Chapter 1

Introduction

1.1. The importance of welded joints and their fatigue behavior

Welding is today the most common joining method for metallic structures. Its industrial application is extremely important and many of the large structures designed and erected in the last decades would not have been possible without modern welding technology. Typical examples are steel bridges, ship structures, and large offshore structures for oil exploitation.

The strength analysis of welded structures does not deviate much from that for other types of structures. Various failure mechanisms have to be avoided through appropriate design, choice of material, and structural dimensions. Design criteria such as yielding, buckling, creep, corrosion, and fatigue must be carefully checked for specific loading conditions and environments. It is, however, a fact that welded joints are particularly vulnerable to fatigue damage when subjected to repetitive loading. Fatigue cracks may initiate and grow in the vicinity of the welds during service life even if the dynamic stresses are modest and well below the yield limit. The problem becomes very pronounced if the structure is optimized by the choice of high strength steel. The very reason for this choice is to allow for higher stresses and reduced dimensions, taking benefits of the high strength material with respect to the yield criterion. However, the fatigue strength of a welded joint is not primarily governed by the strength of the base material of the joining members; the governing parameters are mainly the global and local geometry of the joint. Hence, the yield stress is increased, but the fatigue strength does not improve significantly. This makes the fatigue criterion a major issue. The fatigue strength will alone give the requirements for the final dimensions of the structural members such as plates and stiffeners. To overlook this fact may result in fatigue facture and serious consequences.

1.2. Objectives and scope of the book

This book is confined to steel structures made by fusion welding and most of the examples are taken from the offshore industry. The book is divided into three parts which cover the following subjects:

– Part 1: common practice:

- the basic understanding of the fatigue behavior of welded joints based on theoretical considerations and experimental results (Chapters 2, 3 and 4),
- the S-N approach with reference to current rules and regulations (Chapter 5),
- the fracture mechanics approach with numerical computations (Chapter 6).

– Part 2: uncertainties in crack growth and life predictions:

- reliability modeling and risk assessments,
- the random nature of the fatigue damage process and stochastic modeling (Chapter 7).

– Part 3: recent advances in description of the fatigue behavior:

- recent advances in understanding the fatigue process and estimating the fatigue life (Chapters 8, 9, 10, 11 and 12).

The objective of this book is to disseminate, to practicing engineers, the knowledge possessed by the two authors. The main goal is to teach engineers how to cope with frequently occurring problems related to the fatigue design of welded structures. Hence, the scope of the book is primarily about practical problems in structural design and in-service inspection. For this purpose, industrial cases are included along with spreadsheets for carrying out both S-N calculations and fracture mechanics calculations. Although available models of fatigue behavior may not be perfect, they are very useful tools in engineering assessment if properly understood and used. In most practical situations, the shortcomings of the available fatigue models are less important than the problems related to the uncertainty in the parameters included in the models. Furthermore, fatigue design is experimental, empirical, and theoretical – and in that order. Without testing, fatigue analysis often remains an academic speculation. Hence, our agenda in Part 1 of the book is to put forward rather simple models that fit the experimental facts.

In addition to this strategy, it is important to disseminate knowledge on how to deal with uncertainty in a logical and unified manner. Fatigue life data exhibit considerable scatter even under controlled laboratory conditions and the standard deviation is equally as important as the mean value. Furthermore, typical in-service variable loading may be stochastic in nature and stress calculations may be uncertain. These considerations call for some insight into applied statistics and probability calculations. This is emphasized in Part 2 of the book.

Although the book emphasizes the practical aspects of fatigue life calculations and the assessment of crack growth and criticality, some advances in methods and models are included in Part 3 of the book. Chapter 8 focuses on the statistical background of the S-N curves, whereas Chapter 9 is dedicated to the fatigue process. Chapter 10 suggests a life model where the weld notch stress is replaced by the weld notch stress field as the key parameter for fatigue life. Chapter 11 outlines some recent advances in methods of stress calculation for cracked joints. Finally, Chapter 12 describes and models the effect of an overload. All these chapters present methods and models that deviate from the common practice in current rules and regulations. The proposed models are more in accordance with the realistic fatigue damage behavior of welded joints. The practical impact of the model on fatigue design and inspection planning is important.

The ultimate objective is to achieve optimized structures with respect to fatigue design, dimensions and inspection efforts without compromising reliability and safety.

1.3. The content of the various chapters

Chapter 2 provides basic understanding of the fatigue damage process with reference to some failure cases, and gives an overview of parameters influencing the process. Chapter 3 gives some insight into laboratory fatigue testing, which is the basis for rule-based S-N curves. This chapter also includes a brief overview of common statistical methods to cope with the scatter in fatigue life results. Chapter 4 treats the definition and description of the fatigue load spectrum. Accuracy in applied loading description is crucial for the credibility of fatigue life results. Both the time-series approach and the energy-spectrum approach are presented. After having read Chapter 4, the reader is prepared for an elaborate fatigue life calculation scheme based on the S-N model according to rules and regulations. This is presented in Chapter 5. The basis is the original S-N design rules from the Department of Energy, further developed in the Eurocode 3 design rules. To account for corrosive environments, the Norwegian NORSOK and DNV guidance developed for offshore structures in the North Sea is commented upon. Rules for ship structures are also reviewed. Chapter 5 also gives a qualitative assessment of what is a good detail-design of welded joints and how to obtain improvements in fatigue resistance though post-weld treatment. This chapter may in fact be read directly after Chapters 1 and 2, but we have chosen to present it at the end of the sequence as final practical guidance and to sum up.

The above reading recommendation is given for the practicing engineer mainly involved in detailed design and in choosing dimensions for welded joints. The goal is to achieve sufficiently long predicted fatigue lives compared to the target service life. This is the daily task for many steel structural engineers. If, however, decisions must be made regarding the acceptability of existing flaws or crack-like defects in the joints, then Chapter 6 should be included in the engineer's reading. Chapter 6 is an outline of applied fracture mechanics. In this chapter important questions, such as how fast a crack will grow during service loading and what is the critical crack size that leads to unstable rupture during extreme load, are treated. These are crucial questions to answer at a post-fabrication stage when cracks have been detected and the alternatives are repair or no repair. Furthermore, crack growth behavior is crucial information when planning scheduled in-service inspections.

Chapter 7 gives an outline of common and frequently used reliability methods. First we present some elementary life models, such as the Weibull model and the Lognormal model, for the fatigue life. The latter is the one most often used in rules and regulations. Then we proceed with the Monte Carlo simulation as our main method for reliability calculation. The reason for this choice is twofold: it is a good method from a pedagogical point of view; and it is a powerful method from a practical point of view. Markov chains are also treated in some detail.

Chapter 8 gives a critical reevaluation of the validity of the conventional S-N curves that are used in rules and regulations. Based on experimental fatigue life data, a new stochastic model is suggested. In this model both the fatigue life and the fatigue limit are treated as simultaneous random variables. The model results in a non-linear S-N curve for a log-log scale. These types of curves are in better accord with the experimental results than the conventional S-N curves.

Chapter 9 presents a two-phase model for the damage process in welded joints. The objective of this chapter is to emphasize the importance of the crack initiation phase in welded joints. It is the authors' opinion that this phase is significant for high quality welded components subjected to in-service loading. A model not accounting for this phase may lead to wrong decisions regarding both dimensions and scheduled inspections.

Chapter 10 presents an S-N model based on the weld notch stress field. The model is based on the fact that it is the stresses at the weld toe notch that are the agents for fatigue damage accumulation in the joint. However, the stress situation should not be characterized by the stress concentration factor alone as sometimes recommended in rules and regulations, but rather the entire local stress field in vicinity of the toe weld notch.

Chapter 11 outlines a method for stress calculation in cracked joints and gives a brief presentation of the multi-axial fatigue problem. This is an important issue that still has many unsolved enigmas and the chapter touches on some of the main topics.

Chapter 12 is devoted to the effect of an overload on the crack growth. A new, efficient method is developed for predicting the retardation of the growth rate.

1.4. Other literature in the field

First of all it should be emphasized that good textbooks exist in many of the fields related to the issues in this book. A good textbook on general fatigue is:

– J. Schive, *Fatigue of Structures and Materials*, Kluwer Academic Publishing, 2001

Regarding the fatigue of welded joints, some standard books are:

– T.R. Gurney, *Fatigue of Welded Structures*, Cambridge University Press, 1979

– A. Næss (ed), *Fatigue Handbook*, Tapir, 1985

– S.D. Maddox, *Fatigue Strength of Welded Structures*, Abington Publishing, 1991

The approaches of these books are mainly based on the S-N method, and the chapters dealing with applied fracture mechanics are rather short. Compared with these books, the present text gives the latest updates found in rules and regulations and a more thorough presentation of the fracture mechanics approach. Some computational models based on applied fracture mechanics are also included. Furthermore, the present text emphasizes stochastic modeling of both the S-N and the fracture mechanics approach. Finally, some recent advances that lead to a more precise description of the fatigue behavior of welded joints are included.

For further reading on the fracture mechanics approach, the reader may also consult:

– D. Broek, *The Practical Use of Fracture Mechanics*, Kluwer, 1989

– N. Recho, *Rupture par fissuration des structures*, Hermès, 1995

For a better understanding of the stochastic analysis and the reliability approach, the reader could start with books covering all the fundamental issues:

– J.R. Benjamin and CA Cornell, *Probability, Statistics and Decision for Civil Engineers*, McGraw Hill, 1979

– E.E. Lewis, *Introduction to Reliability Engineering*, John Wiley & Sons, 1994

The following rules and regulations are used for illustration purposes:

– Land-based structures

- Eurocode 3, Steel Structures, 1993 (Fatigue in air)

– Offshore structures

- NORSOK standard: Design of Steel Structures, Document N-004, Appendix C 1999, and the DNV Fatigue guidance CP-R for offshore structures 2005 (Fatigue in sea-water environment)

– Ship structures

- DNV Rules for Ship Structures 2003
- BV rules for ship structures 1998

– Special guide for damage tolerance assessments

- BSI: “Guide on Methods for Assessing the Acceptability of Flaws in Metallic Structures” BS7910 (2005)

The authors are fully aware of the existence of post-processing tools dealing with fatigue life predictions and crack growth in finite element analysis (FEA) software. We will give examples about how this can be carried out in Chapter 11. It is, however, essential that the user of these programs has the required knowledge to be able to assess the validity of the results from these post-processing modules.

1.5. Why should the practicing engineer apply reliability methods?

As already stated, the fatigue behavior of welded joints is random by nature. Very few load-bearing details exhibit such large scatter in fatigue life as welded joints. This is true even in controlled laboratory conditions. As a consequence, it becomes an important issue to take scatter into consideration, both for the fatigue process and for the final life. Furthermore, the in-services stresses may often be characterized as stochastic processes.

There has been a trend the last two decades to treat the strength problem of a structure by applying statistics and probability calculations. As a consequence, the probability of failure is used as a criterion, instead of the more traditional safety factors, when checking various design criteria. The methods and tools for performing this type of analysis have become available and quite easy to use. The probability of no failure during a given time period is considered to be the reliability of the structure. The methods used for determining the probability are often called reliability methods. Furthermore, if the associated probability of failure is weighed against the consequence of failure we arrive at the risk concept. Achieving high reliability and low risk levels will maintain operational capability and secure life and assets. The more sources of uncertainty there are in a structural problem, the more appropriate will be the application of a reliability approach. For processes where damage is accumulating with time, the probability of failure will increase with service time, depending on decisions made for the design concept, configurations, dimensions, material properties, and in-service inspection strategy. For fatigue of welded joints the following sources of uncertainty are dominant:

– the service stress history;

– the global and local geometry of the joint;

– the material parameters; and

– the performance of the in-service inspection.

A reliability approach pinpoints the sources of uncertainty and treats them in a rational way based on probability models and statistics. An alterative is to hide the uncertainty by fixed parameters often based on “worst case assumptions”. To optimize structures with respect to fatigue strength one should avoid using worst case assumptions. This may result in costly over-dimensioned structures. An optimization of design and member dimensions based on reliability calculations will give lightweight structures. Last but not least, inspection planning should be developed based on risk criteria to avoid unnecessarily costly inspection during service life. This leads to the concept of risk-based inspection.

1.6. How to work with this book

This textbook regards the S-N approach and the fracture mechanics approach as equally important tools. Furthermore, both approaches are enhanced by introducing more advanced statistical models for the S-N approach and adding an initiation phase to the fracture mechanics approach. The problem of uncertainty is recognized and dealt with in a rational and consistent manner using stochastic methods.

The first six chapters of the book can be regarded as a diffusion of basic understanding and practical skill, whereas Chapter 7 deals with uncertainty modeling. Chapters 8 to 11 present recent advances in the knowledge of the fatigue behavior of welded joints. In these chapters, new methods and models are proposed, which are based on experimental facts, and their practical consequences are discussed. These chapters are intended for readers who wish a deeper understanding of fatigue behavior and have ambitions towards research work within the field.

It is our belief that knowledge is gained through both reading the text and studying the cases and examples given. Calculations tools in an Excel spreadsheet format are included to give hands-on experience. These spreadsheets are so constructed that they may be used for real industrial cases. Another important use of these spreadsheets is in sensitivity analysis: which parameters have the strongest bearing on the crack growth rate and fatigue life. Hence, the application of various calculation methods through the use of the spreadsheets is essential to the learning process. Three spreadsheets are provided in a weblink which readers can use to apply their knowledge. These can be accessed at the following address: http://www.iste.co.uk/static/flaws.html.

1.7. About the authors

The two authors have a vast experience related to fatigue problems, within research projects, teaching, and industrial consultancy work.

Professor Tom Lassen was educated at the Norwegian University of Science and Technology, Trondheim in 1973. He graduated with a Masters in naval architecture with specialization in structural analysis and strength of materials. He submitted his PhD thesis entitled “Experimental investigation and stochastic modeling of the fatigue behavior of welded steel joints” at the Aalborg University, Denmark in 1997. He has published numerous articles in international journals on the fatigue of welded joints. He has been with Det Norske Veritas in Oslo and with Elf Aquitaine Research Centre in Pau, France. He has, for a long time, taught strength analysis and fracture mechanics at Agder University College in Grimstad. He also teaches aircraft maintenance for the Norwegian Royal Air Force. He has worked extensively with moored floaters for offshore oil exploitation in collaboration with Advanced Production and Loading in Arendal, Norway. For these types of installations, the fatigue behavior of welded joints is a major concern. He has recently been a visiting professor at University Blaise Pascal in Clermont, France. It was during this period the work with the present textbook was initiated in collaboration with Naman Recho. He is at present with the University of Stavanger in Norway.

Professor Naman Recho was educated at the French University of Pierre and Marie Curie in Paris. He graduated from this university as Doctor Ingenieur in 1980 and *Docteur d’Etat Es-Sciences Physiques* in 1987. He has been a university Professor since 1988. From 1978 to 1988 he was with CTICM (*Centre Technique Industriel de la Construction Métallique*) in Paris. Between 1988 and 1993, he was a Professor at the University of Haute Alsace in Mulhouse (France). Between 1993 and 2005, he was a Professor at the University Blaise Pascal in Clermont Ferrand, France. He has written two textbooks about fracture mechanics. He has worked extensively with conceptual and applied aspects of fracture mechanics. He has worked, in particular, with welded offshore structures, and reliability analysis of cracked structures. In the past ten years, he directed more than 15 theses dealing with fracture mechanics and fatigue design of welded joints. He participated in several research programs with industries such as CETIM-Senlis, Bureau Veritas in La Défense, Giat Industries in Borges, Michelin in Clermont Ferrand, CEA-Saclay, Trelleborg Industrie. In 1986, Naman Recho founded the program MMS (*Mécanique des Matériaux et Structures*) at EPF – Ecoles d’Ingénieurs in Sceaux, near Paris. He is still managing this program. Since 1985 he has also been teaching at CHEC (*Centre des Hautes Etudes de la Construction* – Paris). He is a Guest Professor at HUT (Hefei University of Technology in China). He is at present with CNRS (National Centre of Scientific Research) in Paris.