FATIGUE DESIGN OF STEEL AND COMPOSITE STRUCTURES
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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
# TABLE OF CONTENTS

**FOREWORD** ix  
**PREFACE** xi  
**ACKNOWLEDGMENTS** xiii  
**SYMBOLOGY** 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)\(^\text{35}\)

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 +0.350 m\(^{40}\)

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**\(^{43}\)

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**\(^{51}\)

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\(^{59}\)
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.5  Masts, towers and chimneys</td>
<td>62</td>
</tr>
<tr>
<td>3.1.6  Silos and tanks</td>
<td>71</td>
</tr>
<tr>
<td>3.1.7  Tensile cable structures, tension components</td>
<td>71</td>
</tr>
<tr>
<td>3.1.8  Other structures</td>
<td>72</td>
</tr>
<tr>
<td>3.2  Damage equivalent factors</td>
<td>73</td>
</tr>
<tr>
<td>3.2.1  Concept</td>
<td>73</td>
</tr>
<tr>
<td>3.2.2  Critical influence line length</td>
<td>76</td>
</tr>
<tr>
<td>3.2.3  Road bridges</td>
<td>77</td>
</tr>
<tr>
<td>3.2.4  Railway bridges</td>
<td>83</td>
</tr>
<tr>
<td>3.2.5  Crane supporting structures</td>
<td>86</td>
</tr>
<tr>
<td>3.2.6  Towers, masts and chimneys</td>
<td>94</td>
</tr>
<tr>
<td>3.3  Calculation of stresses</td>
<td>95</td>
</tr>
<tr>
<td>3.3.1  Introduction</td>
<td>95</td>
</tr>
<tr>
<td>3.3.2  Relevant nominal stresses</td>
<td>96</td>
</tr>
<tr>
<td>3.3.3  Stresses in bolted joints</td>
<td>98</td>
</tr>
<tr>
<td>3.3.4  Stresses in welds</td>
<td>99</td>
</tr>
<tr>
<td>3.3.5  Nominal stresses in steel and concrete composite bridges</td>
<td>101</td>
</tr>
<tr>
<td>3.3.6  Nominal stresses in tubular structures (frames and trusses)</td>
<td>103</td>
</tr>
<tr>
<td>3.4  Modified nominal stresses and concentration factors</td>
<td>106</td>
</tr>
<tr>
<td>3.4.1  Generalities</td>
<td>106</td>
</tr>
<tr>
<td>3.4.2  Misalignments</td>
<td>109</td>
</tr>
<tr>
<td>3.5  Geometric stresses (Structural stress at the hot spot)</td>
<td>116</td>
</tr>
<tr>
<td>3.5.1  Introduction</td>
<td>116</td>
</tr>
<tr>
<td>3.5.2  Determination using FEM modelling</td>
<td>118</td>
</tr>
<tr>
<td>3.5.3  Determination using formulas</td>
<td>120</td>
</tr>
<tr>
<td>3.6  Stresses in orthotropic decks</td>
<td>122</td>
</tr>
<tr>
<td>3.7  Calculation of stress ranges</td>
<td>125</td>
</tr>
<tr>
<td>3.7.1  Introduction</td>
<td>125</td>
</tr>
<tr>
<td>3.7.2  Stress range in non-welded details</td>
<td>126</td>
</tr>
<tr>
<td>3.7.3  Stress range in bolted joints</td>
<td>128</td>
</tr>
<tr>
<td>3.7.4  Stress range in welds</td>
<td>134</td>
</tr>
</tbody>
</table>
### Table of Contents

3.7.5 Multiaxial stress range cases 136
   3.7.5.1 Introduction 136
   3.7.5.2 Possible stress range cases 137
   3.7.5.3 Proportional and non-proportional normal stress ranges 139
   3.7.5.4 Non-proportional normal and shear stress ranges 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
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.9 Crane girder details (EN 1993-1-9 Table 8.10)</td>
<td>183</td>
</tr>
<tr>
<td>4.2.10 Tension components details (EN 1993-1-11)</td>
<td>183</td>
</tr>
<tr>
<td>4.2.11 Geometric stress categories (EN 1993-1-9, Annex B, Table B.1)</td>
<td>186</td>
</tr>
<tr>
<td>4.2.12 Particular case of web breathing, plate slenderness limitations</td>
<td>188</td>
</tr>
<tr>
<td>4.3 Determination of fatigue strength or life by testing</td>
<td>188</td>
</tr>
</tbody>
</table>

**Chapter 5**

**RELIABILITY AND VERIFICATION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Generalities</td>
<td>191</td>
</tr>
<tr>
<td>5.2 Strategies</td>
<td>193</td>
</tr>
<tr>
<td>5.2.1 Safe life</td>
<td>193</td>
</tr>
<tr>
<td>5.2.2 Damage tolerant</td>
<td>194</td>
</tr>
<tr>
<td>5.3 Partial factors</td>
<td>195</td>
</tr>
<tr>
<td>5.3.1 Introduction</td>
<td>195</td>
</tr>
<tr>
<td>5.3.2 Action effects partial factor</td>
<td>196</td>
</tr>
<tr>
<td>5.3.3 Strength partial factor</td>
<td>197</td>
</tr>
<tr>
<td>5.4 Verification</td>
<td>200</td>
</tr>
<tr>
<td>5.4.1 Introduction</td>
<td>200</td>
</tr>
<tr>
<td>5.4.2 Verification using the fatigue limit</td>
<td>201</td>
</tr>
<tr>
<td>5.4.3 Verification using damage equivalent factors</td>
<td>209</td>
</tr>
<tr>
<td>5.4.4 Verification using damage accumulation method</td>
<td>215</td>
</tr>
<tr>
<td>5.4.5 Verification of tension components</td>
<td>217</td>
</tr>
<tr>
<td>5.4.6 Verification using damage accumulation in case of two or more cranes</td>
<td>218</td>
</tr>
<tr>
<td>5.4.7 Verification under multiaxial stress ranges</td>
<td>220</td>
</tr>
<tr>
<td>5.4.7.1 Original interaction criteria</td>
<td>220</td>
</tr>
<tr>
<td>5.4.7.2 General interaction criteria in EN 1993</td>
<td>222</td>
</tr>
<tr>
<td>5.4.7.3 Special case of biaxial normal stresses and shear stress ranges</td>
<td>224</td>
</tr>
<tr>
<td>5.4.7.4 Interaction criteria in EN 1994, welded studs</td>
<td>226</td>
</tr>
</tbody>
</table>
### Table of Contents

#### Chapter 6

**BRITTLE FRACTURE**
- 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
  - 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**

- 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 ≤ 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
# TABLE OF CONTENTS

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
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
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 books
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 1\textsuperscript{st}, 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 1993-12 giving the
maximum permissible values of elements thickness to avoid brittle fracture.

Luis Borges
Laurence Davaine
Alain Nussbaumer
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Luis Borges
Laurence Davaine
Alain Nussbaumer
This list of symbols follows the Eurocodes, in particular EN 1993-1-9, and only the fatigue relevant symbols are given below.

**Latin letters**

\[ A \]: Area  
\[ a \]: Crack depth  
\[ b_{\text{eff}} \]: Relevant thickness in Wallin toughness correlation  
\[ c \]: Half crack length  
\[ C \]: Constant representing the influence of the construction detail in fatigue strength expression  
\[ m \]: Fatigue curve slope coefficient  
\[ D, d \]: Damage sum, damage  
\[ G \]: Permanent actions effects  
\[ k_f \]: Stress concentration factor (i.e. geometric stress concentration factor, thus in this publication there is no difference with \( k_t \))  
\[ K_{\text{mat}} \]: Fracture toughness  
\[ I \]: Inertia  
\[ I_2 \]: Inertia of the cracked composite cross section  
\[ M \]: Bending moment  
\[ N, n \]: Number of cycles, number  
\[ N_{\text{tot}} \]: Total number of cycles in a spectrum  
\[ n_0 \]: Short term modular ratio, \( E_a / E_{cm} \)  
\[ n_{\text{insp}} \]: Total number of inspections during services life  
\[ n_{\text{stud}} \]: Number of shear studs per unit length  
\[ P_f \]: Failure probability  
\[ Q \]: Load  
\[ Q_E \]: Damage equivalent fatigue load  
\[ Q_{E,2} \]: Damage equivalent fatigue load related to 2 million cycles  
\[ Q_{K,1} \]: Characteristic value of dominant variable load,  
\[ Q_{K,i} \]: Characteristic value of accompanying variable loads,
SYMBOLS

\( Q_{s}, Q_{fat} \)  Characteristic fatigue load
\( R \)  Stress ratio, \( \sigma_{\text{min}} / \sigma_{\text{max}} \)
\( S \)  Standard deviation, characteristic value of the effects of the concrete shrinkage
\( t \)  Time, thickness
\( t_0 \)  Reference thickness, equal to 1 mm
\( T \)  Temperature
\( T_k \)  Characteristic value of the effects of the thermal gradient
\( T_{K27} \)  Temperature at which the minimum energy is not less than 27 J in a CVN impact test
\( T_{K100} \)  Temperature at which the fracture toughness is not less than 100 MPa m\(^{1/2}\)
\( T_{\text{min,d}} \)  Lowest air temperature with a specified return period, see EN 1991-1-5
\( \Delta T_r \)  Temperature shift from radiation losses of the structural member
\( \Delta T_\sigma \)  Temperature shift for the influence of shape and dimensions of the member, imperfection from crack, and stress \( \sigma_{\text{ed}} \)
\( \Delta T_R \)  Temperature shift corresponding to additive safety element
\( \Delta T_\varepsilon \)  Temperature shift for the influence of strain rate
\( \Delta T_{\text{pl}} \)  Temperature shift from from cold forming

GREEK SYMBOLS

\( \gamma_f \)  Partial factor for fatigue action effects
\( \gamma_{Mf} \)  Partial factor for fatigue strength
\( \lambda \)  Damage equivalent factor
\( \lambda_1 \)  Factor accounting for the span length (in relation with the length of the influence line)
\( \lambda_2 \)  Factor accounting for a different traffic volume than given
\( \lambda_3 \)  Factor accounting for a different design working life of the structure than given
\( \lambda_4 \)  Factor accounting for the influence of more than one load on the structural member,
\( \lambda_{\text{max}} \)  Maximum damage equivalent factor value, taking into account the fatigue limit.
\( \lambda_c \)  Damage equivalent factor for the connection
\( \psi_i \)  Combination factor for frequent loads
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi_{2,i} )</td>
<td>Combination factor for quasi-permanent loads</td>
</tr>
<tr>
<td>( \sigma_{\text{min}} )</td>
<td>Minimum direct or normal stress value (with sign), expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \sigma_{\text{max}} )</td>
<td>Maximum direct or normal stress value (with sign), expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \sigma_{\text{res}} )</td>
<td>Residual stress value, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( v_2 )</td>
<td>Distance from the neutral axis to the relevant fibre in a steel concrete beam</td>
</tr>
<tr>
<td>( \Delta \sigma_C )</td>
<td>Fatigue strength under direct stress range at 2 million cycles, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta \tau_C )</td>
<td>Fatigue strength under shear stress range at 2 million cycles, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta \sigma_D )</td>
<td>Constant amplitude fatigue limit (CAFL) under direct stress range, at 5 million cycles in the set of fatigue strength curves, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta \sigma_{E,2} )</td>
<td>Equivalent direct stress range, computed at 2 million cycles, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta \sigma_L )</td>
<td>Cut-off limit under direct stress range, at 100 million cycles in the set of fatigue strength curves, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta \tau_L )</td>
<td>Cut-off limit under shear stress range, at 100 million cycles in the set of fatigue strength curves, expressed in N/mm(^2)</td>
</tr>
<tr>
<td>( \Delta v_L )</td>
<td>Longitudinal shear force per unit length at the steel-concrete interface</td>
</tr>
</tbody>
</table>
**TERMINOLOGY**

**Associated Eurocode** Eurocode parts that describe the principles and application rules for the different types of structures with the exception of buildings (bridges, towers, masts, chimneys, crane supporting structures, tanks…).

**Classification method** Fatigue verification method where fatigue resistance is expressed in terms of fatigue strength curves for standard classified details. Can refer to both the **nominal stress method** or the **modified nominal stress method**.

**Constant amplitude fatigue limit (CAFL)** The limiting direct or shear stress range value below which no fatigue damage will occur in tests under constant amplitude stress conditions. Under variable amplitude conditions all stress ranges have to be below this limit for no fatigue damage to occur.

**Constructional detail** A structural member or structural detail containing a structural discontinuity (e.g. a weld) for which the nominal stress method is applied. The Eurocodes contain classification tables, with classified constructional details and their corresponding detail categories (i.e. fatigue strength curves).

**Control** Operation occurring at every important, identified, step during the fabrication process and during which various checks are made (e.g. tolerances control, NDE controls of welds, of paint layer thickness, etc.).

**Crack** A sharp flaw or imperfection for which the crack tip radius is close to zero.

**Crack initiation life** Crack nucleation time, micro-cracking stage. The portion of fatigue life consumed before a true crack
<table>
<thead>
<tr>
<th><strong>Terminology</strong></th>
<th><strong>Definition</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>In the order of magnitude of one-tenth of a millimeter</td>
<td>Produced.</td>
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<tr>
<td><strong>Crack propagation life</strong></td>
<td>Portion of fatigue life between crack initiation and failure (according to conventional failure criterion or actual member rupture).</td>
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<tr>
<td><strong>Cut-off limit</strong></td>
<td>Limit below which stress ranges of the design spectrum do not contribute to the calculated cumulative damage.</td>
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<tr>
<td><strong>Cyclic plasticity</strong></td>
<td>Material subjected to cyclic loading up to yield stress in tension and in compression during each cycle. Alternative term for describing oligo-cyclic fatigue.</td>
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<tr>
<td><strong>Design working life</strong></td>
<td>Value of duration of use, lifetime, of a structure fixed at the design stage, also referred to as design service life.</td>
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<tr>
<td><strong>Detail category</strong></td>
<td>Classification of structural members and details (i.e. classified structural details) according to their fatigue strength. The designation of every detail category corresponds to its fatigue strength at two million cycles, $\Delta \sigma_C$.</td>
</tr>
<tr>
<td><strong>Direct stress</strong></td>
<td>Stress which tends to change the volume of the material. In fatigue, relevant stress in the parent material, acting on the detail, together with the shear stress. In EN 1993-1-9, the above is differentiated from the normal stress, which is defined in a weld.</td>
</tr>
<tr>
<td><strong>Flaw</strong></td>
<td>Also referred to as imperfection. An unintentional stress concentrator, e.g. rolling flaw, slag inclusions, porosity, undercut, lack of penetration, etc. Can be within the production/fabrication tolerances (imperfection) or outside them (defect). In this document, it is assumed that flaws are within tolerances.</td>
</tr>
<tr>
<td><strong>Generic Eurocode</strong></td>
<td>Eurocode parts that describe the generic principles for all structures and application rules for buildings (EN 199x-1-y).</td>
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</table>
**Geometric stress**  Also known as **structural stress**. Value of stress on the surface of a structural detail, which takes into account membrane stresses, bending stress components and all stress concentrations due to structural discontinuities, but ignoring any local notch effect due to small discontinuities such as weld toe geometry, flaws, cracks, etc. (see sub-chapters 3.5 and 3.9).

**Geometric stress method**  Fatigue verification method where fatigue resistance is expressed in terms of fatigue strength curves for reference weld configurations applicable to geometric stresses. Also referred to as hot spot stress method.

**Hot spot**  A point in the structure subjected to repeated cycling loading, where a fatigue crack is expected to initiate due to a combination of stress concentrators. The **structural stress at the hot spot** is the value of geometric stress at the weld toe used in fatigue verification. Its definition, and the related design fatigue curve, is not unique since different extrapolation methods exist.

**Imperfection**  See flaw.

**Inspection**  Operation occurring, usually at prescribed intervals, on a structure in service and during which the structure and its members are inspected visually and using NDT methods to report any degradation (e.g. hits and bends, corrosion, cracks, etc.).

**Longitudinal**  In the direction of the main force in the structure or detail (Figure 0.1).
**Maintenance**
Operation made on a structure in service and consisting in corrections and minor repairs on the structure (e.g. painting, cleaning, etc.).

**Mean stress**
The average between the minimum and maximum stress, i.e. \((\sigma_{\text{min}} + \sigma_{\text{max}})/2\).

**Modified nominal stress**
Nominal stress increased by an appropriate stress concentration factor to include the effect of an additional structural discontinuity that has not been taken into account in the classification of a particular detail such as misalignment, hole, cope, cut-out, etc. (see sub-chapter 3.4 and section 3.7.7). The appropriate stress concentration factor is labelled \(k_f\) or \(k_l\) (for hollow sections joints).

**Monitoring**
Operation occurring on a structure in service, during which measurements or observations are made to check the structure’s behavior (e.g. deflection, crack length, strain, etc.).

**Nominal stress**
Stress in a structural member near the structural detail, obtained using simple elastic strength of material theory, i.e. beam theory. Influence of shear lag, or effective widths of sections shall be taken into account. Stress concentrators and residual stresses effects are excluded (see section 3.3.2)

**Normal stress**
A stress component perpendicular to the sectional surface. In fatigue, relevant stress component in a weld, together with shear stress components.
### TERMINOLOGY

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</tr>
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<tr>
<td>S-N curve</td>
<td>Also known as <strong>fatigue strength curve</strong> or <strong>Wöhler’s curve</strong>. A quantitative curve expressing fatigue failure as a function of stress range and number of stress cycles.</td>
</tr>
<tr>
<td>Shear stress</td>
<td>A stress component which tends to deform the material without changing its volume. In fatigue, relevant stress(es) in the parent material together with the <strong>direct stress</strong> or, in a weld, with the <strong>normal stress</strong>.</td>
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<tr>
<td>Stress range</td>
<td>Also known as <strong>stress difference</strong>. Algebraic difference between the two extremes of a particular stress cycle (can be a direct, normal or shear stress) derived from a stress history.</td>
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<tr>
<td>Stress concentration factor</td>
<td>The ratio of the concentrated stress to the nominal stress (see sub-chapter 3.4), used usually only for direct stresses.</td>
</tr>
<tr>
<td>Structural stress</td>
<td>Synonym for geometric stress.</td>
</tr>
<tr>
<td>Transverse</td>
<td>Also referred to as <strong>lateral</strong>. Direction perpendicular to the direction of main force in the structure or detail (Figure 0.1).</td>
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