Design of Plated Structures

Eurocode 3: Design of steel structures
Part 1-5: Design of plated structures

Darko Beg
Ulrike Kuhlmann
Laurence Davaine
Benjamin Braun

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FOREWORD

Plated structures are large steel structures commonly made from steel plates welded together. A typical use is for bridge girders and girders for heavy overhead cranes. Compared to steel structures of rolled profiles, plated structures are more prone to local buckling and therefore require design rules to cover such phenomena. In Eurocode 3 such rules are collected in Part 1-5 “Plated structures”, EN 1993-1-5. I was the convener of the project team that wrote the standard, and this team was made up of some very knowledgeable specialists. We spent many years on comparing and finding the best methods of dealing with the most common buckling phenomena. These have attracted a lot of research efforts not only due to some spectacular bridge failures, but also because buckling of plates, and particularly stiffened plates, are scientifically interesting and have attracted the attention of many sharp brains. The result of our efforts was published as a standard in 2006, but the implementation in the different member countries of CEN follows different time tables.

Already before the standard was published we had many requests for background information. The reason was probably that the project team had collected design rules from different sources and chosen the ones that best fitted available information. Some of those were unfamiliar to many engineers and the requests of background information were reasonable. The contract with the EU commission did not include the task of delivering background documents but the academic participants in the project team decided to write one on their own expense. This document can be found on the ECCS web site with the URL http://www.steelconstruct.com/. It is described as a commentary to EN 1993-1-5 and includes background to the design rules and some explanations. There are also some design examples.

As a third step, ECCS has taken on the task of publishing the present manual that you have in your hands. It is intended for engineers who shall apply the rules of EN 1993-1-5 and I have to admit that it is needed. That does not mean that I think we did a bad job with the standard but that the text in the standard is quite brief and in order to interpret it correctly one needs experience and insight in the problems to be dealt with. This manual will be of great importance for engineers to aid them to apply the standard correctly thanks to its explanations and design examples. The authors have done a very good job and after reviewing the text I fully support it as a proper interpretation of the standard.

Bernt Johansson
Professor Emeritus Steel Structures

PREFACE

Plate buckling related problems in steel structures are inherently linked to complex solution strategies and design procedures. They involve stability analysis in the post-critical state, interaction of different failure modes, imperfection sensitivity, etc.

Eurocode standard EN 1993-1-5 gives a unique opportunity to deal with these problems, at least for typical geometrically more or less regular structural components, by means of fairly simple and consistent set of design procedures, suitable for hand calculations. The main advantage of these design procedures is that generally they were derived from available test results and despite their relative simplicity very often they can be more reliable than advanced numerical simulations. The latter heavily depend on the quality of the applied software tool, the way of modelling, experience of the user, correct interpretation of the results, etc. But even when an experienced design engineer applies advanced numerical simulations for plate buckling problems, a check by means of EN 1993-1-5 design procedures provides comfort and confidence in the results.

The main aim of this Design Manual is to provide practical advice to designers of plated structures for correct and efficient application of EN 1993-1-5 design rules, including several design examples. No deeper theoretical background is given and in this respect the reader is directed to other literature.

The initiative for this Design Manual came from the ECCS that included this Manual into the comprehensive action of preparing the ECCS Eurocode Design Manuals.

The four authors: Darko Beg (University of Ljubljana, Slovenia), Laurence Davaine (SNCF – French National Railway Service), Ulrike Kuhlmann and Benjamin Braun (University of Stuttgart, Germany) worked in close cooperation helping each other and carefully proof-reading parts of the text prepared by other authors. Nonetheless, the leading authors of individual chapters are:

Chapters 2.2, 2.4, 2.9 and all short numerical examples in Chapter 2: Darko Beg
Chapters 1, 2.5, 2.6, 2.10, 3: Ulrike Kuhlmann and Benjamin Braun
Chapters 2.3, 2.7, 2.8, 2.11: Laurence Davaine
Chapter 4: Laurence Davaine and Benjamin Braun

It should be mentioned that Franci Sinur and Blaž Čermelj helped in the preparation of the short numerical examples of Chapter 2 and Primož Može and Mojca Jelančič helped at the final editing of the text, all four coming from the University of Ljubljana.

At the end of this short Preface it is important to express strong wishes and expectations of the authors that this Manual will find a place on the working desks of design engineers helping them design excellent plated structures. In the authors' opinion the manual will also be helpful to students of structural engineering on their way of getting familiar with plated structures.

Darko Beg
Ulrike Kuhlmann
Laurence Davaine
Benjamin Braun

SYMBOLS

a	length of a stiffened or unstiffened plate
b	width of a stiffened or unstiffened plate
b_f	flange width
$b_{c,loc,i}$	width of the compressed part of each individual sub-panel i
b_{eff}	effective width (for elastic shear lag or local plate buckling)
b_1	height of the loaded sub-panel taken as the clear distance between the loaded flange and the longitudinal stiffener
b_w	clear width between welds
c	distance between plastic hinges in the flanges
e_{max}	maximum distance from the edge of the stiffener to the centroid of the stiffener
f_y	yield strength of steel
f_{yf}	flange yield strength
f_{yw}	web yield strength
h_f	distance between mid-planes of flanges
h_w	clear web depth between flanges
h_{wi}	clear height of sub-panel i
k_F	buckling coefficient for transverse loading
$k_{\sigma,p}$	plate buckling coefficient
k_τ	shear buckling coefficient of the web between flanges
$k_{\tau,i}$	shear buckling coefficient of sub-panel i
$k_{\tau s\ell}$	shear buckling coefficient of a web stiffened with longitudinal stiffeners
ℓ_y	effective loaded length
s_s	length of stiff bearing
t	thickness of the plate
t_f	flange thickness
t_w	web thickness
w_{el}	elastic deflection of the stiffener
w_0	equivalent geometric imperfection of the stiffener

A_s	gross cross sectional area of the stiffener
A_{sl}	total area of all the longitudinal stiffeners of a stiffened plate
A_{st}	gross cross sectional area of one transverse stiffener
A_{eff}	effective cross sectional area
$A_{c,eff}$	effective area of the compression zone of the stiffened or unstiffened plate
$A_{c,eff,loc}$	effective section areas of all the stiffeners and sub-panels that are fully or partially in the compression zone
$A_{sl,eff}$	sum of the effective sections of all longitudinal stiffeners with gross area A_{sl} located in the compression zone
$A_{sl,1}$	gross cross sectional area of the stiffener and the adjacent parts of the plate
$A_{sl,1,eff}$	effective cross sectional area of the stiffener and adjacent parts of the plate with due allowance for plate buckling of sub-panels
E	elastic modulus of steel
F_{Ed}	design transverse force
F_{Rd}	design resistance to transverse loading
F_{cr}	elastic critical load at transverse loading
F_y	yield load at transverse loading
G	shear elastic modulus
I_p	polar second moment area of the stiffener alone around the edge fixed to the plate
I_{st}	minimum required second moment of the area of a transverse stiffener to be considered as rigid
I_t	St. Venant torsional constant of the stiffener alone (without contributing plating)
I_w	warping cross section constant of the stiffener alone around the edge fixed to the plate
L_{eff}	effective length for resistance to transverse forces
$I_{s\ell}$	sum of the second moment of area of all longitudinal stiffeners
$I_{s\ell,1}$	second moment of area of the gross cross section of the stiffener and the adjacent parts of the plate, relative to the out-of-plane bending of the plate

I_{st}	second moment of the area of a stiffener for a cross section for the axis parallel to the web plate
$I_{st,act}$	actual second moment of area of the transverse stiffener
M_{Ed}	applied design bending moment
$M_{pl,Rd}$	design plastic moment resistance of the cross section (irrespective of cross section class)
$M_{f,Rd}$	design plastic moment resistance of a cross section consisting of the flanges only
N_{Ed}	design axial force
$N_{st,ten}$	axial force in the intermediate stiffener imposed by the tension field action
N_{cr}	Euler elastic critical force
$N_{cr,st}$	Euler elastic critical force of the stiffener
V_{Ed}	design shear force including shear from torque
$V_{bw,Rd}$	contribution from the web to the design shear resistance
$V_{bf,Rd}$	contribution from the flanges to the design shear resistance
$V_{b,Rd}$	design shear resistance
W_{eff}	effective elastic section modulus
$\alpha_{\mathrm{ult,k}}$	minimum load amplifier for the design loads to reach the characteristic value of the resistance
α_{cr}	minimum load amplifier for the design loads to reach the elastic critical value of the plate
β	effective width factor for elastic shear lag
β_{ult}	effective width factor for the effect of shear lag at the ultimate limit state
χ_c	reduction factor due to column buckling
χ_F	reduction factor for transverse loading
χ_w	reduction factor for shear buckling

$$\varepsilon = \sqrt{\frac{235}{f_y\left[MPa\right]}}$$

γ_M	partial safety factor
η	factor depending on the steel grade
η_1	utilisation level of the design resistance to direct stresses
η_2	utilisation level of the design resistance to transverse loading

η_3	utilisation level of the design shear resistance
$\bar{\lambda}_F$	slenderness for transverse loading (in EN 1993-1-5 the term "modified slenderness" is used according the Corrigendum (April 2009). In this document a shorter version, i.e. "slenderness", is systematically used for the sake of simplicity)
$\bar{\lambda}_p$	plate slenderness
$\bar{\lambda}_{p,red}$	reduced plate slenderness
$\bar{\lambda}_w$	web slenderness for shear
ν	Poisson coefficient of steel
ρ	plate buckling reduction factor
ρ_x; ρ_z	reduction factors
$\rho_{loc,i}$	reduction factor for each sub-panel i
$\sigma_{cr,p}$	elastic critical plate buckling stress
$\sigma_{cr,c}$	elastic critical column buckling stress
$\sigma_{cr,sl}$	elastic critical column buckling stress of a single stiffener
$\sigma_{com,Ed}$	maximum design compressive stress
$\sigma_{eq,Ed}$	equivalent design stress
σ_E	Euler stress
$\sigma_{cr,x}$; $\sigma_{cr,z}$; τ_{cr}	elastic critical buckling stress
$\sigma_{x,Ed}$; $\sigma_{z,Ed}$; τ_{Ed}	design stresses
τ_{cr}	elastic critical shear buckling stress
ψ	stress ratio along edges

Chapter 1

INTRODUCTION

1.1 PLATE BUCKLING IN STEEL STRUCTURES

State-of-the-art steel structures are characterised by a lightweight, slender and fabrication-optimised design. Especially the progress in welding technology since the 1930s has facilitated the increased application of steel plated structures, see Fig. 1.1. The significant knowledge gained since then has clearly influenced the design as well as the development of the design standards. With the Eurocodes, harmonised European rules have been established of which standard EN 1993-1-5 "Design of steel structures – Plated structural elements" (CEN, 2006a) deals with the design of plated structural elements in steel structures.

Fig. 1.1: Assembly of Haseltal road bridge near Suhl, Germany

Based on EN 1993-1-5 the designer can choose, considering national allowance, mainly between two different types of design methods according to Fig. 1.2. The effective width method, also comprising resistance models for shear force and transverse force, is very efficient for standard geometries because it accounts not only for the post-critical reserve in a single plate element but also for load shedding between cross sectional elements. The reduced stress method abstains from load shedding between cross sectional elements, but it fully accounts for the post-critical reserve in a single plate element. Beyond that, its general format facilitates its use for serviceability verifications and for the design of non-uniform members such as haunched beams, beam webs with openings and plates with non-orthogonal stiffeners. In addition, a verification methodology based on the finite element method is given in section 2.11. It is the most versatile verification method, however, it requires a lot of experience. It can be used for the determination of the "real" buckling resistance by means of a nonlinear analysis considering imperfections and for the calculation of elastic critical stress values by means of a linear bifurcation analysis.

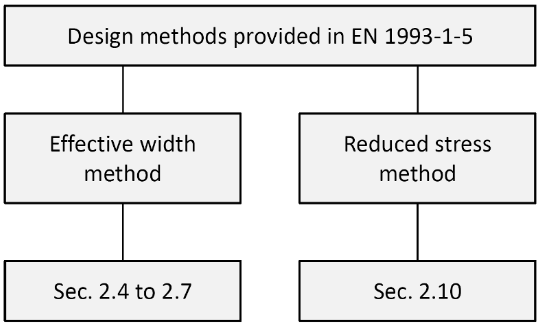

Fig. 1.2: Overview of design methods in EN 1993-1-5 and their references to the sections in this book

1.2 PURPOSE OF THIS BOOK

This book intends to provide the designer of steel plated structures with a practically oriented guide to assess EN 1993-1-5 (CEN, 2006a). This design manual is part of a comprehensive series of ECCS publications dealing with accompanying documentation to the Eurocodes. Its aim is to complement the comprehensive theoretical background given in the

Commentary to EN 1993-1-5 (Johansson *et al*, 2007) with practical knowledge for daily usage. Nevertheless, fundamental knowledge of structural mechanics is expected.

This book gives explanations and examples, advice and warnings, all of which intend to give the user considerably more insight and confidence in applying the rules of EN 1993-1-5. In order not to prejudice the use of EN 1993-1-5 where national choices are possible, Eurocode recommendations have been adopted throughout. This has to be kept in mind and, if required, the nationally determined parameters have to be adjusted when applying EN 1993-1-5 in the various member states.

1.3 STRUCTURE OF THIS BOOK

The layout of this book deliberately follows the layout of EN 1993-1-5 in order to allow for easy navigation and reference.

Chapter 2 gives a concise overview of the stability behaviour of plates in steel structures and the corresponding design rules in EN 1993-1-5. Relevant knowledge and terms about load-carrying mechanisms in plates and plated structures under direct stress, shear stress and transverse stress are introduced in order to ease the understanding of the design rules. The main components of Chapter 2 are the explanations of the verification methods which correspond to sections in this book as shown in Fig. 1.2. In this book, small design examples in each section address specific issues of these design rules.

In addition, chapters 3 and 4 present two comprehensive design examples of a crane runway beam and a box-girder bridge. In both examples not only the verification methods are illustrated, but also the big picture of the whole design is given. Besides general information on geometry and material properties, firstly loads and governing internal forces are determined. Based on cross section classification, and while adhering to the objective of this book, the examples finally focus on the plate buckling verifications.

Chapter 2

OVERVIEW OF DESIGN RULES

2.1 INTRODUCTION

Chapter 2 gives a commented overview of the EN 1993-1-5 design rules following the structure of the standard. At the end of each main section short numerical examples illustrate practical application of the design rules. The Contents of the Annexes are included in the corresponding sections of chapter 2, except that FEM analysis (Annex C of EN 1993-1-5) is given in section 2.11 and that plate girders with corrugated webs (Annex D of EN 1993-1-5) are not addressed in this Manual.

2.2 BASIS OF DESIGN AND MODELLING

2.2.1 General

When designing plated structures the effects of shear lag, plate buckling and interaction of both effects should be taken into account at the ultimate, serviceability or fatigue limit states. Possible simplifications for global analysis are given in section 2.2.2. EN 1993-1-5 (CEN, 2006a), as a generic Eurocode standard does not provide the values of partial factors γ_{M0} and γ_{M1}. These values should be taken from relevant application parts of Eurocode standards or National Annexes to these standards, whenever the values are different from the recommended ones. This means that for example for buildings γ_{M0} and γ_{M1} should be taken from EN 1993-1-1 (CEN, 2005), in bridge design from EN 1993-2 (CEN, 2006b) and for crane runway girders from EN 1993-6 (CEN, 2007).

Three approaches to the analysis of plated structures are covered by EN 1993-1-5:

- Effective width method (sub-chapter 2.3-2.9 of this publication)
- Reduced stress method (sub-chapter 2.10 of this publication)
- Finite element analysis (FEA) (sub-chapter 2.11 of this publication)

For effective width and reduced stress methods very detailed design procedures are given, while for FEA only general principles are described. The first two methods are meant to be predominantly used in the design of plated structures and the FEA may be successfully used to calculate elastic critical stresses to be used in the first two approaches. A complete design by FEA is possible but requires experience, appropriate software and a very careful interpretation of results.

In relation to the effective width method, EN 1993-1-5 introduces three different designations for three types of effective widths:

- Effective^{s} width – shear lag effects
- Effective^{p} width – local buckling of plates
- Effective width – interaction of shear lag and local buckling

2.2.2 Effective width models for global analysis

Shear lag and plate buckling reduce the stiffness of plated structures and should in principle be accounted for in the global analysis.

The effect of shear lag of flanges in global analysis may be taken into account by means of the effective width method. For simplicity this effective^{s} width may be taken as constant over the length of each span, see Fig. 2.1.

The effect of plate buckling in elastic global analysis may also be taken into account by means of the effective^{p} width method (see section 2.4.2 and 2.4.7 and references Johansson *et al* (2007), Sedlacek *et al* (2008)). This effect may be neglected when the effective cross sectional area of an element in compression in the ultimate limite state is larger than ρ_{lim} times the gross cross sectional area of the same element. The recommended value is ρ_{lim} = 0.5, but different values may be given in the National Annex. Only very slender plates will violate this criterion.

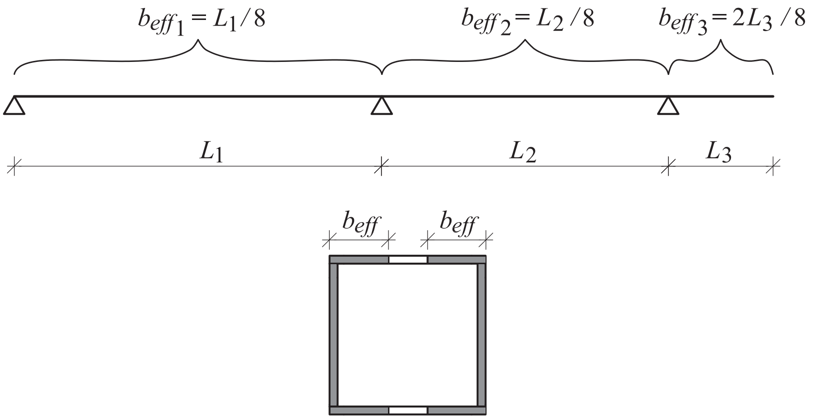

Fig. 2.1: Effective^s widths for global analysis

2.2.3 Uniform and non-uniform members

The design procedures for plate buckling that are based on the effective width method (see sub-chapter 2.3 to 2.9) were developed for web or flange panels of uniform width. Usually these panels are stiffened or unstiffened plates between rigid transverse stiffeners. The panels may be considered as uniform when:

- The shape of the panel is rectangular or almost rectangular. In the latter case the angle α (see Fig. 2.2) should not exceed 10°.
- The diameter of any unstiffened hole or cut-out does not exceed 0.05 b, where b is the width of the panel.

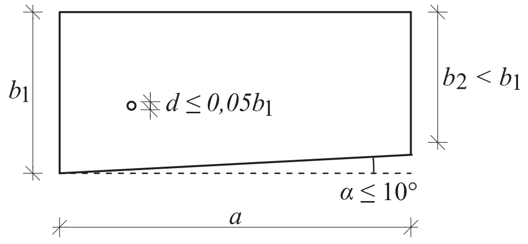

Fig. 2.2: Nominally uniform panels

If angle α is larger than 10°, then the panel may be conservatively treated as rectangular with the width equal to the larger of widths on both ends of the panel (Fig. 2.3).

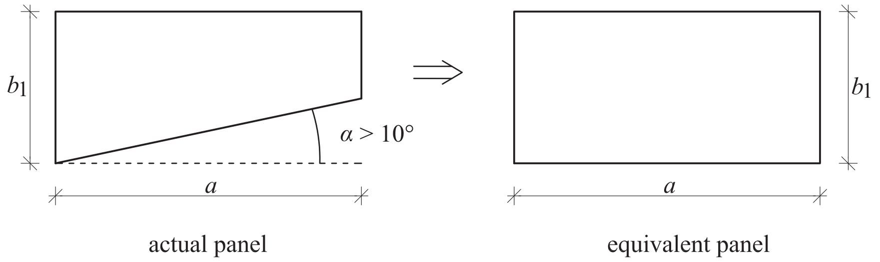

Fig. 2.3: Non-uniform panel transformed to equivalent uniform panel

Another more general possibility for non-uniform members (e.g. haunched members, not rectangular panels) or members with large openings is to take advantage of sub-chapter 2.10 or to apply FE analysis.

For the calculation of stresses at the serviceability and fatigue limit states only the effective^s area due to shear lag, which is based on purely elastic assumption, may be used if parameter $\rho_{lim} > 0.5$. For the ultimate limit state the effective area due to combined effects of shear lag and plate buckling (see section 2.3.5) should be used.

2.2.4 Reduced stress method

When the reduced stress method is applied, the stresses in each panel should not exceed the limiting values calculated according to sub-chapter 2.10 and the cross sections may be treated as Class 3 sections.

2.3 SHEAR LAG IN MEMBER DESIGN

2.3.1 Phenomenon

When the flange width of an I-girder or box-girder is not negligible compared to the girder span, the transverse distribution of the longitudinal normal stresses is no more uniform over the whole width of the flange due to shear deformation. In a given cross section the value of maximum normal stress in the flange is reached at the junction between the web and the flange and this stress progressively decreases when moving transversally away across the flange width. See Fig. 2.4.

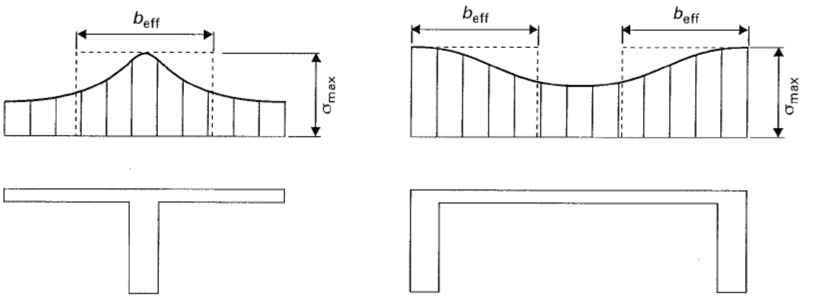

Fig. 2.4: Transverse distribution of the longitudinal normal stresses in a wide flange compared to the span length

In EN1993-1-5, the concept of taking shear lag into account is based on an effective^s width of the flange. This effective^s width is defined in order to have the same total normal force in the gross flange subjected to the real transverse stress distribution as in the effective flange subjected to a uniform stress equal to the maximum stress of the real transverse distribution:

$$\int_{b_f} \sigma_x(y) \cdot t_f \cdot dy = b_{eff} t_f \cdot \sigma_{x,\max} \tag{2.1}$$

Then the following aspects should be highlighted:

- Shear lag effects should be taken into account for the global analysis as well as for the section analysis.
- Shear lag effects are a first order effect (no out-of-plane deformations in the flange) that should not be confused with the second order plate buckling effect (also dealt with in EN1993-1-5 through the definition of an effective^p width).
- As a consequence of the previous comment, shear lag can occur in tension flange as well as in compression flange. In compression flange, interaction should be considered between shear lag and plate buckling effects.
- Shear lag should be considered for Serviceability Limit State (SLS)