Fatigue Design of Steel and Composite Structures
2nd Edition

Eurocode 3: Design of Steel Structures
Part 1-9: Fatigue
Eurocode 4: Design of Composite Steel and Concrete Structures

Alain Nussbaumer
Luís Borges
Laurence Davaine

ECCS Eurocode Design Manuals

WILEY

ECCS
CECM
EKS

Ernst & Sohn
A Wiley Brand

Join the ECCS and receive the journal Steel Construction

Ernst & Sohn
A Wiley Brand

ECCS
CECM
EKS

- 20% discount on ECCS publications
- Journal Steel Construction print + online for the annual member subscription fee € 190,–* net
- ECCS conferences at reduced prices
- Access to exclusive information via the ECCS homepage "Member Area"
- ECCS newsletter

Steel Construction Design and Research

Volume 11, 2018. 4 issues per year.
Published in English.
Editor-in-Chief: Dr.-Ing. Karl-Eugen Kurrer
Annual subscription 2018
€ 190,–* net (print + online for ECCS Individual Members)

Steel Construction unites in one journal the holistic approach to steel construction. In the interests of "construction without depletion", – it skillfully combines steel with other forms of construction employing concrete, glass, cables and membranes to form integrated systems. This journal is therefore aimed at all structural engineers, whether active in research or practice.

The journal publishes peer-reviewed papers covering the entire field of steel in construction. The scientific and technical papers in Steel Construction are primary publications. An internationally renowned Editorial Board assures a highly interesting selection of topics and guarantees the high standard of the contributions.

Take advantage of this offer and join the ECCS as an Individual Member.
Find more information at: www.steelconstruct.com

Fax Order Form to ECCS, Portugal: +351 239 091 216

☐ I wish to apply for individual membership of the ECCS. Membership begins in 2018 and is automatically renewed for a further year unless I cancel my membership at least six months prior to the end of the year. Please send me an invoice for 190, –* net to cover the annual subscription.

☐ I would like to receive more information about membership of the ECCS plus a sample issue of the journal Steel Construction – Design and Research.

Company / Institution

Contact Person | Phone

Street, No. | Postcode, Town

Country | E-Mail

☐ Payment with Visa or Mastercard

Card details

Card number | Expiry date

Card Verification Number (CVV) (Three digit number printed on back of your card)

✕
Date, Signature

www.ernst-und-sohn.de/steel-construction

CMM – Portuguese Steelwork Association

Business Center
Leonardo da Vinci
Coimbra iParque – Lote 3
3040-540 Antanhol, PORTUGAL

Phone +351 239 098 422
Fax +351 239 091 216
members@steelconstruct.com

*Subject to alterations. 1065106_dp

FATIGUE DESIGN OF STEEL AND COMPOSITE STRUCTURES

2ND EDITION

ECCS EUROCODE DESIGN MANUALS

DESIGN OF STEEL STRUCTURES – 2ND EDITION
Luís Simões da Silva, Rui Simões and Helena Gervásio

FIRE DESIGN OF STEEL STRUCTURES – 2ND EDITION
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 – 2ND EDITION
Alain Nussbaumer, Luís Borges and Laurence Davaine

DESIGN OF COLD-FORMED STEEL STRUCTURES
Dan Dubina, Viorel Ungureanu and Raffaele Landolfo

DESIGN OF JOINTS IN STEEL AND COMPOSITE STRUCTURES
Jean-Pierre Jaspart and Klaus Weynand

DESIGN OF STEEL STRUCTURES FOR BUILDINGS IN SEISMIC AREAS
Raffaele Landolfo, Federico Mazzolani, Dan Dubina, Luís Simões da Silva and Mario d'Aniello

ECCS – SCI EUROCODE DESIGN MANUALS

DESIGN OF STEEL STRUCTURES, UK EDITION
Luís Simões da Silva, Rui Simões and Helena Gervásio
Adapted to UK by Graham Couchman

DESIGN OF JOINTS IN STEEL STRUCTURES, UK EDITION
Jean-Pierre Jaspart and Klaus Weynand
Adapted to UK by Graham Couchman and Ana M. Girão Coelho

ECCS EUROCODE DESIGN MANUALS – BRAZILIAN EDITIONS

DIMENSIONAMENTO DE ESTRUTURAS DE AÇO
Luís Simões da Silva, Rui Simões, Helena Gervásio, Pedro Vellasco and Luciano Lima

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

2nd Edition

Alain Nussbaumer
Luís Borges
Laurence Davaine

WILEY

ECCS
CECM
E K S

Ernst & Sohn
A Wiley Brand

Fatigue Design of Steel and Composite Structures

2nd Edition, 2018

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

ISBN (ECCS): 978-92-9147-139-3
ISBN (Ernst & Sohn): 978-3-433-03220-6

Legal dep.: Printed in Sersilito, Empresa Gráfica Lda, Maia, Portugal
Photo cover credits: Alain Nussbaumer (front cover), Thierry Delémont (back cover)

TABLE OF CONTENTS

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, previsouly 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

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 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 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 1993-12 giving the maximum permissible values of elements thickness to avoid brittle fracture.

Luís Borges
Laurence Davaine
Alain Nussbaumer

ACKNOWLEDGMENTS

This document was written under the supervision of the ECCS Editorial Committee. It was reviewed by the members of this committee, whom the authors would like to thank:

Luís Simões da Silva (Chairman - ECCS),
António Lamas (Portugal)
Jean-Pierre Jaspart (Belgium)
Reidar Bjorhovde (USA)
Ulrike Kuhlmann (Germany)

The document was also reviewed by the ECCS Technical Committee 6, working group C. Their comments and suggestions were of great help to improve the quality of the document. Many thanks to all contributive former and current members:

Ömer Bucak, Matthias Euler, Hans-Peter Günther (Chairman WG-C), Senta Haldimann-Sturm, Rosi Helmerich, Stefan Herion, Henk Kolstein, Bertram Kühn, Mladen Lukic (Chairman TC6), Johan Maljaars and Joël Raoul.

Many thanks are also due to all the other persons, too numerous to mention here, who offered their continuous encouragement and suggestions. A large part of the figures were made or adapted by ICOM's talented draftsman and more, Claudio Leonardi.

Finally, thanks are due to Ms. Joana Albuquerque for formatting the text before publication.

Luís Borges
Laurence Davaine
Alain Nussbaumer

SYMBOLOGY

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_{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_{mat}	Fracture toughness
I	inertia
I_2	inertia of the cracked composite cross section
M	Bending moment
N, n	Number of cycles, number
N_{tot}	Total number of cycles in a spectrum
n_0	short term modular ratio, E_a / E_{cm}
n_{insp}	Total number of inspections during services life
n_{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,
Q_i,Q_{fat}	Characteristic fatigue load

R	Stress ratio, $\sigma_{\min} / \sigma_{\max}$
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_{KV27}	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 $MPa \cdot m^{1/2}$
$T_{\min,d}$	Lowest air temperature with a specified return period, see EN 1991-1-5
ΔT_r	Temperature shift from radiation losses of the structural member
ΔT_σ	Temperature shift for the influence of shape and dimensions of the member, imperfection from crack, and stress σ_{Ed}
ΔT_R	Temperature shift corresponding to additive safety element
$\Delta T_{\dot{\varepsilon}}$	Temperature shift for the influence of strain rate
$\Delta T_{\varepsilon pl}$	Temperature shift from from cold forming

Greek Symbols

γ_{Ff}	Partial factor for fatigue action effects
γ_{Mf}	Partial factor for fatigue strength
λ	Damage equivalent factor
λ_1	Factor accounting for the span length (in relation with the length of the influence line)
λ_2	Factor accounting for a different traffic volume than given
λ_3	Factor accounting for a different design working life of the structure than given
λ_4	Factor accounting for the influence of more than one load on the structural member,
$\lambda_{\max}$	Maximum damage equivalent factor value, taking into account the fatigue limit.
λ_v	Damage equivalent factor for the connection
ψ_1	Combination factor for frequent loads
$\psi_{2,i}$	Combination factor for quasi-permanent loads

$\sigma_{\min}$	Minimum direct or normal stress value (with sign), expressed in N/mm^2
$\sigma_{\max}$	Maximum direct or normal stress value (with sign), expressed in N/mm^2
σ_{res}	Residual stress value, expressed in N/mm^2
v_2	distance from the neutral axis to the relevant fibre in a steel concrete beam
$\Delta\sigma_C$	Fatigue strength under direct stress range at 2 million cycles, expressed in N/mm^2
$\Delta\tau_C$	Fatigue strength under shear stress range at 2 million cycles, expressed in N/mm^2
$\Delta\sigma_D$	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
$\Delta\sigma_{E,2}$	Equivalent direct stress range, computed at 2 million cycles, expressed in N/mm^2
$\Delta\sigma_L$	Cut-off limit under direct stress range, at 100 million cycles in the set of fatigue strength curves, expressed in N/mm^2
$\Delta\tau_L$	Cut-off limit under shear stress range, at 100 million cycles in the set of fatigue strength curves, expressed in N/mm^2
Δv_L	longitudinal shear force per unit length at the steel-concrete interface

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 (in the order of magnitude of one-tenth of a millimeter) is produced.

Crack propagation life	Portion of fatigue life between crack initiation and failure (according to conventional failure criterion or actual member rupture).
Cut-off limit	Limit below which stress ranges of the design spectrum do not contribute to the calculated cumulative damage.
Cyclic plasticity	Material subjected to cyclic loading up to yield stress in tension and in compression during each cycle. Alternative term for describing oligo-cyclic fatigue.
Design working life	Value of duration of use, lifetime, of a structure fixed at the design stage, also referred to as **design service life**.
Detail category	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, $\Delta\sigma_C$.
Direct stress	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.
Flaw	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.
Generic Eurocode	Eurocode parts that describe the generic principles for all structures and application rules for buildings (EN 199x-1-y).
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).

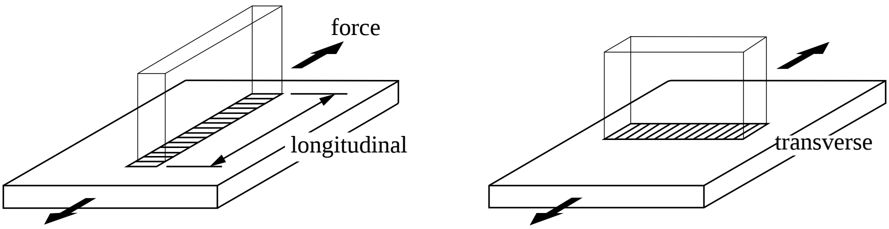

Figure 0.1 – Orientation of the attachment with respect to the main force

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. $(\sigma_{min} + \sigma_{max})/2$.

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_1 (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.

S-N curve — Also known as **fatigue strength curve** or **Wöhler's curve**. A quantitative curve expressing fatigue failure as a function of stress range and number of stress cycles.

Shear stress — 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 **direct stress** or, in a weld, with the **normal stress**.

Stress range — Also known as **stress difference**. Algebraic difference between the two extremes of a particular stress cycle (can be a direct, normal or shear stress) derived from a stress history.

Stress concentration factor — The ratio of the concentrated stress to the nominal stress (see sub-chapter 3.4), used usually only for direct stresses.

Structural stress Synonym for geometric stress.

Transverse Also referred to as **lateral**. Direction perpendicular to the direction of main force in the structure or detail (Figure 0.1).

Chapter 1

INTRODUCTION

1.1 BASIS OF FATIGUE DESIGN IN STEEL STRUCTURES

1.1.1 General

Fatigue is, with corrosion and wear, one of the main causes of damage in metallic members. Fatigue may occur when a member is subjected to repeated cyclic loadings (due to action of fluctuating stress, according to the terminology used in the EN 1993-1-9) (TGC 10, 2006). The fatigue phenomenon shows itself in the form of cracks developing at particular locations in the structure. These cracks can appear in diverse types of structures such as: planes, boats, bridges, frames (of automobiles, locomotives or rail cars), cranes, overhead cranes, machines parts, turbines, reactors vessels, canal lock doors, offshore platforms, transmission towers, pylons, masts and chimneys. Generally speaking, structures subjected to repeated cyclic loadings can undergo progressive damage which shows itself by the propagation of cracks. This damage is called *fatigue* and is represented by a loss of resistance with time.

Fatigue cracking rarely occurs in the base material remotely from any constructional detail, from machining detail, from welds or from connections. Even if the static resistance of the connection is superior to that of the assembled members, the connection or joint remains the critical place from the point of view of fatigue.

Figure 1.1 shows schematically the example of a steel and concrete composite road bridge subjected to traffic loading. Every crossing vehicle results in cyclic actions and thus stresses in the structure. The stresses induced are affected by the presence of attachments, such as those connecting the cross girders to the main girders. At the ends of attachments, particularly at the toes of the welds which connect them with the rest of the structure, stress concentrations occur due to the geometrical changes from the presence of attachments. The very same spots also show discontinuities resulting from the welding process.

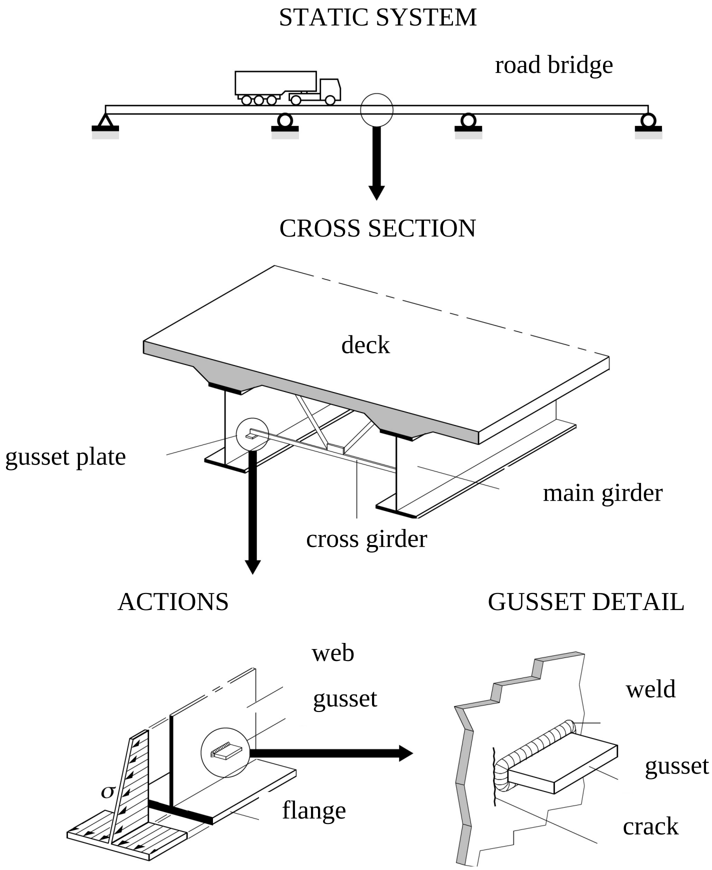

Figure 1.1 – Possible location of a fatigue crack in a road bridge (TGC 10, 2006)

Numerous studies were made in the field of fatigue, starting with Wöhler (1860) on rail car axles some 150 years ago. These demonstrated that the combined effect of discontinuities and stress concentrations could be the origin of the formation and the propagation of a fatigue crack, even if the applied stresses remain significantly below the material yield stress