand the buckling behavior of the stiffened plates.

6. Printout

6.1 Printout report

First, the program generates a printout report for the PLATE-BUCKLING results, to which graphics and descriptions can be added. In the printout report, you can select the data to be included in the printout.

The printout report is described in detail in the RSTAB or RFEM manual [3]. In particular, chapter 10.1.3.4 *Selecting Data of Add-on Modules* provides information on the selection of input and output data in add-on modules for the printout.

For large structural systems with many design cases, it is recommended to split the data into several printout reports, thus allowing for a clearly-arranged printout.

6.2 PLATE-BUCKLING Graphic Printout

In PLATE-BUCKLING, every picture that is displayed in the program's work window can be transferred to the printout report or sent directly to a printer.

Printing graphics is described in [3], chapter 10.2.

PLATE-BUCKLING model with loads

To print the current PLATE-BUCKLING graphic, click

File → Print Graphic

or the respective button in the toolbar.

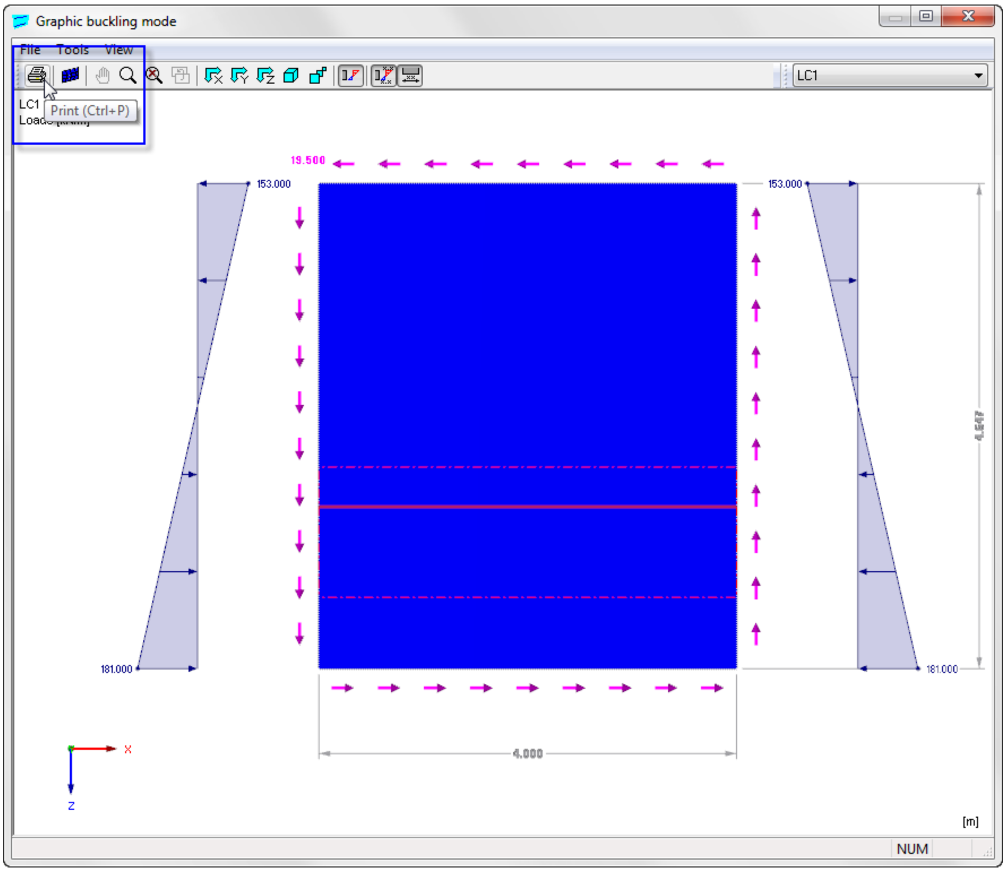


Figure 6.1: Button *Print* in the toolbar of the main window

The following dialog box appears:

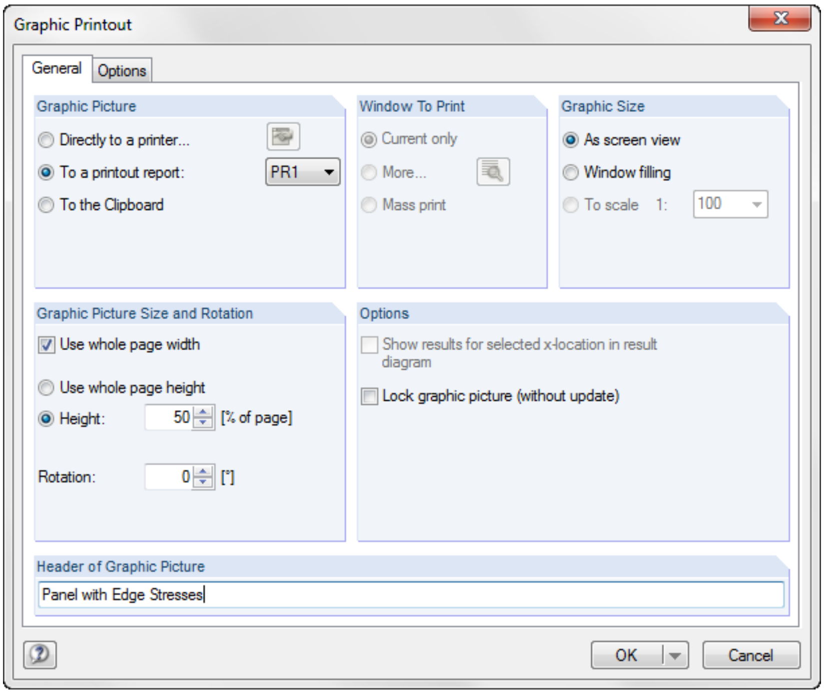
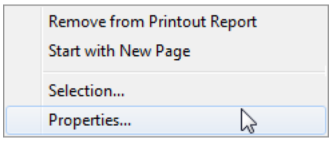


Figure 6.2: Dialog box *Graphic Printout*, tab *General*

This dialog box is described in [3], chapter 10.2. The RSTAB manual also describes the *Options* and *Color Spectrum* tab.

A graphic can be moved anywhere within the printout report by using the drag-and-drop function.



To adjust a graphic subsequently in the printout report, right-click the relevant entry in the navigator of the printout report. The option *Properties* in the context menu opens the dialog box *Graphic Printout*, offering various options for adjustment.

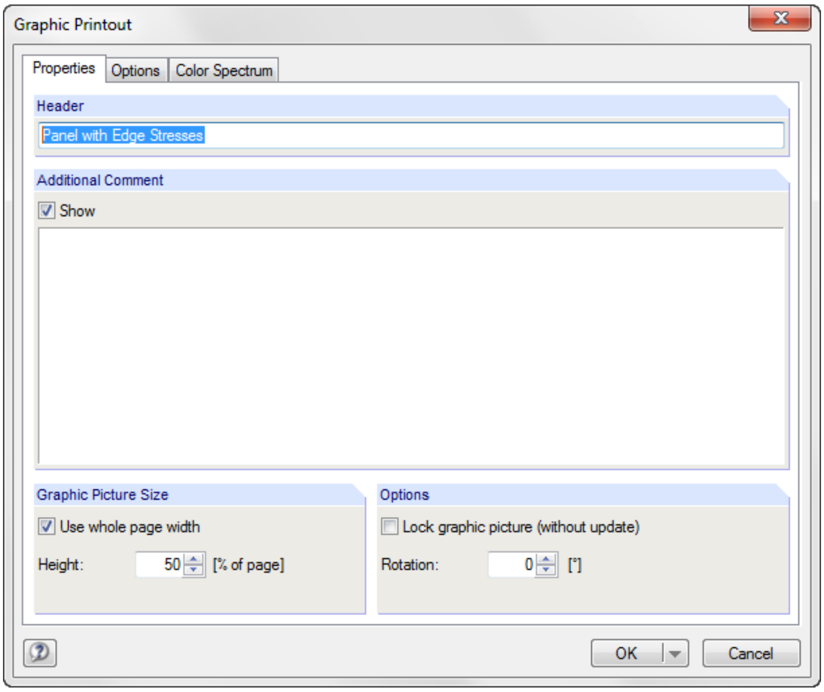


Figure 6.3: Dialog box *Graphic Printout*, tab *Options*

7. General Functions

The final chapter describes useful menu functions as well as export options for the designs.

7.1 Design Cases

With the design cases you can, for example, group the buckling panels from the model or check variants.

Create a New Design Case

To create a new design case, use the PLATE-BUCKLING menu and click

File → New Case.

The following dialog box appears:

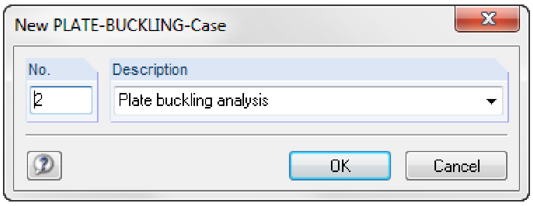


Figure 7.1: Dialog box *New PLATE-BUCKLING-Case*

In this dialog box, enter a *No.* (one that is still available) for the new design case. The corresponding *Description* will make the selection in the load case list easier.

Click [OK] to open the PLATE-BUCKLING Window 1.1 *General Data* where you can enter the design data.

Rename a Design Case

To change the description of a design case, use the PLATE-BUCKLING menu and click

File → Rename Case.

The following dialog box appears:

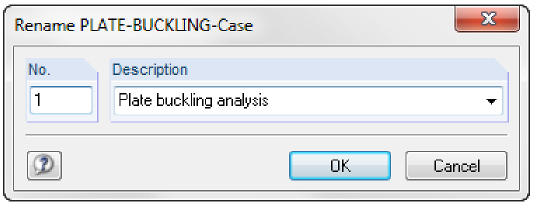


Figure 7.2: Dialog box *Rename PLATE-BUCKLING-Case*

In this dialog box, you can define a different *Description* as well as a different *No.* for the design case.

Copy a Design Case

To copy the input data of the current design case, use the PLATE-BUCKLING menu and click

File → Copy Case.

The following dialog box appears:

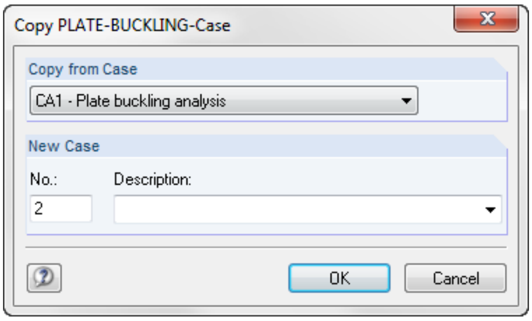


Figure 7.3: Dialog box *Copy PLATE-BUCKLING-Case*

Define the *No.* and, if necessary, a *Description* for the new case.

Delete a Design Case

To delete design cases, use the PLATE-BUCKLING menu and click

File → Delete Case.

The following dialog box appears:

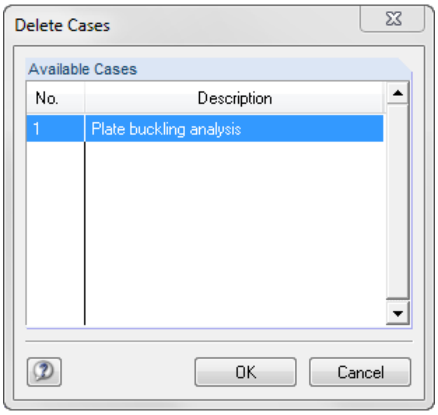


Figure 7.4: Dialog box *Delete Case*

The design case can be selected in the list *Available Cases*. To delete the selected case, click [OK].

7.2 Units and Decimal Places

Units and Decimal Places are managed in one dialog box for RFEM/RSTAB and the add-on modules. In PLATE-BUCKLING, you can use the menu to define the units. To open the corresponding dialog box, click on the menu

Settings → **Units and Decimal Places**.

The program opens the following dialog box that you already know from RSTAB or RFEM. The module PLATE-BUCKLING is preset.

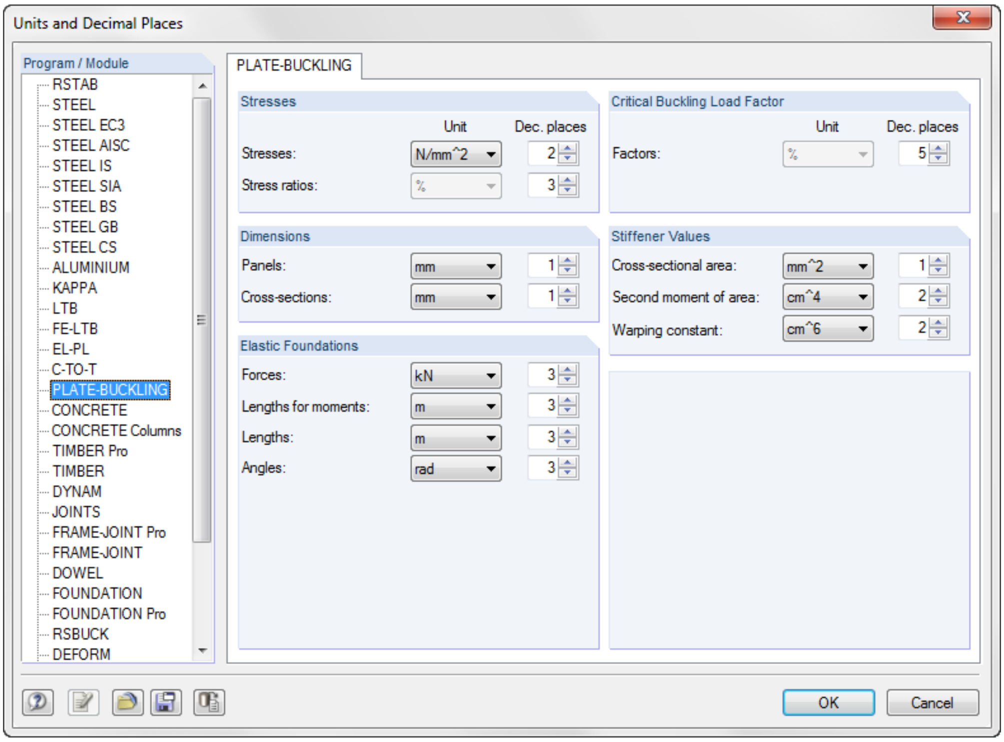


Figure 7.5: Dialog box *Units and Decimal Places*

The settings can be saved as user profile und reused in other models. These functions are described in [3], chapter 11.1.3.

7.3 Export of Results

The PLATE-BUCKLING results can also be used in other programs.

Clipboard

To copy cells selected in the results tables to the Clipboard, press the keys [Ctrl]+[C]. To insert the cells, for example in a word-processing program, press [Ctrl]+[V]. The headers of the table columns will not be transferred.

Printout report

The data of the PLATE-BUCKLING add-on module can be printed into the global printout report (see chapter 6.1, page 29) to export them subsequently. Then, in the printout report, click

File → **Export to RTF**.

This function is described in [3], chapter 10.1.11.

Excel / OpenOffice

PLATE-BUCKLING provides a function for the direct data export to MS Excel, OpenOffice.org Calc, or the file format CSV. To open the corresponding dialog box, click

File → Export Tables.

The following export dialog box appears.

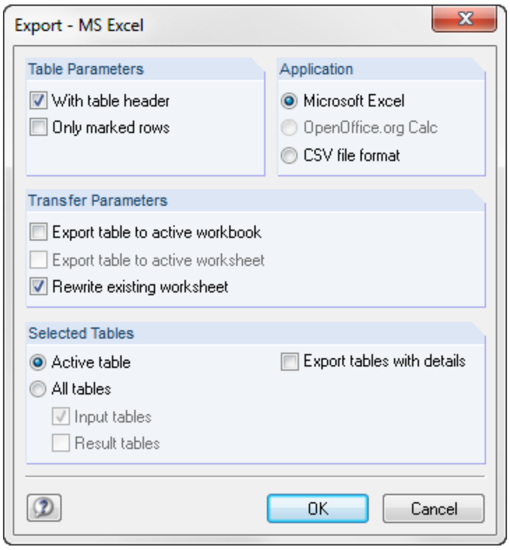


Figure 7.6: Dialog box *Export - MS Excel*

When you have selected the relevant parameters, you can start the export by clicking [OK]. Excel or OpenOffice will be started automatically, that is, the programs do not have to be opened first.

A	B	C	D	E	F	G
	Load		Eigenvalue	Design		
No.	Case	Description	No.	Ratio		Design According to Formula
1	LC1		1	0,981	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5
2				0,932	≤ 1	107) Torsional buckling of stiffeners acc. to Ch. 9.2.1 (8)
3			2	0,977	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5
4				0,932	≤ 1	107) Torsional buckling of stiffeners acc. to Ch. 9.2.1 (8)
5			3	0,877	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5
6				0,932	≤ 1	107) Torsional buckling of stiffeners acc. to Ch. 9.2.1 (8)
7			4	0,828	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5
8				0,932	≤ 1	107) Torsional buckling of stiffeners acc. to Ch. 9.2.1 (8)
9			5	0,788	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5
10				0,932	≤ 1	107) Torsional buckling of stiffeners acc. to Ch. 9.2.1 (8)
11			6	0,728	≤ 1	104) Interaction according to Ch. 10, Eq. 10.5

Figure 7.7: Result in *Excel*

8. Theoretical Background

8.1 DIN 18800-3

Buckling means that plane thin-walled plates whose plate thickness *t* is significantly smaller than the surface geometry $a \cdot b$ and that are subjected to normal and shear stresses deflect perpendicular to the plate plane. Rectangular plates prone to buckling are called buckling panels.

When you analyze a buckling problem, you must consider the plate's states of stress and deformation. For this, you have to consider the following parameters:

- Position of the web and flange zones most prone to buckling
- Dimensions of the buckling panels
- Supports of the buckling panel edges
- Loading in the form of the stresses acting upon the edge surfaces

The program PLATE-BUCKLING is based on the finite element method and can be used to determine critical buckling load factors. The following is assumed for the calculation (linear buckling analysis):

- At the beginning of the loading, the plate is completely plane.
- The buckling deformations rectangular to the plate plane are small.
- The loading acts only on the plate's center plane.
- The material is assumed to behave in an ideal linear elastic way.

With these assumptions for plate buckling, a bifurcation problem arises. Linear buckling analysis is only used to determine a plate slenderness ratio. The reduction factors κ required for plate buckling analysis depend on the plate slenderness.

8.1.1 Terms and Definitions

Critical plate buckling stress

Under this loading, the plate can still remain in its original position. If the loading is increased further, the plate buckles.

$\sigma_{xPi} = k\sigma_x * \sigma_E$ Critical buckling stress with sole action of edge stresses σ_x

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-\mu^2)} \cdot \left(\frac{t}{b}\right)^2$$ Euler's critical stress

With these input values, you can determine the critical plate buckling stress for the sole action of σ_x, σ_x and τ. The smallest critical plate buckling stress and, therefore, the smallest buckling value are governing for buckling. The buckling value and thus the critical plate buckling stress depend on the following influences:

- Boundary conditions (support conditions)
- Type of action
- Side ratio α
- Type and position of stiffeners

In PLATE-BUCKLING, the buckling values are usually determined by using the FE method, solving the eigenvalue problem.

Critical plate buckling stress

With reference to the linear buckling analysis, the reduction factors κ for the critical plate buckling stress are determined in relation to the panel dimensions, the support and load conditions, as well as the plate slenderness ratio. The following factors also influence the calculation of the critical plate buckling stress:

- Structural components without local buckling effects (pure bending)
- Structural components with local buckling effects (bending beams with compressive force / compression columns with bending moments)
- Plates without local buckling behavior
- Plates with local buckling behavior

Critical plate buckling stress without buckling effects

The critical plate buckling stresses are determined according to the following equations.

$$\sigma_{xP,R,d} = \kappa_x \cdot f_{y,k} / \gamma_M$$

$$\sigma_{yP,R,d} = \kappa_y \cdot f_{y,k} / \gamma_M$$

$$\tau_{P,R,d} = \kappa_\tau \cdot f_{y,k} / \left(\sqrt{3} \cdot \gamma_M\right)$$

Critical plate buckling stresses with buckling effects

If the buckling panel is part of a compression member, the reciprocal influence of plate buckling and local buckling must be considered. This is achieved by reducing the critical plate buckling stress with the reduction factor κ_K for local buckling.

$$\sigma_{xP,R,d} = \kappa_K \cdot \kappa_x \cdot f_{y,k} / \gamma_M$$

To determine κ_K, see DIN 18 800 part 2, el. (304) equation (4a) - (4c).

Critical plate buckling stress with local buckling behavior

Local buckling behavior is found in a plate which is pushed in longitudinal direction and that has too small a side ratio. Then, a support of the central plate zones on the plate edges is not given. Thus, the plate, like buckling members - has no more supercritical load capacity and has to be classified between the failure modes *global buckling* and *local buckling*. This is done by using the weighting factor ρ. If weighting factor $\rho > 0$, the critical plate buckling stress must be determined by using the reduction factor κ_{PK} .

$$\rho = \frac{\Lambda - \sigma_{xPi} / \sigma_{xKi}}{\Lambda - 1} \geq 0$$

In PLATE-BUCKLING, σ_{xKi} is determined analytically. It is the Euler buckling stress of the buckling panel with unsupported longitudinal edges. For the reduction factor for local buckling behavior, according to DIN 18 800, part 3, element (603):

$$\kappa_{PK} = \left(1 - \rho^2\right) \cdot \kappa_\sigma + \rho^2 \cdot \kappa_K$$

The reduction factor κ_K is determined according to DIN 18 800 part 2, Eq. (4a), (4b), or (4c) according to buckling curve b.

The critical plate buckling stresses are calculated according to DIN 18 800, part 3, element (502) as follows.

$$\sigma_{P,R,d} = \frac{\kappa_{PK} \cdot f_{y,k}}{\gamma_M} \leq 1$$

$$\tau_{P,R,d} = \frac{\kappa_\tau \cdot f_{y,k}}{\gamma_M \cdot \sqrt{3}} \leq 1$$

Interaction condition

If several stress components σ_x, σ_x, and τ act simultaneously, you must perform the interaction design. These are always stresses that are assigned to each other.

Deviating from this provision, the maximum value is imported from every stress type when you import these stresses from RSTAB or RFEM,

$$e_1 = 1 + \kappa_{\sigma_x}{}^4$$

$$e_2 = 1 + \kappa_{\sigma_y}{}^4$$

$$e_3 = 1 + \kappa_{\sigma_x} \cdot \kappa_{\sigma_y} \cdot \kappa_\tau{}^2$$

$$V = (\kappa_x \cdot \kappa_y)^6$$

$$\left(\frac{|\sigma_x|}{\sigma_{xP,R,d}}\right)^{e_1} + \left(\frac{|\sigma_y|}{\sigma_{yP,R,d}}\right)^{e_2} - V\left[\frac{|\sigma_x \cdot \sigma_y|}{\sigma_{xP,R,d} \cdot \sigma_{yP,R,d}}\right] + \left(\frac{\tau}{\tau_{P,R,d}}\right)^{e_3} \leq 1$$

8.2 EN 1993-1-5

For every plate buckling analysis according to EN 1993-1-5, the reduced stresses are implemented in PLATE-BUCKLING. The Eurocode offers two methods for the plate buckling analysis.

- Effective width method (EN 1993-1-5, chapter 4-7)
- Reduced stress method (EN 1993-1-5, chapter 10)

The method of reduced stresses compares the stresses acting on the buckling panel with a limit stress condition reduced accounted for the VON MISES yield condition. The plate buckling analysis is performed on the basis of the entire stress field. This approach corresponds with the one from DIN 18800-3, however, with the significant difference that in EN 1993-1-5 a single global slenderness ratio is determined on the basis of the entire stress field. Thus, the analysis of the single loading and the subsequent merging via the interaction criterion is omitted.

As the determination of buckling values is based on numerical calculation in EN 1993-1-5, in PLATE-BUCKLING the input parameters can easily be determined by using the eigenvalue method.

In EN 1993-1-5, chapter 9, the designs for the possibly existing stiffeners are still required. For longitudinal and transverse stiffeners, the following analyses must be performed successfully:

- Elastic stress analysis with internal forces according to second order analysis
- Deformation analysis
- Torsional buckling analysis

The design procedure is described in detail in [18].

8.2.1 Determination of Critical Plate Buckling Stresses

The Annex to EN 1993-1-5 provides analytical formulas for calculation of the critical buckling stresses of unstiffened and stiffened buckling plates. In general, the following applies:

$$\sigma_{cr,p} = k_{cr,p} * \sigma_e$$ *Annex A, (A.1)*

For **unstiffened buckling plates**, the buckling values are computed according to Table 4.1 or Table 4.2 based on the existing edge stress condition.

- Buckling plates supported on two sides *Table 4.1*
- Buckling plates supported on one side *Table 4.2*

For **stiffened buckling plates**, the following variants of the arrangement of the stiffeners within the buckling plate are distinguished:

- Three or more longitudinal stiffeners in buckling panel *Annexes (A.1), (A.3)*
- One longitudinal stiffener in compression zone of buckling panel *Annexes (A.1), (A.2.2.2), (A.3)*
- Two longitudinal stiffeners in compression zone of buckling panel *Annexes (A.1), (A.2.2.1), (A.3)*

These formulas or their application are bound to provisions that must be considered. If these conditions are not met, PLATE-BUCKLING automatically calculates the critical plate buckling stresses by using the eigenvalue method.

8.2.2 Interaction Design

The stresses acting on the buckling panel are compared with a limit stress state reduced taking into account the von Mises yield condition. In EN 1993-1-5, only a single global slenderness ratio is determined on the basis of the entire stress field. The following parameters are relevant for the interaction design:

Slenderness ratio of sheet metal plate

$$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$$ *Eq. 10.2*

$$\frac{1}{\alpha_{ult,k}} = \left(\frac{\sigma_{x,Ed}}{f_y}\right)^2 + \left(\frac{\sigma_{z,Ed}}{f_y}\right)^2 - \left(\frac{\sigma_{x,Ed}}{f_y}\right) \cdot \left(\frac{\sigma_{z,Ed}}{f_y}\right) + 3 \cdot \left(\frac{\tau_{Ed}}{f_y}\right)^2$$ *Eq. 10.3*

$$\frac{1}{\alpha_{cr}} = \frac{1+\psi_x}{4 \cdot \alpha_{cr,x}} + \frac{1+\psi_z}{4 \cdot \alpha_{cr,z}} + \left[\left(\frac{1+\psi_x}{4 \cdot \alpha_{cr,x}} + \frac{1+\psi_z}{4 \cdot \alpha_{cr,z}}\right)^2 + \frac{1-\psi_x}{2 \cdot \alpha^2{}_{cr,x}} + \frac{1-\psi_z}{2 \cdot \alpha^2{}_{cr,z}} + \frac{1}{\alpha^2{}_{cr,\tau}}\right]^{0,5}$$ *Eq. 10.6*

Reduction factors ρ_i

There are two possible approaches to determine the reduction factors: The individual factors can be calculated for every existing stress component. Alternatively, a single reduction factor is determined globally for all existing stresses. This approach is related to the selection of the corresponding buckling curve.

For *various* buckling curves, the reduction factors are as follows:

Reduction factor for x-direction *ρ_x according to chapter 4.4 (2)*

Reduction factor for z-direction *ρ_z according to Annex B.1*

Reduction factor for shear buckling *χ_w according to Table 5.1*

If you use the *generalized* buckling curve:
Reduction factor *ρ_i according to Annex B.1*

Interaction between plate and local buckling behavior

To obtain the final reduction factor of the respective direction, an interaction between plate type and local buckling behavior must be determined.

$$\rho_i = (\rho - \chi_c) \cdot \xi \cdot (2 \cdot \xi) + \chi_c$$ *according to Eq. 4.13*

where: χ_c according to chapter 4.5.3 (5)

ξ according to chapter 4.5.4 (1)

Interaction criterion according to *Eq. 10.5*:

$$\left(\frac{\sigma_{x,Ed}}{\rho_x \cdot f_y / \gamma_{M1}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{\rho_z \cdot f_y / \gamma_{M1}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{\rho_x \cdot f_y / \gamma_{M1}}\right) \cdot \left(\frac{\sigma_{z,Ed}}{\rho_z \cdot f_y / \gamma_{M1}}\right) + 3 \cdot \left(\frac{\tau_{Ed}}{\chi_w \cdot f_y / \gamma_{M1}}\right)^2$$

8.2.3 Elastic Stress Design of the Stiffeners

EN 1993-1-5 requires an elastic-elastic stress design for transverse stiffeners according to second order analysis. Here, you must consider a precamber of the transversal stiffener, the skew loads on the adjacent partial panels as well as the stress on the buckling panel. The existing stresses may not exceed the yield stress f_y/y_{M1}.

These formulas are mainly analytical. They are described in detail in [18].

8.2.4 Deformation Analysis of the Stiffeners

The maximum deformation of the stiffener is limited to the value *b/300*. Here, you have to consider that the deformation results from the precamber and the actual deformation of the stiffener.

These formulas are also described in [18].

8.2.5 Torsional Buckling Design

To avoid torsional buckling of transverse and longitudinal stiffeners with open cross-sections, the following designs must be carried out successfully:

$$\frac{J}{I_p} \geq 5.3 \cdot \frac{f_y}{E}$$ *according to Eq. 9.3*

where: J St. Venant torsional constant stiffener cross-section

I_p Polar moment of inertia

If the warping stiffness of the stiffener is considered, *Eq. 9.3* or *Eq. 9.4* should be satisfied.

$$\sigma_{cr} \geq \theta \cdot f_y$$ *according to Eq. 9.4*

where: θ Factor used to ensure elastic behavior ($\theta = 6$)

9. Examples

9.1 DIN 18800

9.1.1 Unstiffened Buckling Panel with Local Buckling Behavior

Material: Steel St 37

Yield strength $f_{y,k} = 240$ N/mm²

Partial safety factor: $\gamma_M = 1,1$

Parameters of the structural system:

Length of the buckling panel	a	=	1000 mm
Width of the buckling panel	b	=	1200 mm
Plate thickness	t	=	10 mm

→ Side ratio $\alpha = \frac{a}{b} = \frac{1000}{1200} = 0.833$

Governing stresses:

Axial compressive stress	σ_1	=	80 N/mm²
Axial compressive stress	σ_2	=	80 N/mm²
Shear stress	τ	=	12 N/mm²

Edge stress ratio related to the maximum compression stress:

$$\psi = \frac{\sigma_2}{\sigma_1} = \frac{80}{80} = 1.0$$

Euler critical stress:

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-0.3^2)} \cdot \left(\frac{t}{b}\right)^2 = \frac{3.14^2 \cdot 210000}{12 \cdot (1-0.3^2)} \cdot \left(\frac{10}{1200}\right)^2 = 13.18\,\text{N/mm}^2$$

Calculation of the buckling values according to DIN 4114, Table 6, rows 3 and 5:

$$\alpha = 0.833 < 1 \quad \text{and} \quad \psi = 1$$

$$k_\sigma = \left(\alpha + \frac{1}{\alpha}\right)^2 \cdot \frac{2{,}1}{\psi + 1.1} = \left(0.833 + \frac{1}{0.833}\right)^2 \cdot \frac{2{,}1}{1+1.1} = 4.4134$$

$$k_\tau = 4.00 + \frac{5.34}{\alpha^2} = 4{,}00 + \frac{5.34}{0.833^2} = 11.69$$

Critical plate buckling stress if edge stresses σ according to DIN 18 800 part 3, El. (113) are effective:

$$\sigma_{Pi} = k_\sigma \cdot \sigma_E = 4.13 \cdot 13.18 = 54.43\ \text{N/mm}^2$$

Critical plate buckling stress if edge stresses *τ* are effective:

$$\tau_{Pi} = k_\tau \cdot \sigma_E = 11{,}69 \cdot 13{,}18 = 154.07\,\text{N/mm}^2$$

Reference slenderness ratio:

$$\lambda_a = \pi \cdot \sqrt{\frac{E}{f_{y,k}}} = 3.14 \cdot \sqrt{\frac{210000}{240}} = 92.93$$

Plate slenderness (axial stress):

$$\lambda_P = \pi \cdot \sqrt{\frac{E}{\sigma_{Pi}}} = 3{,}14 \cdot \sqrt{\frac{210000}{54.49}} = 195.03$$

Plate slenderness (shear stress):

$$\lambda_P = \pi \cdot \sqrt{\frac{E}{\tau_{Pi} \cdot \sqrt{3}}} = 3{,}14 \cdot \sqrt{\frac{210000}{154.07 \cdot \sqrt{3}}} = 88.13$$

Plate slenderness ratio (axial stress) according to DIN 18 800 Part 3, El. (113):

$$\overline{\lambda}_P = \frac{\lambda_p}{\lambda_a} = \frac{195.03}{92.93} = 2.098$$

Plate slenderness ratio:

$$\overline{\lambda}_P = \frac{\lambda_p}{\lambda_a} = \frac{88.13}{92.93} = 0.948$$

Reduction factor for plate buckling according to DIN 18 800 Part 3, Table 1:

$$\kappa_\sigma = c \cdot \left(\frac{1}{\overline{\lambda}_P} - \frac{0.22}{\overline{\lambda}_P{}^2} \right) \quad \text{where } c = 1.25 - 0.25 \cdot \psi, \text{ but } c \leq 1.25$$

$$c = 1.25 - 0.25 \cdot 1.0 = 1.00$$

$$\kappa_\sigma = 1.0 \cdot \left(\frac{1}{2.098} - \frac{0.22}{2.098^2} \right) = 0.427$$

$$\kappa_\tau = \frac{0.84}{\overline{\lambda}_P} = \frac{0.84}{0.948} = 0.886$$

Plate buckling with local buckling behavior according to DIN 18 800 Part 3, El. (602):

$$\rho = \frac{\Lambda - \sigma_{Pi}/\sigma_{Ki}}{\Lambda - 1} \geq 0 \qquad \Lambda = \overline{\lambda}_P{}^2 + 0.5, \text{ but } 2 \leq \Lambda \leq 4$$

$$\sigma_{Pi}/\sigma_{Ki} = k_\sigma \cdot \alpha^2 = 4.134 \cdot 0.833^2 = 2.838$$

$$\Lambda = 2.098^2 + 0.5 = 4.902 > 4 \Rightarrow \Lambda = 4$$

$$\rho = \frac{4 - 2.868}{4 - 1} = 0.377$$

According to DIN 18 800 Part 3, El. (603):

$$\lambda_P > 0.2 \Rightarrow \kappa_K = \frac{1}{\left(k + \sqrt{k^2 - \lambda_P{}^2}\right)}$$

$$k = 0.5 \cdot \left[1 + 0.34 \cdot (\lambda_P - 0.2) + \lambda_P{}^2\right]$$

$$k = 0,5 \cdot \left[1 + 0.34 \cdot (2.098 - 0,2) + 2.098^2\right] = 3.023$$

$$\kappa_K = \frac{1}{\left(3.023 + \sqrt{3.023^2 - 2.098^2}\right)} = 0.192$$

Reduction factor with local buckling behavior

$$\kappa_{PK} = \left(1 - \rho^2\right) \cdot \kappa_\sigma + \rho^2 \cdot \kappa_K = \left(1 - 0.377^2\right) \cdot 0.427 + 0.377 \cdot 0.192 = 0.393$$

Calculation of critical plate buckling stresses according to DIN 18 800 Part 3, El. (502):

$$\sigma_{P,R,d} = \frac{\kappa_{PK} \cdot f_{y,k}}{\gamma_M} = \frac{0.393 \cdot 240}{1.1} = 85.88\,\mathrm{N/mm^2}$$

$$\tau_{P,R,d} = \frac{\kappa_\tau \cdot f_{y,k}}{\gamma_M \cdot \sqrt{3}} = \frac{0.886 \cdot 240}{1.1 \cdot \sqrt{3}} = 111.5\,\mathrm{N/mm^2}$$

Analysis of the buckling panel according to DIN 18 800 Part 3, El. (501):

$$\frac{\sigma}{\sigma_{P,R,d}} = \frac{80}{85.88} = 0.931 < 1$$

$$\frac{\tau}{\tau_{P,R,d}} = \frac{12}{111.5} = 0.107 < 1$$

Analysis for simultaneous occurrence of edge stresses (interaction) according to DIN 18 800 Part 3, El. (504):

$$e_1 = 1 + \kappa_\sigma{}^4 = 1 + 0.393^4 = 1.023$$

$$e_3 = 1 + \kappa_\sigma \cdot \kappa_\tau{}^2 = 1 + 0.393 \cdot 0.886^2 = 1.308$$

$$\left(\frac{\sigma}{\sigma_{P,R,d}}\right)^{e_1} + \left(\frac{\tau}{\tau_{P,R,d}}\right)^{e_3} \leq 1$$

$$\left(\frac{80}{85,82}\right)^{1,023} + \left(\frac{12}{111,5}\right)^{1,308} = 0.984 \leq 1$$

The plate buckling safety is sufficient!

9.1.2 Stiffened Panel

The following example is extracted from [11]. It describes the plate buckling analysis for a stiffened buckling panel.

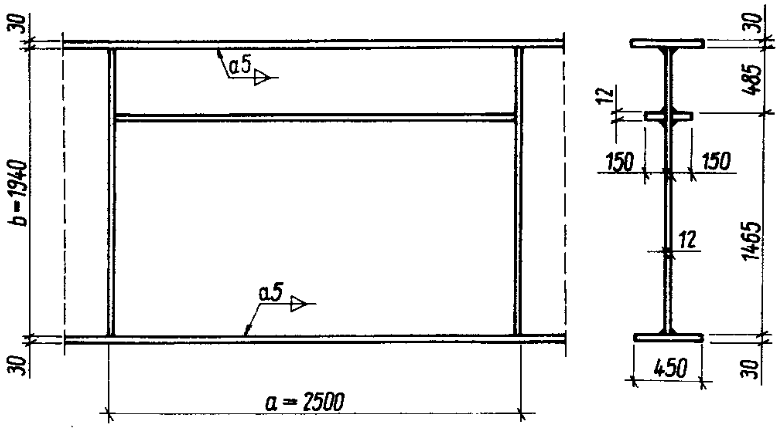


Figure 9.1: *Sketch of structural system including dimensions and loads*

Material:	Steel St 37		
	Yield strength $f_{y,k}$ = 240 N/mm²		
Partial safety factor:	γ_M = 1.1		
Parameters of the structural system:			
Length of the buckling panel	a	=	2500 mm
Width of the buckling panel	b	=	1940 mm
Plate thickness	t	=	12 mm

→ Side ratio $\alpha = \frac{a}{b} = \frac{2500}{1940} = 1.29$

Stiffener:			
Height:	h	=	150 mm
Length:	a	=	2500 mm
Thickness:	t	=	12 mm
Stiffener position:	y	=	485 mm (from upper edge)
Stiffener parameters::	$I_{y,Stiffener}$	=	3040 cm⁴
	$A_{y,Stiffener}$	=	36 cm²
	$\delta = 0.155$		acc. to DIN 18 800, part 3, el. (114)
	$\gamma = 99$		acc. to DIN 18 800 part 3, el. (114)

We obtain from these initial values according to [13]:

	$k_{\sigma x}$	=	84
	k_{τ}	=	12

Governing stresses:

Axial compressive stress	σ_1	= 130 N/mm²
Axial tensile stress	σ_2	= - 130 N/mm²
Shear stress	τ	= 52 N/mm²

Edge stress ratio related to maximum compressive stress:

$$\psi = \frac{\sigma_2}{\sigma_1} = \frac{13}{-13} = -1.0$$

Euler critical stress:

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-0.3^2)} \cdot \left(\frac{t}{b}\right) = \frac{3.14^2 \cdot 210000}{12 \cdot (1-0.3^2)} \cdot \left(\frac{1.2}{194}\right)^2 = 0.73\,\text{kN/cm}^2$$

Calculation of the buckling values according to DIN 4114, Table 6, rows 3 and 5:

$\alpha = 1.29 > 1$ and $\psi = -1$

Critical plate buckling stress if edge stresses *σ* according to DIN 18 800 Part 3, El. (113) are effective:

$$\sigma_{Pi_x} = k_\sigma \cdot \sigma_E = 84 \cdot 0.73 = 61.3\,\text{kN/cm}^2$$

Critical plate buckling stress if edge stresses *τ* are effective:

$$\tau_{Pi} = k_\tau \cdot \sigma_E = 12 \cdot 0.73 = 8.8\,\text{kN/cm}^2$$

Related slenderness ratio:

$$\lambda_a = \pi \cdot \sqrt{\frac{E}{f_{y,k}}} = 3{,}14 \cdot \sqrt{\frac{210000}{240}} = 92.93$$

Plate slenderness ratio (axial stress):

$$\lambda_{P_{\sigma_x}} = \pi \cdot \sqrt{\frac{E}{\sigma_{Pi}}} = 3.14 \cdot \sqrt{\frac{21000}{61.3}} = 58.12$$

Plate slenderness ratio (shear stress):

$$\lambda_P = \pi \cdot \sqrt{\frac{E}{\tau_{Pi} \cdot \sqrt{3}}} = 3{,}14 \cdot \sqrt{\frac{21000}{8.8 \cdot \sqrt{3}}} = 116.55$$

Relative plate slenderness ratio (axial stress) according to DIN 18 800 Part 3, El. (113):

$$\overline{\lambda}_{P_{\sigma_x}} = \frac{\lambda_P}{\lambda_a} = \frac{58.12}{92.93} = 0.625$$

Relative plate slenderness ratio (shear stress):

$$\overline{\lambda}_P = \frac{\lambda_P}{\lambda_a} = \frac{116.55}{92.93} = 1.254 < 1.38$$

Reduction factor for plate buckling according to DIN 18 800 Part 3, Table 1:

$$\kappa_{\sigma_x} = c \cdot \left(\frac{1}{\bar{\lambda}_P} - \frac{0.22}{\bar{\lambda}_P^{\ 2}} \right) \quad \text{where } c = 1.25 - 0.25 \cdot \psi \text{, but } c \le 1.25$$

$$c = 1.25 - 0.25 \cdot -1.0 = 1.50 ==> 1.25$$

$$\kappa_{\sigma_x} = 1.25 \cdot \left(\frac{1}{0.625} - \frac{0.22}{0.625^2} \right) = 1.296 ==> 1.0$$

$$\kappa_\tau = \frac{0.84}{\bar{\lambda}_P} = \frac{0.84}{1.255} = 0.669$$

Calculation of critical plate buckling stresses according to DIN 18 800 Part 3, El. (502):

$$\sigma_{xP,R,d} = \frac{\kappa \cdot f_{y,k}}{\gamma_M} = \frac{1.0 \cdot 240}{1.1} = 218\,\text{N/mm}^2$$

$$\tau_{P,R,d} = \frac{\kappa_\tau \cdot f_{y,k}}{\gamma_M \cdot \sqrt{3}} = \frac{0.669 \cdot 240}{1.1 \cdot \sqrt{3}} = 84\,\text{N/mm}^2$$

Analysis of the buckling panel according to DIN 18 800 Part 3, El. (501):

$$\frac{\sigma_x}{\sigma_{xP,R,d}} = \frac{13}{21.8} = 0.60 < 1$$

$$\frac{\tau}{\tau_{P,R,d}} = \frac{5.2}{8.4} = 0.62 < 1$$

Analysis for simultaneous occurrence of edge stresses (interaction) according to DIN 18 800 Part 3, El. (504):

$$e_1 = 1 + \kappa_{\sigma_x}^{\ 4} = 1 + 1^4 = 2$$

$$e_3 = 1 + \kappa_{\sigma_x} \cdot \kappa_\tau^{\ 2} = 1 + 1.0 \cdot 0.669^2 = 1.447$$

$$\left(\frac{|\sigma_x|}{\sigma_{xP,R,d}} \right)^{e_1} + \left(\frac{\tau}{\tau_{P,R,d}} \right)^{e_3} \le 1$$

$$\left(\frac{13}{21.8} \right)^2 + \left(\frac{5.2}{8.4} \right)^{1.447} = 0.73 \le 1$$

The plate buckling safety is sufficient!

9.2 EN 1993-1-5

9.2.1 Unstiffened Buckling Panel with Local Buckling Behavior

The following example is extracted from [6]. It describes the plate buckling analysis for an unstiffened buckling panel.

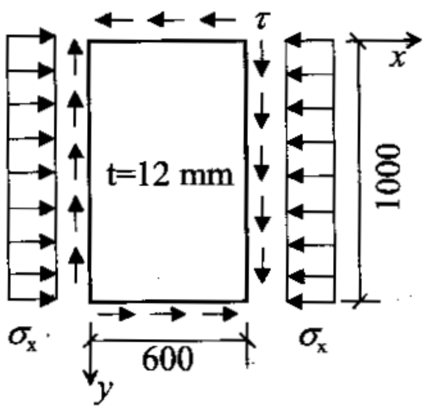


Figure 9.2: *Sketch of structural system including dimensions and loads*

Material: Steel S355

Yield strength $f_{y,k} = 355$ N/mm²

Partial safety factor: $\gamma_M = 1.1$

Parameters of the structural system:

Length of the buckling panel	a	=	600 mm
Width of the buckling panel	b	=	1000 mm
Plate thickness	t	=	12 mm

→ Side ratio $\alpha = \frac{a}{b} = \frac{600}{1000} = 0.60$

Governing stresses:

Axial compressive stress	σ_1	=	100 N/mm²
Axial compressive stress	σ_2	=	100 N/mm²
Shear stress	τ	=	50 N/mm²

Edge stress ratio related to the maximum compressive stress:

$$\psi = \frac{\sigma_2}{\sigma_1} = \frac{100}{100} = 1.0$$

Euler critical stress:

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1-0.3^2)} \cdot \left(\frac{t}{b}\right)^2 = \frac{3.14^2 \cdot 210000}{12 \cdot (1-0.3^2)} \cdot \left(\frac{12}{1000}\right)^2 = 27.33 \text{ N/mm}^2$$

Calculation of buckling values according to EN 1993-1-5, Table 4 and Annex A.3/A.5:

$\alpha = 0.6 < 1$ and $\psi = 1$

$k_\sigma = 4.0$

$k_\tau = 4.00 + \frac{5.34}{\alpha^2} = 4.00 + \frac{5{,}34}{0.60^2} = 18.83$

Critical plate buckling stress if edge stresses *σ* according to EN 1993-1-5, Annex A.1 are effective:

$\sigma_{cr,p,x} = k_{\sigma,x} \cdot \sigma_E = 4.0 \cdot 27.33 = 109.32\ \text{N/mm}^2$

Critical plate buckling stress if edge stresses *τ* are effective:

$\tau_{cr} = k_\tau \cdot \sigma_E = 18{,}83 \cdot 27.33 = 514.75\ \text{N/mm}^2$

Yield criterion according to EN 1993-1-5, Eq. (10.3):

$$\alpha_{ult,k} = \frac{f_y}{\sigma_{v,Ed}} = \frac{355}{132.29} = 2.6835$$

where: $\sigma_{v,Ed} = \sqrt{\sigma_{x,Ed}^{\ 2} + 3 \cdot \tau_{Ed}^{\ 2}} = \sqrt{100^2 + 3 \cdot 50^2} = 132.29\ \text{N/mm}^2$

Eigenvalues of the stress components according to EN 1993-1-5, Eq. (10.6):

$$\alpha_{cr,x} = \frac{\sigma_{cr,p,x}}{\sigma_{x,Ed}} = \frac{109.32}{100} = 1.0932$$

$$\alpha_{cr,\tau} = \frac{\tau_{cr}}{\tau_{Ed}} = \frac{514.75}{50} = 10.295$$

Critical load factor according to EN 1993-1-5, Eq. (10.6):

$$\frac{1}{\alpha_{cr}} = \frac{1+\psi_x}{4 \cdot \alpha_{cr,x}} + \sqrt{\left(\frac{1+\psi_x}{4 \cdot \alpha_{cr,x}}\right)^2 + \frac{1-\psi_x}{2 \cdot \alpha_{cr,x}^{\ 2}} + \frac{1}{\alpha_{cr,\tau}^{\ 2}}}$$

$\alpha_{cr} = 1.081$

Plate slenderness ratio according to EN 1993-1-5, Eq. (10.2):

$$\bar{\lambda}_P = \bar{\lambda}_w = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}} = \sqrt{\frac{2.6835}{1.081}} = 1.576$$

Reduction factors for plate buckling according to EN 1993-1-5, section 4.4 and Table B.1

Check:

$\bar{\lambda}_P \geq 0.5 + \sqrt{0.085 - 0.055 \cdot \psi}$

$1.576 \geq 0.673$

$$\rho_p = \frac{\bar{\lambda}_P - 0.055(3+\psi)}{\bar{\lambda}_P^{\ 2}} \leq 1.00$$

$$\rho_p = \frac{1.576 - 0.055(3+1.0)}{1.576^2} \leq 1.00$$

$\rho_p = 0.546 \leq 1.00$

Using Table 5.1 and the option "Non-rigid end post":

$$\chi_w = \frac{0{,}83}{\overline{\lambda}_p} = \frac{0.83}{1.576} = 0.527$$

Plate buckling with local buckling behavior according to EN 1993-1-5, section 4.5.4 (1):

$$\xi = \frac{\sigma_{cr,p}}{\sigma_{cr,c}} - 1 \le 1$$

where: $$\sigma_{cr,c} = \frac{\pi^2 \cdot E \cdot t^2}{12 \cdot \left(1-\nu^2\right) \cdot a^2} = \frac{\pi^2 \cdot 210000 \cdot 12^2}{12 \cdot \left(1-0.3^2\right) \cdot 600^2} = 75.92 \text{ N/mm}^2$$

$$\xi = \frac{109.32}{75.92} - 1 = 0.44 \le 1$$

The total buckling panel shows a local buckling behavior.

Reduction factor with local buckling behavior:

$$\rho_c = \left(\rho_p - \chi_c\right) \cdot \xi \cdot \left(2 - \zeta_x\right) + \chi_c = \left(0.546 - 0.342\right) \cdot 0.44 \cdot \left(2 - 0.44\right) + 0.342 = 0.482$$

where: $$\chi_c = \frac{1}{\left(\theta_p + \sqrt{\theta_p{}^2 - \overline{\lambda}_p{}^2}\right)} = \frac{1}{\left(1.886 + \sqrt{1.886^2 - 1.576^2}\right)} = 0.342$$

$$\theta_p = 0.5 \cdot \left(1 + 0.21 \cdot \left(1.576 - 0.2\right) + 1.576^2\right) = 1.886$$

Analysis (interaction condition) according to EN 1993-1-5, Eq. (10.5):

$$\left(\frac{\sigma_{x,Ed}}{\rho_c \cdot f_y / \gamma_{M1}}\right)^2 + 3 \cdot \left(\frac{\tau_{Ed}}{\chi_w \cdot f_y / \gamma_{M1}}\right)^2 \le 1$$

$$\left(\frac{100}{0.482 \cdot 355/1.1}\right)^2 + 3 \cdot \left(\frac{50}{0.527 \cdot 355/1{,}1}\right)^2 = 0.672 \le 1$$

The plate buckling safety is sufficient!

9.2.2 Stiffened Buckling Panel

The following example is extracted from [18]. It describes the plate buckling analysis for a stiffened buckling panel.

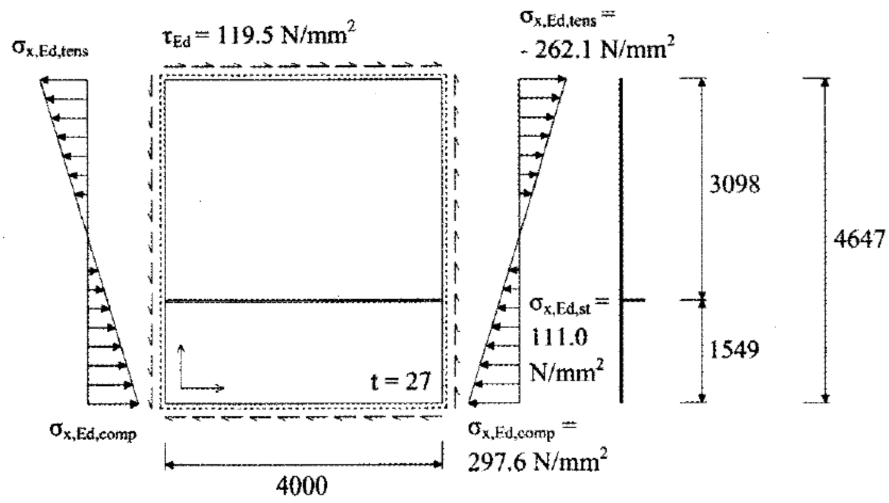


Figure 9.3: *Sketch of structural system including dimensions and loads*

Material:	Steel S355		
	Yield strength $f_{y,k}$ = 345 N/mm² (for t = 30 mm)		
Partial safety factor:	$\gamma_M = 1.1$		
Parameters of the structural system:			
Length of the buckling panel	a	=	4000 mm
Width of the buckling panel	b	=	4647 mm
Plate thickness	t	=	27 mm

$$\rightarrow \text{ Side ratio} \qquad \alpha = \frac{a}{b} = \frac{4000}{4647} = 0.861$$

Stiffener:			
Height:	h	=	300 mm
Length:	a	=	4000 mm
Thickness:	t	=	30 mm
Stiffener position:	z	=	3098 mm (from upper edge)
Governing stresses:			
Axial compressive stress	σ_2	=	297.6 N/mm²
Normal shear stress	σ_1	=	-262.1 N/mm²
Shear stress	τ	=	119.5 N/mm²

Determination of critical plate buckling stresses according to EN 1993-1-5, Annex A:

For a longitudinal stiffener in the compression zone it follows according to Annex A.2.2:

Critical buckling stress $\sigma_{cr,p}$

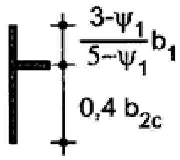


Figure 9.4: *Figure A.1, Annex A*

- Determination of effective widths:

$$\psi_1 = \frac{\sigma_{sl,1}}{\sigma_1} = \frac{111.03}{297.6} = 0.373 \geq 0 \quad \rightarrow \text{okay}$$

$$b_1 = 1549\,\text{mm}$$

$$b_{1,inf} = \frac{3-0.373}{5-0.373} \cdot 1549 = 879.45\,\text{mm}$$

$$b_{2,c} = \frac{\sigma_{sl,1}}{m} = \frac{111.03}{0.1204} = 922.76\,\text{mm}$$

$$b_{2,sup} = 0{,}4 \cdot 922.76 = 369.10\,\text{mm}$$

$$\Rightarrow \underline{\underline{A_{sl,1} = 42711\,\text{mm}^2}}$$

$$\Rightarrow \underline{\underline{I_{sl,1} = 2.549 \cdot 10^9\,\text{mm}^4}}$$

- according to Eq. (A.4), Annex A:

$$a_c = 4.33 \cdot \sqrt[4]{\frac{I_{sl,1} \cdot b_1^2 \cdot b_2^2}{t^3 \cdot b}} = 12241\,\text{mm} \quad > \quad a = 4000\,\text{mm}$$

$$\sigma_{cr,sl} = \frac{\pi^2 \cdot E \cdot I_{sl,1}}{A_{sl,1} \cdot a^2} + \frac{E \cdot t^2 \cdot b \cdot a^2}{4 \cdot \pi^2 \cdot (1-\upsilon^2) \cdot A_{sl,1} \cdot b_1^2 \cdot b_2^2}$$

$$\sigma_{cr,sl} = \frac{\pi^2 \cdot 210000 \cdot 2.549 * 10^9}{42711 \cdot 4000^2} + \frac{210000 \cdot 27^2 \cdot 4647 \cdot 4000^2}{4 \cdot \pi^2 \cdot (1-0.3^2) \cdot 42711 \cdot 1549^2 \cdot 3098^2}$$

$$\sigma_{cr,sl} = 796.1\,\text{N/mm}^2$$

The critical buckling stress $\sigma_{cr,p}$ is obtained by extrapolating the edge subjected to pressure:

$$\sigma_{cr,p} = \sigma_{cr,sl} \cdot \frac{\sigma_1}{\sigma_{sl,1}} = 796.1 \cdot \frac{297.6}{111.03} = 2134.41\,\text{N/mm}^2$$

Critical buckling stress τ_{cr}

- Determination of effective widths

  According to EN 1993-1-5, Figure 5.3, the minimum widths are used for the effective widths.

$$\min b = 15 \cdot \varepsilon \cdot t_w$$

$$\min b = 15 \cdot \sqrt{\frac{235}{345}} \cdot 27 = 334.26\,\text{mm}$$

$$\Rightarrow \underline{\underline{A_{sl,1} = 2.786 \cdot 10^4\ \text{mm}^2}}$$

$$\Rightarrow \underline{\underline{I_{sl,1} = 2.315 \cdot 10^9 \text{mm}^4}}$$

- Determination of buckling value according to A.3, Eq. (A.6):

$$\alpha = \frac{a}{h_w} = \frac{4000}{4647} = 0.861 \quad < \quad 3$$

$$k_\tau = 4{,}1 + \frac{6.3 + 0.18 \cdot \dfrac{I_{sl}}{t_w{}^3 * h_w}}{\left(\dfrac{a}{h_w}\right)^2} + 2.2 \cdot \sqrt[3]{\frac{I_{sl}}{t_w{}^3 * h_w}}$$

$$k_\tau = 4.1 + \frac{6.3 + 0.18 \cdot \dfrac{2.315 * 10^9}{27^3 * 4647}}{\left(\dfrac{4000}{4647}\right)^2} + 2.2 \cdot \sqrt[3]{\frac{2.315 * 10^9}{27^3 * 4647}} = 16.22$$

The critical buckling stress τ_{cr} if edge stresses τ are exerted is as follows:

$$\tau_{cr} = k_\tau \cdot \sigma_E = 16.22 \cdot \frac{\pi^2 * 210000}{12 \cdot \left(1 - 0.3^2\right)} \cdot \left(\frac{27}{4647}\right)^2 = 103.9\ \text{N/mm}^2$$

Yield criterion according to EN 1993-1-5, Eq. (10.3)

$$\alpha_{ult,k} = \frac{f_y}{\sigma_{v,Ed}} = \frac{345}{362.5} = 0.952$$

where: $\sigma_{v,Ed} = \sqrt{\sigma_{x,Ed}{}^2 + 3 \cdot \tau_{Ed}{}^2} = \sqrt{297.6^2 + 3 \cdot 119.5^2} = 362.5\,\text{N/mm}^2$

Eigenvalues of the stress components according to EN 1993-1-5, Eq. (10.6):

$$\alpha_{cr,x} = \frac{\sigma_{cr,p,x}}{\sigma_{x,Ed}} = \frac{2134{,}41}{297.6} = 7.172$$

$$\alpha_{cr,\tau} = \frac{\tau_{cr}}{\tau_{Ed}} = \frac{103{,}9}{119.5} = 0.869$$

Critical load factor according to EN 1993-1-5, Eq. (10.6):

$$\frac{1}{\alpha_{cr}} = \frac{1 + \psi_x}{4 \cdot \alpha_{cr,x}} + \sqrt{\left(\frac{1 + \psi_x}{4 \cdot \alpha_{cr,x}}\right)^2 + \frac{1 - \psi_x}{2 \cdot \alpha_{cr,x}{}^2} + \frac{1}{\alpha_{cr,\tau}{}^2}}$$

$$\alpha_{cr} = 0.86$$

Plate slenderness ratio according to EN 1993-1-5, Eq. (10.2):

$$\overline{\lambda}_P = \overline{\lambda}_w = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}} = \sqrt{\frac{0.952}{0.86}} = 1.052$$

Reduction factors for plate buckling according to EN 1993-1-5, Eq. (4.2) and Table 5.1:

$$\rho_p = \frac{\overline{\lambda_p} - 0.055 \cdot (3+\psi)}{\overline{\lambda_p}^2} = \frac{1.052 - 0.055 \cdot \left(3 + \left(\frac{-262.1}{297.6}\right)\right)}{1.052^2} = 0.845$$

According to Table 5.1, the contribution of the web in the case of a ridged end post is given by:

$$\chi_w = \frac{0.83}{\overline{\lambda}_p} = \frac{0.83}{1.052} = 0.789$$

Buckling with local buckling behavior according to EN 1993-1-5, section 4.5.4, Eq. (1):

$$\xi = \frac{\sigma_{cr,p}}{\sigma_{cr,c}} - 1 = \frac{2134.41}{2109.8} - 1 = 0.011 \leq 1$$

where: $$\sigma_{cr,c} = \frac{\pi^2 \cdot E \cdot I_{sl,1}}{A_{sl,1} \cdot a^2} \cdot \frac{\sigma_1}{\sigma_{sl,1}} = \frac{\pi^2 \cdot 210000 \cdot 2.549 \cdot 10^9}{42711 \cdot 4000^2} \cdot \frac{297.6}{111.03} = 2109.8\,\mathrm{N/mm^2}$$

The entire buckling field shows a local buckling behavior.

Reduction factor with local buckling behavior:

$$\rho_c = (\rho_p - \chi_c) \cdot \xi \cdot (2 - \zeta_x) + \chi_c = (0.845 - 0.496) \cdot 0.011 \cdot (2 - 0.011) + 0.496 = 0.487$$

$$\chi_c = \frac{1}{\left(\theta_p + \sqrt{\theta_p^2 - \overline{\lambda_p}^2}\right)} = \frac{1}{\left(1.282 + \sqrt{1.282^2 - 1.052^2}\right)} = 0.496$$

where: $$\theta_p = 0.5 \cdot \left(1 + \alpha_e \cdot (1.052 - 0.2) + 1.052^2\right) = 1.282$$

$$\alpha_e = \alpha + \frac{0.09}{i/e} = 0.49 + \frac{0.09}{\sqrt{\frac{2.549 \cdot 10^9}{42711}} \Big/ 129} = 0.537$$

Analysis (interaction condition) according to EN 1993-1-5, Eq. (10.5):

$$\left(\frac{\sigma_{x,Ed}}{\rho_c \cdot f_y / \gamma_{M1}}\right)^2 + 3 \cdot \left(\frac{\tau_{Ed}}{\chi_w \cdot f_y / \gamma_{M1}}\right)^2 \leq 1$$

$$\left(\frac{297.50}{0.487 \cdot 345/1.1}\right)^2 + 3 \cdot \left(\frac{119.50}{0.789 \cdot 345/1.1}\right)^2 = \underline{\underline{4.50 > 1}}$$

The buckling safety is <u>not</u> sufficient!

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