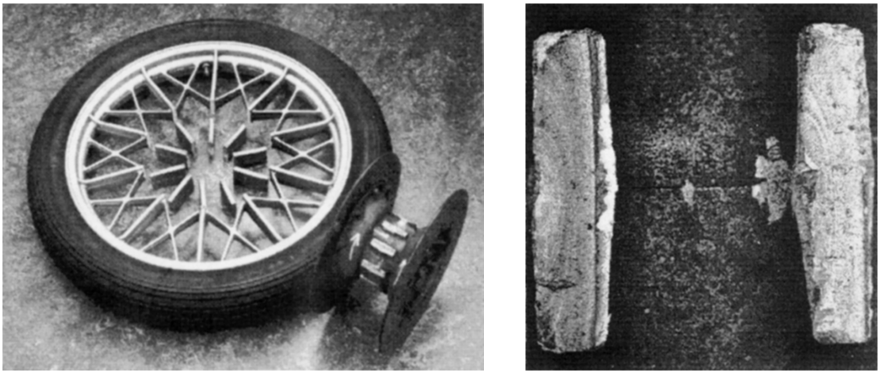
Chapter 1
Introduction to Fatigue of Structures and Materials

Fatigue failures in metallic structures are a well-known technical problem. Already in the 19th century several serious fatigue failures were reported and the first laboratory investigations were carried out. Noteworthy research on fatigue was done by August Wöhler. He recognized that a single load application, far below the static strength of a structure, did not do any damage to the structure. But if the same load was repeated many times it could induce a complete failure. In the 19th century fatigue was thought to be a mysterious phenomenon in the material because fatigue damage could not be seen. Failure apparently occurred without any previous warning. In the 20th century, we have learned that repeated load applications can start a fatigue mechanism in the material leading to nucleation of a small crack, followed by crack growth, and ultimately to complete failure. The history of engineering structures until now has been marked by numerous fatigue failures of machinery, moving vehicles, welded structures, aircraft, etc. From time to time such failures have caused catastrophic accidents, such as an explosion of a pressure vessel, a collapse of a bridge, or another complete failure of a large structure. Many fatigue problems did not reach the headlines of the news papers but the economic impact of non-catastrophic fatigue failures has been tremendous. Fatigue of structures is now generally recognized as a significant problem.

The history of fatigue covering a time span from 1837 to 1994 was reviewed in an extensive paper by Walter Schütz [1]. Historical milestone papers were collected by Hanewinkel and Zenner [2] and Sanfor [3]. John Mann [4] compiled 21075 literature sources on fatigue problems covering the period from 1838 to 1969 in four books. Since that time the number of publications on fatigue has still considerably increased and it may be estimated to be around 100,000 in the year 2000. Fortunately, consulting the literature on specific topics can now be done with computerized literature retrieval systems.

As a result of extensive research and practical experience, much knowledge has been gained about fatigue of structures and the fatigue



(a) Front wheel, broken spikes, axle part with drum brakes

(b) Fatigue fractures

Fig. 1.1 Collapse of the front wheel of a motorcycle by fatigue of the spokes.

mechanism in the material. Qualitatively our understanding of fatigue problems is fairly well developed in the 20th century as discussed in a survey paper by the author [5] (this paper is copied on the CD attached to this book). Much has been learned from laboratory research. However, accident investigations has also highly contributed to the present state of the art. Fatigue failures in service can be most instructive and provide convincing evidence that fatigue may be a serious problem. The analysis of failures often reveals various weaknesses contributing to an insufficient fatigue resistance of a structure. This will be illustrated here by a case history. The front wheel of a heavy motorcycle completely collapsed, see Figure 1.1a. Ten spokes of the light alloy casting were broken. Examination of the failure surfaces indicated that fatigue cracks occurred in all spokes, see Figure 1.1b. Why was the fatigue life of this wheel insufficient? A first question of a failure analysis must be: Was the failure a symptomatic failure or was it an incidental case? If it is a symptomatic failure, all motorcycles of the same type are in danger and immediate action is required. However, the failure may be an incidental case for some special reason applicable to that single motorcycle only: for instance, unusual and severe damage of the material surface. In the case of this motorcycle, the same failure had occurred in several wheels in different countries, although predominantly in motorcycles of the police. The wheel shown in Figure 1 collapsed when a policeman suddenly had to use the brakes to stop before a railway crossing.[1] He survived after some heavy shocks. The two most common questions usually put forward after a fatigue

[1] A policeman from Delft, and a railway crossing in Pijnacker where the author is living.

failure are: (i) was the fatigue resistance of the material too low, or (ii) was the stress level at the failure location too high? However, the list of questions is larger. For instance, (iii) What is so special about the load spectrum of the police motorcycle, and was the fatigue load spectrum known and taken into account by the motorcycle industry? (iv) How was the material surface quality at the location where the fatigue cracks started? This is a production question. Answers to each of these questions could lead to different clues for improvements. Another good question is whether a fatigue test had been done on this wheel before starting large scale production? Actually, the test was done after the failure, and the fatigue failure was reproduced in the test.

A structure should be designed and produced in such a way that undesirable fatigue failures do not occur during the design life of the structure. Apparently there is a challenge which will be referred to as "*designing against fatigue*".[2] It will be discussed in later chapters that various design options can be adopted to ensure satisfactory fatigue properties with respect to sufficient life, safety and economy. They are related to different structural concepts such as more careful detail design, less fatigue sensitive materials, improved material surface treatments, alternative types of joints, and lower design stress levels. Also, less obvious approaches can be considered, e.g. design for damage tolerance (fail safe), damage prevention (e.g. corrosion protection), alleviation of the dynamic loads in service. The spectrum of possibilities is extensive due to the large number of variables which can affect the fatigue behavior of a structure. Scenarios of designing against fatigue are also influenced by questions about the cost-effectivity of design efforts to improve the fatigue quality of a structure.

People working in the design office of an industry usually adopt standardized calculation procedures for predictions on fatigue strength, fatigue life, crack growth and residual strength. Standardized procedures can be useful, but it must be realized that such procedures may be unconservative or overconservative. Such calculation procedures start from some generalized conditions, which need not be similar to the conditions of the structure in service. It requires understanding, experience and engineering judgement to evaluate the significance of calculated results. The predictions may have a limited accuracy and reliability. In cases of doubt about calculated predictions, it is useful to perform supporting fatigue tests. Some people feel that an experiment is highly superior to theoretical calculations. Statements like "Experiments never lie" are well known. Unfortunately, an experiment gives results applicable to the conditions of the

[2] This is the title of a book by R.B. Heywood, published in 1962 [6].

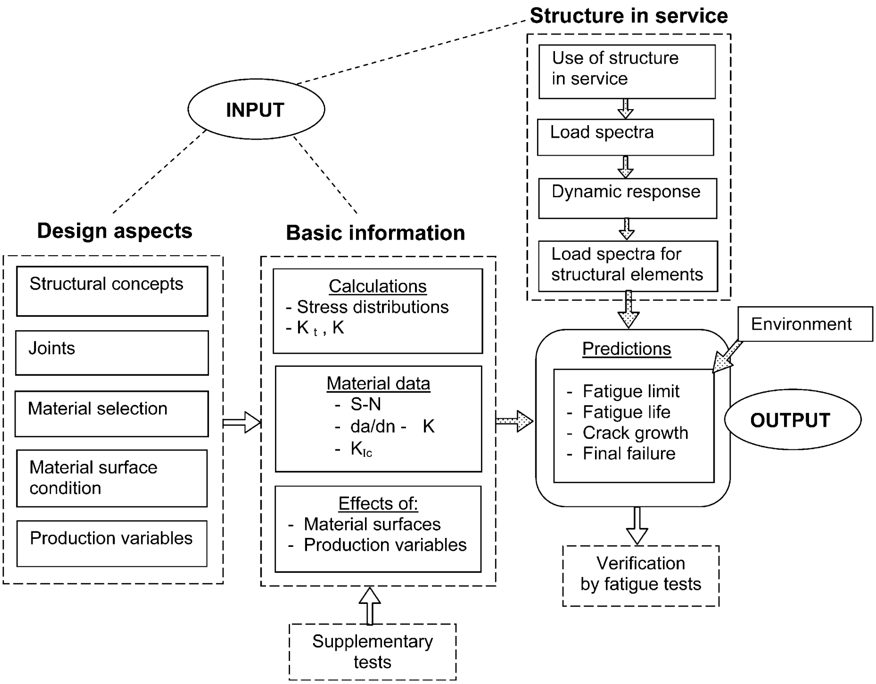


Fig. 1.2 Survey of the various aspects of fatigue of structures, a multidisciplinary problem setting [6].

experiment. The question is, are the test conditions a realistic representation of the conditions in service. Also this question asks for understanding, experience and judgement. In other words, whether designing against fatigue is done by analysis, calculations or experiments, it requires a profound knowledge of the fatigue phenomenon in structures and materials and the large variety of conditions that can affect fatigue. The aim of the present textbook is to present basic knowledge about this multi disciplinary problem setting.

A summary of aspects of fatigue design procedures is given in Figure 1.2. The first column contains major topics of the design work. Various aspects of basic information are listed in the second column. This information should be used for selections of materials, material surface treatments and production variables, but also for detail design issues, noteworthy for joints. In order to arrive at an evaluation of the fatigue quality of a structure, predictions have to be made. It then is a prerequisite to have relevant information on the fatigue loads. This includes a number of steps listed in the third column, starting with considerations about how the structure is used in service. This should lead to load spectra and subsequently to stress spectra for the fatigue critical locations in the structure. As also indicated in Figure 1.2, it may be desirable to do supplementary tests on specific issues or verification tests to cover uncertainties of predictions.

A special issue is how to account for environmental effects. Experimental data used in the predictions are generally obtained under laboratory conditions and relatively high testing frequencies. However, in service corrosive environments may be present and the load frequency can be much lower. As an example, think of a welded structure for a drilling platform in the sea. The environment is salt water, and the loading rate of water waves is relatively low.

About the contents of the book

Topics of Figure 1.2 are discussed in separate chapters, but a number of questions somewhat hidden in this diagram are also covered, such as notch effect, size effect, residual stress, statistics of fatigue. The book starts with chapters on basic issues:

- Fatigue as a phenomenon occurring in the material (Chapter 2). Some knowledge of basic aspects of the fatigue mechanism is essential to understand the various influencing factors of fatigue.
- Because stress concentrations in a structure are of paramount importance for fatigue, stress distributions around notches and stress concentration factors (K_t) are discussed in Chapter 3.
- Residual stresses can have a significant effect on fatigue. A special chapter is presented on these stresses (Chapter 4).
- After fatigue cracks have been nucleated, the stress intensity factor (K) is a controlling parameter for the severity of the stress distribution around the crack tip and fatigue crack growth. The concept of the stress intensity factor is discussed in Chapter 5.
- Fatigue properties, including the fatigue limit, S-N curves, fatigue diagrams, and also fatigue crack growth are discussed in Chapters 6 to 8. Some prediction problems are discussed in these chapters.

Chapters 2 to 8 cover the basic aspects of fatigue of materials and this is Part I of the book (see the list of chapters in the Contents).

The subjects of Part II are load spectra and fatigue under variable-amplitude loading. Fatigue load spectra are discussed in Chapter 9, starting with a description of various types of loads in service and the statistical analysis of load histories obtained by counting methods. Fatigue predictions without a load spectrum are impossible. If the load spectrum contains loads of different amplitudes, prediction problems require a fatigue damage accumulation model. This topic is discussed in Chapter 10 for fatigue lives and in Chapter 11 for fatigue crack growth.

Part III covers fatigue testing and scatter of fatigue properties. In view of uncertainties about predictions, it is desirable to verify the results by experiments. Fatigue tests are also important for obtaining material data and for exploring various effects on fatigue properties by comparative tests. Aspects of fatigue tests are discussed in Chapter 13. Unfortunately, fatigue properties can show significant scatter. It then must be recognized that scatter of the fatigue behavior of a structure in service is usually caused by different conditions than scatter in fatigue tests. Problems about scatter are discussed in Chapter 12.

Different conditions which are important for fatigue are treated in Part IV. Surface treatments can have a large effect on the fatigue properties as discussed in Chapter 14. Fretting corrosion is usually unfavorable for the fatigue life. This is the subject of Chapter 15. Environmental effects including the influence of corrosion on the fatigue performance are considered in Chapter 16. The effect of temperature, both high and low temperatures are briefly reviewed in Chapter 17. Actually, high-temperature fatigue is somewhat outside the scope of this book because it is more a problem of material selection and material development rather than primarily a problem of designing against fatigue.

Fatigue of joints and structures is discussed in Part V. Joints are often the most fatigue critical part of a structure. Moreover, the variety of joints is large. Chapter 18 covers different types of joints except welded joints which are covered in Chapter 19. The discussion in Chapter 20 offers general reflections on fatigue of structures with comments on how to deal with fatigue of structures as a design problem, also in view of uncertainties, safety and economic issues.

Finally, the last chapter, Chapter 21, covers fiber-metal laminates. The fiber-metal laminates (Arall and Glare) developed in Delft are a new class of hybrid materials with a high fatigue resistance. A new addition to this family of fiber-metal laminates is CentrAl. With these laminated materials, the designer does not only design the geometry of the structure, but also the lay-up parameters of the laminate in order to achieve optimal properties for specific fatigue critical components.

The major aspects of each chapter are summarized in the last section (except for this Chapter 1). These summaries are useful to reconsider the contents of a chapter. References used in the text are added to each chapter. Some general references are added for further study of the subject of a chapter. They are listed because the author has consulted these references, but the list cannot be expected to give a full coverage of all relevant publications. Moreover, each year numerous publications appear. For further in depth research more information should be retrieved.

About using the book

As pointed out in the Preface, the present book is written as a textbook for engineers, designers, researchers, students and teachers, and also for self-tuition. It is not a material data handbook. The main emphasis is on understanding the analysis of fatigue problems of structures. It requires that the fatigue mechanism in terms of fatigue crack nucleation and fatigue crack growth must be understood, as well as the influence of relevant variables on the fatigue mechanism. Fortunately, fatigue is no longer a mysterious phenomenon in the material. In qualitative terms, the fatigue mechanism is reasonably well understood. It is because of this understanding that we must accept that quantitative predictions in many cases can only be an approximation without being absolutely precise and accurate.

The prerequisites for the book are elementary knowledge of materials (material structure and material properties) and linear-elastic structural analysis (stress and strain distributions, tension, bending and torsion). The first edition of the book has been used in courses for students and in workshop courses for people in the industry, research institutes and other agencies involved in fatigue of structures, and safety and durability issues. In courses a teacher can use specific chapters and omit other ones depending on the background of the participants. If participants are already acquainted with linear-elastic stress analysis and fracture mechanics, Chapters 3 and 5 can be omitted or briefly summarized as a refreshment. Chapter summaries compiled in the last section of Chapters 2 to 20 should be useful for the evaluation of personal understanding. Questions on the topics of these chapters are compiled on the CD attached to this book. They can be useful for examinations, refreshing of knowledge and self-tuition.

In any course, case-histories about fatigue failures in service are most important. Several case-histories are discussed in the book. More case histories are presented on the CD with comments on design aspects, failure analysis and typical fatigue issues. In a course a teacher should also bring in his own case-histories together with the hardware of broken parts. Participants can then hold these parts in their own hands and observe fractures with their own eyes, a magnifying glass and a microscope. Attention should be focused on the initiation point of the fatigue failure.

Fatigue tests to be carried out as part of a course can be instructive, but they are time consuming. Demonstrations of fatigue experiments and explaining the purpose of the test can be much more rewarding.

About the CD attached to this book

Additional information is provided on a separate CD to keep the size of the book manageable. The information on the CD should not be considered to be an essential part of the various chapters in the book itself. It is supplementary to the book.

The CD encloses four parts. The first part contains exercises. It covers questions on various chapters and hints for answers in a separate section. The objective of the questions is to verify whether the important concepts are well understood. It can be useful for course work, both for students and teachers, and also for self-tuition. A summary of chapters is included for refreshing purposes.

In the second part selected case histories are summarized. The purpose is to indicate how accident investigations can be evaluated in order to be instructive for remedial activities and future fatigue issues.

The third part is covering two topics associated with designing against fatigue and planning experimental fatigue programs respectively. The discussion is addressing people engaged in designing against fatigue as well as others involved in research on fatigue problems.

In the fourth part, questions about the objectives of research topics are approached from a more philosophical point of view. Which research should be done, and why should it be done. Is it worthwhile? And is it a challenge? These questions must be considered by research institutes and university in view of research strategies. As a kind of an addendum to the fourth part, the text of a paper published in 2003 [5] has been included. The title is “Fatigue of structures and materials in the 20th century and the state of the art”. The future is in the 21st century.

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