



Alfredo Boracchini

Design and Analysis of Connections in Steel Structures

Fundamentals and Examples

WILEY

 **Ernst & Sohn**
A Wiley Brand

Design and Analysis of Connections in Steel Structures

Fundamentals and Examples

Alfredo Boracchini

Author

Alfredo Boracchini, P. E.
info@steeldesign.info

Cover

Detail of a Moment Connection
in a Composite Building Structure
("InterPuls spa" Building, Reggio Emilia,
Italy)

Photo: Alfredo Boracchini

TG
300
B64
2018

All books published by Ernst & Sohn are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.:

applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2018 Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Rotherstraße 21, 10245 Berlin, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Coverdesign Sophie Bleifuß, Berlin, Germany

Typesetting SPi Global, Chennai, India

Printing and Binding Strauss GmbH, Mörlenbach,

Print ISBN: 978-3-433-03122-3

ePDF ISBN: 978-3-433-60606-3

ePub ISBN: 978-3-433-60607-0

oBook ISBN: 978-3-433-60605-6

Printed in the Federal Republic of Germany.

Printed on acid-free paper.

00077851

Contents

Acknowledgments *xxi*

List of Abbreviations *xxiii*

1	Fundamental Concepts of Joints in Design of Steel Structures	1
1.1	Pin Connections and Moment Resisting Connections	1
1.1.1	Safety, Performance, and Costs	1
1.1.2	Lateral Load Resisting System	2
1.1.3	Pins and Fully Restrained Joints in the Analysis Model	7
1.2	Plastic Hinge	8
1.2.1	Base Plates	9
1.2.2	Trusses	11
	References	12
2	Fundamental Concepts of the Behavior of Steel Connections	13
2.1	Joint Classifications	13
2.2	Forces in the Calculation Model and for the Connection	14
2.3	Actions Proportional to Stiffness	17
2.4	Ductility	18
2.5	Load Path	19
2.6	Ignorance of the Load Path	20
2.7	Additional Restraints	21
2.8	Methods to Define Ultimate Limit States in Joints	21
2.9	Bolt Resistance	22
2.10	Yield Line	22
2.11	Eccentric Joints	22
2.12	Economy, Repetitiveness, and Simplicity	22
2.13	Man-hours and Material Weight	23
2.14	Diffusion Angles	23
2.15	Bolt Pretensioning and Effects on Resistance	24
2.15.1	Is Resistance Affected by Pretensioning?	24
2.15.2	Is Pretensioning Necessary?	24
2.15.3	Which Pretensioning Method Should Be Used?	25

2.16	Transfer Forces	25
2.17	Behavior of a Bolted Shear Connection	25
2.18	Behavior of Bolted Joints Under Tension	27
	References	29
3	Limit States for Connection Components	31
3.1	Deformation Capacity (Rotation) and Stiffness	31
3.1.1	Rotational Stiffness	32
3.2	Inelastic Deformation due to Bolt Hole Clearance	33
3.3	Bolt Shear Failure	34
3.3.1	Threads Inside the Shear Plane	35
3.3.2	Number of Shear Planes	37
3.3.3	Packing Plates	37
3.3.4	Long Joints	38
3.3.5	Anchor Bolts	39
3.3.6	Stiffness Coefficient	39
3.4	Bolt Tension Failure	40
3.4.1	Countersunk Bolts	41
3.4.2	Stiffness Coefficient	41
3.5	Bolt Failure in Combined Shear and Tension	42
3.6	Slip-Resistant Bolted Connections	42
3.6.1	Combined Shear and Tension	44
3.7	Bolt Bearing and Bolt Tearing	44
3.7.1	Countersunk Bolts	49
3.7.2	Stiffness Coefficients	49
3.8	Block Shear (or Block Tearing)	49
3.9	Failure of Welds	52
3.9.1	Weld Calculation Procedures	54
3.9.1.1	Directional Method	54
3.9.1.2	Simplified Method	57
3.9.2	Tack Welding (Intermittent Fillet Welds)	58
3.9.3	Eccentricity	58
3.9.4	Fillet Weld Groups	58
3.9.5	Welding Methods	60
3.9.6	Inspections	60
3.9.6.1	Visual Testing	60
3.9.6.2	Penetrant Testing	60
3.9.6.3	Magnetic Particle Testing	60
3.9.6.4	Radiographic Testing	60
3.9.6.5	Ultrasonic Testing	61
3.10	T-stub, Prying Action	61
3.10.1	T-stub with Prying Action	62
3.10.2	Possible Simplified Approach According to AISC	64
3.10.3	Backing Plates	65
3.10.4	Length Limit for Prying Forces and T-stub without Prying	66
3.10.5	T-stub Design Procedure for Various "Components"	
	According to Eurocode	67

3.10.5.1	Column Flange	67
3.10.5.2	End Plate	71
3.10.5.3	Angle Flange Cleat	71
3.10.6	T-stub Design Procedure for Various "Components"	
	According to the "Green Book"	71
3.10.6.1	ℓ_{eff} for Equivalent T-stubs for Bolt Row Acting Alone	74
3.10.6.2	ℓ_{eff} to Consider for a Bolt Row Acting Alone	77
3.10.6.3	ℓ_{eff} to Consider for Bolt Rows Acting in Group	79
3.10.6.4	Examples of ℓ_{eff} for Bolts in a Group	80
3.10.7	T-stub for Bolts Outside the Beam Flanges	81
3.10.8	Stiffness Coefficient	81
3.11	Punching	82
3.12	Equivalent Systems	82
3.13	Web Panel Shear	82
3.13.1	Stiffness Coefficient	84
3.14	Web in Transverse Compression	84
3.14.1	Transformation Parameter β	86
3.14.2	Formulas for Other Local Buckling Limit States	87
3.14.3	Stiffness Coefficient	88
3.14.4	T-stub in Compression	88
3.15	Web in Transverse Tension	88
3.15.1	Stiffness Coefficient	89
3.16	Flange and Web in Compression	89
3.17	Beam Web in Tension	89
3.18	Plate Resistance	90
3.18.1	Material Properties	90
3.18.2	Tension	90
3.18.2.1	Staggered Bolts	92
3.18.3	Compression	92
3.18.4	Shear	92
3.18.5	Bending	93
3.18.6	Design for Combined Forces	93
3.18.7	Whitmore Section	93
3.19	Reduced Section of Connected Profiles	93
3.19.1	Shear Lag	95
3.20	Local Capacity	99
3.21	Buckling of Connecting Plates	100
3.21.1	Gusset Plate Buckling	100
3.21.2	Fin Plate (Shear Tab) Buckling	101
3.22	Structural Integrity (and Tie Force)	103
3.23	Ductility	105
3.24	Plate Lamellar Tearing	106
3.25	Other Limit States in Connections with Sheets and Cold-formed Steel Sections	108
3.26	Fatigue	108
3.27	Limit States of Other Materials in the Connection	109
	References	109

4	Connection Types: Analysis and Calculation
	Examples 113
4.1	Common Symbols 113
4.1.1	Materials 113
4.1.2	Design Forces 113
4.1.3	Bolts 113
4.1.4	Geometric Characteristics of Plates and Profiles 114
4.2	Eccentrically Loaded Bolt Group: Eccentricity in the Plane of the Faying Surface 115
4.2.1	Elastic Method 115
4.2.1.1	Example of Eccentricity Calculated with Elastic Method 116
4.2.2	Instantaneous Center-of-Rotation Method 118
4.2.2.1	Example of Eccentricity Calculated with the Instantaneous Center-of-Rotation Method 119
4.3	Eccentrically Loaded Bolt Group: Eccentricity Normal to the Plane of the Faying Surface 120
4.3.1	Neutral Axis at Center of Gravity 121
4.3.1.1	Example of Eccentricity Normal to Plane Calculated with Neutral Axis at Center-of-Gravity Method 122
4.3.2	Neutral Axis Not at Center of Gravity 123
4.3.2.1	Example of Eccentricity Normal to Plane Calculated with Neutral Axis not at Center-of-Gravity Method 124
4.4	Base Plate with Cast Anchor Bolts 125
4.4.1	Plate Thickness 125
4.4.1.1	AISC Method 125
4.4.1.2	Eurocode Method 130
4.4.2	Contact Pressure 135
4.4.2.1	AISC Method 135
4.4.2.2	Eurocode Method 136
4.4.3	Anchor Bolts in Tension 139
4.4.3.1	AISC Method 139
4.4.3.2	Eurocode Method 140
4.4.3.3	Other Notes 141
4.4.4	Welding 142
4.4.5	Shear Resistance 142
4.4.5.1	Friction 142
4.4.5.2	Anchor Bolts in Shear 143
4.4.5.3	Shear Lugs 144
4.4.6	Rotational Stiffness 144
4.4.7	Measures to Improve Ductility 145
4.4.8	Practical Details and Other Notes 145
4.4.9	Fully Restrained Schematization of Column Base Detail 148
4.4.10	Example of Base Plate Design According to Eurocode 149
4.4.10.1	Uplift and Moment 149
4.4.10.2	Shear 152
4.4.10.3	Welding 153
4.4.10.4	Joint Stiffness 153

4.4.10.5	Comparison with AISC Method for SLU1	153
4.5	Chemical or Mechanical Anchor Bolts	153
4.6	Fin Plate/Shear Tab	154
4.6.1	Choices and Possible Variants	155
4.6.1.1	Pin Position	155
4.6.1.2	Location of Plate Welded to Primary Member	156
4.6.1.3	Notches (Copes) in Secondary Member	157
4.6.1.4	Reinforcing Beam Web	158
4.6.2	Limit States to Be Considered	161
4.6.3	Rotation Capacity	161
4.6.4	Measures to Improve Ductility	162
4.6.5	Measures to Improve Structural Integrity	162
4.6.6	Design Example According to DIN	162
4.6.6.1	Bolt Shear	163
4.6.6.2	Bearing	165
4.6.6.3	Block Shear	166
4.6.6.4	Plate Resistance	167
4.6.6.5	Beam Resistance	167
4.6.6.6	Plate Buckling	168
4.6.6.7	Local Check for Primary-Beam Web	168
4.6.6.8	Welding	168
4.6.6.9	Rotation Capacity	169
4.6.6.10	Ductility	169
4.6.6.11	Structural Integrity	169
4.7	Double-Bolted Simple Plate	169
4.7.1	Rotation Capacity	170
4.7.2	Ductility	170
4.7.3	Structural Integrity	171
4.7.4	Beam-to-Beam Example Designed According to Eurocode	171
4.7.4.1	Bolt Shear	172
4.7.4.2	Bearing	173
4.7.4.3	Block Shear	174
4.7.4.4	Plate Resistance	174
4.7.4.5	Beam Resistance	174
4.7.4.6	Plate Buckling	174
4.7.4.7	Primary-Beam Web Local Check	174
4.7.4.8	Welding, Ductility, and Structural Integrity	174
4.8	Shear ("Flexible") End Plate	175
4.8.1	Variants and Rotation Capacity	175
4.8.2	Limit States to be Considered	177
4.8.3	Rotational Stiffness	177
4.8.4	Ductility	178
4.8.5	Structural Integrity	178
4.8.6	Column-to-Beam Example Designed According to IS 800	178
4.8.6.1	Bolt Resistance	179
4.8.6.2	Rotation Capacity and Structural Integrity	179
4.8.6.3	Bearing	180

4.8.6.4	Block Shear	180
4.8.6.5	Plate Check	180
4.8.6.6	Beam Shear Check	180
4.8.6.7	Column Resistance	180
4.8.6.8	Welds	181
4.8.6.9	Conclusion	181
4.9	Double-Angle Connection	181
4.9.1	Variants	183
4.9.2	Limit States to Be Considered	183
4.9.3	Structural Integrity, Ductility, and Rotation Capacity	183
4.9.4	Practical Advice	183
4.9.5	Beam-to-Beam Example Designed According to AISC	184
4.10	Connections in Trusses	186
4.10.1	Intermediate Connections for Compression Members	186
4.11	Horizontal End Plate Leaning on a Column	188
4.11.1	Limit States to be Considered	189
4.12	Rigid End Plate	189
4.12.1	Column Web Panel Shear	191
4.12.2	Lever Arm	191
4.12.3	Stiffeners	192
4.12.4	Supplementary Web Plate Check	193
4.12.5	Check for Column Stiffeners in Compression Zone	193
4.12.6	Check for Column Stiffeners in Tension Zone	195
4.12.7	Check of Column Diagonal Stiffener for Panel Shear	196
4.12.8	Shear Due to Vertical Forces	196
4.12.9	Design with Haunches	196
4.12.10	Beam-to-Beam Connections	196
4.12.11	BS Provisions	197
4.12.12	AISC Approach	197
4.12.13	Limit States to Be Considered	199
4.12.14	Rotational Stiffness	200
4.12.15	Simplifying the Design	201
4.12.16	Practical Advice	201
4.12.17	Structural Integrity, Ductility, and Rotation Capacity	201
4.12.18	Beam-to-Column End-Plate Design Example According to Eurocode	202
4.12.18.1	Column Flange Thickness Check for Bolt Row 1	204
4.12.18.2	Column Web Tension Check for Bolt Row 1	204
4.12.18.3	Beam End-Plate Thickness Check for Bolt Row 1	205
4.12.18.4	Beam Web Tension Check for Bolt Row 1	205
4.12.18.5	Final Resistant Value for Bolt Row 1	205
4.12.18.6	Column Flange Thickness Check for Bolt Row 2 Individually	205
4.12.18.7	Column Web Tension Check for Bolt Row 2 Individually	206
4.12.18.8	Beam End-Plate Thickness Check for Bolt Row 2 Individually	206
4.12.18.9	Beam Web Tension Check for Bolt Row 2 Individually	206

4.12.18.10	Column Flange Thickness Check for Bolt Row 2 in Group with Bolt Row 1	207
4.12.18.11	Column Web Tension Check for Bolt Row 2 in Group with Bolt Row 1	207
4.12.18.12	Beam End-Plate Thickness Check for Bolt Row 2 in Group with Bolt Row 1	207
4.12.18.13	Beam Web Tension Check for Bolt Row 2 in Group with Bolt Row 1	207
4.12.18.14	Final Resistant Value for Bolt Row 2	208
4.12.18.15	Vertical Shear	208
4.12.18.16	Web Panel Shear	209
4.12.18.17	Column Web Resistance to Transverse Compression	209
4.12.18.18	Stiffener Design	210
4.12.18.19	Welds	210
4.12.18.20	Rotational Stiffness	210
4.13	Splice	212
4.13.1	Calculation Model and Limit States	213
4.13.2	Structural Integrity, Ductility, and Rotation Capacity	215
4.13.3	Column Splice Design Example According to AS 4100	215
4.13.3.1	Flanges	216
4.13.3.2	Web	217
4.13.3.3	Conclusions and Final Considerations	217
4.13.3.4	Possible Alternative	217
4.14	Brace Connections	217
4.14.1	AISC Methods: UFM and KISS	220
4.14.1.1	KISS Method	222
4.14.1.2	Uniform Force Method	222
4.14.1.3	UFM Variant 1	223
4.14.1.4	UFM Variant 2	224
4.14.1.5	UFM Variant 3	225
4.14.1.6	UFM Adapted to Existing Connections	226
4.14.2	Practical Recommendations	227
4.14.3	Complex Brace Connection Example According to CSA S16	227
4.14.3.1	Friction Connection for Brace	227
4.14.3.2	Brace and Gusset Bearing	228
4.14.3.3	Block Shear	228
4.14.3.4	Channel Shear Lag	229
4.14.3.5	Whitmore Section for Tension Resistance and Buckling of Gusset Plate	229
4.14.3.6	UFM Forces	229
4.14.3.7	Gusset-to-Column Shear Tab	229
4.14.3.8	Gusset-to-Beam Weld	229
4.14.3.9	Beam-to-Column Shear Tab	229
4.14.3.10	Ductility and Structural Integrity	230
4.15	Seated Connection	230
4.16	Connections for Girts and Purlins	233
4.17	Welded Hollow-Section Joints	236

4.18	Connections in Composite (Steel-Concrete) Structures	236
4.19	Joints with Bolts and Welds Working in Parallel	236
4.20	Expansion Joints	237
4.21	Perfect Hinges	238
4.22	Rollers	239
4.23	Rivets	240
4.24	Seismic Connections	241
4.24.1	Rigid End Plate	242
4.24.2	Braces	243
4.24.3	Eccentric Braces and "Links"	244
4.24.4	Base Plate	244
	References	246
5	Choosing the Type of Connection	249
5.1	Priority to Fabricator and Erector	249
5.2	Considerations of Pros and Cons of Some Types of Connections	249
5.3	Shop Organization	250
5.3.1	Plates or Sheets	250
5.3.2	Concept of "Handling" One Piece	250
5.4	Culture	252
	References	252
6	Practical Notes on Fabrication	253
6.1	Design Standardizations	253
6.1.1	Materials	253
6.1.2	Thicknesses	253
6.1.3	Bolt Diameters	253
6.2	Dimension of Bolt Holes	254
6.2.1	Bolt Hole Clearance in Base Plates	255
6.3	Erection	256
6.3.1	Structure Lability	256
6.3.2	Erection Sequence and Clearances	256
6.3.3	Bolt Spacing and Interferences	257
6.3.4	Positioning and Supports	257
6.3.5	Holes or Welded Plates for Handling and Lifting	258
6.4	Clearance Needed to Operate Tightening Wrenches	258
6.4.1	Double Angles in Connections	259
6.5	Bolt Spacing and Edge Distances	260
6.6	Root Radius Encroachment	260
6.7	Notches	264
6.8	Bolt Tightening and Pretensioning	265
6.8.1	Calibrated Wrench	266
6.8.2	Turn of the Nut	266
6.8.3	Direct Tension Indicators	270
6.8.4	Twist-Off Type Bolts	271
6.8.5	Hydraulic Wrenches	273

6.9	Washers	274
6.9.1	Tapered (Beveled) Washers	275
6.9.2	Vibrations	277
6.10	Dimensions of Screws, Nuts, and Washers	277
6.10.1	Depth of Bolt Heads and Nuts	277
6.10.2	Washer Width and Thickness	277
6.11	Reuse of Bolts	278
6.12	Bolt Classes	279
6.13	Shims	280
6.14	Galvanization	281
6.14.1	Tubes	281
6.14.2	Plate Welded over Profiles as Reinforcement	281
6.14.3	Base Plates	282
6.15	Other Finishes After Fabrication	282
6.16	Camber	283
6.17	Grout in Base Plates	284
6.18	Graphical Representation of Bolts and Connections	286
6.19	Field Welds	287
6.20	Skewed Joints	287
	References	291

7 Connection Examples 293

Index	355
--------------	------------

The book introduces all the aspects needed for the safe and economic design and analysis of connections using bolted joints in steel structures. It provides an introduction into key concepts, as well as an in-depth description for the design of structural steel connections by explaining how to set up connections within the main calculation model, how to choose the connections types, and how to check them by calculation considering the limit states. This is not treated according to any specific standard but making comparison among the different norms and methodologies used in the engineering practice, e.g. Eurocode, AISC and many others across the world.

Several examples are solved and illustrated in detail, giving the reader all the tools necessary to tackle also complex connection design problems. Furthermore, the author offers an excellent software tool (SCS – Steel Connection Studio) which is illustrated in the book and may be used as an aid to assist in the comprehension of connection design. For information about accessing the software, see the book.

The book also delivers some practical suggestions for the professional engineer: how to talk about bracings to the architect, and how to interact with fabricators showing an understanding of erection and fabrication.

Alfredo Boracchini is a professional engineer licensed in Italy, Canada, and the United States. His professional experience is mainly in steel structures that he has designed and calculated for many applications and in various parts of the world. He is an active member in some international steel associations and the owner of an engineering firm with offices in Europe, Asia, and the United States. This allowed him to collect extensive international experience in the field of steel connection design that he shares in this book with other engineers interested in this field.

