
FATIGUE DESIGN OF STEEL AND COMPOSITE 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

FATIGUE DESIGN OF STEEL AND COMPOSITE STRUCTURES

Alain Nussbaumer, Luís Borges and Laurence Davaine

AVAILABLE SOON

DESIGN OF COLD-FORMED STEEL STRUCTURES

Dan Dubina, Viorel Ungureanu and Raffaele Landolfo

DESIGN OF COMPOSITE STRUCTURES

Markus Feldman and Benno Hoffmeister

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

FATIGUE DESIGN OF STEEL AND COMPOSITE STRUCTURES

Eurocode 3: Design of Steel Structures

Part 1-9 – Fatigue

**Eurocode 4: Design of Composite Steel and
Concrete Structures**

Alain Nussbaumer

Luis Borges

Laurence Davaine



**ECCS
CECM
E K S**

 **WILEY-BLACKWELL**

 **Ernst & Sohn**
A Wiley Company

Fatigue Design of Steel and Composite Structures

1st Edition, 2011

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 © 2011 ECCS – European Convention for Constructional Steelwork

ISBN (ECCS): 978-92-9147-101-0

ISBN (Ernst & Sohn): 978-3-433-02981-7

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

Photo cover credits: Alain Nussbaumer

TABLE OF CONTENTS

FOREWORD	ix
PREFACE	xi
ACKNOWLEDGMENTS	xiii
SYMBOLOLOGY	xv
TERMINOLOGY	xix

Chapter 1

INTRODUCTION	1
1.1 Basis of fatigue design in steel structures	1
1.1.1 General	1
1.1.2 Main parameters influencing fatigue life	3
1.1.3 Expression of fatigue strength	7
1.1.4 Variable amplitude and cycle counting	10
1.1.5 Damage accumulation	13
1.2. Damage equivalent factor concept	16
1.3. Codes of practice	18
1.3.1 Introduction	18
1.3.2 Eurocodes 3 and 4	19
1.3.3 Eurocode 9	22
1.3.4 Execution (EN 1090-2)	24
1.3.5 Other execution standards	30
1.4 Description of the structures used in the worked examples	31
1.4.1 Introduction	31
1.4.2 Steel and concrete composite road bridge (worked example 1)	32
1.4.2.1 Longitudinal elevation and transverse cross section	32
1.4.2.2 Materials and structural steel distribution	33
1.4.2.3 The construction stages	35

TABLE OF CONTENTS

1.4.3 Chimney (worked example 2)	35
1.4.3.1 Introduction	35
1.4.3.2 General characteristics of the chimney	38
1.4.3.3 Dimensions of socket joint located at +11.490 m	39
1.4.3.4 Dimensions of ground plate joint with welded stiffeners located at the bottom, at +0.350m	40
1.4.3.5 Dimensions of manhole located between +1.000 m and +2.200 m	40
1.4.4 Crane supporting structures (worked example 3)	41
1.4.4.1 Introduction	41
1.4.4.2 Actions to be considered	42

Chapter 2

APPLICATION RANGE AND LIMITATIONS

2.1 Introduction	43
2.2 Materials	44
2.3 Corrosion	44
2.4 Temperature	45
2.5 Loading rate	47
2.6 Limiting stress ranges	47

Chapter 3

DETERMINATION OF STRESSES AND STRESS RANGES

3.1 Fatigue loads	51
3.1.1 Introduction	51
3.1.2 Road Bridges	52
3.1.2.1 Fatigue load model 1 (FLM1)	53
3.1.2.2 Fatigue load model 2 (FLM2)	53
3.1.2.3 Fatigue load model 3 (FLM3)	54
3.1.2.4 Fatigue load model 4 (FLM4)	56
3.1.2.5 Fatigue load model 5 (FLM5)	57
3.1.3 Railway bridges	58
3.1.4 Crane supporting structures	59

3.1.5 Masts, towers and chimneys	62
3.1.6 Silos and tanks	71
3.1.7 Tensile cable structures, tension components	71
3.1.8 Other structures	72
3.2 Damage equivalent factors	73
3.2.1 Concept	73
3.2.2 Critical influence line length	76
3.2.3 Road bridges	77
3.2.4 Railway bridges	83
3.2.5 Crane supporting structures	86
3.2.6 Towers, masts and chimneys	94
3.3 Calculation of stresses	95
3.3.1 Introduction	95
3.3.2 Relevant nominal stresses	96
3.3.3 Stresses in bolted joints	98
3.3.4 Stresses in welds	99
3.3.5 Nominal stresses in steel and concrete composite bridges	101
3.3.6 Nominal stresses in tubular structures (frames and trusses)	103
3.4 Modified nominal stresses and concentration factors	106
3.4.1 Generalities	106
3.4.2 Misalignments	109
3.5 Geometric stresses (Structural stress at the hot spot)	116
3.5.1 Introduction	116
3.5.2 Determination using FEM modelling	118
3.5.3 Determination using formulas	120
3.6 Stresses in orthotropic decks	122
3.7 Calculation of stress ranges	125
3.7.1 Introduction	125
3.7.2 Stress range in non-welded details	126
3.7.3 Stress range in bolted joints	128
3.7.4 Stress range in welds	134

TABLE OF CONTENTS

3.7.5	Multiaxial stress range cases	136
3.7.5.1	<i>Introduction</i>	136
3.7.5.2	<i>Possible stress range cases</i>	137
3.7.5.3	<i>Proportional and non-proportional normal stress ranges</i>	139
3.7.5.4	<i>Non-proportional normal and shear stress ranges</i>	139
3.7.6	Stress ranges in steel and concrete composite structures	141
3.7.7	Stress ranges in connection devices from steel and concrete composite structures	146
3.8	Modified nominal stress ranges	150
3.9	Geometric stress ranges	152
 Chapter 4		
FATIGUE STRENGTH		163
4.1	Introduction	163
4.1.1	Set of fatigue strength curves	163
4.1.2	Modified fatigue strength curves	167
4.1.3	Size effects on fatigue strength	169
4.1.4	Mean stress influence	171
4.1.5	Post-weld improvements	171
4.2	Fatigue detail tables	172
4.2.1	Introduction	172
4.2.2	Non-welded details classification (EN 1993-1-9, Table 8.1)	173
4.2.3	Welded plated details classification (general comments)	175
4.2.4	Longitudinal welds, (built-up sections, EN 1993-1-9 Table 8.2), including longitudinal butt welds	176
4.2.5	Transverse but welds (EN 1993-1-9 Table 8.3)	176
4.2.6	Welded attachments and stiffeners (EN 1993-1-9 Table 8.4) and load-carrying welded joints (EN 1993-1-9 Table 8.5)	177
4.2.7	Welded tubular details classification (EN 1993-1-9 Tables 8.6 and 8.7)	182
4.2.8	Orthotropic deck details classification (EN 1993-1-9 Tables 8.8 and 8.9)	182

4.2.9 Crane girder details (EN 1993-1-9 Table 8.10)	183
4.2.10 Tension components details (EN 1993-1-11)	183
4.2.11 Geometric stress categories (EN 1993-1-9, Annex B, Table B.1)	186
4.2.12 Particular case of web breathing, plate slenderness limitations	188
4.3 Determination of fatigue strength or life by testing	188
Chapter 5	
RELIABILITY AND VERIFICATION	191
5.1 Generalities	191
5.2 Strategies	193
5.2.1 Safe life	193
5.2.2 Damage tolerant	194
5.3 Partial factors	195
5.3.1 Introduction	195
5.3.2 Action effects partial factor	196
5.3.3 Strength partial factor	197
5.4 Verification	200
5.4.1 Introduction	200
5.4.2 Verification using the fatigue limit	201
5.4.3 Verification using damage equivalent factors	209
5.4.4 Verification using damage accumulation method	215
5.4.5 Verification of tension components	217
5.4.6 Verification using damage accumulation in case of two or more cranes	218
5.4.7 Verification under multiaxial stress ranges	220
5.4.7.1 <i>Original interaction criteria</i>	220
5.4.7.2 <i>General interaction criteria in EN 1993</i>	222
5.4.7.3 <i>Special case of biaxial normal stresses and shear stress ranges</i>	224
5.4.7.4 <i>Interaction criteria in EN 1994, welded studs</i>	226

TABLE OF CONTENTS

Chapter 6

BRITTLE FRACTURE **231**

6.1 Introduction	231
6.2 Steel quality	233
6.3 Relationship between different fracture toughness test results	235
6.4 Fracture concept in EN 1993-1-10	240
6.4.1 method for toughness verification	240
6.4.2 method for safety verification	243
6.4.3 Flaw size design value	245
6.4.4 Design value of the action effect stresses	247
6.5 Standardisation of choice of material: maximum allowable thicknesses	249

REFERENCES **259**

Annex A

STANDARDS FOR STEEL CONSTRUCTION **271**

Annex B

FATIGUE DETAIL TABLES WITH COMMENTARY **277**

Introduction	277
B.1. Plain members and mechanically fastened joints (EN 1993-1-9, Table 8.1)	278
B.2. Welded built-up sections (EN 1993-1-9, Table 8.2)	281
B.3. Transverse butt welds (EN 1993-1-9, Table 8.3)	283
B.4. Attachments and stiffeners (EN 1993-1-9, Table 8.4)	286
B.5. Load carrying welded joints (EN 1993-1-9, Table 8.5)	288
B.6. Hollow sections ($T \leq 12.5$ mm) (EN 1993-1-9, Table 8.6)	291
B.7. Lattice girder node joints (EN 1993-1-9, Table 8.7)	293
B.8. Orthotropic decks – closed stringers (EN 1993-1-9, Table 8.8)	295
B.9. Orthotropic decks – open stringers (EN 1993-1-9, Table 8.9)	297
B.10. Top flange to web junction of runway beams (En 1993-1-9, Table 8.10)	298

B.11. Detail categories for use with geometric (hot spot) stress method (EN 1993-1-9, Table B.1)	300
B.12. Tension components	302
B.13. Review of orthotropic decks details and structural analysis	304

Annex C

MAXIMUM PERMISSIBLE THICKNESS TABLES **309**

Introduction	309
C.1. Maximum permissible values of element thickness t in mm (EN 1993-1-10, Table 2.1)	310
C.2. Maximum permissible values of element thickness t in mm (EN 1993-1-12, Table 4)	311

FOREWORD

Steel structures have been built worldwide for more than 120 years. For the majority of this time, fatigue and fracture used to be unknown or neglected limit states, with the exception in some particular and “obvious” cases. Nevertheless, originally unexpected but still encountered fatigue and fracture problems and resulting growing awareness about such have that attitude reappraised. The consequent appearance of the first ECCS recommendations on fatigue design in 1985 changed radically the spirit. The document served as a basis for the fatigue parts in the first edition of Eurocodes 3 and 4. Subsequent use of the latter and new findings led to improvements resulting in the actual edition of the standards, the first to be part of a true all-European set of construction design standards.

As with any other prescriptive use of technical knowledge, the preparation of the fatigue parts of Eurocodes 3 and 4 was long and based on the then available information. Naturally, since the publication of the standards, have evolved not only structural materials but also joint techniques, structural analysis procedures and their precision, measurement techniques, etc., each of these revealing new, previously unknown hazardous situation that might lead to fatigue failure. The result is that even the most actual standards remain somewhat unclear (but not necessarily unsafe!) in certain areas and cover some others not sufficiently well or not at all. Similar reasoning can be applied for the fracture parts of Eurocode 3, too.

Having all the above-mentioned in mind, the preparation of this manual was intended with the aim of filling in some of the previously revealed gaps by clarifying certain topics and extending or adding some others. For the accomplishment of that task, the manual benefited from a years-long experience of its authors and its proofreaders in the fields treated in it; it is a complete document with detailed explanations about how to deal with fatigue and fracture when using Eurocodes... but also offering much, much more. This is probably the most exhaustive present-day fatigue manual on

FOREWORD

the use of Eurocodes 3 and 4, checked and approved by members of ECCS TC6 “Fatigue and Fracture”.

This document outlines all the secrets of fatigue and fracture verifications in a logical, readable and extended (in comparison to the standards) way, backed by three thoroughly analysed worked examples. I am convinced that a manual as such cannot only help an inexperienced user in the need of some clarifications but can also be hailed even by the most demanding fatigue experts.

Mladen Lukić

CTICM, Research Manager

ECCS TC6 Chairman

PREFACE

This book addresses the specific subject of fatigue, a subject not familiar to many engineers, but relevant for achieving a satisfactory design of numerous steel and composite steel-concrete structures. Since fatigue and fracture cannot be separated, they are indeed two aspects of the same behaviour, this book also addresses the problem of brittle fracture and its avoidance following the rules in EN 1993-1-10.

According to the objectives of the ECCS Eurocode Design Manuals, this book aims at providing design guidance on the use of the Eurocodes for practicing engineers. It provides a mix of “light” theoretical background, explanation of the code prescriptions and detailed design examples. It contains all the necessary information for the fatigue design of steel structures according to the general rules given in Eurocode 3, part 1-9 and the parts on fatigue linked with specific structure types.

Fatigue design is a relatively recent code requirement. The effects of repetitive loading on steel structures such as bridges or towers have been extensively studied since the 1960s. This work, as well as lessons learned from the poor performance of some structures, has led to a better understanding of fatigue behaviour. This knowledge has been implemented in international recommendations, national and international specifications and codes since the 1970s. At European level, the ECCS recommendations (ECCS publication N° 43 from 1985) contained the first unified fatigue rules, followed then by the development of the structural Eurocodes. Today, fatigue design rules are present in many different Eurocode parts : EN 1991-2, EN 1993-1-9, EN 1993-1-11, EN 1993-2, EN 1993-3, etc. as will be seen throughout this book.

Chapter 1 introduces general aspects of fatigue, the main parameters influencing fatigue life, damage and the structures used in the worked examples. The design examples are chosen from typical structures that need to be designed against fatigue: i) a steel and concrete composite bridge which is also used in the ECCS design manual on EN 1993-1-5 (plate

buckling), ii) a steel chimney and iii) a crane supporting structure. Chapter 2 summarizes the application range of the Eurocode and its limitations in fatigue design. Chapters 3 to 5 are the core of this book, explaining the determination of the parts involved in a fatigue verification namely: applied stress range, fatigue strength of details, fatigue design strategies and partial factors, damage equivalent factors. For each of the parts a theoretical background is given, followed by explanation of the code prescriptions and then by application to the different design examples. Finally, chapter 6 deals with steel selection, which in fact is the first step in the design process but is separated from fatigue design in the Eurocodes. In this chapter, the theory and application of EN 1993-1-10 regarding the selection of steel for fracture toughness are discussed. Note that the selection of material regarding through-thickness properties is not within the scope of this book. The book also includes annexes containing the fatigue tables from EN 1993-1-9, as well as detail categories given in other Eurocode parts (cables). The tables include the corrections and modifications from the corrigendum issued by CEN on April 1st, 2009 (changes are highlighted with a grey background). These tables also contain an additional column with supplementary explanations and help for the engineer to classify properly fatigue details and compute correctly the stress range needed for the verification. The last annex contains the tables from EN 1993-1-10 and EN 1993-1-12 giving the maximum permissible values of elements thickness to avoid brittle fracture.

Luis Borges

Laurence Davaine

Alain Nussbaumer