
DESIGN OF PLATED STRUCTURES

ECCS EUROCODE DESIGN MANUALS

ECCS EDITORIAL BOARD

Luís Simões da Silva (ECCS)

António Lamas (Portugal)

Jean-Pierre Jaspart (Belgium)

Reidar Bjorhovde (USA)

Ulrike Kuhlmann (Germany)

DESIGN OF STEEL STRUCTURES

Luís Simões da Silva, Rui Simões and Helena Gervásio

FIRE DESIGN OF STEEL STRUCTURES

Jean-Marc Franssen and Paulo Vila Real

DESIGN OF PLATED STRUCTURES

Darko Beg, Ulrike Kuhlmann, Laurence Davaine and Benjamin Braun

AVAILABLE SOON

DESIGN OF COLD-FORMED STEEL STRUCTURES

Dan Dubina, Viorel Ungureanu and Raffaele Landolfo

FATIGUE DESIGN OF STEEL AND COMPOSITE STRUCTURES

Alain Nussbaumer, Luís Borges and Laurence Davaine

DESIGN OF JOINTS IN STEEL AND COMPOSITE STRUCTURES

Jean-Pierre Jaspart, Klaus Weynand and Jurgen Kuck

INFORMATION AND ORDERING DETAILS

For price, availability, and ordering visit our website www.steelconstruct.com.
For more information about books and journals visit www.ernst-und-sohn.de

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**



Design of Plated Structures

1st Edition, 2010

Published by:

ECCS – European Convention for Constructional Steelwork

publications@steelconstruct.com

www.steelconstruct.com

Sales:

Wilhelm Ernst & Sohn Verlag für Architektur und technische Wissenschaften
GmbH & Co. KG, Berlin

All rights reserved. No parts of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the copyright owner.

ECCS assumes no liability with respect to the use for any application of the material and information contained in this publication.

Copyright © 2010 ECCS – European Convention for Constructional Steelwork

ISBN (ECCS): 978-92-9147-100-3

ISBN (Ernst & Sohn): 978-3-433-02980-0

Legal dep.: 320032/10- Printed in Multicomp Lda, Mem Martins, Portugal

Photo cover credits: Vincent de Ville de Goyet

TABLE OF CONTENTS

FOREWORD	vii
PREFACE	ix
SYMBOLS	xi
Chapter 1	
INTRODUCTION	1
1.1. Plate buckling in steel structures	1
1.2. Purpose of this book	2
1.3. Structure of this book	3
Chapter 2	
OVERVIEW OF DESIGN RULES	5
2.1. Introduction	5
2.2. Basis of design and modelling	5
2.2.1. General	5
2.2.2. Effective width models for global analysis	6
2.2.3. Uniform and non uniform members	7
2.2.4. Reduced stress method	8
2.3. Shear lag in member design	8
2.3.1. Phenomenon	8
2.3.2. Shear lag in global analysis (calculation of internal forces and moments)	10
2.3.3. Elastic shear lag in section analysis (calculation of stresses at SLS and fatigue ULS)	11
2.3.4. Elastoplastic shear lag in section analysis (calculation of stresses at ULS)	14
2.3.5. Interaction between shear lag and plate buckling at ULS	15

TABLE OF CONTENTS

2.3.6. Design examples	16
2.4. Plate buckling effects due to direct stresses (including annexes A and E where applicable)	22
2.4.1. Introduction	22
2.4.2. Effective width method	25
2.4.2.1. <i>General requirements</i>	25
2.4.2.2. <i>Principles of effective width calculation</i>	27
2.4.2.3. <i>Hybrid girders</i>	30
2.4.2.4. <i>Plate-like and column-like buckling</i>	31
2.4.3. Plate-like buckling	32
2.4.3.1. <i>Unstiffened plates</i>	32
2.4.3.2. <i>Longitudinally stiffened plates</i>	36
2.4.4. Column-like buckling	42
2.4.4.1. <i>Unstiffened plates</i>	42
2.4.4.2. <i>Longitudinally stiffened plates</i>	43
2.4.5. Interpolation between plate-like and column-like buckling	45
2.4.6. Verification of the cross section resistance in ultimate limit states	48
2.4.7. Verification of plated structural elements in the serviceability limit states	50
2.4.8. Design examples	51
2.5. Resistance to shear (including annex A where applicable)	83
2.5.1. Collapse behaviour	83
2.5.2. Design according to section 5, EN 1993-1-5	84
2.5.3. Design example	92
2.6. Resistance to transverse loading	93
2.6.1. Collapse behaviour	93
2.6.2. Design according to section 6, EN 1993-1-5	94
2.6.3. Design example	102
2.7. Interaction	109
2.7.1. Interaction between bending moment and shear force in a web panel	109

2.7.2. Interaction between axial force, bending moment and shear force in a web panel	112
2.7.3. Interaction between axial force, bending moment and shear force in a flange panel	112
2.7.4. Interaction between axial force, bending moment and transverse force	113
2.7.5. Interaction between shear force and transverse force in a web panel	115
2.7.6. Design examples	117
2.8. Flange induced buckling	118
2.9. Stiffeners and detailing	121
2.9.1. Introduction	121
2.9.2. Transverse stiffeners	124
2.9.2.1. <i>Direct stresses</i>	124
2.9.2.2. <i>Shear</i>	127
2.9.2.3. <i>Simultaneous action of direct stresses and shear</i>	131
2.9.2.4. <i>Introduction of reaction forces and other large transverse forces</i>	134
2.9.3. Longitudinal stiffeners	135
2.9.3.1. <i>Direct stresses</i>	135
2.9.3.2. <i>Shear</i>	137
2.9.4. Torsional buckling of stiffeners	137
2.9.5. Structural detailing related to plate buckling	140
2.9.5.1. <i>Transverse welds in the plate</i>	140
2.9.5.2. <i>Cut-outs in stiffeners</i>	141
2.9.5.3. <i>Welds</i>	142
2.9.6. Design examples	143
2.10. Reduced stress method (including Annexes A and B where applicable)	160
2.10.1. General	160
2.10.2. Choice of reduction factors	164
2.11. FEM	166
2.11.1. Introduction	166

TABLE OF CONTENTS

2.11.2. Modelling	168
2.11.3. Definition of initial imperfections in the FE model	168
2.11.4. Definition of material behaviour in the FE model	172
2.11.5. Design examples	173
Chapter 3	
CRANE RUNWAY BEAM EXAMPLE	181
<hr/>	
3.1. Description of the crane	181
3.2. Description of the crane runway beam	182
3.2.1. Geometry	182
3.2.2. Material properties and material partial factors	184
3.2.3. Cross section classification	184
3.3. Actions and load partial factors	186
3.3.1. General	186
3.3.2. Crane actions	187
3.4. Internal forces and stresses	189
3.4.1. General	189
3.4.2. Transverse forces and stresses	190
3.4.3. Maximum bending moments and stresses	192
3.4.4. Maximum shear forces and stresses	193
3.5. Verifications in general	194
3.6. Buckling verifications according to sections 4 to 7, EN 1993-1-5	194
3.6.1. Resistance to shear forces	195
3.6.2. Resistance to transverse forces	197
3.6.3. Interaction checks	199
3.7. Buckling verifications according to section 10, EN 1993-1-5	200
3.8. Flange induced buckling verification	204
3.9. Stiffener verifications	205
3.9.1. Bearing stiffeners	205
Chapter 4	
BOX-GIRDER BRIDGE EXAMPLE	209
<hr/>	
4.1. Description of the bridge	209
<hr/>	

TABLE OF CONTENTS

4.1.1. Longitudinal elevation	209
4.1.2. Cross section of the composite deck	209
4.1.3. Material properties and partial factors	210
4.1.3.1. <i>Structural steel</i>	210
4.1.3.2. <i>Reinforced concrete</i>	211
4.1.3.3. <i>Partial factors</i>	211
4.1.4. Structural steel distribution	211
4.2. Internal forces and moments, Stresses	214
4.2.1. Actions and load partial factors	214
4.2.2. Transient design situation (launching phase)	215
4.2.3. Permanent design situation	215
4.3. Web buckling verification for the launching phase	217
4.3.1. Patch loading verification	218
4.3.1.1. <i>Resistance load for a single wheel ($ss = 0$)</i>	220
4.3.1.2. <i>Resistance load for a patch length $ss = 1500$ mm</i>	220
4.3.1.3. <i>Patch loading verification</i>	221
4.3.2. Interaction between patch loading and bending moment	221
4.4. Effective cross section of the stiffened bottom flange at internal support P1 (uniform compression)	222
4.4.1. First step: shear lag effect according to EN1993-1-5, 3.2 and 3.3	222
4.4.2. Second step: Critical plate buckling stress according to EN1993-1-5, Annex A	223
4.4.3. Third step: Effective cross section	225
4.4.3.1. <i>Step A: Local buckling of sub-panels</i>	225
4.4.3.2. <i>Step B: Global buckling of the whole stiffened bottom flange</i>	227
4.5. Effective cross section of the stiffened web at internal support P1 (bending)	230
4.5.1. Local buckling of sub-panels	232
4.5.2. Global buckling of the whole stiffened web in bending	234
4.5.2.1. <i>Column like behaviour</i>	234

TABLE OF CONTENTS

4.5.2.2. <i>Plate like behaviour</i>	236
4.5.2.3. <i>Interpolation between plate like and column like behaviour</i>	237
4.5.3. Torsional buckling of the longitudinal web stiffener	238
4.6. Checking of the box-girder section under bending at support P1	239
4.7. Shear resistance of the stiffened web panel closest to the internal support P1	240
4.8. Interaction between bending and shear at support P1	246
4.9. Intermediate transverse stiffener design	247
4.9.1. Transverse web stiffeners	247
4.9.1.1. <i>Axial forces from the tension field action</i>	247
4.9.1.2. <i>Transverse deviation forces from adjacent compressed panels</i>	247
4.9.1.3. <i>Verification of the transverse stiffener</i>	248
4.9.2. Lower flange transverse stiffeners	250
4.9.2.1. <i>Cross section class check</i>	251
4.9.2.2. <i>Strength and stiffness check of the stiffener</i>	252
4.9.2.3. <i>Shear resistance of the stiffener web</i>	253
4.10. Buckling verifications at internal support P1 according to section 10, EN 1993-1-5	254
4.10.1. General	254
4.10.2. Stiffened bottom flange	254
4.10.2.1. <i>General</i>	254
4.10.2.2. <i>Determination of ρ_{loc} to account for local buckling</i>	256
4.10.2.3. <i>Determination of ρ_c to account for global buckling</i>	257
4.10.3. Stiffened bottom flange	260
4.10.3.1. <i>General</i>	260
4.10.3.2. <i>Determination of ρ_{loc} to account for local buckling</i>	261
4.10.3.3. <i>Determination of ρ_c to account for global buckling</i>	263
REFERENCES	267

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

FOREWORD

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.

ix

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

PREFACE

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