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**Fatigue of structures and materials in the 20th century and the
state of the art**

Plotting paper

Part I

Introduction

When I was preparing the text of the manuscript of the first edition of the textbook I considered the question whether exercises should be included in the textbook itself. Although this is fairly usual, questions in a textbook are often rather simple, or just pretty difficult. Examples of simple questions are substitution exercises associated with certain equation. The difficult questions require experience and a profound insight in fundamental aspects. The approach adopted here is to have questions which can be considered to be exercises to gather understanding of basic concepts. Especially for students, it cannot be expected that they have already experience with practical engineering or research problems. Simple and elementary questions are then justified. For people already involved in engineering or research problems these questions can still be helpful to check whether the basic aspects of fatigue problems are really understood. After all, dealing with fatigue problems is largely a question of understanding, experience and judgement, rather than calculations. It is hoped that the exercises presented here will be helpful to contribute to developing the right attitude to problems associated with fatigue of structures and materials.

Teachers using questions for examinations should recognize different types of questions:

- Questions asking for answers which the student should know. Knowledge based questions.
- Questions for application of knowledge. Understanding based questions.
- Questions asking for describing a scenario for handling a problem.
- Questions about a large variety of design issues.

Both written and verbal examinations are possible. My preference is a verbal examination.

The book contains 21 chapters with some 600 pages. If all chapters are to be covered in a single course, the body of the course is quite heavy, although it has been done in special post-academic courses during four or five days, usually with a number of invited speakers.

Teachers in universities or technical schools may want to use a number of selected chapters. The more elementary chapters may be used in a preliminary course, and the more technical chapters in a later course. It is for this purpose that the book has been split in different parts listed below:

1. Introductory chapters on fatigue (Chapters 1 to 8).
2. Load spectra and fatigue under variable-amplitude loading (Chapters 9 to 11).
3. Fatigue tests and scatter (Chapters 12 and 13).
4. Special fatigue conditions (Chapters 14 to 17).
5. Fatigue of joints and structures (Chapters 18 to 20).

The last chapter, Chapter 21, on fiber-metal laminates (Arall and Glare) should be considered as a special topic.

The present exercises, perhaps it is better to say the present questions, are given for each chapter of the book separately (see Section I-1). Before entering the questions the reader should have studied the particular chapter. If he feels to be already familiar with the subject of the chapter, he still should read the last section of the chapter which covers the main topics treated in that chapter. For convenience, the last sections are compiled on the CD (Section I.3). Answers to all questions have been added in Section I.2, either as simple arguments, or in numerical format. If this is not feasible, the reader must consult the text of the book. References to specific sections of the book are then indicated.

Several case histories of fatigue failures in service are presented in the book, and other cases are discussed on this CD, see Part II. Teachers should try to collect their own case histories, including broken parts. Showing these parts to the audience, emphasizing the fractographic features, and explaining the circumstances of the events are most instructive. The educational impact can be considerable. In courses attended by participants of the industry we always invite participants to bring in fatigue problems and failures of their own products with all relevant circumstances. As part of courses or in workshops, it is also instructive to visit a fatigue testing laboratory. A fatigue test to be carried out by participants is not always feasible because of the time-consuming aspect. However, a demonstration of current fatigue tests and also fatigue fractures of specimens and components is much advised.

As mentioned in the Introduction of the book, Part III of the CD is addressing people engaged in designing against fatigue and planning experimental research. Part IV offers personal reflections on objectives of research on fatigue of materials in the future. It is a kind of an addendum to a paper published in 2003 with the title: "Fatigue of structures and materials

in the 20th century and the state of the art” (reprinted with kind permission from *Int. J. of Fatigue*, Vol. 25, No. 8, 2003, 679–702). The paper is copied on the present CD (File name: Research in the 20th century).

Jaap Schijve
Delft, October 2008

Part I

Exercises and Summaries

- I.1 Exercises
- I.2 Answers
- I.3 Summaries of chapters
- I.4 Plotting paper

Section I.4 contains two pages to be used for plotting S-N data and $da/dN-\Delta K$ graphs respectively in a double log graph. They are added here for plotting some data by hand instead of directly using a spread sheet program.

I.1 Exercises

There are no questions on Chapter 1, the introduction of the book.

Questions of chapter 2: Fatigue as a phenomenon in the material

- 2.1 The fatigue life is characterized by a crack initiation period, a crack growth period, and final failure.
 - a: Which factors are significant for these three phases?
 - b: What is the most essential feature of the initiation period?
 - c: What is an important difference between the crack initiation and crack growth period?
 - d: What is an important material characteristic in the crack growth period?
- 2.2 Discuss the significance of crystallographic aspects for crack initiation and crack growth.
- 2.3 What is the significance of inclusions for crack initiation and crack growth?

- 2.4 Why do microcracks sometimes stop growing?
- 2.5 Give two different definitions of the fatigue limit S_f .
- 2.6 The number of fatigue crack nuclei on a fatigue fracture surface can be rather small (e.g. just one), and it can be large.
 - a: Why can it be small?
 - b: When may it be large?
- 2.7 Various effects on the crack initiation period and the crack growth period can be significantly different.
 - a: Explain why.
 - b: Indicate different effects for the two periods.
 - c: Which condition can have a similar effect for both periods?
- 2.8 Surface effects can have a large effect on the fatigue limit, and a relatively small effect on the fatigue strength at low endurances (high-level fatigue). Explain why.
- 2.9 What is the difference between fatigue under cyclic tension and cyclic torsion?
- 2.10 The fracture surface of a fatigue failure is characterized by microscopic and macroscopic features.
 - a: Which are the microscopic features? Explain why these features occur.
 - b: Same question for the macroscopic features.
- 2.11 If a failure in service can be caused by either fatigue, stress corrosion or static overloading, which features should be checked to decide on the type of failure?
- 2.12 Which observations can be significant to answer the question whether a fatigue failure is an incidental failure and not a symptomatic failure?
- 2.13 If a failure in service is due to fatigue:
 - a: Which observations may tell that a high fatigue load was applicable?
 - b: Which observations may indicate that a low fatigue load was applicable?

- c: The failure in service produces two mating fracture surfaces. Why should both surfaces be examined?

Questions of chapter 3: Stress concentrations at notches

- 3.1 The stress concentration factor can be based on the nominal net stress (K_t) or on the nominal gross stress (K_{tg}).
 - a: Which definition is the usual one, e.g. in the book by Peterson?
 - b: Which basic definition is made for the definition of K_t ?
 - c: Is K_{tg} smaller than K_t ?
- 3.2 An infinite sheet with a circular hole is loaded in tension (stress S) in the vertical direction (Y axis).
 - a: $K_t = ?$
 - b: What is the tangential stress at the top of the hole?
 - c: How does the tangential stress vary along the edge of the hole?
 - d: How does σ_y vary along the Y axis, and what is the stress gradient, $d\sigma_y/dx$, at the edge of the hole?
- 3.3 The stress gradient of question 3.2d can be compared with the variation of the tangential stress along the edge of the hole.
 - a: What is the difference between the two gradients?
 - b: Which one is the technically more important one? Why?
- 3.4 Which dimension of a notched component is the most important one for the stress concentration?
- 3.5 What is the equation for K_t of an elliptical hole in an infinite sheet loaded in tension?
- 3.6 A strip (width W) with a central hole (diameter D) is loaded in tension.
 - a: Sketch K_t as a function of D/W .
 - b: What is the approximating equation for this function?
- 3.7
 - a: What is the dimension of K_t ? And what does the answer imply for geometrically similar notch configurations of different sizes?
 - b: Are stress gradients around notches depending on the size of the notch?

- 3.8 Manufacturers of large castings prefer to have their name on the casting. This can be done by letters protruding from the surface or letters intruding into the surface, see the cross sections in Figure E3.8. Consider K_t -values in Peterson to compare stress concentrations for both cases and to decide on which method should be preferred.

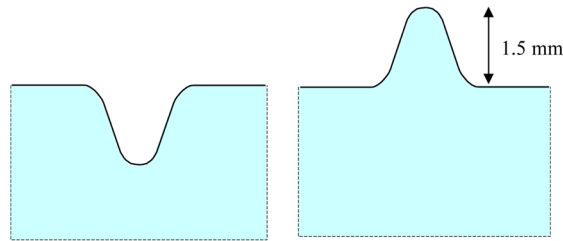


Fig. E3-8 Cross sections of an intruding and protruding letter system on large castings.

- 3.9 Figure 3.16 shows a stress relieving groove at a shoulder in an axle. Consider the following case: At the shoulder the diameter changes from 30 to 40 mm. If a stress relieving groove is not present, the root radius would be 1 mm. However, if the groove is present, the radius can be 3 mm. Determine the reduction of the peak stress if bending is considered.
- 3.10 Figure E3.10 shows three specimens. $D/W = 0.25$, $H = W$.

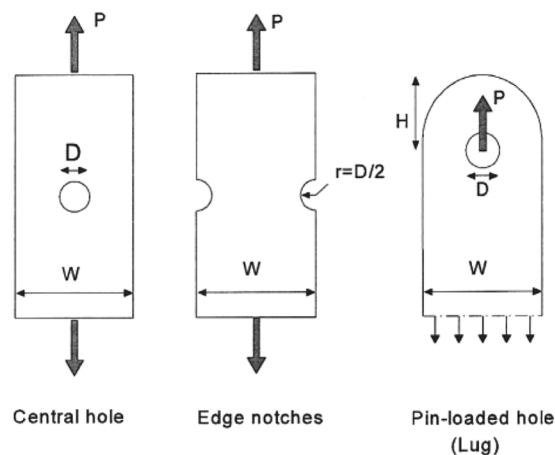


Fig. E3-10 Three different types of specimens.

- a: Determine K_t for the three specimens.
 b: Discuss the differences.
 c: For a central hole specimen the dimensions are: $W = 60$ mm, $D = 10$ mm, thickness 5 mm and $P = 50$ kN. How large is the peak stress at the edge of the hole?
 d: Further to question c: Does K_t depend on P ?
- 3.11 Consider an open hole in a large plate loaded under shear.
- a: Define the stress concentration factor and how large is K_t ?
 b: Is the loading at the critical point of the hole biaxial or uniaxial?
- 3.12 Figure E3.12 shows a sheet with a circular hole. The loading is biaxial tension with a biaxiality ratio $\beta = 0.5$. Three different stress cycles are considered. In the first one, the biaxial tension loads occur fully synchronized as it would occur in a pressure vessel. In the two other cases, S1 and S2 do not occur in a synchronized way. Assuming that the sheet is very large as compared to the hole diameter (approximation: infinite sheet), calculate the stress cycle occurring at the critical point A for the three biaxial stress cycles.

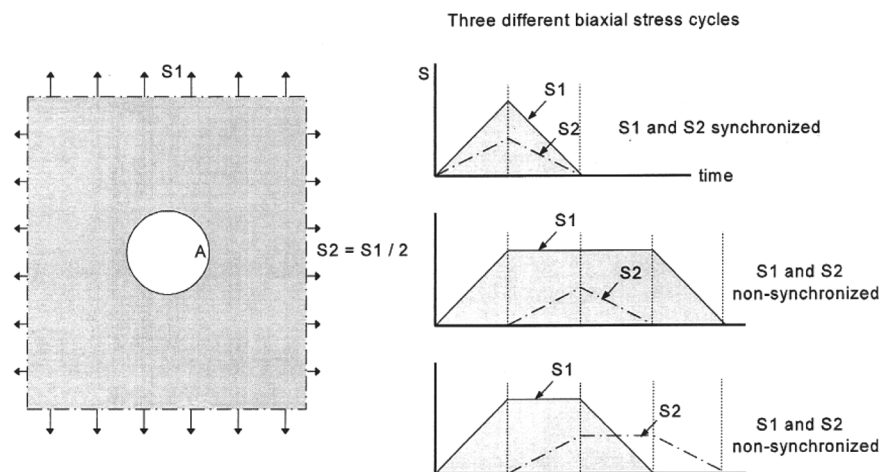


Fig. E3-12 Biaxial loading of a plate with a hole. Three different stress cycles.

- 3.13 An opening has to be made in a large tension field for passing of hydraulic lines. The opening is designed as a transverse slit with the dimensions shown in Figure E3.13.

- a: What is the K_t -value?
- b: Suggest a simple improvement of the geometry.
- c: If the slit would be rotated by 90° (longitudinal hole), which K_t -value is then obtained?
- d: If fatigue cracks are initiated at the transverse hole and the longitudinal hole, what can be said about the comparison of the crack growth rate in these two cases? Consider small cracks (much smaller than the radius) and larger cracks (in the order of the radius).

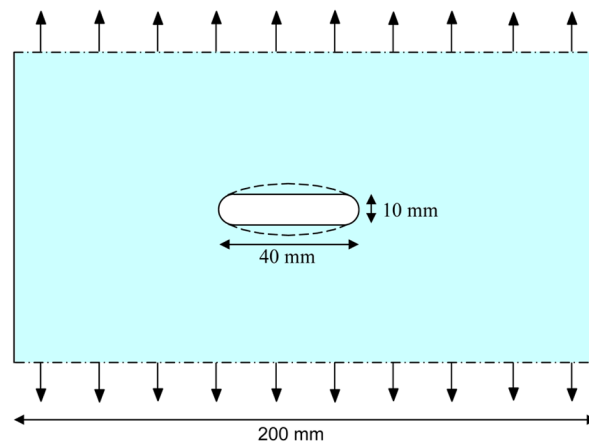


Fig. E3-13 Large tension field with a transverse slit.

- 3.14 A lug is designed for a specified values of the width (W) and the thickness (t). The lug is loaded by a constant cyclic load with $P_{\max} = P$ and $P_{\min} = 0$. The hole diameter (D) can still be chosen as a design parameter. Which D/W should be adopted to obtain a minimum peak stress at the edge of the hole? Use the curve in Figure 3.19 for $H/W \geq 1$.
- 3.15 For the prediction of the fatigue limit of a component, a K_t -value of the critical section is required. The K_t -value is not available in the literature. Because a reasonable accuracy is desirable, measurements or calculations are necessary.
 - a: Which types of measurements or calculations can be used?
 - b: Which advantages and disadvantages of these procedures should be considered?

Questions of chapter 4: Residual stresses

- 4.1 a: Give a definition of a residual stress distribution.
 b: What is characteristic for a residual stress distribution.
- 4.2 a: What is the effect of residual stresses on cyclic slip in the beginning of the fatigue life?
 b: And what is the effect on the subsequent microcrack growth?
- 4.3 What is warpage? Can it be avoided?
- 4.4 Inhomogeneous plastic deformation will introduce residual stresses. Mention different sources of inhomogeneous plastic deformation which may lead to significant residual stresses.
- 4.5 Should a heat treatment always lead to residual stresses?
- 4.6 What is the meaning of $\Delta\ell$ in Figure 4.2 for points A' and B'?
- 4.7 What is the maximum residual compressive stress to be obtained in two well-known aluminium alloys applied in aircraft structures: the 2024-T3 ($S_U = 450$ MPa, $S_{0.2} = 320$ MPa, elongation 20%) and the stronger 7075-T6 alloy ($S_U = 540$ MPa, $S_{0.2} = 480$ MPa, elongation 10%)?
- 4.8 Estimate the maximum thermal stress which might occur in the Concorde aircraft (maximum temperature at supersonic speed 120°C, aluminium alloy with thermal coefficient of expansion $\alpha = 24 \times 10^{-6}$ and Young's modulus of 72000 MPa).
- 4.9 Figure 4.3 shows how a high tensile load can introduce residual compressive stresses. In a similar way, a high compression load also introduces a plastic zone, but the zone now is smaller than it was before. This will cause residual tensile stresses.
 a: What is the effect of these residual stresses on fatigue crack growth?
 b: Should a similar effect occur after applying a high negative load to the lug joint shown in Figure 3.17?
- 4.10 If plastic hole expansion is applied to a lug (Figure 4.7), residual compressive stresses in the tangential direction around the hole are introduced. This is favorable for fatigue. The compressive residual

stresses must be balanced by tensile stresses. Where does this occur, and might it be alarming?

- 4.11 Can residual stresses be removed from a component?

Questions of chapter 5: Stress intensity factors of cracks

- 5.1 The stress intensity factor K is defined by the equation $K = \beta S \sqrt{\pi a}$.
- a: Explain the symbols in the equation.
 - b: What is the unit of K in the International Systems of Units (SI)? Which is the unit often used in the USA and the UK? What is the conversion factor between the two units?
 - c: How would you define the stress intensity factor in words?
 - d: Which basic assumptions are made to define the stress intensity factor?
 - e: K and K_I are essentially different concepts. Why? However, β and K_I serve a similar purpose. Which purpose?
 - f: What is the general equation for stresses around the crack tip?
- 5.2 Is it possible that β has a constant value independent of the crack length?
- 5.3 What are σ_x and σ_y on the crack surface close to the crack tip?
- 5.4 The equation of question 5.1f suggests that an infinite stress should occur at the crack tip. In reality, this does not occur because a small plastic zone is created around the crack tip.
- a: Is the equation still valid in the plastic crack tip zone?
 - b: Explain why K can still be a useful parameter in spite of some limited plasticity at the crack tip.
- 5.5 Fatigue crack growth tests are frequently carried out on center-cracked tension (CCT) specimens (also called M(T) specimens). K is a function of a/W , see Figure 5.5 and the Feddersen equation (5.12). Is K independent of the length of the specimen ($2H$)?
- 5.6 The Comet accidents were due to a fatigue crack at window, see Figure 5.9a. Actually, fatigue started at a rivet hole close to the edge of the window. The cracked situation then was a crack from the edge

of the window to the rivet hole and continuing at the other side of the rivet hole. Would this effect the definition of the effective crack length?

- 5.7 In a notched element loaded under tension or bending a very small semi-elliptical crack is present at the root of the notch.
- a: How is an estimate of the K -value obtained?
 - b: What to do if more accurate information is desirable?
- 5.8 What are the advantages and disadvantages of the compact tension (CT) specimens if compared to the center-cracked tension (CCT) specimens?
- 5.9 Displacements at the crack tip (u, v):
- a: The stress singularity at the crack tip implies that the stress increases with $1/\sqrt{r}$ for a decreasing r -value. How is the correlation with r for displacements?
 - b: What is the difference between crack tip opening displacements for plane strain and plane stress?
 - c: What is the shape of the crack tip opening profile?
- 5.10 Why is the tip of a through crack in a thick plate at low stress levels in plane strain (approximately) and why is that not true for a thin sheet?
- 5.11 Eqs. (5.35) and (5.36) give approximate sizes of the plastic zone. What is strange about these equations?
- 5.12 What is the meaning of the crack driving force?

Questions of chapter 6: Fatigue properties of materials

- 6.1 What is the difference between high-cycle fatigue and low-cycle fatigue?
- 6.2 An S-N curve has an upper and a lower horizontal asymptote. Explain why.
- 6.3 On a double-log scale, an S-N curve often has a large linear part. Which equation describes this part?

- 6.4 a: The fatigue limit for $S_m = 0$ for a particular alloy system (e.g. steels, Al-alloys, etc.) is often linearly related to the ultimate strength of the materials. It implies that a stronger material should have a higher fatigue limit. Is this a useful trend for material selection?
- b: The linear relation between S_f and S_u for steel is not always continued for very high-strength steels. Why?
- 6.5 The fatigue diagram indicates the mean stress effect on the fatigue limit and the fatigue strength. When is a large mean-stress effect on the fatigue limit observed?
- 6.6 Fatigue properties of a material as obtained in tests on unnotched specimens are often considered to be basic material properties. For which reasons is this idea questionable?
- 6.7 The fatigue limit under cyclic torsion is about 0.58 times the fatigue limit under cyclic tension. But for some materials the correlation factor is significantly higher. For which materials and why?
- 6.8 Why is low-cycle fatigue so much different from high-cycle fatigue?

**Questions of chapter 7: The fatigue strength of notched material.
Analysis and predictions**

- 7.1 The prediction of the fatigue limit of a notched component is usually based on a comparison with the fatigue limit on unnotched material (similarity concept). Mention possible limitations of the similarity.
- 7.2 a: Why is it possible that a size effect on fatigue properties can occur?
- b: What is the relevant size of the notch?
- c: Are the prediction methods in Section 7.2.2 rational or empirical?
- 7.3 The fatigue strength reduction factor, K_f , can be significantly smaller than the theoretical stress intensity factor, K_t .
- a: Is this favorable?
- b: Is it equally true for low-strength materials and high-strength materials?

- 7.4 The mean-stress sensitivity in a certain materials group (e.g. steels) is more significant for high-strength materials than for low-strength materials. Why is this so?
- 7.5 What is special about fatigue under cyclic torsion for:
- a: An axle with a transverse hole?
 - b: An axle with a shoulder?
- 7.6
- a: At the edge of a hole in a component under tension, bending or torsion, is the state of stress uniaxial or biaxial?
 - b: At the edge of a circumferential notch of an axle under tension, is the state of stress uniaxial or biaxial?
- 7.7 What can be said of the significance of the surface finish for the fatigue limit, for high-cycle fatigue and for low-cycle fatigue?
- 7.8 Why do we not have a rational procedure to predict an S-N curve of a notched component?

Questions of chapter 8: Fatigue crack growth. Analysis and predictions

- 8.1 Which conditions have to be satisfied for the application of the similarity concept to the prediction of fatigue crack growth in a component under CA loading?
- 8.2
- a: How should constant ΔK tests be carried out?
 - b: Mention an advantage and a disadvantage of this type of crack growth test.
- 8.3 What is characteristic for the three crack growth regimes in a da/dN - ΔK plot?
- 8.4
- a: What is the problem associated with ΔK_{th} and small cracks?
 - b: Is the small-size effect depending on the type of material?
- 8.5
- a: What is the Paris crack growth relation?
 - b: Which effect is not accounted for in this relationship?
 - c: The Paris relation has a constant C and an exponent m . Are C and m depending on the units used for da/dN and ΔK ?
 - d: The Paris relation for SAE 4340 in Figure 8.14 can be written as $da/dN = 17.9 \times 10^6 \times \Delta K^{2.675}$ with da/dN in mm/kc and ΔK in $\text{MPa}\sqrt{\text{m}}$.

Rewrite this relation for the units inch/cycle and ksi $\sqrt{\text{inch}}$ for da/dN and ΔK .

- 8.6
 - a: What is the meaning of plasticity-induced crack closure?
 - b: Is this crack closure depending on the stress ratio?
 - c: Is crack closure at a positive stress still possible if $S_{\min} < 0$?
 - d: Is crack closure of a through crack depending on the thickness of the material? Explain.
 - e: Why do crack fronts of a through crack in a plate often have a curved shape?
 - f: What can be said about crack closure along the crack front of a semi-elliptical surface crack?
- 8.7 A component is loaded under CA loading, the stress level is increased by 30%. How much faster will fatigue cracks grow if the Paris relation of question 8.5d is applicable?
- 8.8 If the strength of an alloy is increased by a heat treatment, does it lead to improved fatigue crack growth resistance?
- 8.9 Is the $da/dN = f_R(\Delta K)$ affected by an anisotropic material structure?
- 8.10 What is meant by a structural sensitive crack growth in a Ti-alloy?
- 8.11
 - a: Crack growth should be predicted for a sheet with a central hole with two edge cracks under CA loading with $R = 0$ and $S_{\max} = 80$ MPa, see Figure E8.11a. The basic material crack growth data are given in Figure E8.11b. The initial crack length is $\ell_0 = 4$ mm. Prediction is requested until a crack length $\ell = 36$ mm. An effective crack length as indicated in Figure E8.11a may be assumed (see the discussion on Figure 5.8). The Feddersen width correction should be applied (Eq. 5.11). Solve the problem by setting up a table with incremental crack growth ($\Delta a = 4$ mm). Calculate the number of cycles, (ΔN), spent in each increment, and also the crack growth life as a function of the crack length (i.e. the crack growth curve).
 - b: The Δa -value in the previous question is 4 mm which is fairly large. Consider the question whether a smaller value, e.g. $\Delta a = 1$ mm would give a significant improvement of the accuracy?

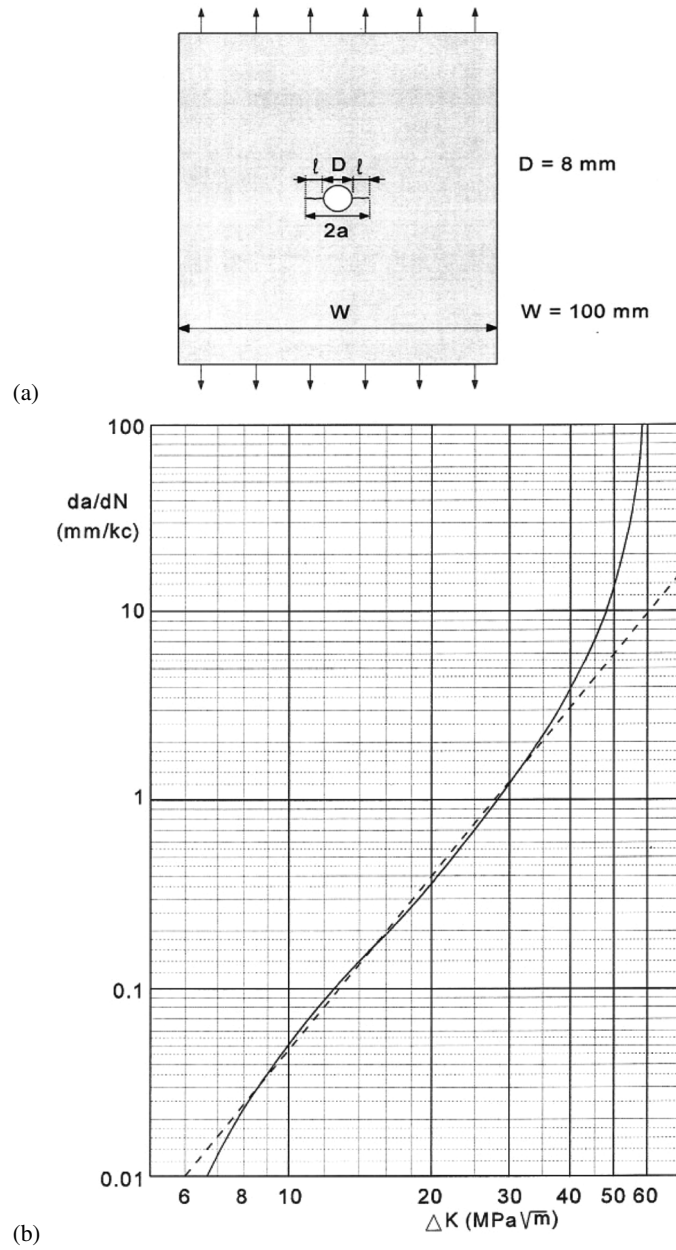


Fig. E8.11 (a) Plate with a central hole and two edge cracks used for the crack growth prediction in question 8.11b. Material data in Figure E8.11b. (b) Crack growth data for 2024-T3 ($R = 0$).

- c: The crack growth data in Figure E8.11b is approximated by a solid line in the graph which represents the Paris relation (Eq. 8.4). Determine C and m for this line.
 - d: Calculate the crack growth life with the Paris relation and ignore the width correction (i.e. $\beta = 1$).
- 8.12 During an inspection of a large and expensive component (non-destructive inspection) a sub-surface defect is observed, probably a material defect and not a fatigue crack. If the defect would not grow under the service fatigue load, repair or replacement of the component is not necessary. What about using the ΔK_{th} concept to judge this question?
- 8.13 What should be done if reasonably accurate predictions for crack growth in a component have to be obtained?

Questions of chapter 9: Load spectra

- 9.1 What is meant by deterministic loads and by stochastic loads?
- 9.2 A statistical analysis of load-time histories can lead to tables or graphs with numbers of level crossings, peak values, or load ranges. Which information is lost in such a representation?
- 9.3 What should be associated with a stationary load-time history and a non-stationary load-time history?
- 9.4
- a: What is characteristic for narrow-band random loading? And what for broad-band random loading?
 - b: What is the definition of the irregularity factor of a random load history?
- 9.5
- a: What is plotted in a one-dimensional load spectrum?
 - b: What is the difference between a steep and a flat load spectrum?
- 9.6
- a: What is a matrix presentation of a spectrum of peak loads?
 - b: Is the sequence events again fully lost?
- 9.7 The rainflow count method:
- a: What is the counting criterion?
 - b: Why is this counting method preferred to other counting methods?

- c: Is information on the sequence of cycles lost?
- 9.8 A structure is loaded in service to the same nominal maximum load and after some time returning to a zero minimum load (actually CA loading). However, a small spike load occurs occasionally. Is this important for considering the cyclic load on the structure?
- 9.9
 - a: A load spectrum is essential for any prediction on the endurance of a structure. How should the assessment of the load spectrum be started?
 - b: How can it be quantified?
 - c: Load spectra can be measured? How should it be done?
- 9.10 A structure is loaded in service with large numbers of cycles: many small cycles, probably below the fatigue limit. The number of severe cycles is relatively small. Which load cycles (below the fatigue limit, slightly above the fatigue limit, very severe load cycles) will cause crack nucleation, crack growth and final failure respectively?
- 9.11 Based on Figure 9.21 a discussion is presented on possible loads of a traveling crane beam structure. The loads in this figure are applied by hoisting and putting down different weights. Which other types of loads should be considered?

Questions of chapter 10: Fatigue under variable-amplitude loading

- 10.1
 - a: Fatigue cycles induce fatigue damage. What is fatigue damage in the structure of the material?
 - b: Why can fatigue damage not be represented by a single damage parameter?
- 10.2 The Miner rule has three obvious shortcomings.
 - a: Which are these shortcomings?
 - b: Can they lead to $\Sigma n/N$ -values smaller or larger than 1, or both?
- 10.3 Deviations of the Miner rule, are they equally possible for unnotched and notched specimens? Explain.
- 10.4 Is the sequence of cyclic loads significant for fatigue under VA loading?

- 10.5 A load spectrum can be simulated in a fatigue test by a so-called block-program loading or by a random sequence of the load cycles. Which sequence should be used?
- 10.6 The Miner rule ignores fatigue damage of cycles with an amplitude below the fatigue limit. How can this be accounted for? Is this a fully rational approximation?
- 10.7 Is the strain-history model accounting for shortcomings of the Miner rule?
- 10.8 Service-simulation fatigue tests offer certain openings to overcome prediction problems.
- a: Which advantages of these tests can be important?
 - b: What is a limitation?
- 10.9 A high tension load on a notched specimen can be beneficial for the fatigue life, whereas a high compression load can reduce the fatigue life. Is this also true for a component with a macrocrack?
- 10.10 a: Truncation of high loads in a service-simulation fatigue test should be considered. Explain why.
b: Is this equally true for a steep and a flat load spectrum? Explain.
- 10.11 a: Is a Miner rule calculation reliable for comparing the severity of different load spectra?
b: Is the rule useful for estimating the effect of the design stress level on the endurance of a component?

Questions of chapter 11: Fatigue crack growth under variable-amplitude loading

- 11.1 What is meant by non-interaction during fatigue crack growth under VA loading?
- 11.2 a: What is the effect of an OL cycle on fatigue crack growth under CA loading?
b: And what is the effect of an UL cycle?
c: And what is the effect of an UL cycle after an OL cycle?
- 11.3 What is the significance of crack closure during fatigue crack growth under VA loading?

- 11.4 Crack growth retardation after an OL cycle:
- a: What is the effect of material thickness?
 - b: What is the effect of increasing the yield stress of an alloy?
 - c: What is the effect of a block of OL cycles instead of single OL?
- 11.5 What is delayed retardation?
- 11.6 Is fatigue crack growth under block-program loading and random loading (same load spectrum) a similar process?
- 11.7 A fatigue crack starting from a notch (e.g. an open hole) can start with a decreasing crack growth rate. Is that strange and what is the reason?
- 11.8 Is the truncation problem of high loads of a load spectrum more important for crack growth than for the crack initiation fatigue life of notched components?
- 11.9 The more recent crack growth models for VA loading predict the variation of the crack closure stress level in order to obtain cycle-by-cycle crack growth increments from the ΔK_{eff} -value of each cycle.
- a: Should it be expected that the predicted crack growth is slower than predicted by a more simple non-interaction prediction?
 - b: What should be done to be sure that the predictions are sufficiently reliable?
- 11.10 Crack growth prediction models for fatigue crack growth under VA loading can be checked by a comparison between predictions and test results.
- a: Why is it not satisfactory to compare the crack growth live covered by crack growth from some initial crack length until a large size of interest?
 - b: How should the comparison be made?

Questions on chapter 12: Fatigue and scatter

- 12.1 If fatigue test results show scatter, what is the most important question?

- 12.2 Possible sources of scatter can be essentially different for scatter in laboratory test series and in service. Which sources are different?
- 12.3 Scatter is larger for the crack initiation period than for the crack growth period. Why is this so?
- 12.4 In fatigue tests scatter at high stress amplitudes is usually smaller than at low stress amplitudes. Why is this so?
- 12.5 What is the problem of the fatigue life distribution function in test series with a stress amplitude close to the fatigue limit?
- 12.6 Why is the normal (Gauss) distribution function of $\log N$ physically a strange function?
- 12.7 The 3-parameter Weibull distribution function has a lower limit. Is it possible to introduce a lower limit to the normal distribution function?
- 12.8 Is it easy to decide on the basis of experimental data whether the normal distribution function or the Weibull distribution function is more in agreement with the test results?
- 12.9 Are fractographic observations of specimens important for considerations on scatter?
- 12.10 What are the problems of obtaining scatter data on the fatigue strength and the fatigue limit?
- 12.11 What can be said about scatter in fatigue test series with a VA load spectrum?
- 12.12 If a fatigue limit of a component has to be predicted in order to be sure that fatigue failures will not occur in service, how should a safety factor be obtained?

Questions of chapter 13: Fatigue tests

- 13.1 If fatigue tests are carried out to evaluate the fatigue performance of a new material in comparison to a current material, which type of tests should be carried out and which type of specimens should be used?

- 13.2 If comparative tests are carried out for different design options for a certain component, which type of tests should be carried out and which type of specimens should be used?
- 13.3 Which information should be given in a paper or report about the conditions of the fatigue tests and the results.
- 13.4 Marker loads (Figures 13.9 and 13.10) are sometimes introduced in CA fatigue tests. Why is this done?
- 13.5 Sometimes fatigue research programs include fatigue tests carried out in different laboratories. Which precautions are essential?
- 13.6 If part of a fatigue diagram has to be determined, should test series be carried out at different S_m -values or at different R ratios.
- 13.7 In order to measure the crack length in a fatigue crack propagation test, should the fatigue machine be stopped at zero load?
- 13.8 If the fatigue limit should be determined, the testing procedures described in Chapter 12 can be adopted, but it requires a large number of specimens and much testing time. Some information about scatter is obtained. In Figure 13.2, a more simple approximation procedure for obtaining an indication of the fatigue limit is indicated. Why should this method be considered?
- 13.9 In the second half of the previous century, a significant development of fatigue machines occurred. Which development and what is a major advantage?

Questions of chapter 14: Surface treatments

- 14.1 Several industrial surface treatments are applied for other reasons than fatigue. Which reasons?
- 14.2
 - a: Three different aspects of a surface layer are important for fatigue. Which are these aspects?
 - b: Which fatigue properties are primarily affected by these aspects?
- 14.3 Which aspects of the surface can be unfavorable for fatigue?

- 14.4 Why is surface-nitriding of low-alloy high-strength steel favorable for fatigue?
- 14.5 Surface treatments can lead to subsurface crack initiation. Why does this occur?
- 14.6 a: Why is shot peening favorable for fatigue?
b: Which other aspects are associated with shot peening?
- 14.7 How is surface roughness accounted for in prediction problems of the fatigue limit?
- 14.8 Which guide lines should be considered in research on surface treatments for application on specific components?
- 14.9 Consider the effect on the fatigue limit of: (i) a hardness indentation of a Rockwell B measurement, (ii) an impact damage by hitting the surface by a foreign object (a dent), (iii) a scratch made by a sharp object (a nick).
- 14.10 How important is surface roughness if the load spectrum represent VA loading?

Questions of chapter 15: Fretting corrosion

- 15.1 a: Is fretting primarily a matter of surface damage or corrosion, or both?
b: Is fretting a risk for most technical materials?
- 15.2 a: What is the effect of fretting corrosion on an S-N curve?
b: What can be said about the effect of the clamping pressure between the mating surfaces?
- 15.3 What is the remedy against the occurrence of fretting corrosion?
- 15.4 a: Is fretting corrosion significant for lugs and for riveted and bolted joints?
b: If a bolt is connecting two parts, is fretting still possible if the bolt does not transmit any load from one part to the other one?

Questions of chapter 16: Corrosion fatigue

- 16.1 Corrosion in a liquid environment:
- a: Which periods of the fatigue life are affected by corrosion?
 - b: Why is the effect of corrosion on the fatigue limit so large?
 - c: During a load cycle, when is the corrosion contributing to crack growth?
 - d: Is corrosion fatigue depending on the frequency?
 - e: Is corrosion fatigue depending on the wave shape?
 - f: What can be said about holding times at S_{\max} ?
- 16.2 Corrosion fatigue crack growth in a gaseous environment:
- a: For Al-alloys and some steels, which gaseous component contributes to corrosion fatigue?
 - b: For Al-alloy, the effect of a low temperature can be favorable. Why is this so?
- 16.3 What is the significance of corrosion pitting for fatigue?
- 16.4 Fatigue crack growth in salt water is faster than in air. Corrosion products are created inside the crack. Are the corrosion products harmful?
- 16.5 What is the best method to combat corrosion fatigue?

Chapter 17: High-temperature and low-temperature fatigue

There are no questions about this chapter.

Questions of chapter 18: Fatigue of joints

- 18.1 Why is fatigue of joints such an important subject?
- 18.2 For which reason is the prediction of fatigue properties of joints a different problem as the prediction of notched elements with notches as an open hole, a fillet, a shoulder, etc.?
- 18.3 For fatigue of non-symmetric joints, such as a lap joint, an extra fatigue aspect has to be considered. Which aspect? Why is it unfavorable?

- 18.4 a: Why is the fatigue limit of a lug very low?
b: Why is the size effect different from the size effect for an open hole configuration?
- 18.5 A prediction method for lugs was proposed by Larsson. What is the fundamental difference between this method and the prediction methods discussed in Chapter 7 for simple notched configurations?
- 18.6 The mean-stress effect on the fatigue strength was discussed in Section 6.3.2 (p.124) with reference to the Gerber parabola, the modified Goodman diagram and the Schütz mean-stress sensitivity parameter. Why is the problem essentially different for lugs and what can be said about the fatigue diagram of lugs for $R < 0$.
- 18.7 The fatigue limit of a lug can be improved by using a bush with a substantial interference fit, and also by plastic hole expansion without using an interference fit bolt. The improvements of the two methods are associated with different mechanisms. Explain these mechanisms.
- 18.8 a: In a riveted or bolted lap joint, stress concentrations around the fastener holes occur for different reasons. Which ones?
b: How can the fatigue strength of the joint be improved?
- 18.9 In a bolted joint (bolts loaded in shear), the clamping of the bolt can be increased by applying a controlled torque to the nut.
a: What is the effect on the load transmission?
b: What is the effect on the fatigue life?
- 18.10 The fatigue strength of a bolted joint with the bolt loaded in tension can be increased by pre-tensioning of the bolt. Why is this beneficial?
- 18.11 What is the difference between fatigue of a riveted and an adhesive-bonded lap joint with the same dimensions?

Questions of chapter 19: Fatigue of welded joints

- 19.1 Fatigue of welded structures is a completely different problem as compared to fatigue on non-welded structures. Mention two prominent types of differences.

- 19.2 Designing against fatigue of welded joints, mention the most relevant aspects.
- 19.3 A connection between two parts of a dynamically loaded steel structure to be produced in large quantities can be made as a welded joint or a bolted joint. Welding may be cheaper, but fatigue has to be considered. How should this problem be handled?

Chapter 20: Fatigue of structures, design procedures

This chapter gives a survey of the various lessons of previous chapters with Figure 1.2 of the Introduction as a framework of the problem setting of fatigue of engineering structures. Chapter 20 includes procedures of designing against fatigue and evaluations of fatigue predictions. The significance of practical aspects associated with safety, production and economy are emphasized. Because of the nature of Chapter 20, specific exercise questions are not presented, but it should be recommended to read the Introduction (Chapter 1) and Chapter 20 (especially the final section with summarizing conclusions). These two chapters offer a résumé of the context of the book in dealing with fatigue of structures and materials.

Chapter 21: The fatigue resistance of the fiber-metal laminates Arall and Glare

The last chapter of the book has been added because the fiber-metal laminates Arall and Glare were developed in Delft as highly fatigue resistant materials. In view of the good fatigue properties of the fiber-metal laminates, most chapters of the book are not fully relevant to these materials. Questions on Chapter 21 are not presented.

I.2 Answers

Answers to questions of chapter 2

- 2.1
 - a: See Figure 2.1.
 - b: It is a surface phenomenon.
 - c: Crack growth in the crack growth period is no longer a surface phenomenon.
 - d: The crack growth resistance of the material.
- 2.2 Section 2.5.1 and the discussion on Figure 2.5.
- 2.3 Section 2.5.2 and the discussion on Figure 2.17.
- 2.4 Section 2.5.3.
- 2.5 Section 2.5.3.
- 2.6 a: and b: Section 2.5.4.
- 2.7 Discussion on Figure 2.21.
- 2.8 Discussion on Figure 2.23.
- 2.9 Section 2.5.8.
- 2.10 Section 2.6.
- 2.11 Fatigue is transgranular, stress corrosion in most materials is intergranular. Fatigue can show striations, stress corrosion does not. Static overloading shows macroplastic deformation, whereas fatigue and stress corrosion show crack initiation areas void of macroplastic deformation.
- 2.12 Incidental fatigue failures may be due to surface damage or an unacceptable material flaw. This should be revealed by a fractographic examination.
- 2.13
 - a: A small crack fatigue crack nucleus and a relatively large final failure area. Also a large number of crack nuclei with steps at the overlap of the nuclei (Figure 2.33).
 - b: A single and relatively large crack nucleus on the fracture surface.

- c: One of the two may be damaged at the crack nucleation site. Moreover, sometimes certain evidence is clearly visible one of the two mating surfaces only.

Answers to questions of chapter 3

- 3.1 a: K_t .
 b: Linearly-elastic behavior of the material.
 c: K_{tg} is larger because the remote gross stress is smaller than the nominal net section stress.
- 3.2: a: $K_t = 3.0$.
 b: $-S$.
 c: Eq. (3.7)
 d: Eqs. (3.9) and (3.10)
- 3.3 a: Along the X axis, σ_y is steeply going to σ_{peak} at the edge of the hole. However, the tangential stress along the edge of the hole (Eq. 3.7) goes through a maximum which implies a relatively slow variation.
 b: The latter one is the more important one because crack initiation occurs at the edge of the hole. Moreover, the variation of the stress along the edge of the hole is relatively small which implies a relatively large area at the root of the notch where the initiation can start.
- 3.4 The root radius of the notch.
- 3.5 Eq. (3.6b).
- 3.6 a: See Figure 3.10.
 b: The Heywood equation (Eq. 3.12)
- 3.7 a: K_t is dimensionless. It thus can be a function of ratios of the dimensions only. Specimens of a different size but with the same ratios of dimensions should thus have the same K_t .
 b: Yes. The gradient is not dimensionless. According to Eq. (3.10), a larger size will lead to a less steep stress gradient and thus a larger volume of highly stressed material.
- 3.8 K_t -value for the geometries in Figure E3.8 are not available in the book by Peterson. However, it is possible to obtain an impression of

the magnitude of K_t . The K_t -value for the intruding notch with an estimated root radius of 0.5 mm according to figure 15 of Peterson ($t/r = 1.5/0.5 = 3$, symbols of Peterson) is equal to 4.8, a high but probably a fair estimate. For the protruding notch, the root radius is also estimated to be about 0.5 mm. The closest geometry in Peterson's book is found in his figure 71 for $t/W \sim 1$, while $r/W \sim 0.5/1.5 = 0.33$. The graphs then give $K_t = 1.64$ which applies to $D/d \sim 2$. A better estimate would be obtained for a D/d -value closer to 1. As suggested by the graph, a significant smaller K_t -value may then be expected. In other words, the intruding notch is much more severe than the protruding notch, see also Figure 3.12.

- 3.9 K_t -values interpolated from a graph in Peterson (figure 78) are approximately 2.35 and 1.68 without and with the stress relieve groove respectively. The reduction is almost 30%!
- 3.10 a: Central hole specimen: $K_t = 2.42$;
Specimen with edge notches: $K_t = 2.30$;
Lug: $K_t = 4.4$.
b: The difference between the K_t -values of the first two specimens is still small which is only true as long as the size of the notch is relatively small (see Figure 3.10). For the lug, K_t is significantly larger because the load application by the pin occurs close to the critical location at the edge of the hole.
- 3.11 a: The stress concentration factor is defined as $K_t = \sigma_{\text{peak}}/\tau$ where τ is the applied shear stress. For an infinite plate $K_t = 4.0$ (Figure 3.20).
b: At the edge of the hole the loading can only be unidirectional.
- 3.12 For the first case, the stress at point A, S_A , varies between $S_{\text{max}} = 2.5S_1$ and $S_{\text{min}} = 0$. For the second and the third case, $S_{\text{max}} = 3.0S_1$. For the second case, S_{min} is again zero, but a small extra cycle occurs at S_{max} between $3S_1$ and $2.5S_1$. For the third case, $S_{\text{min}} = -0.5S_1$.
- 3.13 a: The transverse slit can be approximated by an elliptical hole with the same tip radius (discussion on Figure 3.28). For an infinite plate the result is $K_t = 1 + 2\sqrt{(a/\rho)}$ (Eq. 3.6a) which gives $K_t = 5$ (high value!). A finite width correction according to Peterson (figure 131) gives a reduction with a factor 0.825, and

the result is 4.125 (still a high value). Note that the Heywood equation (Eq. 3.12) would suggest a reduction factor of 0.837, practically the same result.

- b: A circular hole with the finite width correction gives $K_t = 2.51$.
 - c: The geometry for the 90° rotated slit is covered by Peterson in his figure 139. With the symbols of this figure: $r/b = 0.5$ and $b/a = 1/4$ for which $K_t = 2.25$. The width correction is unknown but will probably small. The K_t -value after the rotation is almost halved!
 - d: For small cracks, the stress intensity factor, K , is proportional to the K_t -value, and thus crack growth would be much faster for the transverse hole (Eq. 5.14). For the larger cracks, the equivalent crack length would be much larger for the transverse hole, and again a faster crack growth would occur.
- 3.14 With P , W and t fixed and D as a design parameter, the gross stress, $S = P/(Wt)$ remains constant. With K_{tg} (Eq. 3.3), the peak stress is $\sigma_{\text{peak}} = K_{tg} \cdot S$. A minimum σ_{peak} is obtained by minimizing K_{tg} . The relation between K_{tg} and K_t (see Eq. 3.3) is $K_{tg} = K_t/(1 - D/W)$. With this relation and the K_t graph in Figure 3.19, a graph of K_{tg} can be made. The graph will show that the minimum K_{tg} occurs at $D/W \approx 0.45$. Furthermore, it will show that the minimum is a relatively flat minimum. The value of $K_t/(1 - D/W)$ does hardly change in the D/W -range 0.4–0.5. This is favorable because it implies that σ_{peak} in this range of D/W is hardly sensitive for the exact value chosen.¹
- 3.15 a: Measurements can be made by strain gages or photo-elastic models. Calculations are possible with FE techniques.
- b: Advantages and disadvantages are discussed in Section 3.7. A major problem for measurements is the occurrence of steep stress gradients at the root of a notch.

Answers to questions of chapter 4

- 4.1 a: Section 4.1.

¹ In optimization calculations it is of practical interest to know whether a maximum or minimum is relatively flat (favorable) or sharp (unfavorable). In the latter case the result is sensitive for the design parameter chosen and for the approximate nature of the analysis. This aspect should not be overlooked as part of the optimization.

- b: A residual stress distribution is an equilibrium distribution. It implies that residual compressive stresses are always accompanied by residual tensile stresses at another location.
- 4.2
 - a: Cyclic slip in the nucleation phase is depending on cyclic shear stresses and not on a constant residual stress.
 - b: During subsequent microcrack growth a residual tensile stress will open the microcrack which will enhance further growth. A residual compressive stress tries to keep the microcrack closed which will hamper microcrack growth.
- 4.3 Warpage is an undesirable distortion of the shape of a component due to residual stresses. It may be caused by machining and by shot peening. It can be avoided by symmetric machining or symmetric shot peening.
- 4.4 Section 4.2.
- 4.5 If the deformations during the heat treatment remain elastic, then residual stresses will not be present after cooling down.
- 4.6 $\Delta \ell$ in B' is the elastic elongation of bar 2, while in point A' it is the elastic + plastic elongation of bar 1.
- 4.7 The maximum compressive residual stress to be obtained is of the order of the yield stress in compression. If elastic unloading after inhomogeneous plastic deformation would lead to a higher magnitude of the residual stress, then reversed plasticity occurs which will flatten the residual stress distribution. Higher residual compressive stresses can be introduced in the stronger and more fatigue-sensitive alloy. As a result it may become less fatigue-sensitive.
- 4.8 Warming up from room temperature (about 20°C) to 120°C with an assumed full restraint on thermal expansion by the cool deep structure implies a compressive stress of the order of $\alpha E \cdot \Delta T \sim 170 \text{ MPa}$.
- 4.9
 - a: The residual tensile stress will enhance fatigue crack growth, especially as long as the crack is growing in the plastic zone.
 - b: No, the situation is entirely different. Reversing the load P implies that the pressure distribution on the upper side of the bore of the hole is now applied on the lower side. A high compression

load will not induce a compressive stress in the critical net section of the lug.

- 4.10 The residual tensile stresses will still have a tangential orientation with respect to the hole, but they occur further away from the hole and will remain positive at the periphery of the lug head. This should not be a problem unless the material is sensitive to stress corrosion.
- 4.11 Section 4.5.

Answers to questions of chapter 5

- 5.1 a: S is the remote gross stress, ' a ' is the crack length and β is the geometry factor accounting for the shape of the component. The geometry factor is a function of non-dimensional ratio's which include the crack length as a dimension of the shape.
- b: The unit of K in the SI system is $\text{MPa}\sqrt{\text{m}}$, but sometimes the unit $\text{N}\cdot\text{mm}^{3/2}$ is used. The conversion between the two units is $1 \text{ MPa}\sqrt{\text{m}} = 31.62 \text{ N}\cdot\text{mm}^{3/2}$ ($= \sqrt{1000}$). The unit often used in the USA and UK is $\text{ksi}\sqrt{\text{in}}$. The conversion factors are $1 \text{ MPa}\sqrt{\text{m}} = 0.910 \text{ ksi}\sqrt{\text{in}}$ (less than 10% difference) or $1 \text{ ksi}\sqrt{\text{in}} = 1.099 \text{ MPa}\sqrt{\text{m}}$.
- c: The stress intensity factor is a field parameter for the severity of the stress field around the tip of a crack which accounts for the applied load, the shape of the component and the crack length.
- d: The K factor is based on an assumed elastic behavior. Secondly, the K factor is significant only around the crack tip where the distance to the crack tip is small as compared to the crack size.
- e: K_I is dimensionless and independent of the applied load. K depends on the load and is not dimensionless. However, β and K_I are both dimensionless and account for geometrical effects.
- f: Eq. (5.10a).
- 5.2 This is possible in an infinite plate if the crack length is the only characteristic dimension. Such a case occurs in Figure 5.11, case 1 (Eqs. 5.17 and 5.18). Another case is an infinite plate with a single crack loaded in tension ($\beta = 1$).
- 5.3 The stress σ_y is perpendicular to the crack surface and thus must be zero. The stress σ_x is obtained from Eq. (5.4a) by substitution

of $\theta = 180^\circ$ which gives $\sigma_x = -S$. For an infinite sheet this value applies to the entire crack length.

- 5.4 a: Plasticity upsets the elastic solution in this zone.
 b: See the discussion in Section 5.8 on the K -dominated zone.
- 5.5 No. If the specimen is short, then an effect of the length becomes significant depending on the end conditions of the specimen (constant displacement or constant stress). The more realistic case for experiments is constant displacements and the length effect becomes noticeable for $2H/W < 1$ (see [3, 5] of Chapter 5).
- 5.6 No.
- 5.7 a: Obtain the K_t -value of the notch and assume that the peak stress is the relevant stress level. Calculate K with the equation for a circular crack (Eq. 5.22) and apply the free surface correction factor 1.122 (Eq. 5.14).
 b: More accurate information requires FE calculations. Experience for this kind of problems is necessary.
- 5.8 See the discussion on Figure 5.12.
- 5.9 a: The displacements decrease with \sqrt{r} for decreasing r .
 b: The displacements are smaller for plane strain by a factor of $(1 - \nu^2)$, i.e. about 10% smaller, not very much.
 c: The theoretical shape is parabolic $(\nu^2 \div r)b$. The real shape is different because of crack tip plasticity.
- 5.10 See Section 5.7.
- 5.11 Strange aspects of these equations are: (i) The plastic zone is assumed to have one dimension only, whereas it has at least a 2D shape. (ii) The size is calculated using equations valid to the elastic behavior. (iii) A yield limit is used, usually $S_{0.2}$. This is an arbitrary choice. If $S_{0.1}$ is adopted (a yield limit which has been used in the UK), the size would be larger.
- 5.12 The crack driving force is another name for the strain energy release rate which is associated with the crack extension (Section 5.9). It is sometimes useful to use the term crack driving force because the energy balance wants the crack to grow. The crack growth resistance

of the material is opposing the crack extension. The crack driving force and the stress intensity factor are not synonyms.

Answers to questions of chapter 6

- 6.1 The more relevant difference between the two conditions is that low-cycle fatigue is associated with macroplastic deformation in every cycle. High-cycle fatigue is more related to elastic behavior on a macroscale of the material. High-cycle fatigue is the more common case in practice, whereas low-cycle fatigue is associated with specific structures and load spectra.
- 6.2 The upper asymptote occurs at $S_m + S_a = S_{\max} = S_U$, see the discussion on Figure 6.3. The lower asymptote is associated with the fatigue limit.
- 6.3 The Basquin equation, Eq. (6.2).
- 6.4 a: A stronger material may have a higher fatigue limit for unnotched specimens, but in general a stronger material is more fatigue notch sensitive. The more relevant fatigue data for material selection should come from test data of specimens with realistic notches for the application.
b: See the discussion in Section 2.5.2.
- 6.5 See the discussion on Figure 6.11.
- 6.6 Fully unnotched specimens cannot be made (Figure 6.13). Moreover, the test results depend on the size, the shape of the cross section and the surface quality. This must be kept in mind when using the data of unnotched specimens for the prediction of fatigue properties of notched components, see Chapter 7.
- 6.7 See the discussion on Table 6.1 and Figure 6.14.
- 6.8 In low-cycle fatigue macroplastic deformation does occur in every cycle, whereas in most cycles of high-cycle fatigue only macroelastic deformations occur.

Answers to questions of chapter 7

- 7.1 In a notched component, the size of the highly stressed area, and possibly the shape of the cross section and the surface roughness of the material are not the same as for the specimens used for the determination of the fatigue limit of the unnotched material. Even the material may not exactly be the same.
- 7.2 a: See the discussion in Section 7.2.2, and also Section 6.3.3.
b: The relevant size is the root radius of the notch.
c: The methods are empirical and may thus have a limited accuracy.
- 7.3 a: If $K_f < K_t$, then the notch effect is smaller than expected. It is favorable.
b: High-strength materials are usually more fatigue notch sensitive than low-strength materials, i.e. for high-strength materials, differences between K_f and K_t may be negligible.
- 7.4 Low-strength materials usually have a relatively lower yield stress (as compared to S_U). As a result, a peak stress at the root of the notch is more easily leveled off. This can occur more readily for a positive mean stress, see Figure 7.8.
- 7.5 a: The K_{tg} -value is fairly high (Figure 7.12) which can lead to fatigue crack initiation at the edge of the hole (unidirectional tension) with crack growth under 45° (see Figure 3.21).
b: Crack initiation will occur at the root of the notch, but crack growth will meet with problems as discussed on Figure 6.15.
- 7.6 a: At the edge of the hole where the hole is intersecting the outer surface of the material, stresses can exist in one direction only which is along the edge of the hole. The state of stress thus is unidirectional.
b: Biaxial, see the discussion on Figure 7.14.
- 7.7 The significance of the surface finish for the fatigue limit is large. A rough surface finish can decrease the fatigue limit considerably because of promoting crack initiation which would not occur for a smooth finish. The same is true for high-cycle fatigue although to a lesser extent because crack initiation will occur anyway. For low-cycle fatigue, the surface finish is relatively unimportant because the initiation of microcracks will start immediately.

- 7.8 The prediction of a fatigue life asks for the prediction of a crack initiation life and a crack growth period. Fully rational procedures for both predictions have a limited accuracy. Moreover, the transition from the initiation period to the crack growth period should also be predicted. As a consequence, estimates of S-N curves are usually based on empirical trends as discussed in Section 7.8.

Answers to questions of chapter 8

- 8.1 The elementary conditions are equal ΔK and R -values and similar material. In addition, the conditions of the crack growth experiments should be relevant for the component. Test frequency, environment, material thickness, structure of the material, direction of loading with respect to the material orientation can imply certain differences between the conditions of the component and the test specimen. Such differences should be considered.
- 8.2 a: See Section 8.2.3.
b: Advantage: constant fatigue conditions for research purposes.
Disadvantage: only one data point of the correlation between da/dN and ΔK .
- 8.3 See Section 8.3. Recall the asymptotic behavior in the threshold region (I) and the stable tearing crack growth region (III).
- 8.4 a: Small cracks can be initiated and grow at ΔK -values below ΔK_{th} , see the discussion in Section 8.3.
b: Yes. The fatigue fracture mechanism and the meaning of ΔK as a crack driving force are easily affected by the material structure, depending on the elastic anisotropy of the crystalline structure of the material, the cyclic slip systems, grain boundaries, grain sizes, etc., see Chapter 2. It is quite remarkable that elementary fracture mechanics can be applied to fairly small cracks in Al-alloy. This does not apply to several other alloy systems.
- 8.5 a: Eq. (8.4).
b: The effect of the stress ratio R .
c: C is depending on the units used; the exponent m is not.
d: $da/dN = 17.9 \times 10^{-6} \times \Delta K^{2.675}$ (mm/kc for da/dN and MPa \sqrt{m} for ΔK) is equivalent to: $da/dN \times 25400 = 17.9 \times 10^{-6} \times (\Delta K \times 1.099)^{2.675}$ with inch/c for da/dN and ksi \sqrt{in} for ΔK ,

which implies: $da/dN = 0.907 \times 10^{-9} \times \Delta K^{2.675}$ with the latter units.

- 8.6 a: Crack can be closed at the crack tip while the material is still loaded in tension due to plastic deformation left in the wake of the crack due to previous cycles.
 b: Yes, because the reversed plasticity is depending on S_{\min} .
 c: Yes, see Figure 8.12.
 d: Yes because the plastic zone size is depending on the material thickness, and thus also the plasticity in the wake of the crack.
 e: See the discussion on Figure 8.13a.
 f: See the discussion on Figure 8.13b.
- 8.7 The K -values are increased with a factor 1.3 and thus da/dN with a factor $1.3^{2.675} = 2.02$. The crack growth life is approximately halved.
- 8.8 The increased strength usually implies that the yield stress is also increased. Peak stresses at the crack tip are not so easily leveled off. The sensitivity for crack extension can increase and the crack growth rate may be faster. For example, see Figure 8.15.
- 8.9 Yes. Even if the material is elastically isotropic (on a macroscale), the crack growth resistance can be different in the longitudinal and the transverse direction of the material structure.
- 8.10 Section 8.5.
- 8.11 a: The initial effective crack length is $a_0 = 8$ mm. The crack growth prediction is shown in Table E8.11. The first and the last column give the predicted crack growth curve. The crack growth life is 66.13 kc.
 b: Although the Δa interval appears to be large, it must be realized that the prediction is an approximation of the integration of a graph of the inverse crack growth rate (Eq. 8.19). The approximation should not be expected to be significantly dependent of the Δa interval. A similar tabular calculation with Δa equal to 1 mm gives a crack growth life of 68.02 kc which is only 3% larger than the result of the table.
 c: The dotted line in Figure E8.11b is a reasonable approximation of the non-linear graph. The two constants of the Paris relation, C and m , can be obtained from the dotted line by considering two points of the line. Substitution in the Paris relation of $da/dN =$

Table E8.11

a (mm)	ΔK (MPa \sqrt{m})	da/dN (mm/kc) (1)	ΔN (kc) (2)	$\Sigma \Delta N$ (kc) (3)
8	12.89	0.11	–	0
12	16.11	0.195	26.23	26.23
16	19.16	0.32	15.53	41.76
20	22.29	0.50	9.76	51.52
24	25.73	0.75	6.40	57.92
28	29.72	1.18	4.15	62.06
32	34.65	2.1	2.44	64.50
36	41.23	4.5	1.21	65.72
40	51.02	15.0	0.41	66.13

(1) Values read from Figure E8.11b at ΔK -values in previous column.

(2) Number of cycles spent in Δa interval of 4 mm using the average da/dN of the interval. Example: Average $da/dN = (0.11 + 0.195)/2 = 0.1525$, $\Delta N = 4/0.1525 = 26.23$.

(3) Summing of ΔN in previous column.

0.01 mm/kc at $\Delta K = 6$ MPa \sqrt{m} and $da/dN = 16$ mm/kc at $\Delta K = 70$ MPa \sqrt{m} gives the following solution: $da/dN = 46.06 \times 10^{-6} \times \Delta K^{3.00}$. (da/dN in mm/kc and ΔK in MPa \sqrt{m}). If the da/dN -values in Table 8.11a are calculated with this equation instead of reading the values from the graph in Figure E8.11b the crack growth life obtained is 67.73 kc, i.e. 2.4% larger than the value in the table.

- d: A fully analytical solution with integration of the Paris relation is possible only if the geometry effect is ignored, e.g. by assuming that $\beta = 1$. The integration with Eq. (8.23) then gives a crack growth life of 94.15 kc. This is substantially larger than the above values due to ignoring the width correction.

Comment: Keep in mind that a highly precise prediction is generally illusory because of the limited reliability of the basic crack growth data. However, the relevance of the ΔK -values must always be considered.

- 8.12 The application of ΔK_{th} is questionable because the crack front obtained in fatigue experiments to determine ΔK_{th} and the edge of a material defect are essentially different. The crack driving force and the crack growth resistance are different. Only if defects are really flat and have well delineated edges calculated K -values can give an indication about how serious the defect may be.

- 8.13 In such a case it is essential to have accurate K -values and relevant crack growth data. Accurate K -values in most cases will require calculations, and relevant crack growth data should come from fatigue crack growth tests on the material from which the component is made.

Answers to questions of chapter 9

- 9.1 Section 9.2.
- 9.2 The sequence in which these events have occurred.
- 9.3 Stationary load-time histories: the statistics of the load history do not change. Non-stationary load-time histories: the statistics do change, which may be due a change of how the structure is used.
- 9.4 a: The load-time history of narrow-band random loading looks like a sinusoidal signal with a constant frequency, but with an amplitude modulation. Broad band random loading is not characterized by a single dominant frequency and shows more irregular load variations.
b: Eq. (9.3).
- 9.5 a: The number of certain events in a specified period. The events may be level crossings, peak values above a level, etc.
b: Steep load spectrum: many small cycles and not many large cycles. Flat load spectrum: relatively many large cycles and not that much small cycles, closer to CA loading (see Figure 9.10).
- 9.6 a: The matrix presentation of a load spectrum is a two-dimensional presentation. It gives numbers of peak load ranges (again in certain period) where ranges are characterized by two parameters, a peak load level and the directly successive peak load level (going from one level to another level).
b: Each number in the matrix gives the range between two successive peak values, but the sequence of these ranges is lost.
- 9.7 a: Figure 9.12 and Eqs. (9.3a) and (9.3b).
b: See text on the Rainflow count method.
c: Not fully lost, especially for the small ranges. Large ranges are counted while many smaller intermediate ranges may have occurred.

- 9.8 Yes, see the discussion on Figure 9.15 and also Figure 9.5.
- 9.9
- a: Consider possible scenarios for the usage of the structure. Think in terms of mission analysis and list all types of loads (Section 9.4).
 - b: Sometimes by calculation if the loads are deterministic and well specified. In many cases measurements can be necessary, especially if the types of loads are not very well known.
 - c: A frequently used method employs strain gages. Small sized equipment is commercially available including software for statistical analysis.
- 9.10 Crack nucleation is predominantly depending on the larger cycles, anyhow above the fatigue limit. Crack growth can occur by cycles below and above the fatigue limit. Final failure will be caused by a severe load.
- 9.11 The loads in Figure 9.21 are considered as being static loads. However, dynamic loads can occur during moving of the crane and coming to a standstill. Furthermore, dynamic loads can also be induced at the moment of starting the hoisting or releasing the weight. It is difficult to estimate these types of loads, but strain gage measurements will easily indicate the occurrence of such superimposed loads.

Answers to questions of chapter 10

- 10.1
- a: The damage includes the amount of fatigue cracking, the cyclic and the monotonic plastic deformation around the crack tip and in the wake of the crack, and the strain hardening and residual stresses involved.
 - b: For a specific crack length, the other aspects of answer (a) can be significantly different depending on the previous load history.
- 10.2
- a: The shortcomings are associated with (i) small cycles with an amplitude below the fatigue limit, (ii) notch root plasticity and (iii) the crack length at failure, see Sections 10.2.1 to 10.2.3.
 - b: The first shortcoming can lead to $\Sigma n/N < 1$, the second one can lead to $\Sigma n/N$ -values both larger and smaller than 1 depending on the residual stresses. The third shortcoming is the least important one, but it can also lead to $\Sigma n/N$ -values smaller or larger than 1.

- 10.3 Deviations of the Miner rule can be large for notched specimens because of residual stresses due to notch root plasticity. This does not happen in unnotched specimens.
- 10.4 The sequence of cyclic loads of a load spectrum can be highly significant, specifically due to changing residual stresses as a result of notch root plasticity.
- 10.5 In the block-program fatigue tests, the sequence of load cycles is artificial. In reality, the sequence has a random character.
- 10.6 This can be done by extending the S-N curve below the fatigue limit, see Section 10.4.2. It is correct that cycles below the fatigue limit can contribute to fatigue damage, but it remains questionable whether the Miner rule is correctly accounting for the damage.
- 10.7 The aim of the strain-history model (Section 10.4.4) to predict the strain history at the notch root. However, the Miner rule is still part of this model, although the shortcomings may become less important.
- 10.8
 - a: The service-simulation fatigue tests give a more reliable indication of the fatigue life for the load spectrum applied, i.e. more reliable than CA tests or Miner calculations can do. This also applies to comparative test programs.
 - b: The limitation is that the results apply to the load spectrum adopted and not necessarily to a different load spectrum.
- 10.9 No. A crack is a severe stress raiser under a tension load. As a result of crack tip plasticity a highly extended crack growth life is possible. However, under a compressive load, the crack is closed and is no longer a stress raiser and crack growth is not really accelerated.
- 10.10 See Section 9.5.
- 10.11
 - a: Not at all, see Section 10.5.4.
 - b: Consider the Basquin relation for service-simulation fatigue tests, see Section 10.5.2.

Answers to questions of chapter 11

- 11.1 Non-interaction implies that crack growth at every moment is not depending on the preceding load-time history which produced the

fatigue crack length. In each cycle, the crack length increment is assumed to depend on the severity of that load cycle only (Section 11.2, non-interaction behavior).

- 11.2 a: In general a most significant crack growth retardation, long delay periods.
 b: An UL cycle has an almost negligible effect on fatigue crack growth.
 c: An UL cycle following an OL cycle eliminates the major part of the delay which would occur if the OL had been applied only (see Figure 11.3).
- 11.3 Crack closure reduces the effective stress intensity range which leads to a smaller crack length increment. The prediction according to the similarity concept has to be based on ΔK_{eff} .
- 11.4 a: A larger thickness leads to smaller plastic zones (more plane strain), less crack closure after the OL and the crack growth retardation will be less.
 b: Increasing the yield stress of an alloy has the same effect.
 c: More OL cycles in a single block will cause more retardation because it leaves more plastic deformation in the wake of the crack.
- 11.5 See the discussion on Figures 11.7 to 11.9.
- 11.6 In view of variations of the crack closure level, it should be expected that fatigue crack growth under block-program loading and equivalent random loading are different. In the latter case, the crack closure stress level can change from cycle to cycle whereas during blocks of similar cycles this will not occur so excessively. Different crack growth rates should be expected.
- 11.7 It is strange because ΔK increases immediately. However, when the crack is small the plasticity induced crack closure wake is still being built up. After some stabilization of the wake field, the crack growth rate will increase again (Figure 11.15).
- 11.8 Yes, it is more important because of the larger interaction effects during crack growth by high loads and smaller effects of negative loads.

- 11.9 a: Yes, this should be expected because the interaction effects are predominantly favorable for macrocracks.
b: If the predicted results are important for decisions on the fatigue performance of a component, an experimental verification must be strongly advised. Some service-simulation fatigue tests should be carried out with test conditions relevant for the component, i.e. same material and thickness.
- 11.10 See the discussion on Figures 11.21 and 11.22.

Answers to questions of chapter 12

- 12.1 To know the sources of scatter.
- 12.2 See Table 12.1.
- 12.3 The initiation is depending on various surface effects whereas crack growth is mainly depending on the crack growth resistance of the material and not on surface effects.
- 12.4 At high stress amplitudes, crack initiation can occur more easily and it thus is less subjected to scatter than at low amplitudes.
- 12.5 Some specimens will not fail (run-outs). They produce a lower limit of the fatigue life only.
- 12.6 The function goes from $-\infty$ to $+\infty$. These limits are physically meaningless.
- 12.7 Yes, by replacing $\log N$ as the variable by $\log(N - N_0)$ with N_0 as the lower limit. The distribution function then becomes a 3-parameter function.
- 12.8 No, it requires a large number of test results, usually larger than 20.
- 12.9 Yes, because it may reveal that crack initiation was due to a non-representative cause, e.g. unintentional surface damage.
- 12.10 See the discussion in Sections 12.3 and 12.4.

- 12.11 Scatter will be mainly determined by the more severe load cycles of the spectrum which take care of the crack initiation. Scatter thus may be relatively low (see Figure 12.9).
- 12.12 A safety factor based on scatter of the fatigue limit of unnotched specimens is not a realistic approach. A safety factor has to be selected by engineering judgement.

Answers to questions of chapter 13

- 13.1 A variety of tests should be carried out including CA tests and characteristic service-simulation fatigue tests. Also different types of specimens should be used, e.g. simply notched specimens (moderate K_t -value), some types of joints, crack growth specimens. The selection of types of tests and specimens should be guided by the structural application of the new material. It is not obvious that unnotched specimens should also be tested.
- 13.2 The type of test and the specimen geometry and production (e.g. surface quality) should be representative for the component.
- 13.3 Of course all test conditions should be given in detail. However, sometimes missing data include the specimen thickness, the surface quality of the specimens and the material properties, including the elongation. With respect to the results, quite often nothing is said about fractographic observations of the fatigue failures and that should be done in any case.
- 13.4 The marker loads can indicate how the crack front has grown through the material and how fast this has occurred. This is especially important for studying part through cracks to verify fracture mechanics predictions for such cracks.
- 13.5 All specimens should be made from a single homogeneous batch of material by a single workshop. Test conditions should be the same in all laboratories and testing machines should be well calibrated. (It might well be better if all tests were performed in one laboratory.)
- 13.6 Different S_m -values give a better spread of the data points in the fatigue diagram, especially for high endurances (verify with a drawing).

- 13.7 The machine should be stopped at a positive stress level which keeps the crack in the open position to facilitate observation of the crack tip. This can be done at the mean stress, and not necessarily at S_{\max} . (The static S_{\max} may be slightly larger than the dynamic S_{\max} in computer controlled fatigue machines.)
- 13.8 The classical methods of determining the fatigue limit by experiments are expensive. Furthermore, scatter of the test results cannot simply be transferred to the fatigue limit of a component. It then might be more attractive to adopt the test procedure of Figure 13.2. Of course, this should preferably be done on the component itself.
- 13.9 The major breakthrough was the introduction of the computer controlled closed-loop load actuator. A major advantage is that any complex load-time history can now be generated and thus becomes a realistic load history rather than a complex load history.

Answers to questions of chapter 14

- 14.1 See Section 14.2.
- 14.2 a: See Section 14.2.
b: The fatigue limit and the high-cycle fatigue strength. Low-cycle fatigue is less affected.
- 14.3 – A soft surface layer, e.g. by decarburizing. Also a cladding layer on aluminium alloys.
– A roughly machined surface, see the results in Figure 2.22.
– Pitting phenomena, e.g. by corrosion.
- 14.4 The prime reason is the increased fatigue resistance of the surface layer.
- 14.5 See the discussion of Figures 14.5 and 14.6.
- 14.6 a: The prime reason is that it introduces favorable residual compressive stresses and it is difficult for microcracks to grow through the surface layer with these residual stresses.
b: The surface roughness increases and distortions of the component can occur (warping).

- 14.7 This is done by a reduction factor γ (Eq. 7.23) discussed in Section 7.2. It is an empirical factor.
- 14.8 Apart from using the same material for the specimen as for the component, the geometry of the notch in the specimen should also be representative for the component. This implies a similar notch root radius to obtain a similar stress gradient.
- 14.9 (i) A Rockwell B indentation is spherical and will have a relatively low K_t -value. Moreover, the indentation is causing some plastic deformation which leaves some residual compressive stress. The effect on a fatigue limit will not be significant. (ii) A dent by foreign object damage may have a more unpleasant shape with sharp corners. The possibility of favorable residual compressive stresses remains. The effect is hard to predict. (iii) A nick by a sharp object can be a cut with a sharp radius and probably not much plastic deformation. This surface damage is the most severe one.
- 14.10 Crack nucleation under VA loading is mainly controlled by the cycles with the larger amplitudes. If these amplitudes are significantly beyond the fatigue limit, crack nucleation will occur. The surface roughness effect on crack nucleation is then relatively small. However, if the more severe cycles are just above the fatigue limit, surface roughness can have a significant influence of the fatigue life.

Answers to questions of chapter 15

- 15.1 a: It starts with surface damage, usually of oxide layers. Corrosion escalates the process but is not the prime cause.
b: Unfortunately most technical materials are sensitive to fretting corrosion.
- 15.2 a: Because fretting corrosion damage primarily affects the crack initiation period, the fatigue limit can be much lower and the high-cycle range also shows a reduced fatigue strength. In the low-cycle fatigue range the effect is small.
b: Already a small clamping pressure is sufficient for fretting. An increased pressure in many test series has shown a relatively moderate effect.

- 15.3 The best remedy is to prevent metallic contact between the mating surfaces.
- 15.4 a: Yes, see Sections 18.2 and 18.5.
b: Yes, see the discussion on Figure 15.14.

Answers to questions of chapter 16

- 16.1 a: Corrosion is affecting crack initiation and crack growth.
b: Corrosion can lead to pitting. These pits are causing serious stress concentrations. Corrosion is then assisting subsequent microcrack growth and macrocrack growth which leads to a fatigue failure.
c: This occurs during the upper part of the load range when going from S_{\min} to S_{\max} .
d: In general, corrosion fatigue is more disastrous at lower frequencies. There is more time in a load cycle for corrosion.
e: Yes. An important aspect is how fast the load is raised from S_{\min} to S_{\max} , see the discussion on Frequency and wave shape effects.
f: Holding at S_{\max} is not necessarily detrimental, see the discussion on Figure 16.8.
- 16.2 a: Water vapor.
b: The water vapor effect on fatigue crack growth depends on the absolute amount of water vapor (and on the frequency), and not on the relative humidity. The maximum water vapor content decreases considerably at low temperatures.
- 16.3 Corrosion pits are notches. Although being small, the stress concentration can be significant due to the shape of the pit. If corrosion pits occur at the root of a notch, the effect on the fatigue limit can be large, especially for high-strength materials which are often fatigue notch sensitive.
- 16.4 Although the corrosion process inside a fatigue crack and particularly at the crack tip is complex and not always well understood, it is possible that the corrosion products are filling the crack (propping) and thus cause a kind of crack closure which may reduce the stress intensity at the crack tip.
- 16.5 To prevent corrosion.

Chapter 17: High-temperature and low-temperature fatigue

There are no questions about this chapter.

Answers to questions of chapter 18

- 18.1 In general, fatigue properties of joints are not very good. Because joints are essential in many types of structures, it turns out that fatigue cracks in service often occur at joints.
- 18.2 The prediction of fatigue properties of notched specimens is based on the similarity of fatigue in notched and unnotched material. However, fatigue in various types of joints is started by fretting fatigue damage which does not occur during fatigue of unnotched specimens. The similarity does not exist.
- 18.3 In non-symmetric joints, secondary bending occurs due to the eccentricity in the joint. The bending also occurs at the critical section of the joint, which is unfavorable.
- 18.4 a: Because of fretting corrosion between the pin (or bolt) in the hole and the bore of the hole. Due to fretting damage cracks can be initiated at very low stress amplitudes.
b: Because the fretting damage causing crack initiation is depending on the fretting movements rather than some weakest link mechanism causing the size effect in specimens where fretting does not occur.
- 18.5 The Larsson prediction is an extrapolation from a standard lug to other lugs. In Chapter 7, the prediction was an extrapolation from data of unnotched specimens to notched configurations.
- 18.6 The difference is due to the fact that the stress distribution in the critical section of a lug is essentially different for a positive and a negative load, see the discussion on Figure 18.4. It leads to the unusual shape of constant N lines for $R < 0$ shown in this figure.
- 18.7 For the bushed hole, see the discussion on Figure 15.15. For the improvement by plastic hole expansion, see the discussion on Figure 15.16. Plastic hole expansion does not prevent fretting corrosion, but small cracks initiated by the fretting damage can

hardly grow in the surface layer with high residual compressive stresses around the hole.

- 18.8 a: Stress concentrations at the holes are due to load transmission by the fastener in the hole, and by-pass loads of the other fastener rows. Furthermore, secondary bending is causing another increase of the stress at the critical location of the holes.
- b: The fatigue strength of a riveted lap joint is depending on the geometry of the joint (effects on load transmission by different rows and secondary bending), the quality of the riveting process, hole filling and the type of fastener, see the discussion in Section 18.5. It should be recalled that a symmetric joint is highly preferred because it avoids secondary bending and improves the load transmission. Solutions selected in practice are depending on the economy of the production process.
- 18.9 a: Part of the load transmission occurs by frictional forces between the clamped parts.
- b: The fatigue life is improved by increasing the clamping force until fatigue cracks are no longer initiated at the bore of the hole but away from the hole, see the discussion on Figure 18.10.
- 18.10 A part of the load transmission does not occur through the bolt. The mean load of the bolt is increased but the load amplitude is decreased, see the discussion on Figure 18.15.
- 18.11 The most striking difference is that load transmission in a riveted lap joint occurs at a number of points only, i.e. by the fasteners. In the bonded lap joint, load transmission occurs along the entire overlap, which also implies less secondary bending. Moreover, the notch effect at the edge of the bonded overlap is less severe than for the rivet rows.

Answers to questions of chapter 19

- 19.1 The fatigue quality of a welded structure is highly depending on the quality of the welding process in view of weld defects and the local geometry of the weld line. Secondly, a continuous connection between the joined parts is generally adopted. Even butt welds are possible. As a result the structural design concepts are entirely different for welded and non-welded structures.

- 19.2 Designing against fatigue of welded structures is a complex problem. Apart from all aspects of controlling and inspecting the quality of a welded structure, two different fatigue design aspects must be recognized. First, the overall design of a welded structure is to some extent depending on the possibilities to produce the desired structural concept by welding. It then is a matter of good design to minimize stress levels at the welds (compare the alternative design solutions in Figure 19.3. Second, the notch effect of a weld, assuming that the quality of the weld is good, is highly depending on the local geometry of the weld profile. A profile as given in Figure 19.4 for the double strap joint is a rather unfavorable geometry in view of the stress concentration at the root of the weld.
- 19.3 It may well be expected that fatigue failures are not acceptable. It then can be tried to estimate the fatigue strength of the two types of joints, bolted or welded. Stress analysis can be most helpful to decide on satisfactory design options of the joints in order to avoid severe stress concentrations and also in view of the cost-effectivity of the production. However, to be sure about the fatigue strength, it may be advisable to produce prototypes for measurements of the load spectrum in service and relevant fatigue experiments.

I.3 Summaries of chapters

A list of chapter titles is presented first followed by chapter summaries except for Chapter 1.

Chapter 1 Introduction to fatigue of structures and materials

Introductory Chapters on Fatigue

Chapter 2 Fatigue as a phenomenon in the material

Chapter 3 Stress concentrations at notches

Chapter 4 Residual stress

Chapter 5 Stress intensity factors of cracks

Chapter 6 Fatigue properties of materials

Chapter 7 The fatigue strength of notched specimens. Analysis and predictions

Chapter 8 Fatigue crack growth. Analysis and predictions

Load Spectra and Fatigue under Variable-Amplitude Loading

Chapter 9 Load spectra

Chapter 10 Fatigue under variable-amplitude loading

Chapter 11 Fatigue crack growth under variable-amplitude loading

Fatigue Tests and Scatter

Chapter 12 Fatigue and scatter

Chapter 13 Fatigue tests

Special Fatigue Conditions

Chapter 14 Surface treatments

Chapter 15 Fretting corrosion

Chapter 16 Corrosion fatigue

Chapter 17 High-temperature and low-temperature fatigue

Fatigue of Joints and Structures

Chapter 18 Fatigue of joints (except welded joints)

Chapter 19 Fatigue of welded joints

Chapter 20 Designing against fatigue of structures

Fiber-Metal Laminates

Chapter 21 The fatigue resistance of fiber-metal laminates

Chapter 2: Fatigue as a phenomenon in the material

1. The fatigue mechanism in metallic materials should basically be associated with cyclic slip and the conversion into crack initiation and crack extension. Details of the mechanism are dependent on the type of material.
2. The fatigue life until failure comprises two periods, the crack initiation period and the crack growth period. The crack initiation period includes crack nucleation at the material surface and crack growth of micro-structurally small cracks. The crack growth period covers crack growth away from the material surface.
3. In many cases the crack initiation period covers a relatively large percentage of the total fatigue life.
4. Fatigue in the crack initiation period is a surface phenomenon, which is very sensitive to various surface conditions, such as surface roughness, fretting, corrosion pits, etc.
5. In the crack growth period, fatigue is depending on the crack growth resistance of the material and not on the material surface conditions.
6. Micro-structurally small cracks can be nucleated at stress amplitudes below the fatigue limit. Crack growth is then arrested by micro-structural barriers. The fatigue limit as a threshold property is highly sensitive to various surface conditions. At high stress amplitudes, and thus relatively low fatigue lives, the effect of the surface conditions is much smaller.
7. In view of possible effects during the crack initiation period, it can be understood that scatter of the fatigue limit and large fatigue lives at low stress amplitudes can be large, whereas scatter of lower fatigue lives at high amplitudes will be relatively small.
8. Aggressive environments can affect both crack initiation and crack growth. The load frequency and the wave shape are then important variables.
9. Predictions on fatigue properties are basically different for the crack initiation life and for the crack growth period.
10. The various characteristics of fatigue fractures can be understood in terms of crack initiation and crack growth mechanisms. These characteristics are essential in failure analysis, but they are also relevant to understand the significance of technically important variables of fatigue properties.

Chapter 3: Stress concentrations at notches

The major results of the present chapter are recollected.

1. The most important variable for the stress concentration factor K_t is the root radius ρ . Sharp notches can give unnecessarily high K_t -values.
2. Loads applied close to the notch root usually give higher K_t -values than remotely applied loads.
3. Pin-loaded holes are a more severe stress raiser than open holes.
4. The gradient of the peak stress at the notch root to lower values away from the root surface ($d\sigma_y/dy$) is inversely proportional to the root radius ρ , and linearly proportional to the peak stress at the root of the notch, σ_{peak} . This gradient is relatively high and σ_y drops off rapidly away from the material surface. Contrary to this large gradient, the tangential stress along the material surface at the notch root decreases relatively slowly. This observation is significant for considering notch size effects on fatigue and notch surface qualities.
5. Superposition of notches can lead to a multiplication effect on K_t ($= K_{t1} \times K_{t2}$).
6. Accurate K_t -values can be calculated with FE techniques. With the current computers, these calculations are more accurate and cost-effective in comparison to measurements of stress distributions around notches.

Chapter 4: Residual stress

1. Residual stresses are usually caused by inhomogeneous plastic deformation. Due to permanent plastic deformation, the plastic zone no longer fits stress-free in the elastic surrounding, which introduces a residual stress system.
2. Residual stresses can be introduced on purpose (shot-peening, plastic hole expansion). They can also occur unintentionally (production processes, heat treatment). Another important source is assembling of components, which can cause significant built-in stresses.
3. A residual stress system is an equilibrium system. There is never a favorable compressive residual stress without an unfavorable tension residual stress at an other location.
4. Residual stresses can have a significant effect on fatigue and stress corrosion. During machining residual stresses can cause warpage.

5. Measuring of residual stresses at the root of a notch introduced by a high load is not a simple technique. An estimate can be obtained with a simple calculation technique. FE calculations of a residual stress distribution with an FE analysis is possible but it requires experience.

Chapter 5: Stress intensity factors of cracks

1. The stress intensity factor $K = \beta S \sqrt{\pi a}$ gives an indication of the stress severity around the tip of a crack. S accounts for the stress level, a for the crack length, and the geometry factor β for the shape of the specimen or structure. The equations presented for stresses and displacements in the crack tip area are valid only at a relatively short distance from the crack tip. The stress intensity factor K is essentially an elastic concept. The singular character of the equations ($r^{-1/2}$) lead to infinite stresses at the crack tip, which causes plastic deformation at the crack tip. As long as the plastic zone is relatively small, the stress intensity factor still gives a good indication of the stress system acting on the K -dominated zone around the crack tip. K can thus still be used for two purposes: (i) To describe the fatigue crack growth resistance properties of a material, usually as $da/dN = f(\Delta K, R)$. (ii) Such data can be used for predictions on fatigue crack growth in other specimens and structures.
2. A large amount of data on K -values (actually on β -values) is available in the literature and in software packages, but it is generally related to well defined shapes, and not to more complex geometries. First estimates can be obtained by considering more simple geometries, in particular for small edge cracks. For large cracks at notches an effective crack length including the notch size can also yield good K estimates. More accurate K -values can be obtained by calculations. Part-through cracks and curved crack fronts offer 3D problems with K -values varying along the crack front. Expertise on such calculations and substantial computer capacity are then required.
3. The state of stress conditions at the tip of a crack can vary from plane strain ($\varepsilon_z = 0$) to plane stress ($\sigma_z = 0$). If lateral contraction along the crack front is difficult, plane strain will prevail. At the material surface plane stress applies. The state of stress has a significant influence on the size of the plastic zone. Smaller plastic zones occur

under plane strain. Crack tip plasticity allows more lateral contraction and thus promotes plane stress.

4. The application of the K factor to fatigue cracks is based on the similarity concept. An essential question to be considered is whether the crack tip conditions of the laboratory specimen and the structural part are sufficiently similar to allow predictions based on relevant K -values.

Chapter 6: Fatigue properties of materials

1. Fatigue limits and S-N curves for unnotched specimens are generally supposed to be basic materials properties. However, it should be recognized that these properties depend on the size and the shape of the unnotched specimens used, and also on the surface finish of the specimens. This is especially relevant to the fatigue limit because this property is mainly controlled by nucleation of microcracks at the material surface.
2. For a group of similar alloys, the fatigue limit of unnotched specimens (S_{f1}) for $S_m = 0$ increases with the ultimate tensile strength of a material if the higher strength is obtained by changing the alloy composition or an other heat treatment. As a first estimate for the fatigue limit, the linear relation $S_{f1} = \alpha S_U$ can be used with a characteristic α -value for a group of similar materials.
3. A large part of the S-N curve can be approximated by the Basquin relation, $S_a^k N = \text{constant}$, a linear relation on a double log scale.
4. The fatigue properties on unnotched material can be described by fatigue diagrams. Lines for constant fatigue lives in such a diagram can be approximated by the Gerber parabola or by the modified Goodman relation. The Gerber parabola agrees more with the results of materials with a reasonable ductility whereas the modified Goodman relation is more applicable to the high-strength low-ductility materials.
5. The effect of the stress amplitude is more significant for the fatigue properties of a material than the effect of the mean stress, especially for high fatigue lives and the fatigue limit. The mean stress effect for different materials can be characterized by the slope factor M defined by Schütz (Figure 6.11). It indicates an increasing mean stress effect for an increasing strength of a material.
6. Fatigue is less significant for a compressive mean stress.

7. Fatigue under cyclic tension and cyclic bending is a similar phenomenon. However, under cyclic torsion it is different, both for crack nucleation and crack growth. The fatigue limit under cyclic torsion hardly depends on the mean shear stress.
8. For combined loading cases, e.g. cyclic bending and torsion, the fatigue limit can be described by an empirical relation. Complex problems are offered if combined loadings occur out of phase.
9. High-cycle fatigue and low-cycle fatigue refer to a significantly different behavior of the material. Under high-cycle fatigue, the material response is still macroscopically elastic. The fatigue life of specimens then is largely dominated by the crack initiation period while the crack growth period is relatively short. For low-cycle fatigue, macroscopic plasticity occurs in every cycle. Fatigue cycles should then be expressed in terms of strain amplitudes instead of stress amplitudes.

Chapter 7: The fatigue strength of notched specimens. Analysis and predictions

1. *The fatigue limit of notched specimens for $S_m = 0$*
The fatigue limit depends on K_t (notch effect) and the root radius ρ (size effect). The fatigue limit can be predicted by adopting the similarity principle in its most simple form, which is $K_f = K_t$. The prediction will be conservative in most cases, i.e. $K_f < K_t$. A reasonable prediction of the fatigue limit is possible with empirical equations to account for the notch effect, the size effect, and the strength of the material. The Neuber equation (Eq. 7.8) gives reasonable estimates. However, for high-strength materials with a low ductility it is advised to adopt $K_f = K_t$.
2. *The fatigue limit of notched specimens, $S_m > 0$*
Prediction of the fatigue limit is complicated because local plastic deformation at the root of the notch can level off the peak stress. The mean stress effect can be accounted for by adopting a Gerber parabola for ductile materials with a low or moderate strength level. For high-strength low-ductility materials, the modified Goodman relation should be advised. In the latter case it is even more safe to apply K_t to both S_a and S_m . Useful indications on the mean stress effect are obtained by the methods of Schütz (Eq. 6.5).

3. *The fatigue limit under cyclic torsion*
For a shaft with a stepped diameter it is advisable to adopt $K_f = K_t$. The mean stress effect should be expected to be small.
4. *The surface finish effect on the fatigue limit of notched elements*
Predictions on the fatigue limit should include the effect of the surface finish in addition to the notch and the size effect. Reduction factors (γ) of the literature are indicative.
5. *S-N curves of notched specimens*
Predictions on the fatigue life until final failure are complicated because a finite fatigue life consists of a crack initiation period and a crack growth period. Estimations of S-N curves using the Basquin relation are possible.
6. Important variables for the prediction of the fatigue strength of a notched element are K_t , the size of the notch, surface finish and mean stress. Mechanistic aspects of these variables are reasonably well understood in a qualitative way. Because of this understanding, it is obvious that limitations on the accuracy of fatigue strength predictions should be present. Empirical trends are helpful in making engineering estimates. In fatigue critical cases, experiments are indispensable.

Chapter 8: Fatigue crack growth. Analysis and prediction

1. The fatigue crack growth resistance of a material can be described as $da/dN = f(\Delta K, R)$. This function is obtained from fatigue crack growth tests on simple specimens. The results can be presented in graphs, equations and tables. They should be considered to be empirical data representing the fatigue crack growth resistance of a material.
2. Fatigue crack growth can occur in three regions of ΔK : (i) the threshold region, (ii) the Paris region, and (iii) the stable-tearing crack growth region. The technical relevance of the threshold region is problematic, due to a changing crack growth mechanism at low ΔK -values. The Paris relation, $da/dN = C \times \Delta K^m$, is an approximation of empirical results. Deviations of this linear relation (log-log scale) are observed.
3. The Paris relation is useful for estimating the effect of the design stress level on the crack growth life.

4. Plasticity induced crack closure (Elber) is an important phenomenon to understand the macrocrack growth behavior. Crack closure is more significant at the material surface in view of the plane stress situation, and less important under plane strain conditions in thick sections of materials with a relatively high yield stress.
5. The crack closure concept has led to the ΔK_{eff} concept which is helpful in accounting for the stress ratio R . The $\Delta K_{\text{eff}} - R$ equations are based on empirical evidence.
6. The fatigue crack growth resistance depends on the material, and more specifically on the yield strength of a material as obtained by the material production and heat treatment. Increasing the yield strength by a heat treatment usually leads to a reduction of the fatigue crack growth resistance. It is remarkable that the fatigue crack growth resistance of steels with a significantly different static strength is not so much different. Materials with a very high static strength usually have a relatively low fatigue crack growth resistance.
7. The predictions of fatigue crack growth in a structure is based on the similarity principle. The value of ΔK is used as the crack driving force to obtain the corresponding da/dN from the basic material fatigue crack growth data of the material. The most simple case is a prediction of crack growth of a through crack in a plate under cyclic tension. Curved crack fronts occur for corner cracks and for through cracks under combined tension and bending. Depending on the purpose of the predictions, some simplifications of the prediction procedure can be justified to obtain estimates of ΔK -values. However, more accurate predictions require that data on the K variation along the crack front. It may imply that FE calculations should be made, but information is also available in data banks.
8. The prediction of the crack growth life starting from a small crack length a_0 is strongly depending on the size of a_0 . The predicted life increases substantially for smaller values of a_0 . The prediction can be unconservative if crack growth at a_0 is still affected by the small crack phenomenon which can occur for $\Delta K < \Delta K_{\text{th}}$. Extrapolation of the Paris equation to low ΔK -values below the threshold value should then be considered.

Chapter 9: Load spectra

1. A load history applied to a structure in service is characterized by a sequence of successive maxima and minima (peaks) of the load on the structure. A load spectrum is a statistical representation of these maxima and minima, obtained by counting the numbers of peak values in load intervals, or counting the number of exceedings of load levels. The data can be presented in tables or graphs in which the magnitude of the load is indicated by a single load parameter. One-parameter load spectra can be instructive for general impressions of the spectrum severity and comparing load spectra of different severities.
2. Counting of load ranges between successive maxima and minima is also possible with results collected in a matrix. This is a two-parameter statistical representation of a load history which provides more information than a one-parameter counting method. The matrix gives information about load ranges between successive maxima and minima, but information about the sequence of these ranges is lost.
3. The rainflow count method is a range count method which counts intermediate smaller ranges separately. The rainflow count method should be preferred for a statistical analysis of load-time histories because it is more realistic in considering the fatigue damage of combined maximum and minimum loads.
4. Characteristic classifications of loads in service are: deterministic loads (especially maneuver type loads) and stochastic loads (in particular random loads). Another classification is stationary load spectra versus non-stationary load spectra.
5. Narrow band random loading looks like an amplitude modulated signal. Broad band random load has a more irregular character.
6. Continuous load-time records are most informative to show characteristic features of the load history which are not easily deduced from load counting results.
7. Load spectra for structures can vary from very simple (e.g. almost constant-amplitude loading of a pressure vessel) to rather complex (e.g. superposition of different types of loads from different sources with varying intensities and probabilities of occurrence).
8. Load spectra are essential for the analysis and predictions of fatigue critical structures. The spectrum of the stress in the structure is not

- linearly related to the load spectrum on the structure, depending on the dynamic response of the structure on external loads.
9. Assessments of load spectra for a structure should start with listing all types of loads occurring in service and their characteristic properties. Quantitative assessments of the spectra can be difficult due to lack of information. Load measurements should then be considered for which well developed techniques are available.
 10. Quantitative information on load histories is also essential for planning service- simulation fatigue tests.

Chapter 10: Fatigue under variable-amplitude loading

1. The most simple method for fatigue life predictions is to use the Miner rule, $\Sigma n/N = 1$. Unfortunately, this rule is not reliable, because of some elementary shortcomings. Two important deficiencies are: (i) Cycles with a stress amplitude below the fatigue limit are supposed to be non-damaging. In reality, these cycles can extend fatigue damage created by cycles with amplitudes above the fatigue limit. (ii) Notch root plasticity leads to residual stresses which can affect the fatigue damage contribution of subsequent cycles. This interaction effect is also ignored by the Miner rule.
2. The Miner rule and several other prediction models assume that fatigue damage can be fully characterized by a single damage parameter ($\Sigma n/N$ in the Miner rule), which is physically incorrect. Fatigue damage also includes local plasticity and residual stress.
3. Results of $\Sigma n/N$ -values at failure quoted in the literature vary from much smaller than 1 to significantly larger than 1. Small values are promoted by unnotched specimens and a zero mean stress. High values are prompted by notched specimens in combination with a positive mean stress, and also by steep load spectra (low numbers of severe load cycles). Residual stresses are important to explain high $\Sigma n/N$ -values.
4. The sequence of different load cycles in a VA-load history can have a large effect on $\Sigma n/N$ at failure. This is more true for block-program fatigue load sequences than for sequences with random loads or mixtures of deterministic and random loads. Block-program tests should be discouraged for practical problems.
5. If fatigue life predictions are made with the Miner rule, it should be realized that the results are associated with uncertainties of the

reliability of the rule, and also with the relevance of the S-N curves adopted. If the Miner rule is still adopted, it must be recommended to extrapolate S-N curves below the fatigue limit in order to assign fatigue damage contributions to small cycles below the fatigue limit. At best, the Miner rule gives a rough estimate of the fatigue life.

6. Improvements of life prediction methods have been proposed in the literature, but it is still questionable whether they offer a good solution for practical design problems.
7. The only reasonable alternative is to obtain test results of relevant service-simulation fatigue tests. Such tests should be relevant with respect to the material, notch configuration and material surface condition, as well as the load history expected in service.
8. Service-simulation fatigue tests are also recommended for comparative investigations of materials, surface treatments, joints and components in general, and also for comparing the severity of different load spectra. The Miner rule is not reliable for these purposes.

Chapter 11: Fatigue crack growth under variable-amplitude loading

1. Significant interaction effects can occur during fatigue crack growth under VA loading. It implies that the crack growth rate (da/dN) in a cycle is dependent on the load history of the preceding cycles, and it is not necessarily the same as in a CA test.
2. A load cycle with a high S_{\max} (an overload, OL) can significantly reduce the crack growth rate in subsequent cycles (positive interaction effect). A load cycle with a low S_{\min} (an underload, UL) can slightly increase the crack growth rate, while it can also reduce the retardation effect of previous OLs (negative interaction effects). In general, the positive interaction effects will overrule the negative ones during crack growth under service load spectra. As a result, non-interaction predictions for fatigue crack growth under VA loading will usually give conservative results.
3. Plasticity induced crack closure is a significant phenomenon to explain interaction effects. Experiments with simple VA-load histories have essentially contributed to understanding these effects. Similar interaction effects occur during more complex service simulating load histories.

4. Larger interaction effects occur in materials with a relatively low yield stress and in thinner materials, due to larger crack tip plastic zones.
5. Three types of prediction models for fatigue crack growth under VA loading have been proposed in the literature; yield zone models, crack closure models and strip yield models. The yield zone models do not agree with the present knowledge of interaction effects. The crack closure models account for the occurrence of plasticity induced crack closure and the transition of plane strain to plane stress. The strip yield models are the most sophisticated models, which include calculations of plasticity induced crack closure. These models predict delayed retardation after an OL. The calculation algorithm of the strip yield models is complicated.
6. Empirical verification of prediction models is unfortunately rather limited. Verifications should not be restricted to predictions on crack growth lives, but should include predictions on crack growth rate as a function of crack length. Non-interaction predictions should also be made to indicate whether significant interaction effects occurred. Fractographic observations are recommended for investigations on prediction models.
7. Crack growth predictions for practical engineering problems should be validated by service-simulation fatigue tests.

Chapter 12: Fatigue and scatter

1. Scatter of fatigue lives is mainly scatter of the crack initiation period. This period is easily affected by different conditions at the material surface. Scatter of macrocrack growth is significantly smaller.
2. Scatter of fatigue lives is less at high stress amplitudes and more significant at low amplitudes near the fatigue limit.
3. Several important sources of scatter in laboratory investigations and in service are essentially different (Table 12.1). Scatter in service is hardly predictable from scatter observed in laboratory investigations.
4. As a consequence of the previous conclusion, the application of safety factors on the fatigue limit of a structural component is a difficult question.
5. In a statistical analysis of a fatigue problem, a distribution function is usually assumed, but it is difficult to prove that application of the function is reliable.

6. Scatter under VA loading is predominantly controlled by the larger load cycles of the load spectrum. Scatter under VA loading cannot be deduced from scatter data obtained in CA tests.
7. Low scatter is promoted by sharp notches (poor design). Significant scatter is possible for long fatigue lives of carefully designed structural elements (low K_t -values) of high-strength materials. Accounting for scatter should then occur by adopting a suitable safety factor on the design stress level. Selection of this factor requires engineering judgement of all possible sources which can contribute to scatter of the structure in service.

Chapter 13: Fatigue tests

Several comments on planning and carrying out programs of fatigue tests are discussed in the present chapter. These comments will not be summarized here, but a few specific recommendations are recalled below:

1. The selection of specimens and fatigue loads should be carefully considered in relation to the purpose of the fatigue test program. Different options will apply to engineering problems and research investigations.
2. After completing a fatigue test, the results of the test should be immediately evaluated in order to allow a reassessment of subsequent tests.
3. An evaluation of the results of a fatigue test should always include a fractographic analysis of the fatigue fracture surfaces.

Chapter 14: Surface treatments

1. Material surface treatments are carried out for various purposes: improvement of fatigue properties, protection against corrosion, improved wear resistance, improving a poor surface quality, and cosmetic reasons. The variety of surface treatments is large.
2. The effect of surface treatments on the fatigue properties of a structure is associated with the fatigue resistance of the surface layer of the material, with residual stresses in this layer, and with surface roughness.

3. Surface treatments can be very effective under high-cycle fatigue. Significant increases of the fatigue limit are possible. Surface treatments are less important for low-cycle fatigue.
4. Shotpeening is used for improving fatigue properties, but also for restoring the fatigue resistance of structural elements with a poor surface finish quality resulting from the production.
5. The effect of surface treatments for a specific application should be verified by experiments on component-type specimens with cyclic loads representative for the application of the structure in service.
6. Quality control of a surface treatment process during production is indispensable.

Chapter 15: Fretting corrosion

1. Fretting corrosion under cyclic load cannot be avoided if metallic materials are in contact at mating surfaces. Very small rubbing displacements will occur and produce surface damage. The fatigue strength in the high-cycle fatigue region is reduced by this surface damage. Considerable reductions of the fatigue limit are common, especially for high-strength materials, due to the high notch sensitivity of these materials.
2. The fretting corrosion mechanism is affected by several variables, such as pressure on the interface surface, the amplitude of rubbing movements, the materials, surface roughness, environment, and the cyclic stress level. Although some systematic trends of the influence of these variables are recognized and partly understood in a qualitative way, the fretting corrosion mechanism is a complex phenomenon to describe in physical detail.
3. Methods to avoid detrimental effects of fretting corrosion fatigue in structures, and particularly in joints, are based on two principles: (i) Avoid metallic contact by structural detail design, or non-metallic interlayers, and (ii) surface treatments to improve surface wear resistance or introduce compressive residual stresses.

Chapter 16: Corrosion fatigue

1. Corrosion fatigue is a complex phenomenon due to the corrosion aspects involved. Detrimental effects of corrosion on crack

initiation and crack growth under fatigue loading depend on the type of material and environment. Systematic effects have been recognized, but these effects are not generally applicable to all material/environment combinations.

2. Corrosion fatigue effects are usually associated with material dissolution at the material surface and at the crack tip. At the material surface it will shorten the crack initiation period and substantially reduce the fatigue limit. At the crack tip it will accelerate crack growth which in addition may be increased by some weakening of the cohesive strength of the material at the crack tip.
3. Corrosion damage of the material surface and noteworthy corrosion pits, can lead to a large reduction of the fatigue limit.
4. Some typical aspects of corrosion fatigue are: (i) Damage contribution of corrosion to fatigue crack growth primarily occurs during crack extension in the load-increasing part of the load cycles. The loading rate in this part of the cycle is important. As a consequence, the load frequency can also be important. (ii) Holding times at maximum load are not necessarily contributing to crack extension. (iii) The water vapor pressure is an important variable of gaseous environments.
5. In most investigations, corrosion fatigue experiments were carried out as constant-amplitude tests on unnotched specimens or crack growth specimens under closely controlled environmental conditions. However, the conditions for corrosion fatigue of a structure in service are significantly different, especially with respect to the load-time history, the variable environment and long exposure times (years). These differences should be considered in practical problems.
6. Design considerations on corrosion fatigue are frequently based on the prevention of corrosion. It can be done by prevention of the access of the environment to fatigue critical locations of a structure, selection of a suitable corrosion resistant material, and application of material surface treatments.

Chapter 17: High-temperature and low-temperature fatigue

High-temperature fatigue is in the first place a problem associated with the stability of the material structure. Essential information is related to the load- and temperature-time histories. Where ambient temperature fatigue problems can considerably benefit from stress analysis calculations, material

research is more essential for high-temperature fatigue. Temperature limits beyond which the material stability deteriorates should be determined, and fundamental understanding of the material behavior is important. As an example, it has occasionally been overlooked that the creep resistance can significantly depend on the strain-hardening (dislocation structure) of the original material. High-temperature fatigue problems require experimental research while knowledge of material science is indispensable for planning the research.

Low-temperature fatigue is a fully different problem. Plastic deformation at low temperatures is more difficult than at room temperature which has consequences with respect to fracture toughness and fatigue crack growth at high ΔK -values. These aspects should be recognized if the operational environment of the structure includes low temperatures. Designing for fatigue durability in terms of avoiding stress concentrations and limitations on allowable stress levels still remain relevant. The transition from ductile failures to brittle failures at low temperature, especially of low-carbon steels, is a special issue to be considered for (welded) structures of these materials.

Chapter 18: Fatigue of joints (except welded joints)

1. The load transmission in joints is essentially different for lugs, joints with bolts in tension, bolted and riveted joints with shear loaded fasteners and adhesive bonded joints.
2. The fatigue limit of joints can be very low due to severe stress concentrations, fretting corrosion and secondary bending. In spite of a high static strength of a joint, the fatigue limit can be low.
3. Prediction of the fatigue life, fatigue strength and fatigue limit is a complex problem for joints because the crack initiation and initial growth of small cracks cannot easily be compared to a similar behavior in unnotched specimens. This excludes predictions based on basic material fatigue properties. Fatigue properties of joints should be derived from fatigue properties of similar joints for which data are available.
4. The size effect on the fatigue limit of lugs is large. The low fatigue limit of lugs can be significantly improved by plastic hole expansion.
5. Bolts loaded in cyclic tension have a relatively low fatigue strength which can be substantially increased by pre-tensioning.
6. The fatigue strength of symmetric butt joints (riveted or bolted) is superior to the fatigue strength of lap joints. The former joints have no

eccentricities, whereas the eccentricity in lap joint causes unfavorable secondary bending and a more complex loading of the fastener on the hole.

7. Hole filling is of great importance to riveted joints. A high rivet squeeze force leads to significant life improvements due to plastic hole expansion and a better clamping between the sheets.
8. Fretting corrosion and local load transmission by fasteners are eliminated in adhesive bonded lap joints. It results in a higher fatigue strength in comparison to similar riveted lap joints. But due attention must be paid to the quality and durability of the bonded joint.

Chapter 19: Fatigue of welded joints

1. The fatigue behavior of welded joints is entirely different from the behavior of joints with fasteners. The fatigue critical locations of welded structures occur at the welds, while the nominal stress level at these welds depends on the layout of the welded structure. Furthermore, the variety of welding processes is large and several geometric imperfections and defects in the weld itself can occur. The S-N curve of a welded structure depends very much on the design of the joints and the quality of the welding. Preliminary information on S-N curves is given in the Welding Codes.
2. Estimates of the fatigue life of welded structures loaded by a variable-amplitude load history can be obtained with a Miner calculation. But the S-N curves should then be extended to high N -values for damage contributions of fatigue cycles with amplitudes below the fatigue limit.
3. Environmental and load frequency effects for welded structures in sea water should be accounted for by safety factors while periodic inspections are desirable.
4. A worst case analysis must be considered for welded structures if serious safety or economic problems are a relevant issue if fatigue cracks can occur. The fatigue life must be assumed to be fully covered by fatigue crack growth starting from a possible initial defect. The life prediction is then replaced by a crack growth prediction. The result is significantly depending on the assumed size of the initial defect.

Chapter 20: Designing against fatigue of structures

1. The present chapter is a collection of reflections on problems encountered when designing against fatigue. Various problem settings are reviewed and apparently the variety of aspects involved is large. Structural design options are related to the lay-out of the structure, design of fatigue critical notches in the structure, various types of joints, material selection, surface treatments and production variables. Another essential part of the problem is associated with load spectra in service. Load spectra depend on the operator of the structure, but in various cases also on environmental conditions such as air turbulence, sea waves, road roughness and other usage circumstances. The designer should carefully consider all aspects of dealing with a particular fatigue problem.
2. The purpose of designing against fatigue is to achieve satisfactory fatigue properties, but the definition of this goal can be highly different for different types of structures. Three different categories of structures are considered: (i) structures for which fatigue failures are unacceptable, (ii) structures in which fatigue cracks may occur, but the risk of a complete failure must be maintained at a very low level, and (iii) structures for which crack initiation and growth until failure after a reasonable lifetime are acceptable.
3. Designing against fatigue is more than avoiding high stress concentrations and selecting fatigue resistant materials. It also includes considerations on stiffness variations in the structure, load flow in the structure, avoidance of eccentricities, application of surface treatments, etc. Special problems are associated with joints.
4. The present knowledge about fatigue crack initiation and crack propagation in metallic materials is qualitatively well developed but quantitatively limited, and because of this it must be concluded that accurate predictions are illusory. Methods for qualitative estimates of fatigue properties can be adopted, but in case of doubt about the results, experimental verifications should be considered.
5. An experimental verification of predictions or estimates of fatigue properties of a structure should be obtained in service-simulation fatigue tests. Both fatigue critical details of the structure and the applied load history should be representative for the particular problem.
6. Safety factors can be applied on estimated load spectra, predictions of fatigue lives, fatigue limit and crack growth, design stress levels and

stress levels applied in supporting experiments. The choice of safety factors should take into account various conditions and uncertainties, as well as the economic and safety consequences of premature fatigue failures. Here, engineering judgement and experience are essential.

7. The problem of corrosive environments is primarily a problem of corrosion prevention. If this is not feasible, safety factors and realistic experiments should be considered.
8. Nowadays, the tools for dealing with structural fatigue problems are powerful. FE analysis of load and stress distributions in a structure is well developed. Experimental tools for realistic fatigue tests can also meet the most demanding questions. Finally, techniques for load history measurement can provide extensive information about load histories in service. The question is how and when to adopt these tools into the scenarios of current problems of designing against fatigue.
9. Designing against fatigue requires imagination, understanding and experience. It is a real challenge.

Chapter 21: The fatigue resistance of fiber-metal laminates

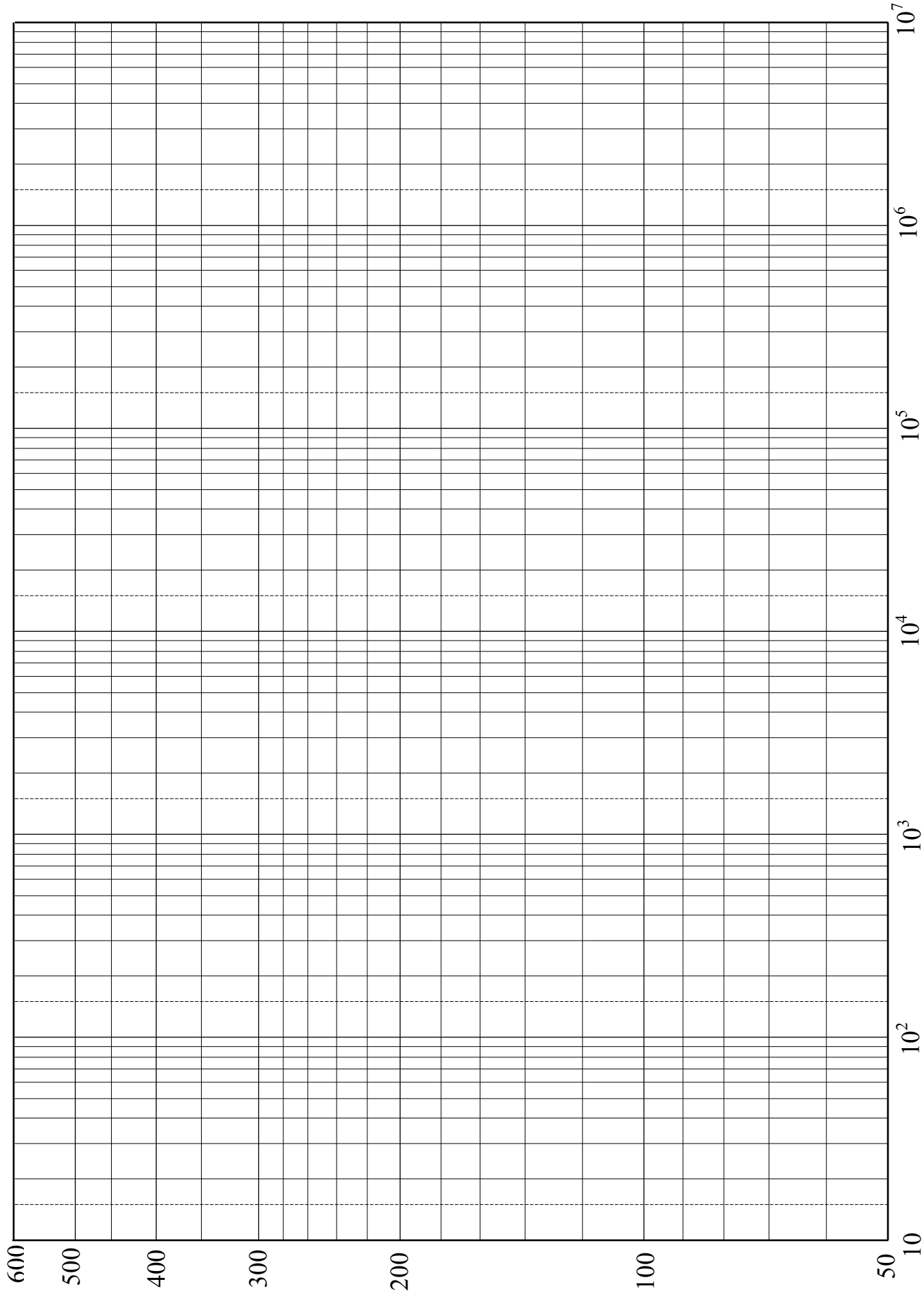
Several decades ago it was shown that the fatigue properties of laminated sheet material, at that time still without fibers, gave interesting results in fatigue tests. Further improvements were then obtained by adding fibers in the adhesive layers between the laminated sheets. Moreover, it was understood that thinner sheets were essential for large improvements. Along these lines, fiber-metal laminates were born which initially were built up with a number of thin metal layers (e.g. 0.3–0.5 mm). The sheets are bonded together with prepreg layers consisting of high-strength fibers embedded in an epoxy adhesive as a matrix material. Initially, aramid fibers were and the material was named “Arall”. Later advanced glass fibers were adopted in “Glare”.

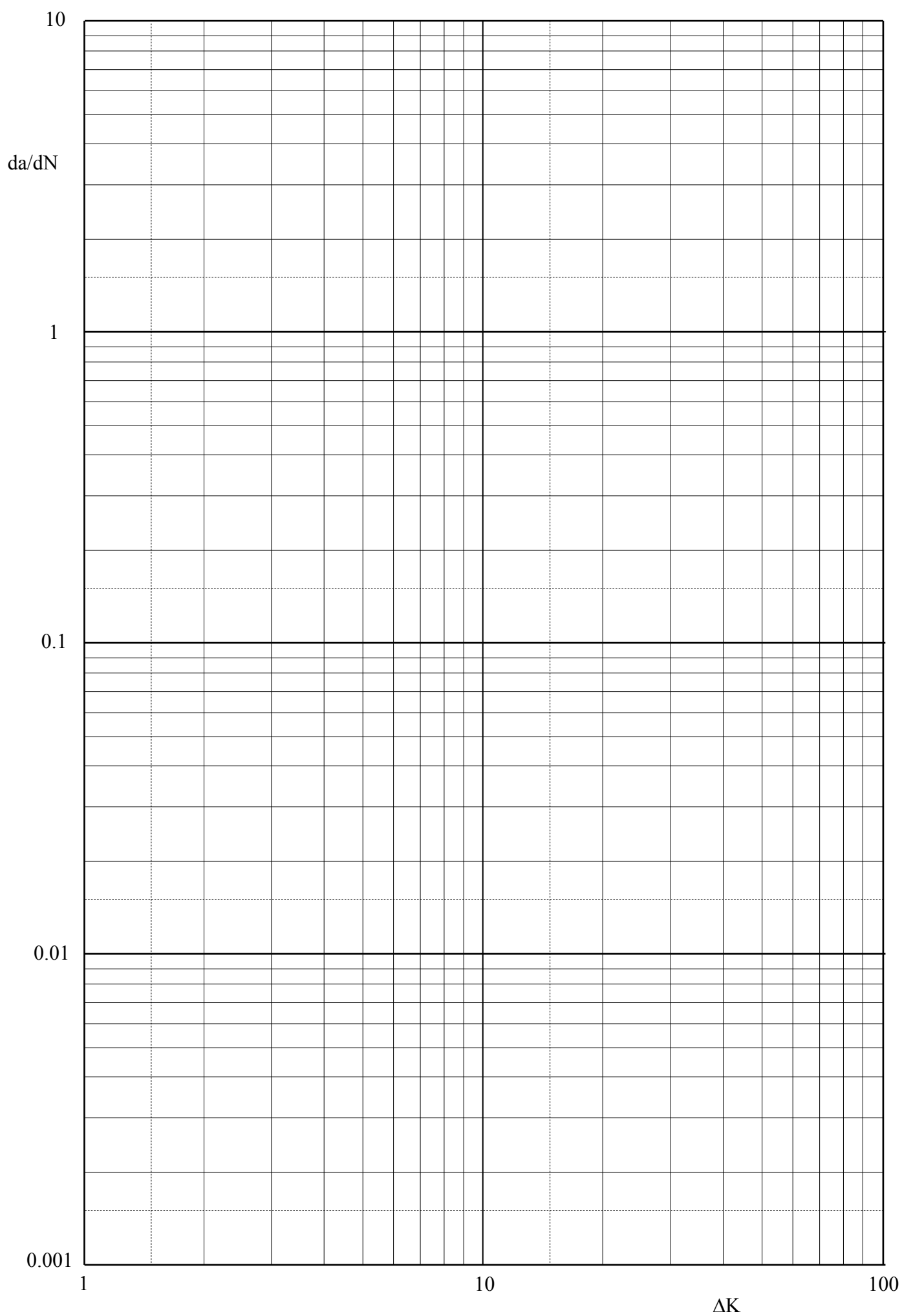
The fiber-metal laminates were originally developed to obtain a fatigue resistant material. Extensive investigations have shown that the fatigue crack growth resistance is very good. The fiber-metal laminates if compared to single sheet material also have a better corrosion resistance, a more damage tolerant impact behavior and an improved fire resistance. The specific weight is slightly lower than for the solid material. The stiffness is also somewhat lower. Results of several fatigue tests are presented.

As a result of the lamination obtained in an autoclave production cycle, the fiber-metal laminate concept also allows to manufacture very large panels for the production of an aircraft fuselage. Several joints can then be eliminated. Furthermore, a recent development has been proposed to combine fiber-metal laminates with thicker solid sheets which can lead to interesting hybrid combinations for wing structures. Actually, it implies that designing a structures with fiber-metal laminates also includes designing the constitution of the material for a specific structural element.

I.4 Plotting paper

Diagrams for plotting S-N data and da/dN -DK results in a double log graph are shown on the following two pages respectively. Files with these diagrams are presented on this CD (file names: S-N log-log and da/dN -DK log-log, respectively). The diagrams are added for plotting some data by hand instead of directly using a spread sheet program.





Part II

Case Histories

- II.1 Introduction
- II.2 Fatigue fracture of all spokes of the front wheel of a heavy motorcycle
- II.3 Blade spring failures
- II.4 Landing gear case
- II.5 Helicopter blade failure
- II.6 Expansion coupling failure
- II.7 The lamp-post case
- II.8 The Comet case
- II.9 Lug connections

II.1 Introduction

Fatigue failures in service of steel structures were already reported in the 19th century. Numerous failures occurred in the 20th century in a large variety of structure of different materials. Many fatalities were involved and the economic consequences were impressive. It has stimulated investigations on fatigue of structures and materials. Actually it was learning the hard way. And even now it is still important that fatigue failures in service are carefully examined in order to know why and how the unexpected fatigue failure could occur. It has led to a kind of a discipline called “accident investigations”. In this Part II of the CD a number of accident investigations is summarized in an apparently somewhat anecdotal way. The purpose is to see which aspects have been overlooked in designing the structure or using the structure (operation in service).

Before presenting the case histories, some general arguments will be recapitulated which are associated with the analysis of failures in service. It will be followed by practical comments on fatigue failure analysis. After all, the analysis is a kind of a diagnose for which rules and tools exist. Failures in service raise a number of questions:

1. Which type of failure occurred? Quasi-static failure, fatigue, stress corrosion, creep?
2. Where did it start? Any special features at the initiation point?
3. Is the failure an incidental case, or is it possible that it is a symptomatic one?
4. Is immediate action necessary to avoid subsequent failures?
5. Is the failure due to an unsatisfactory design of the structure, or poor maintenance, unsatisfactory inspections? Or is it due to overloading the structure?
6. What about inspections, repairs, replacements, or redesign?

Liability questions may be involved but this aspect is not addressed here. On the other hand safety aspects should be considered, especially if more similar failures can occur.

Some practical comments:

- Accident failures should start at the site of the accident, also because of direct witnesses. A full description should be made about how the failed structure was found. Cleaning of the failure surface should not be done before the broken part has been carefully examined and photographed. Dirt or paint on fracture surface can be a silent witness.
- Always start the examination with the naked eye and a magnifying glass, having good light. Try to explain what you see. Next, observations should be made with larger magnifications, e.g. with a binocular microscope, and if possible in a SEM which allows a large range of magnifications. Also then, it is important to understand all features observed.
- Always try to have both parts of a the component which was separated by the failure in two parts. Quite often, some people want to give you only one part for a fractographic investigation, because they like to keep the other part on their own desk. However, it is of special interest to have both parts to study the crack initiation point. It is possible that certain information is visible on one part and not on the other one.
- The topography of the fracture surface gives a three-dimensional impression about the crack growth path, however, without information of how the crack path was directed by the structure of the material. For instance, it does not show whether the crack was transgranular or intergranular. The latter question requires cross sections which however, give a two-dimensional picture, but at the same time an impression about the structure of the material is also obtained.

- An impression about the question if the material really is what it is expected to be is obtained by a chemical analysis. Also hardness measurements can give useful information.

II.2 Fatigue fracture of all spokes of the front wheel of a heavy motorcycle

As already described in Chapter 1 the front wheel of a heavy motor cycle completely collapsed when a police man on the motor cycle suddenly had to use the brakes. All spokes were broken (see Figure II.1). The fracture surfaces clearly indicated large fatigue cracks due to cycle bending. Similar failures had occurred elsewhere and it thus was a symptomatic failure and not an incidental case. Possible fatigue loads were then considered with the conclusion that bending loads on the spokes should come from braking. It then was tried to calculate the bending stress at the point where the fatigue cracks have started. An average deceleration was estimated. With the mass of the motor cycle and the driver, the deceleration force was calculated which is then used to calculate the bending moment on the spokes. The nominal bending stress follows from the bending moment taking into account the slightly trapezoid cross section of the spokes. The results was $S_{\max} = 67 \text{ MPa}$. The estimated fatigue limit for $S_m = 0$ starting from $S_U = 195 \text{ MPa}$ for the Al-Si cast alloy is about $0.35S_U = 68.25 \text{ MPa}$. With the linear Goodman relation the fatigue limit for $S_{\min} = 0$ ($R = 0$) becomes about $S_{\max} = 100 \text{ MPa}$ which is 1.5 times the calculated nominal stress level. However, there is an unknown stress concentration of the transition of the spokes to the hub. Moreover a rough surface of the casting must also be taken into account. It should be concluded that a risk of fatigue failures is present. The composition of the casting and the structure were checked and both were all right.



Fig. II.1 Wheel with 10 broken spokes and the disk brakes.

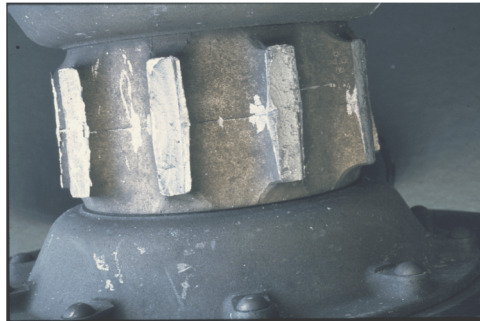


Fig. II.2 Axle hub with fracture surfaces.



Fig. II.3 Two fracture surfaces with crack growth bands.

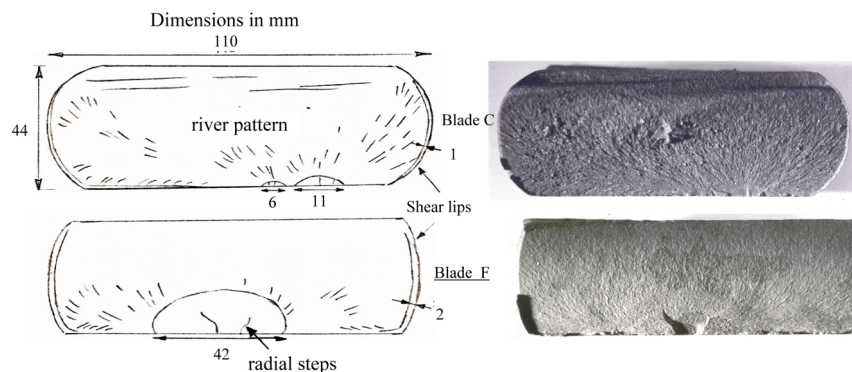
Follow-up: The industry has carried out fatigue tests on wheels which confirmed unsatisfactory fatigue strength. The wheel was redesigned. All owners of the motor cycle could exchange the old wheel for a new one.

Evaluation: What could the industry have done to prevent the incidents? As a first step: carry out the above simplified problem analysis to get some idea about the risk of fatigue problems. Secondly, carry out fatigue tests before the component goes into production. Third: Carry out fatigue load spectra measurements which could be done with strain gages on the spikes of a wheel of a motor cycle driven under different conditions. Such measurements can be most instructive but it requires advanced equipment.

Final comment: An experienced designer could have observed that the transition of the spikes to the hub could be a critical issue to be improved by simple contour modifications.

II.3 Blade spring failures

Failures occurred in blade springs of large trucks carrying goods along various European roads. The fracture surfaces of two blades are shown in the figures below. The fracture surfaces as received were fully covered with a rust layer which could not be removed by cleaning agents. But it was successfully removed by HCl which surprisingly revealed a detailed morphology of the fracture surface. Fatigue nuclei were observed on both fracture surfaces, two small ones for blade C and a single one on blade F. Radial steps were visible in all nuclei which usually implies that the fatigue crack was simultaneously initiated at neighbouring locations. This is usually observed for high-level fatigue. For blade C in comparison to blade F (see the figures below) some characteristic differences were noted. In blade C smaller fatigue cracks have led to final failure. The river pattern in the final failure part of the fracture was also more rough. The microstructure of the two blades was also examined and a more coarse structure was observed in blade C. It may well be concluded that the material of blade C is more brittle than for blade F. This is also confirmed by the width of the shear lips at the side edges of the failure which is only 1 mm for blade C and 2 mm for blade F. The shear lip width is smaller for final failures in more brittle material. A lower ductility in general goes together with a reduced fracture toughness and smaller cracks then can initiate the final failure.

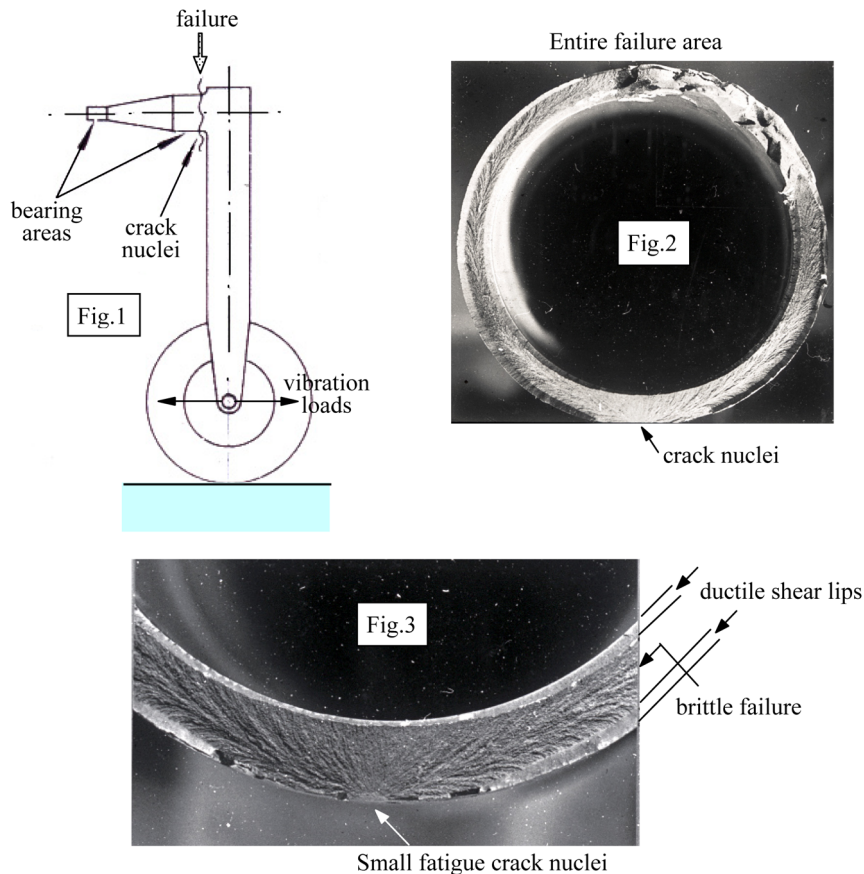


So far the trends which can be understood. But why did fatigue cracks occur? Private information indicated that those trucks were frequently overloaded. The failures started near the edges of the blade clamps. Fretting damage or significant other damage could not be detected apart from some corrosion. Crack initiation may thus be a matter of too high bending stresses, perhaps associated with overloading.

Evaluation: Blades should be heat treated in a way to obtain a fine microstructure, a material argument. Secondly, design modifications should be considered to obtain lower bending stress. Finally, overloading of the trucks should not occur.

II.4 Landing gear case

During landing of a fighter aircraft a landing gear fully collapsed. The fracture occurred in a tubular part of the landing gear at a location where a high stress concentration should be expected, see Figure 1 below. The fracture surface showed very small crack nuclei. A single one can be observed in Figure 3 below, but some smaller ones could also be indicated in the same area at a larger magnification. The fracture surface outside the small crack nuclei is the final failure. A large part of the final failure is covered with a feathery structure, also called hearing bone marks.



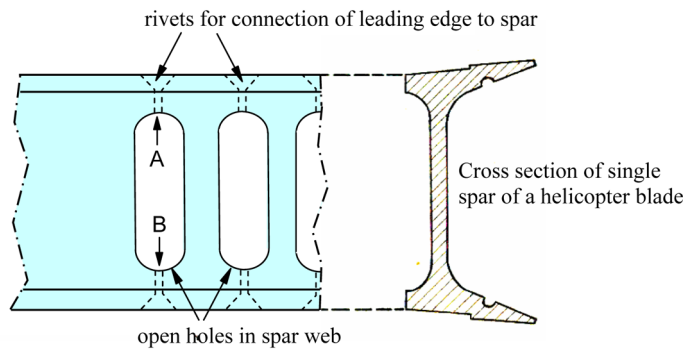
This feature is typical for a quasi-brittle fracture in a low-alloy high-strength steel. The fracture toughness for this type of steels is relatively low. The description so far agrees with high-level fatigue, actually with severe high-level fatigue, because of several very small fatigue crack nuclei

causing an early final failure. It turned out that pilots had experienced severe vibrations during landing on the airfield. At the moment of touch down horizontal loads occur during spin-up of the wheel. In this particular aircraft it has led to severe vibrations causing high-level fatigue. It was not immediately explored in order to prevent the accident.

Evaluation: Fractography of a fracture surface can lead to indications about the predominating type of cyclic loading which has led to the failure. It then is necessary to prove that this type of loading can occur in order to arrive at satisfactory action for failure prevention.

II.5 Blade failure of a small helicopter

A pilot of a small helicopter with two blades wanted to take off. The pilot started with an initial run up of the engine and lost one of the blades. Of course it was immediately followed by a tumbling of the helicopter but fortunately no fire. The main structural part of the blades was a single spar, see the cross section in the figure below. The failure occurred along rivet holes and a hole in the web of the spar, actually a superposition of two stress concentrating elements. Examination of the failure surfaces showed that macroscopic plasticity occurred at hole B, the lower side of the spar, whereas plastic deformation was not observed at hole A, the upper side of the spar. At the upper side the failure was characteristic for fatigue.



View of rivet hole A.
No macro plastic deformation.



View of rivet hole B.
Macro plastic deformation visible.
Hole ovalization. Lateral contraction at right hand edge.

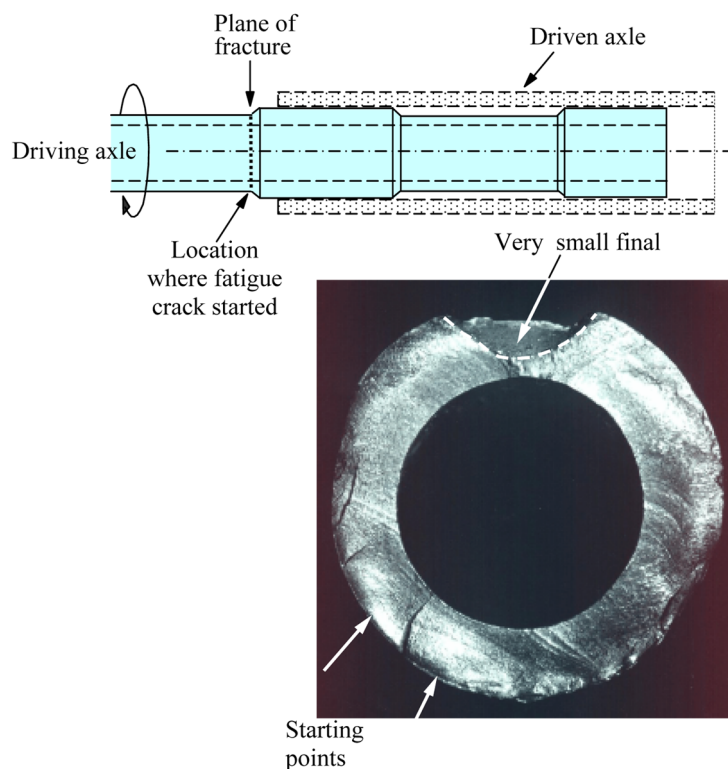
This analysis was accepted by the helicopter industry, but it was noted that in-flight cyclic bending loads on the blade on top of the centrifugal force should lead to fatigue at the lower side of the blade, and not at the upper side. Apparently a discrepancy between the fractographic analysis and the assumed load spectrum. It has taken some time before it was revealed that the helicopter was frequently transported on a truck to which it was firmly

connected. It was brought by road transport to locations where it should carry out hoisting jobs. During transportation of the helicopter on the truck the blades were not supported, and considerable vibrations of the blades occurred. These loads have caused the fatigue failure. Should a warning be included in the operational manual?

Evaluation: It is possible that a structure will see a category of fatigue loads for which it is not designed. Should this still be a matter of concern for the industry? According Murphy's law, the answer is yes. For responsibility and liability questions the answer is difficult. What about joy riding?

II.6 Expansion coupling failure

In a helicopter, a failure occurred in the transmission coupling of the driving axle to a driven axle for the tail rotor. The fracture surface showed some interesting features. First the rather flat surface and the growth bands indicated that it should be a fatigue failure, see the figure below.



Apparently the crack started at the lower left corner. But some steps on the initial part of the fatigue fracture indicate that more crack nuclei were initiated. In the beginning of the fatigue life a significant stress cycles must have been present, perhaps because the corner between the thickness step of the wall of the axle was rather sharp. Actually the axle should be loaded in torsion only and most probably by a small torsion moment to drive the tail rotor. However, the growth bands indicate that the crack was growing under a cyclic bending moment. A most remarkable feature is the extremely small final fracture surface. The fatigue crack could grow until the fatigue crack almost covered the entire cross section. It then should be concluded

that the bending moment was reducing during the fatigue life which can occur if the axle is loaded under a cyclic bending deformation instead of a cyclic bending load. A growing fatigue crack then is reducing the bending stiffness, and a specific bending deformation is obtained with a decreasing bending moment. The bending stress cycle will thus also decrease. This occurs if misalignment is present. The misalignment occurring in the helicopter structure was indeed confirmed. The axle support locations had to be rectified.

Evaluation: In order to obtain information about the fatigue loads which has produced a fatigue failure, it is necessary to examine the entire fatigue failure area. Both the initial fatigue crack growth part and the final fracture part can tell a story which can be significant for remedial action.

II.7 The lamp-post case

The load spectrum problems for the lamp-post were briefly discussed in Chapter 9. The lamp-post is mainly loaded by wind forces which introduce bending and torsion moments at the base of the lamp-post. Somewhat above the base, a large longitudinal hole is made in the tubular cross section of the lamp-post, see Figure II.4b. The opening gives access to electric connections inside the lamp-post. Actually, it is a large cut out, also because the cover does not take part in the load transmission. Long ago fatigue problems have occurred from the edge of the hole. It will be difficult to arrive at reasonable information about the load spectrum by considering aerodynamic wind forces on the lamp body. However, measurements of bending and torsion moments with strain gages are possible. During the presentation of this lamp-post case in a course, it is an interesting question to the audience



(a)



(b)

Fig. II.4 (a) Lamp-post. Bending and torsion due to wind forces. (b) Cover of opening in lamp-post.

to ask for design modifications of the lamp-post which should reduce the severity of the load spectrum. Three obvious solutions should be mentioned. The reader may try.

In addition, fatigue properties of such structures with openings can be improved by modifying the shape of the hole (see Part III, discussion on Figure III-1) and reinforcing the edge of the hole which will not be simple for the lamp-post. A different approach is to have a load carrying cover which for the lamp-post will also be a practically impossible option. However in structures with relatively large panels with an open hole, a load carrying cover may be adopted. However, this solution requires joints between the cover and the panel which can introduce other fatigue problems, also in view of eccentricities (see the discussion in Chapter 20 on Figures 20.5 and 20.6). Moreover, for cost-efficiency and easy operational maintenance load carrying covers may be undesirable.

Evaluation: First, if the load spectrum on a structure is mainly associated with wind forces or turbulence, numerical information about load spectra will require measurements. Second, FE-calculations are indispensable for optimizing the structure for low stress concentrations. Third, edge reinforcements or load carrying covers can be considered. However, that will require that various consequences of possible design scenarios are evaluated.

II.8 The Comet case

An early impact on considering fatigue of aircraft structures occurred by two fatal accidents of the Comet aircraft in 1952. Fatigue cracks in the pressurized fuselage structure initiated a fuselage decompression failure at a high altitude. The two Comet aircraft crashed after very short fatigue lives of 1286 and 903 flights respectively. Unstable crack extension was started by a fatigue crack at the edge of a window in the cockpit section. These failures were discussed in a number of publications, especially by Tom Swift² who analyzed the structures also in terms of fracture toughness. Actually, the structural design was not optimal for fatigue purposes. During a recent international meeting (Damage Tolerance of Aircraft Structures, September 2007, Delft) I was told that during designing the Comet aircraft fuselage, it was proposed by somebody to reinforce the window edges with a bonded doubler. DeHavilland was familiar with adhesive bonding of aluminium sheets. It was a good proposal which unfortunately was dismissed.

One interesting observation about the Comet case is not very well known although it has been mentioned in a book on the DeHavilland aircraft (C.M. Sharp, D.H. – *An Outline of De Havilland History*. Faber and Faber, London 1960). Before the Comet entered into service, a full-scale fatigue test was performed on a large part of the front fuselage including the critical window. Small cracks were found when the test was completed after 16000 flights. The cracks were supposed to be insignificant. However, the life in service was more than approximately 15 times smaller than in the full-scale test. Unfortunately, the same test article had previously been tested under quasi-static loading until a high pressurization design load. In order to save money, the same test article was subsequently used for the fatigue test with pressurization cycles. It implies that the load applied in the static test was a high pre-load for the fatigue test. It has introduced small-scale plastic yielding at the fatigue critical notches where stress concentrations are present. As a result, favorable residual stresses are introduced which will introduce a significant but unrealistic life extension in the full-scale test. Unfortunately this effect was not considered. The argument to use just one expensive full-scale structure for fatigue properties and static strength is to save money. Unfortunately the same argument was used again by another industry many years later.

² Swift, T., *Damage tolerance in pressurized fuselages*, in New Materials and Fatigue Resistant Aircraft Design, Proc. 14th ICAF Symp., Ottawa (1987), D.L. Simpson (Ed.), pp. 1–77. EMAS, Warley (1987).

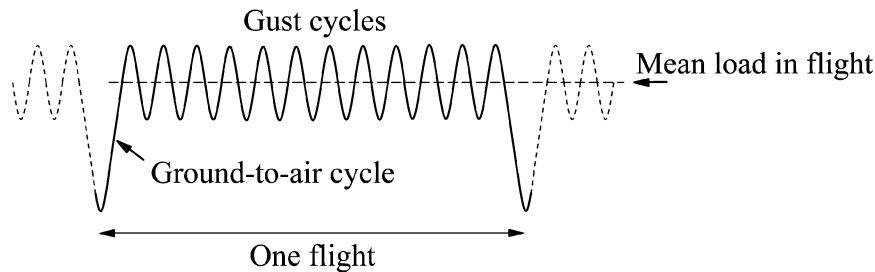


Fig. II.5 Highly simplified load history for an aircraft.

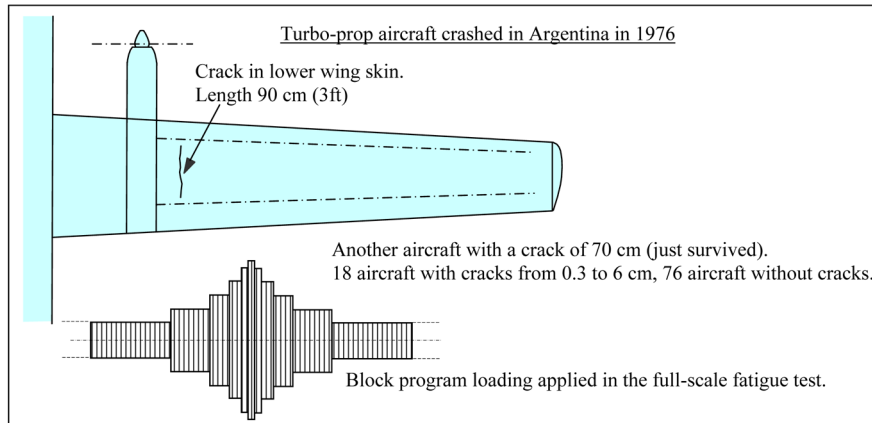


Fig. II.6 Another case of a non-realistic load history in a full-scale fatigue test.

The accidents of the two Comet aircraft were followed by a full-scale fatigue test on a complete aircraft. A flight-by-flight load history was applied. It included ground-to-air cycles, but the spectrum of the gust load cycles on the wing was reduced to a single load level. As a result the same load history was applied in each flight, see the schematic picture in Figure II.5. The gust load amplitude was obtained by a linear damage calculation which should induce the same fatigue damage effect as the full spectrum. By now it is known that the Miner rule is unreliable to justify such a simplification. Indications on fatigue crack initiation lives may even be conservative because the favorable effect of high gust loads are missing. The idea that full-scale tests are necessary was a step forward. However, the concept of a simplified flight-simulation full-scale test with all flights being equal disagrees with the most realistic requirement of a test on the real structure.

More than 20 years after the Comet accidents a twin engined turboprop aircraft crashed in Argentina due to a large fatigue crack in the wing structure, see Figure II.6. Several more cracks were found in other aircraft and it thus was a systematic case. A full-scale fatigue tests had been carried out, but a block-program load history was applied in the test. Again a full-scale test with a non-realistic load history.

In the past I had to face arguments like “why a complex fatigue load if a simple tests can also be carried out”. My response is that a simulation of a realistic load history as it occurs in service is a more simple approach than using an artificially programmed load history which does not occur in service.

Evaluation: First, in fatigue tests on realistic structures or structural elements the fatigue load should be a representative simulation of load histories occurring in service. Second, the test article for the fatigue test should not previously been subjected to a high preload to prove sufficient static strength. After the fatigue test a static test can still be considered if the test article is still in a sufficiently representative condition.

II.9 Lug connections

An instructive movie “Damage Tolerance” was made by the Federal Aviation Administration in Atlantic City. It presents a sketch of a triple lug as an example of a fail-safe design which is reproduced here in Figure II.7. Lugs are known to have a low fatigue limit due to fretting corrosion, see Chapter 18. The movie suggests that serious fatigue cracking in one of the three lugs implies that the other two lugs still have a substantial load carrying capacity. However, a fatigue crack in one of the lugs will substantially reduce the stiffness of the lug and thus the load transmitted by the lug. As a consequence, the other two lugs must carry an increased load. It may not be expected that crack initiation in the other two lugs will wait until the first one has a large crack. Cracks will grow more or less simultaneously in all three lugs. Furthermore, inspection of a triple lug for cracks starting inside the hole requires dismounting of the joint and a special inspection technique, not attractive for the operator. This example illustrates that a realistic scenario of possible failure modes and consequences for maintenance and inspections should always be made.

In view of fatigue safety arguments the so-called back-to-back structures was adopted by some aircraft industries, also for lug connections. Components, usually small ones, were cut in two parallel parts which then were again joined by adhesive bonding. An example is shown in Figure II.8. The idea is similar as for the triple lug although load shedding from one part to the other one is different. Actually, the adhesive layer is more a barrier for fatigue crack growth, but the benefit may still be marginal. Moreover, back-to-back requires extra production steps.

It should be pointed out that good fatigue properties of a structural component can also be achieved by a locally reduced nominal stress level.

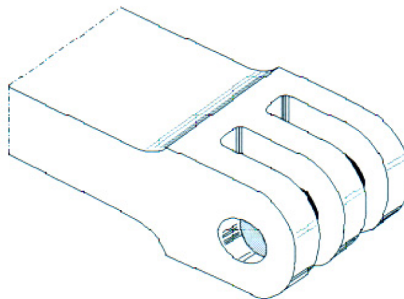


Fig. II.7 Triple lug.

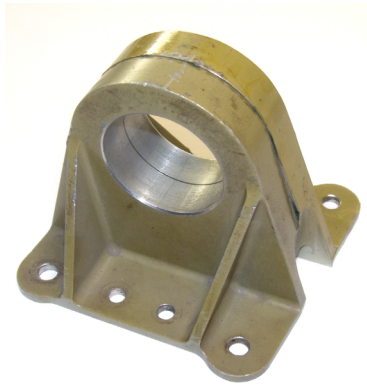


Fig. II.8 Back-to-back component.

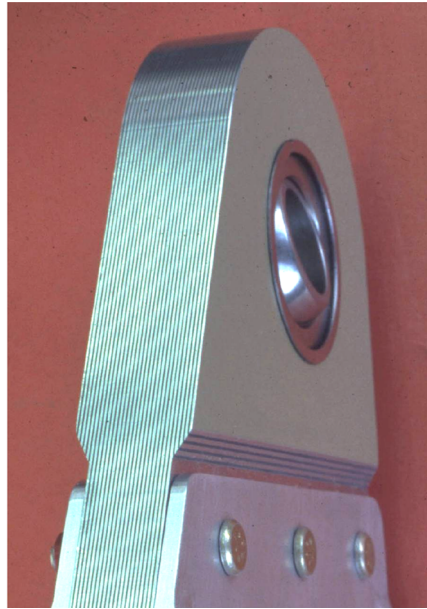


Fig. II.9 Glare lug.

The weight penalty may be limited. Furthermore, a special production treatment can be adopted to introduce favorable compressive residual stresses in the fatigue critical notch area. A well-known example is plastic hole expansion for which apparatus is commercially available. It is a matter of judgement whether a designer will choose for such a “trick”. Some reluctance stems from a more elaborate quality control. Anyway, a good solution for lugs of aluminium alloy components is to insert a bush with an interference fit which causes favorable pre-tension around the hole.

An entirely different approach to fatigue problems is to use fatigue insensitive materials. This applies to fiber-metal laminates which behave more or less as a metallic material, but the crack growth resistance is extremely high, see Chapter 21. An instructive example was obtained in a research program of a masters study. Lug type joints were considered for the connection between the wing and the fuselage of a twin engined turboprop aircraft. The connection occurs by two lug type joints to the wing front spar and another two similar joints to the rear spar. In view of safety the lugs should have a superior fatigue strength which could be obtained by a low design stress level. A lug was made from Glare, thickness 19 mm, 25 thin metal layers, see Figure II.9. In a flight-simulation fatigue test (10 types of different flight severity) the design stress level was increased to

about double the originally intended stress level. Failure did not occur in the lug, but outside the lug component in the clamping of the specimen after 92000 flights. Small cracks were detected in three layers which is insignificant for the static strength. In other words, the nominally fatigue critical wing-fuselage connection was no longer fatigue critical at all.

Part III

Special Topics

- III.1 Designing against Fatigue
 - III.1.1 Introduction
 - III.1.2 How to obtain K_t -values
 - III.1.3 Reduction of a stress level and its effect on fatigue life
- III.2 Fatigue tests, why and how?
 - III.2.1 Introduction
 - III.2.2 Fatigue tests for which purpose?
 - III.2.3 Fatigue tests, how to be carried out?

III.1 Designing against fatigue

III.1.1 Introduction

“Designing against Fatigue” sounds as a logical philosophy for a design office. Perhaps a more encompassing phrase is “Designing for durability of structures” which includes such aspects as corrosion, wearing out, maintenance and safety. As an example, if a structure must operate in an aggressive environment it is obvious that the designer should select a material with a good corrosion resistance or he should adopt a good corrosion resistant surface protection. Apart from durability aspects, a variety of economical arguments will also be important (cost-effectivity). They may depend on production facilities and experience. But anyway, for dynamically loaded structures the occurrence of fatigue problems in service should be considered, also for economical reasons, safety issues and other social consequences. Various aspects are discussed in Chapter 20 of the book. Much can also be learned from the case histories discussed in Part II of this CD. Some additional comments are recapitulated below.

Designing of large structures is associated with building up of the structure from many structural elements (e.g. beam elements, or block

building concepts). It can be attractive for obvious reasons of transport, local assembling and dismantling later. It implies that joints are essential which can be fatigue critical and sensitive to incidental damage. The alternative is to design integral structures which can be attractive for production and other economic aspects. Again scenarios for service utilization are essential and possible endurance problems must be considered. The two alternatives will not be discussed any further here, also because new technical developments can open new innovative design options. A historical example was the introduction of welded joints for large structures. Since that time bolted and riveted joints were replaced by welded joints, e.g. in ship building. Nevertheless, there are still applications where bolted joints are preferred for several reasons including fatigue arguments. The more recent development of friction stir welding allows new possibilities for structural design. Ultimately, economical arguments are the major driving force for the application of new developments. Designing of smaller structural elements is also associated with economical conditions, including fatigue issues. Various aspects which are favorable or unfavorable for fatigue properties are described in several chapters of the book. Many of these aspects are related to material selection, production and surface treatments, low K_t -values and sometimes to fail-safe characteristics. Some examples are also discussed in Part II on case histories. The present discussion is largely restricted to a few design aspects with respect to avoiding stress concentrations which is favorable for a long crack initiation life.

III.1.2 How to obtain K_t -values?

The main reference book for K_t -values is still the book by Peterson, printed in 1974 with a third revised edition in 2008 (revised edition by W.D. Pilkey and D.F. Pilkey, John Wiley and Sons). The accuracy of several graphs may be limited as a result of older techniques to determine these values. In spite of such inaccuracies the data are still instructive. They clearly show how the stress concentration is affected by changing root radii of notches. It may well be expected that the ratio of two K_t -values obtained in the same graph for two different root radii will still be reasonable accurate. In other words, the reduction of a K_t -value for a larger root radius expressed in terms of a percentage will still have an acceptable accuracy. As an example of a trend observation with Peterson, Figure III.1 shows K_t -values from his book for a manhole. The effect of the root radius is obvious. Also, a still lower

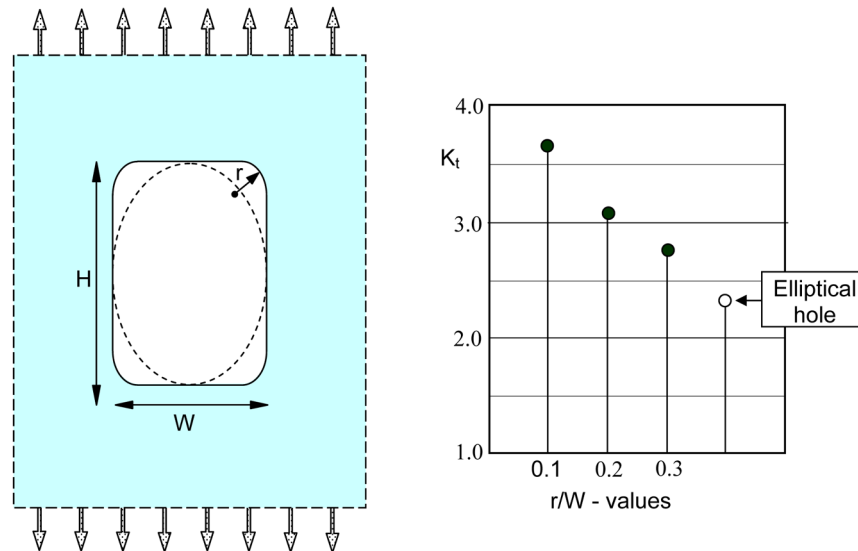


Fig. III.1 Effect of root radius on K_t of a man hole ($H/W = 1.5$). Comparison to elliptical opening.

K_t -value is obtained with an elliptical hole. The data in Figure III.1 apply to an infinite sheet loaded in tension. For finite dimensions but still tensile loading other K_t -values will be applicable which should then be obtained with FE calculations. It may well be expected that the qualitative trend will be maintained. However, for biaxial loading new FE calculations are required.

Although Peterson covers a large variety of geometries, most of the shapes are relatively simple which means that the geometry can be described by a small number of dimensions associated with, e.g., root radius, diameter, width, depth and other dimensions. In practice shapes of structural elements are less simple and K_t -values cannot directly be borrowed from Peterson's book, although clever estimates can sometimes be made. A more general approach is to calculate K_t with FE techniques. Usually calculation for complex shapes are made by specialists, while more simple cases can be handled by adopting general rules for FE algorithms. Aspects to be considered are associated with meshing and boundary conditions for the applied load and edge displacement constraints. In any case, it should be examined whether calculated results agree with expectations. This can be illustrated with experience which I encountered long ago during a demonstration of a simple FE software package for two-dimensional

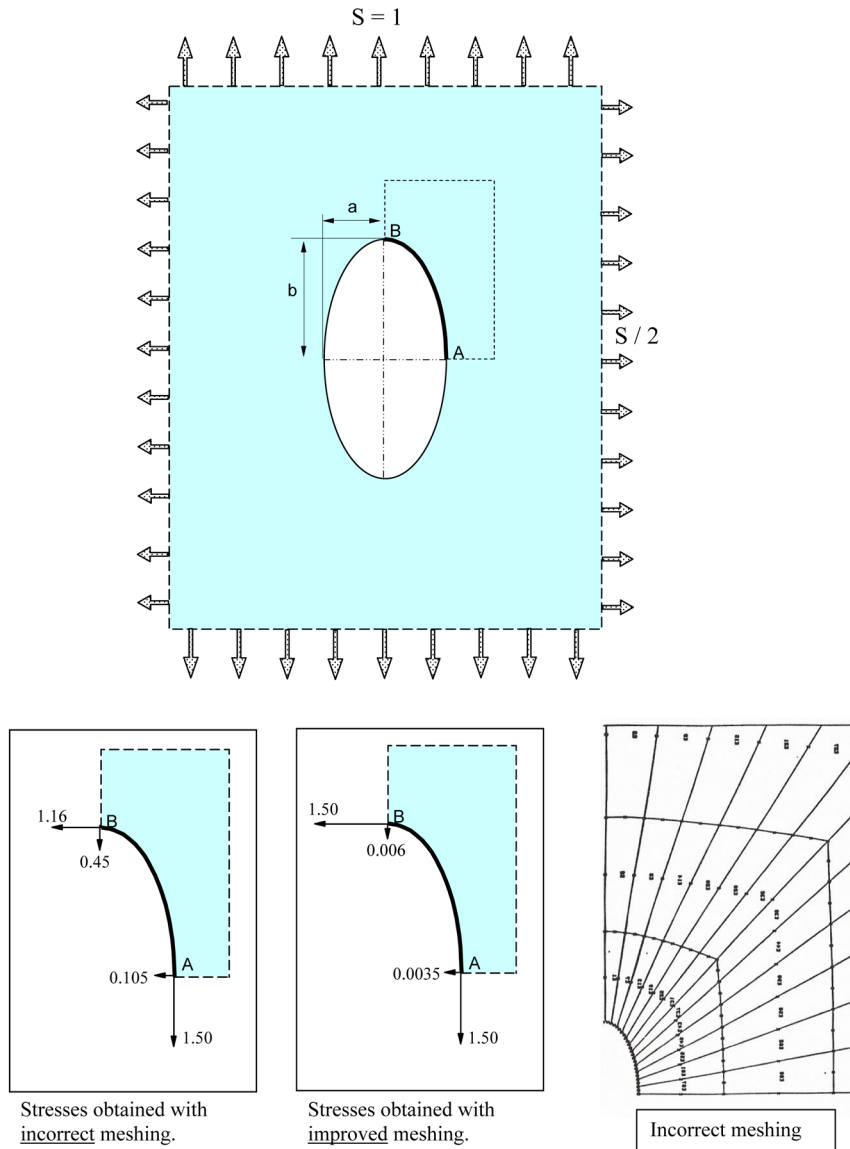


Fig. III.2 FE results for a large plate with an elliptical hole ($a/b = 0.5$) under biaxial loading (width $40a$, length $40b$).

problems. I was asked whether I could mention some geometry for which results would be obtained in seconds. I mentioned a very large plate with an elliptical hole with an axis ratio $a/b = 0.5$ under biaxial loading with a stress ratio $S_2/S_1 = 0.5$, see Figure III.2. I asked to calculate the tangential

stress and the stress perpendicular to the hole edge at points A and B. I knew that the tangential stress at both points for an infinite sheet are 1.5 and the perpendicular stresses are zero. The meshing was made visible in a second, and the stress values after a few more seconds. The meshing initially adopted is shown in the lower right inset in Figure III.2 with many elements along the edge of the ellipse but the elements are rather long which is unacceptable in view of stress gradients in the length direction of the elements. The results of the FE calculations shown in the lower left inset of Figure III-2 are absurd, e.g. a stress of 45% of the applied stress perpendicular to the hole edge in point B. When I mentioned the strange result a new meshing was made with small elements in all directions and now the results shown in the middle inset figure are acceptable. It is a trivial lesson that small elements are required at locations where large stress gradients are present. But sometimes adopting a meshing with extremely large numbers of elements leading to long computer times is an overdone procedure. Specialists on FE analysis know how to handle such problems, but intuitive ideas about stress distributions to be revealed can be instructive.

Boundary conditions should be well defined, especially if the distance between the boundaries and the location of the stress concentration is of the same order as the dimension of the notch. If the distance is significantly larger the definition becomes less critical according to the Saint-Venant's principle. For both cases an elementary example will be given.

Figure III.3 shows an infinite row of holes in an infinite sheet. For $D/W = 0.5$ in this figure $K_t = 1.62$. However, for the strip cut out of the infinite sheet with a single hole $K_t = 2.16$. For this strip the vertical edges are free from any stress. However, this is not true for the same strip in the infinite sheet where stresses in the x -directions are present along the virtual edges. These stresses should be expected in view of an increased lateral contraction between the holes due to the increased stress level in this area. The distribution for σ_x was obtained with FE calculations³ which indicated a maximum value of $\sigma_x = 0.55$. As a consequence K_t is reduced from 2.16 to 1.62.

An example for which boundary conditions are less important is illustrated in Figure III.4 for a plate with an asymmetric thickness. Secondary bending occurs due to the eccentricity. Boundary conditions to be specified for the ends of the plate are associated with the question whether the ends are free to rotate (hinged load application) or cannot rotate (clamped

³ Results obtained by Warden Schijve (1982).

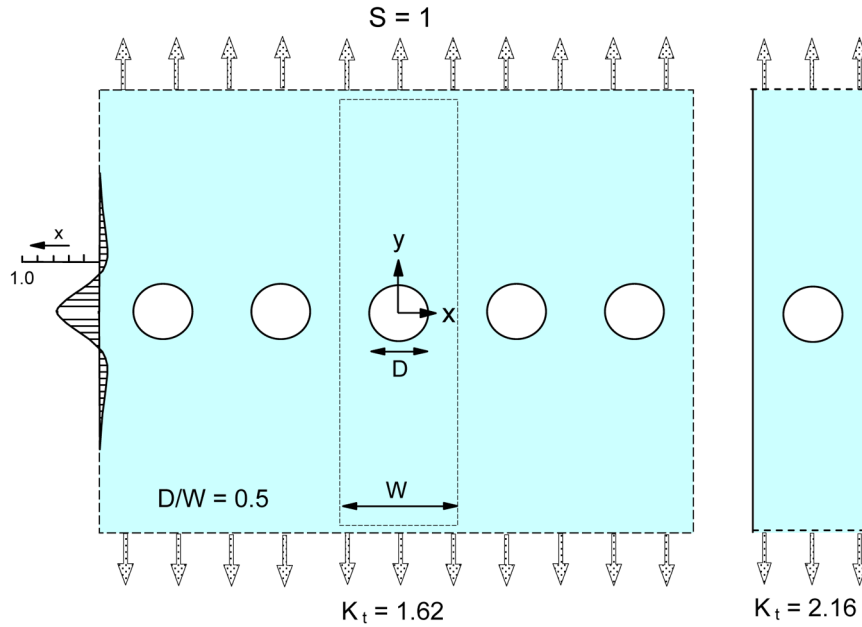


Fig. III.3 Different boundary conditions for strip edges in an infinite sheet ($\sigma_x \neq 0$) and a separate strip ($\sigma_x = 0$). Effect on K_t .

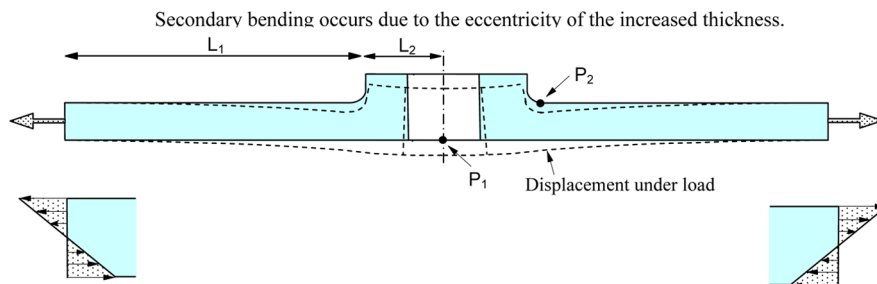


Fig. III.4 Secondary bending occurs due to the eccentricity of the increased thickness. Boundary conditions for the load applications: clamped (no rotation of the end section) or hinged (rotation at the end section allowed). If L_1 much larger than L_2 the stress concentrations at point P_1 and P_2 are practically the same for both boundary conditions (Saint-Venant's principle).

load application). The hinged condition can be transformed to the clamped condition by adding a local bending stress distribution, see Figure III.4. Because this stress distribution does not affect the load on the plate, its effect on the stress concentration at the hole (P_1) and the fillet (point P_2)

is negligible according to the Saint-Venant principle. The same K_t -values thus apply to both boundary conditions.

Another complication can arise if lateral constraint occurs in a structure loaded in tension if the contraction is counteracted by the surrounding structure. In such a case, the tensile load induces a transverse load and the component is subjected to biaxial tension. It will affect stress concentrations around notches in the structure. In such a case FE analysis should be carried out. For large structures FE calculations are recommended anyway in order to observe the load transmission in the entire structure. The load transmission is depending on the stiffness distribution in a structure. A local high stiffness, e.g. due to massive reinforcements around fatigue critical locations in a structure are attracting load transmission to those parts which may imply counterproductive efforts. Talented designers recognizing such aspects should be rewarded.

III.1.3 Reduction of a stress level and its effect on fatigue life

Peak stresses in a structure are significant for the crack initiation fatigue life and the fatigue limit. Peak stresses can be reduced by reducing K_t , but also by reducing the nominal stress level. A lower nominal stress level is obtained by increasing the cross section which can be done by increasing the width or the thickness of the cross section if that is acceptable in view of the geometry of the structural element. It implies more material and thus adding weight; not popular in aircraft structures, but also not in several other structures. However, the weight increase can be limited if the increase of the cross section can be accomplished around the fatigue critical location of the structural element only. This is a design issue.

The reduction of K_t is a question of the geometrical shape of the notch and in many cases of the notch root radius only. Small root radii must be avoided anyway, but it is possible that a small radius is still adopted in view of easy production. True enough, a designer should be aware of production restraints although he should primarily go for a low K_t , and thus a large radius. If this is not possible stress relieving grooves may be considered as shown in Figures 3.16 and 18.12 of the book.

Quarter elliptical fillets were recently considered, see Figure 20.4. Structural applications are not known to the author and probably a designer may think that it may raise production problems. However, with modern computer controlled production techniques, such fillets can be attractive.

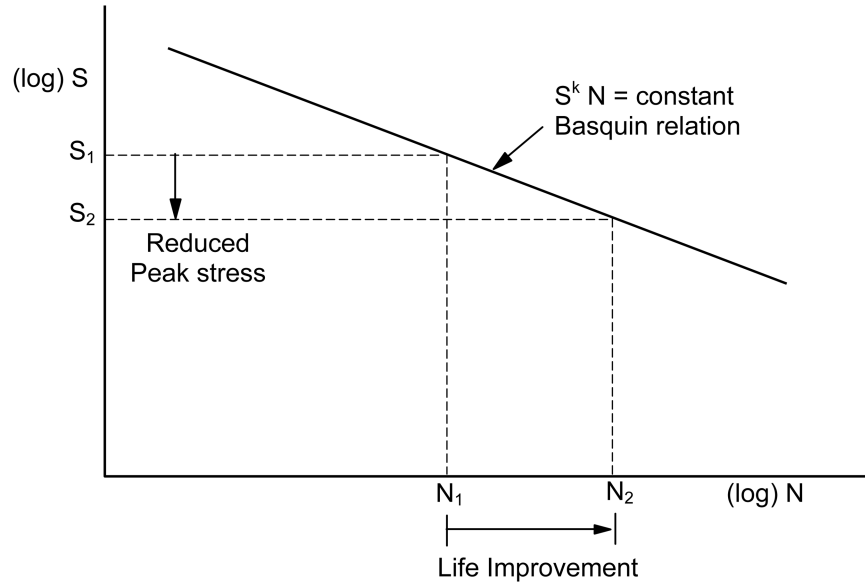


Fig. III.5 Life improvement obtained by a reduced stress level as estimated with the Basquin relation.

It is a good question to ask how much the crack initiation life may be increased by the reduction of the peak stress at the root notch. For CA loading and a finite fatigue life an S-N based approach gives a quantitative indication, see Figure III.5. The life improvement depends on the slope of the S-N curve, which is characterized by the factor k in the Basquin relation:

$$S_1^k N_1 = S_2^k N_2 \rightarrow (N_2/N_1) = (S_1/S_2)^k$$

For a good design (moderate K_t -values) k may be in the order of 5 to 6. For a sharp notch (high K_t) and fatigue crack growth periods lower k -values are observed, say in the order of 3 to 4, i.e. of the same magnitude as the power exponent in the Paris equation as may be expected. Fatigue life improvement ratios calculated with the above equation for a 20% lower peak stress (i.e. $S_2/S_1 = 0.80$) are:

k	6	5	4	3
N_2/N_1	3.8	3.1	2.4	2.0

It is noteworthy that similar k -values have been observed for results of VA loading tests⁴ which intuitively appears to be reasonable, and thus similar life improvements may be expected. For $k = 6$ the fatigue life may be increased about four times if the peak stress is reduced by some 20%. It will be more attractive to achieve such a result by reducing K_t rather than reducing the stress level by increasing the cross section of the element. It still may be repeated here that for critical problems comparative fatigue tests are recommended.

The effect of the reduced peak stress on the fatigue limit may be assumed to be linearly proportional to the peak stress. However, an increased root radius implies that some size effect can be present. The improvement then should be somewhat less, and a size effect must be accounted for as discussed in Section 7.2.2.

III.2 Fatigue tests, why and how?

III.2.1 Introduction

Fatigue tests, why and how. Two logical questions. These questions are discussed in Chapter 13. The reader is supposed to be familiar with this chapter and also Chapter 12 on scatter. The present text here is a concise repetition of these major questions. It is addressing the engineering community also in view of research on engineering aspects. More comments on basic research are presented in Part IV.

The very first step for planning a fatigue test program is to define the purpose of the tests in full detail and as much in depth as possible. What do we want to learn from the tests, which information are we looking for. Starting fatigue tests without a clear definition of the purpose can imply that we obtain not fully relevant evidence for our problem. A proverb: Experiments never lie, but you should ask the right question. Secondly, questions must be considered about the type of specimens and fatigue loads to be used in fatigue tests. It should include possibilities to evaluate the results for the purpose of the tests.

⁴ Schijve, J., *The significance of flight simulation fatigue tests*. In *Durability and Damage Tolerance in Aircraft Design*, Proc. 13th ICAF Symp., A. Salvetti and G. Cavallini (Eds.), EMAS, Warley (1985) pp. 71–170.

III.2.2 Fatigue tests for which purpose?

As discussed in Chapter 1, the variety of structural fatigue problems in service can be very large, and thus the variety of fatigue test programs can also be large. Some typical conditions will be discussed to illustrate different arguments for choosing specimen types and fatigue loads to be applied in a specific test program.

Starting from the concept of designing against fatigue (or redesigning after fatigue failures occurred in service) attention can be concentrated on:

- Material selection
- Fatigue properties of structural elements
- Comparison between different design options
- Full-scale fatigue tests

Comments on the above listing are presented below including a section on load histories which can be adopted in fatigue tests.

Fatigue research on basic aspects is associated with physical understanding of:

- The fatigue phenomenon, i.e. the mechanisms of crack initiation and propagation.
- Various effects on the fatigue phenomenon, e.g. the significance of the environment, but also various other influences on crack nucleation and crack growth.
- Predictions of fatigue properties, both for crack initiation and crack growth.

It may well be expected that requirements for specimens and load histories will be significantly different. Some comments on these aspects are presented in this section, but they are addressed again in Part IV.

Material selection

It is well known that a high tensile stress of a material does not imply superior fatigue properties. High strength alloys usually are fatigue notch sensitive, and also the fatigue crack growth resistance may be relatively poor. Material selection for a fatigue critical element of a structure should be based on fatigue test data. If a designer wants to use an alternative material he should know the fatigue properties, and of course a full range of other properties as well (especially the corrosion behavior and production aspects). For a new material still under development, fatigue tests must also be carried out.

For many people fatigue data are associated with a fatigue limit (S_f) or S-N curves as obtained on unnotched specimens ($K_t \approx 1.0$). However, these data are not really instructive because the designer must consider fatigue in his structures with local stress concentrations. Prediction of fatigue properties for notched elements from data for unnotched specimens is just a large extrapolation step from data for $K_t \approx 1.0$ to K_t -values in the order of 2 to 4 (see Chapter 7). For joints the problem is still more problematic (Chapters 18 and 19). If a new material will be adopted, results of fatigue tests on realistic specimens must be compiled including fatigue tests on notched specimens, joint specimens and crack growth specimens.

Data on fatigue crack growth can be essential for specific structures, e.g. aircraft structures. But it may also be relevant to steel structures with a large material thickness for which the crack growth period may cover a significant part of the total fatigue life. Think about the leak-before-break of pressurized containers. Crack growth properties are required to illustrate the crack growth resistance of a material.

Fatigue properties of structural elements

Fatigue tests on structural elements are carried out to explore various questions about the fatigue behavior of a specific structural element. Such experiments can answer various important questions. Is a sufficient crack initiation life obtained? Where does crack initiation occur, at which location in the structure? Are design improvements possible and desirable? Does crack growth lead to complete failure in a short period? Tests on a structural component implies testing a realistic specimen. As a consequence, a realistic answer of such a test requires that the fatigue load in the tests should also be a realistic representation of the load history occurring in service.

A fatigue test on a structural component is in fact a full-scale test. If the fatigue life until failure is the only recorded result, this is the bare minimum of information. If possible, fatigue cracking during the test should be recorded. Furthermore, the fatigue fracture surface must be examined, at least with the naked eye and a magnifying glass. Usually, the location where crack initiation occurred can be observed which can be important for possible design improvements. In general, crack initiation starts at the material surface at the location of a stress concentration. Fatigue tests may also show crack nucleation at other unexpected locations.

Examination of fatigue fracture surfaces is of special interest for fatigue of joints. In bolted and riveted joints crack initiation may start at any location

where fretting can occur which depends on the clamping in the joint. For fatigue of welded joints crack initiation is usually expected at the toe of the weld. But it can also occur below the material surface due to welding defects or residual stress distributions introduced by the welding process. Anyway, fractographic analysis should always be carried out, and it should be tried to understand the observations. It may also be worthwhile to study the fracture surface in the Scanning Electron Microscope (SEM) which allows a large range of magnifications.

Comparison between different design options

Comparisons between different design and production possibilities are frequently of interest to the industry. Examples of practical questions are: What is the effect of improved detail design, an other material, a different production method, another type of fastener in joints? In many cases the basic objective is associated with economic arguments. In general certain qualitative expectations will be present about alternative solutions but comparative fatigue tests are necessary to obtain quantitative information. As emphasized previously, the fatigue load to be applied in comparative tests should be a realistic representation of the load history in service. Occasionally, it has been reported in the literature that comparative CA tests can give misleading information if the fatigue load in service has a random character. In general, the selection of fatigue loads requires a good understanding of the practical fatigue problem involved. Fatigue loads to be applied are addressed later.

The design stress level is another important variable which can be evaluated in comparative fatigue tests. However, a first estimate of the fatigue life factor can be obtained by adopting the Basquin relation ($S_k N = \text{constant}$) as discussed before.

Full-scale fatigue tests

By now it is recognized that the most realistic approach is fatigue testing of a full-scale structure as obtained from the production line in the industry. However, it also requires that the fatigue load applied in the test includes all specific features of the load history in service. A simplified fatigue load history to be applied on a realistic full-scale item combines conflicting issues.

It also applies to the opposite which is a simplified structure subjected to a realistic load history.

Full-scale tests are carried out to prove that the endurance of a structure is sufficient. In the aircraft industry this leads to full-scale fatigue tests on large parts of the aircraft structure. Also in the automotive industry such tests are performed on the entire structure of a new design of a car (see Figure 13.3). However, in the automotive industry fatigue tests are also carried out on components to check whether the component obtained in mass production has a sufficient fatigue quality. Fatigue tests are then carried out from time to time as a kind of a routine inspection on the quality of components. Nominally similar components after several years of mass production do not necessarily have the same fatigue properties. The production might have seen some changes and components may be ordered from a different supplier. Note: Fatigue tests programs imply investments of time and money. However, the investments should be compared to possible consequences if those tests are not carried out.

III.2.3 Fatigue tests, how to be carried out?

In the previous sections fatigue problems were indicated for which fatigue testing is essential. How should those tests be organized? First a representative specimen must be designed and produced. Second, a test set-up must be arranged in order to apply the fatigue loads on the specimen. Finally, a fatigue load sequence must be chosen which is supposed to be representative for the problem to be explored. Important aspects of carrying out fatigue tests are:

- Type of specimen and test set-up.
- Fatigue loads to be applied.

Type of specimen and test set-up

As discussed in Chapter 13 the specimens should be representative for the problem to be experimentally explored. It requires that the material, the surface conditions and the geometry should be carefully defined in order to obtain relevant information from the tests. A generally recognized problem is associated with the load transmission from the fatigue machine to the specimen. Clamping of the specimen should not be more fatigue critical than

the specimen itself. In other words, the clamping must be designed against fatigue. In various cases this will not offer serious problems but fatigue laboratories usually have quite a collection from failures in the clampings.

Another problem is that the clamping of a specimen must exactly transmit the specified load. If this is a tensile load only, the clamping should not cause some bending of the specimen due to misalignment. In cases of doubt it should be checked by strain gage measurements. Such measurements on some specimens are anyway recommended, just to be sure that the machine is doing what it is expected to do.

Modern fatigue machines are equipped with hydraulic clamping blocks. This is convenient for the test operator. However, it should be realized that fretting can occur between the clamping blocks and the sheet specimen surface. Also alignment problems must be considered. Another option is to use clamping plates which are bolted to the ends of the specimen. The specimen with clamping plates is then mounted in a clevis type lug connection to the test machine by a single pin. This type of clamping is often preferred for thin sheet specimens with a large width. Moreover, it also takes care of a symmetric load application on the specimen.

A particular problem with respect to the size of a welded specimen arises if specimens are used with a transverse welded joint, e.g. for exploring certain welding parameters. If the width of the specimen, and thus the length of the transverse weld bead, is only 5 or 10 cm (2 or 4 inch), it is difficult to see how the results can be representative for long weld beads in a large structure. To some extent this arguments also applies to riveted or bolted joints with large numbers of fasteners in each row of fasteners. It then is recommended to use wide specimens to increase the number of fasteners in a row which then will give better statistical data.

Test set-up

The test set-up in a fatigue machine is relatively simple for specimens to be loaded under cyclic tension. However, if a number of hydraulic cylinders is necessary to apply different loads on a full-scale structure entirely different problems arise in the mechanical design of the test set up, and also in the computer controlled load application, especially if the applied loads have different frequencies and phase angles. This will not be discussed any further here.

Different types of loads to be applied in fatigue tests for research programs

Various types of fatigue loads are described in Chapter 9. The question now is which type of cyclic loads should be adopted in an experimental research program? Of course, the answer should depend on the objectives of a research program. As a consequence, fatigue loads in research on basic aspects of the fatigue phenomena may well be different from load histories in research programs related to designing against fatigue and other practical questions about various conditions which can affect the fatigue properties of structures.

In the former case of research on basic concepts it can be useful to adopt CA loading in fatigue tests in order to have constant fatigue load condition. With respect to studying the growth of macrocracks the same argument can be satisfied in constant- ΔK tests (see Section 8.2.3). Basic research on the fatigue phenomenon under VA loading obviously requires fatigue tests with a VA load history. However, such test are often carried out with simple VA load sequences, such as CA tests with intermittent OL or UL cycles, especially to study interaction effects. Such load histories will rarely occur on structures in service. But, if we do not obtain a basic understanding of a material behavior under simple load sequences, how then will it be possible to understand the fatigue phenomenon under more complex load histories.

The problem setting is different for research on more practical questions discussed earlier. As an example, which kind of fatigue loads should be adopted in comparative tests knowing that VA and CA tests may give different answers? A relatively simple situation may still be possible if crack initiation is not allowed because fatigue failures should not occur. All loads of the spectra in service should then be below a fatigue limit. It implies that the fatigue limit is the relevant property to be considered. Fatigue tests to determine this property should still be CA load tests, see the discussions on the step test (Figure 13.2) and the staircase method (Figure 12.8).

If different types of loads must be considered for finite life time issues, it is a difficult problem to decide on the of fatigue loads to be applied in tests which should give relevant and instructive results. Recall that different life ratios may be obtained in comparative tests under CA loading as compared to results of tests with VA loading. The conclusion that service simulation fatigue tests is the best option is true, but how do we arrive at a load history for such a tests. As pointed out in the summary of Chapter 9: Characteristic classifications of loads in service are: deterministic loads (especially maneuver type loads) and stochastic loads, in particular random

loads which can be narrow band or broad band random load. Another classification is stationary load spectra versus non-stationary load spectra. Fully rational procedures cannot be defined, but some suggestions can be made. First, the various types of loads which are relevant for the problem to be considered should be listed. An example was presented in Chapter 9 (Table 9.1). This problem of indicating significant types of loads on a structure is also essential for the analysis of fatigue failures occurring in service. This topic is addressed in the case histories presented on this CD.

Another approach is to consider the question whether high-cycle fatigue or low-cycle fatigue is involved. In addition, it should be realized whether a steep or a flat load spectrum is applicable. In the latter case the larger load cycles have a predominant fatigue damaging effect. For fatigue tests CA loading can then be acceptable with cycles simulating the larger load cycles of the spectrum. Anyway, straight forward procedures to decide on load histories for fatigue tests is a difficult problem, but with some understanding and judgment reasonable compromises are possible.

Note: If fatigue tests are carried out it must be recommended that a Test Report is written with all conditions of the experiments, a full description of the test set-up, numerical data of all results, the conclusions and possible consequences. Sometimes several years later the test information becomes relevant again if new fatigue problems arise. Furthermore, pictures can be instructive but drawings are also essential. If test series have led to interesting experience, it should be published in international journals.

Part IV

Research on Fatigue Problems in the Future

- IV.1 Introduction
- IV.2 Fatigue crack growth mechanisms
 - IV.2.1 Crack initiation fatigue life and microcrack growth
 - IV.2.2 Macrocrack growth
- IV.3 The significance of fractographic studies
- IV.4 Prediction of fatigue crack growth under VA loading
- IV.5 Fracture mechanics predictions of crack growth and marker loads
- IV.6 Load measurements in service
- IV.7 Research programs
- IV.8 Epilogue

IV.1 Introduction

It is my intention to address some questions about future research on fatigue problems for which the motivation can now be envisaged, either for scientific reasons or practical arguments. Because research on practical problems also starts from lack of knowledge, the main theme will be a plea for research on improving our understanding about the fatigue phenomena occurring in structural materials and the significance for predictions. Of course it is impossible to cover a complete list of unsolved issues, but as far as topics are addressed, I hope that it may trigger ideas for future research. In a way, the present discussion is a follow-up of my paper published in 2003 with the title: *Fatigue of structures and materials in the 20th century and the state of the art* (International Journal of Fatigue, Vol. 25, 2003, pp. 679-702). The paper is reproduced here at the end of Part IV. It was concluded in the paper that the fatigue phenomenon in materials, and also in structures, is reasonably understood in qualitative terms. But for quantitative predictions we are still facing a lot of uncertainties. From a fundamental point of view, the phenomena of fatigue crack nucleation and crack growth mechanisms on

a microscale are still affected with questions for which indisputable answers are not really existing. And for fatigue properties of a structure several uncertainties about predictions are still present.

An entirely different drive for research in the future is coming from new developments. Think of new or improved materials, production techniques, new types of joints and structural concepts. Practical applications can be expected, but at the same time research will be essential to arrive at a physical understanding of potential improvements. The new developments will not be addressed here because it would include a good deal of speculation. But in summary, research of fatigue problems of structures and materials will stay with us in the 21st century.

The following text is arranged under a number of different headings. The discussion should be considered to be personal reflections on selected aspects (or messages if you like). I hope that my comments will stimulate the reader to see whether they are relevant to his personal approach to research still to be done.

The reader may observe that my experience has largely been obtained by research on aircraft fatigue problems. Fatigue of aircraft structures and materials is still a relevant problem requiring a serious evaluation. However, the knowledge obtained with specimens and structures of aerospace materials is also instructive for other structural materials, noteworthy for high-strength materials.

Problem areas

Before entering the discussion on the above items, a general comment should be made first. Research should start with some ideas about the phenomenon to be explored. Before developing speculative theories the phenomenon should be the subject of scientific observations. Or in simple terms, let us first have a look what happens. Actually this approach of making observations has been at the roots of many scientific developments. The sequence is:

ideas → observations → new ideas → verification by observations, etc.

It is an iterative process, a voyage of discovery, success not guaranteed. Obviously “Have a look to see what happens” implies that fractography is indispensable. It may well prevent jumping to conclusions and ill-founded speculations.

The present section of the CD is finished with some comments on preparing a research program (Section IV.7) and an Epilogue.

IV.2 Fatigue crack growth mechanisms

IV.2.1 Crack initiation fatigue life and microcrack growth

As said before, the fatigue phenomenon in structures and materials is reasonable well understood in qualitative terms. However, quantitatively accurate predictions on fatigue properties are difficult. To narrow this problem, we can start from the idea that a finite fatigue life implies that crack nucleation starts immediately as soon as cyclic loads are applied. The crack initiation life includes the crack nucleation and a long period of microcrack growth followed by macrocrack growth until failure. This picture includes the problem of crack nucleation, i.e. the question how the nucleation does occur. For several alloys nucleation can start at microscopically small inclusions. Moreover, it can be stimulated by surface conditions, e.g. surface roughness. Setting aside these nucleation issues, the problem is reduced to predicting the growth of a microcrack. The crack size may be in the range of a few microns to 1000 μm ($= 1 \text{ mm}$). Because cyclic slip on a microscopic level is involved, the problem can be entirely different for materials with a different material structure. Think of mild steel, low-alloy high-strength steel, different Ti- and Al-alloys. Some information about microcrack growth in these materials is available in the literature, but quantitative information is not abundant. An other most serious problem is raised if fatigue under variable-amplitude loading is considered. This topic has extensively been studied for macrocracks but not for microcrack growth in the crack initiation period. Research on this problem is difficult, but it is of great interest because it can occur in any structure, and it then covers a substantial part of the fatigue life. A first start of research should be focused on microscopic observations in order to describe the phenomenon in metal-physical terms, rather than speculating on predictions of microcrack growth employing stress intensity factors which have a doubtful meaning for microcracks. Research on crack nucleation and microcrack growth can also have some practical significance for structures in which fatigue cracks are not acceptable, i.e. problems for which the fatigue limit is the significant fatigue property for designing against fatigue.

IV.2.2 Macroc crack growth

Predictions on macrocrack growth is generally associated with fracture mechanics and the stress intensity factor as a relevant parameter. Extensive research efforts are documented in the literature with predictions of crack growth by employing the stress intensity factor for cycle-by-cycle calculations. In simple terms, similar ΔK cycles (or ΔK_{eff} cycles) in a structure and in a laboratory specimen should produce the same crack extension Δa . This does not imply that we understand the crack growth mechanism. It is just similar conditions should have similar consequences. Knowledge of the crack growth mechanism is not involved. Crack extension in a load cycle is a failure mechanism occurring on a microscale. The size of Δa may be in the order of 1 μm and even much smaller. The crack extension is a local loss of coherence in the material which may occur as shear decohesion or tensile decohesion in the crystal lattice. For aluminium alloys it has been observed that the presence of water vapor increases the crack growth rate whereas perfectly dry oxygen does not. It remains an open question how either H^+ or OH^- are affecting the decohesion mechanism. Although speculative arguments have been published more profound research should shed more light on this intriguing question.

The detrimental effect of salt water on fatigue crack growth has been observed for many technical material. It appears to be some electro-chemical reaction at the crack tip which leads to larger crack extension in a load cycle, but also in this case the exact mechanism is not fully clear. Remember from Chapter 16 that the contribution of the salt water environment on crack extension occurs during the cyclic deformation at the crack tip.

In view of the environmental effects on fatigue crack growth it is a good question to ask how fatigue crack growth occurs in vacuum or an other inert environment. Crack growth most probably still occurs in every cycle but crack growth is relatively slow and striations are not visible.

It appears that there is still ample room for profound research on crack growth mechanisms under cyclic loads. Unfortunately, it may well be expected that significantly different mechanisms will occur in different materials. Moreover, variable-amplitude loading offers another complication. Some comments on these question will follow later in the discussion on fractographic observations, but one comment is made here on crack growth in mild steel (low-carbon steel) under VA loading. This material is widely applied, also in large structures (e.g. ships, bridges, pressure vessels, off-shore structures). Mild steel is a special material for

several reasons: unstable plastic yielding (Lüder bands), cold brittleness, a relatively low fatigue notch sensitivity and a good ductility. Welding of mild steel is a well developed technology, although poor fatigue results of welded specimens and structures have been reported, see Chapter 19. It should be expected that fatigue crack growth in mild steel under VA loading can show a significantly different behavior as observed in high-strength low-ductility structural materials. In view of the extensive application of mild steel it is a most worthwhile topic for basic research. Unfortunately fractography will be a difficult issue.

IV.3 The significance of fractographic studies

Since the “darkness” about the fatigue phenomenon in metals has been taken away by microscopic observations an apparent need for improved microscopes was generally recognized. As present, impressive techniques are available. Two most important observations are: (i) crack nucleation on a microscopic scale occurs in the very beginning of a finite fatigue life, and (ii) crack growth is a cycle-by-cycle phenomenon. It has been shown in many investigations that the path of growing fatigue cracks can be significantly different for different types of materials. To some extent such differences can be understood by considering the cyclic plasticity behavior of the material. It is associated with the number of slip systems and the occurrence of cross slip depending on the stacking fault energy. The less brilliant side of the medal is that the mechanism of crack extension at the crack tip is not really well-known as addressed earlier. Furthermore, materials may show a different crack growth mechanism during high-level fatigue and low-level fatigue. A noteworthy example was mentioned in Chapter 8 (Section 8.5). It was observed that crack growth in a Ti-alloy (Ti-6Al-4V) showed so-called structure-sensitive crack growth with a rough fracture surface at a low stress amplitude in contrast to structure-insensitive crack growth with a relatively flat fracture surface at a high amplitude.

A similar question may be raised for the crack growth mechanism at low ΔK -values close to the threshold value ΔK_{th} . It should be expected that less slip systems with different crystallographic orientations are activated. As a result the micromechanism should differ from the mechanism occurring at ΔK -values in the Paris regime. The problem becomes even more complicated during variable-amplitude loading because cycles with ΔK -values below the threshold value still contribute to crack growth. A

comment should be made here. It is suggested in the literature that ΔK_{th} is a material property which should be known. But it is rarely explained what we can do with this knowledge. Discussions are presented how we can understand a threshold ΔK which is determined in a special type of fatigue test. However, the practical significance of ΔK_{th} is not clear.

The morphology of the fatigue crack fracture surface is an interesting and essential part of describing the macro and micro appearance of fatigue cracks. On a macroscale the occurrence of shear lips (see Figure 2.38) in some materials is one feature which deviates from the flat fracture surface usually considered in analysis based on fracture mechanics. Furthermore, the roughness of the fatigue fracture surface which is visible without optical magnification is another significant aspect. This is discussed in Chapter 16 (see Figure 16.9) where it was shown that the fracture surface of fatigue cracks in aluminium alloy specimens is relatively flat for crack growth in an aggressive environment (salt water) whereas it is more undulated for fatigue crack growth in air, and even more so for crack growth in vacuum. The faster crack growth in salt water may well be expected, but as pointed out in Chapter 16, it is also partly caused by the larger crack driving force per unit length of the crack front because of the more straight crack front if compared to the undulated crack front line in less aggressive environments.

Although a fractographic analysis should always start with visual observations it is nowadays easy to observe fracture surfaces in the SEM with a large range of magnification factors. Increasing the magnification is digging into the microcosmos of fracture surfaces. It can be most surprising what you see. And as some people say, “it opens a world full of incomprehension”. But hopefully, bit by bit you may recognize features which can be attributed to material structural features. Once I studied the fatigue fracture of a fatigue crack in a 2024-T3 sheet specimen grown under CA loading with an inserted severe OL. The fracture surface in the SEM in the area of the crack extension caused by the OL and the following crack growth at the base line CA cycles was tremendously irregular. You must be brave to think that you can predict what happens on a microscale during and after the OL.

In other cases you may feel more happy. A few years ago I opened a fatigue crack in a fairly thick angle section which was supporting a wing in a full-scale fatigue test with a flight-simulation load history. The tests was carried some 30 years ago. The picture shown in Figure IV.1 shows part of the fracture surface. Markings of the more severe flights are easily recognized. In between many less severe flights did not really leave clear striation type lines. However, the entire picture is a matter of fatigue crack

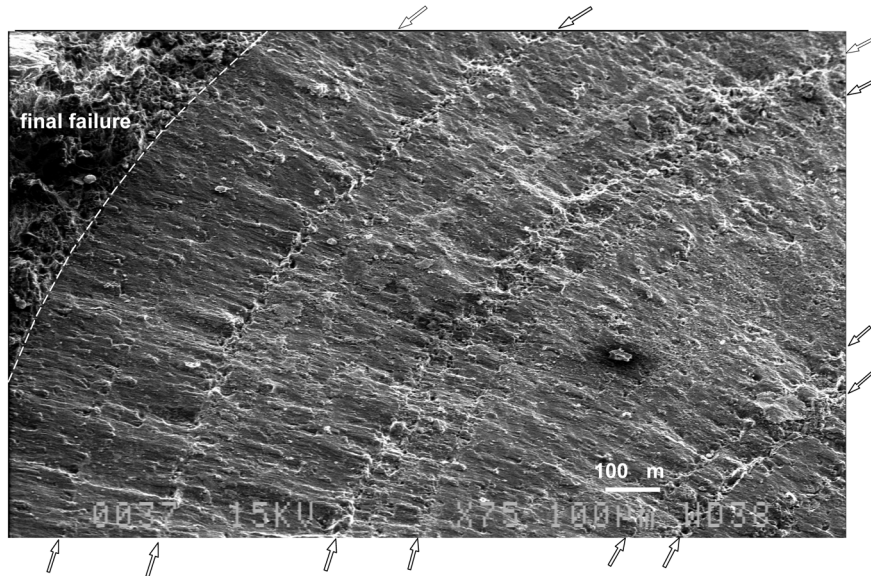


Fig. IV.1 Detail of the fracture surface of a fatigue crack grown under a flight-simulation load history. Marking bands of the more severe flights are indicated by arrows.

growth under numerous load cycles. It is the battle field of interactions between cycles with large and small amplitudes. More refined fracture surface analysis can provide numerical information about the interactions, see the discussion on Figure 11.22 in Chapter 11. It is beyond any doubt that we need such information for verifying the reliability of crack growth prediction models such as the strip-yield models.

Fractography gives a three-dimensional picture of the fracture surface. But it does not show any direct information about the correlation with the underlying material structure. Microscopic cross sections perpendicular to the crack front can indicate the crack growth path and how it is affected by grain boundaries and slip systems. It gives a two-dimensional picture which is a limitation, but more cross sections can lead to a more general impression. In research on the fatigue fracture mechanism both fractography and microscopic cross sections should be employed.

IV.4 Prediction of fatigue crack growth under VA loading

The significance of fatigue lives under variable-amplitude loading was amply discussed in Chapter 10. The Miner rule, its shortcomings and interaction effects were explained. Crack growth under variable-amplitude loading was the subject of Chapter 11. Again interaction effects were mentioned which were explained by considering crack closure. Prediction models were reviewed and it was pointed out that some older models were suffering from inconsistencies because they did not account for crack closure in a logical way. Corpus was a better model with calculations based on history effects due to crack closure. Later the more advanced strip-yield models were proposed. These models can explain the occurrence of delayed retardation after the application of a high load (overload, OL), and also the multiple OL effect. These encouraging findings have been achieved because of modeling cyclic plasticity in the crack tip plastic zone including reversed plasticity. Also reversed plasticity in the wake of the crack during crack closure is accounted for. As a result, crack closure stress levels are predicted rather than using empirical data about crack closure.

The experimental verification of the strip yield models so far is not yet extensive, and almost exclusively done for specimen of aerospace aluminium alloys. Although the strip yield models are the most advanced crack growth prediction models, it should not be overlooked that the strip yield models are still employing the similarity concept, i.e. similarly calculated ΔK_{eff} cycles in VA tests and in CA tests will produce the same Δa . This is a large extrapolation step, also because strain hardening of cyclic plasticity under VA loading is not necessarily similar to cyclic strain hardening under CA loading. Furthermore, we are also left with the plane strain/plane stress transition which requires some experimental tuning of the present strip yield models. It is accepted that plastic zones are larger at the material surface due to the plane stress situation. It implies that crack opening will not occur simultaneously along the entire crack front. In other words, a three-dimensional picture emerges which says that during unloading crack closure will occur earlier at the material surface and at a lower stress level at midthickness. During loading a similar process will occur which implies that ΔK_{eff} is larger at midthickness and smaller at the material surface. As a consequence, curved crack fronts will occur in plates and they have been observed indeed in many experiments. In a qualitative manner the picture is more or less clear, but it will be a difficult issue how to account in some rational way for the variation of crack closure and crack opening

along the crack front. It is a tempting problem, the more so because valid verifications with experimental observations are also difficult. Perhaps a FE model approach should still be adopted. Such an adventure was published in 1989.⁵ Anyway, more research is necessary to arrive at more satisfactory possibilities for predictions. For the industry, the best solution at the moment encompasses realistic service-simulation fatigue tests.

IV.5 Fracture mechanics predictions and marker loads

Marker load cycles are introduced in fatigue tests to obtain typical bands of striations which can be identified in the SEM on the fatigue fracture surface. The purpose of marker bands is to study the shape of an invisible crack front of a fatigue crack, and to see how fast the crack front is moving onwards. Until now marker loads were mainly applied in CA tests on riveted specimens and structural elements of aluminium alloys. Occasionally it has been done in a flight-simulation full-scale fatigue tests on an aircraft. An example of a load history to produce marker bands is shown in Figure IV.2 introduced by NASA to study crack growth in riveted lap joints.⁶ Three different groups of marker loads are applied and then repeated. They will give 3, 9 and 5 bands of the base line cycles embedded in the low amplitude cycles in order to have additional information for the correlation with the progress of the fatigue test. It is a kind of digitizing locations on the fracture surface as previously introduced by Sunder.⁷ An illustration of marker bands is shown in Figure IV.2.

Marker loads should meet some essential requirements. (i) It should be possible to observe the marker load bands or striations on the fatigue fracture surface in the SEM along the larger part of a crack front in order to delineate the entire crack front shape. (ii) It should also be possible to correlate the location of the marker load bands with the fatigue life at which the marker loads were applied in order to reconstruct the growth of the crack as a function of applied load cycles. (iii) Crack growth during the marker load

⁵ R.G. Chermahini, K.N. Shivakumar, J.C. Newman, Jr. and A.F. Blom, *Three-dimensional aspects of plasticity-induced fatigue crack closure*, Engineering Fracture Mechanics, Vol. 34 (1989), pp. 393–401.

⁶ R.S. Piascik and S.A. Willard, *The characteristics of fatigue damage in the fuselage riveted lap joint*. NASA/TP-97-206257 (1997).

⁷ R. Sunder, *Binary coded event registration on fatigue fracture surfaces*. Nat. Aero. Lab., Bangalore, Tech. Memo. TM-MT-8-82 (1982).

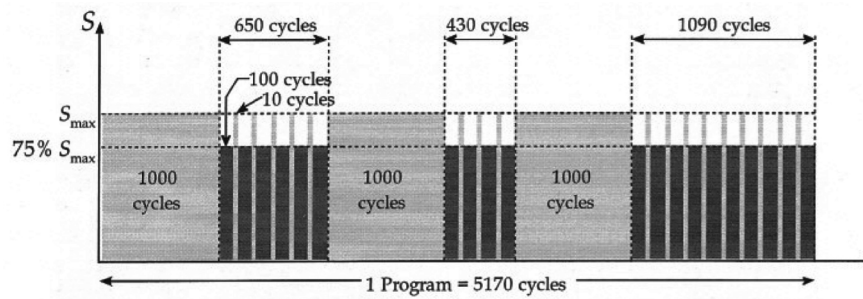


Fig. IV.2a Load history with marker load cycles as proposed by Piascik and Willard (NASA-TP-97-206257, 1997). Three different batches of base line cycles with intermediate smaller marker load cycles ($0.75 S_{\max}$). The purpose is to observe successively 5, 3, and 9 bands, each created by batches of 10 base line cycles.

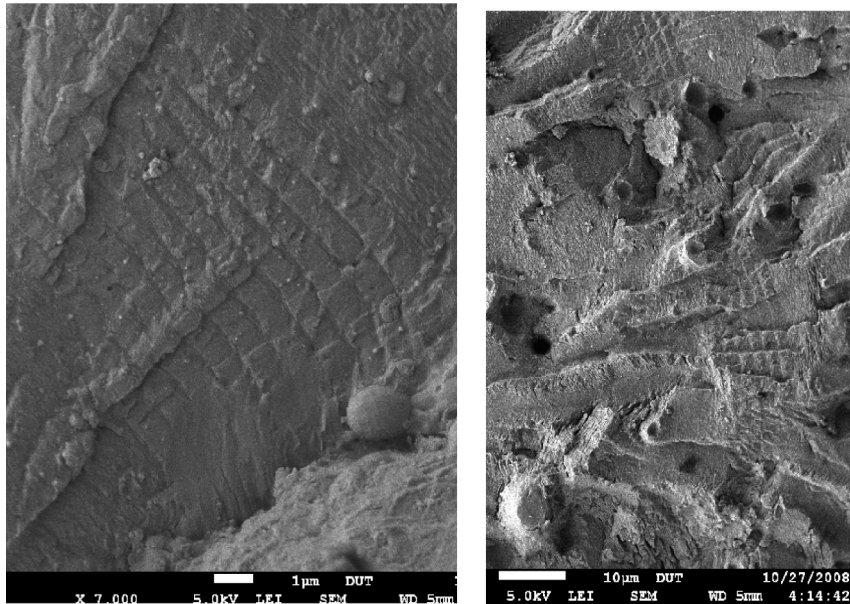


Fig. IV.2b SEM pictures of the fracture surface of a fatigue crack in a riveted lap joint tested with the marker load history shown above. Material 2024-T3. The left picture shows 9 marker load bands, the right picture shows 5 marker load bands. (Pictures Milan Krkoska, Faculty of Aerospace Engineering, Delft)

cycles should be insignificant in comparison to crack growth during the baseline cycles.

In view of the last condition, marker load cycles with S_{\max} exceeding the maximum stress of the baseline cycles are not allowed because they could decrease the crack growth rate during the baseline cycles. Different marker

load histories have been adopted and discussed in the literature, but still other ones can be considered for future research. Moderate OL cycles need not necessarily be excluded.

As said before, with marker loads information about the shape of invisible cracks can be obtained. This information is essential for research on predicting crack growth of invisible cracks. As an example, it should be known how cracks are growing in the non-symmetrically reinforced open hole in Figure 20.6 where crack initiation will start at point P_2 . It should be realized that crack growth prediction also require stress intensity factors for such three-dimensional geometries. It implies that research will certainly be demanding. But even without predictions, fractographic results about how cracks are growing in components with a complex geometry will be instructive for design problems. Research on marker loads as a tool to trace crack growth of invisible cracks should be recommended. The same is true for the prediction and verification of fatigue crack growth in complex geometries of structural elements. For this topic, it should start with predictions for CA loading.

IV.6 Load measurements in service

As explained in my textbook, information about load spectra in service is essential for considering and predicting the fatigue life of structures. Without this information it may become ambiguous to go for a high accuracy of fatigue properties.

Techniques for recording load histories of structures have been developed to a high level of performance, usually with strain gages or accelerometers as sensors. If necessary, measurements can also be made on rotating components, and even wireless data transmission is possible. If information on the load history is obtained, the question arises what are we going to do with it. In the automobile industry such records are sometimes used as command signals in fatigue tests on the automobile itself. It then is a most realistic service-simulation test, not a test with a scientific purpose, but just to see whether the response of the structure is satisfactory.

Another practical purpose of load measurements in service is to see how “severe” the load spectrum is, or to learn about which type of loads are encountered in service.

As shown in the literature (see Chapter 9), statistical analysis is applied to load records in order to learn about typical aspects, and the analysis can be

done in different statistical data formats, for instance in a two-dimensional rainflow count matrix to mention just one example. Such data can be instructive to see what has happened to the structure, but it is quite an other problem to translate the load history into fatigue damage, or in more trivial terms to measure the reduction of the fatigue life. This problem was touched upon in Chapter 20 with the discussion on the Tsing Ma bridge in Hong Kong. Most relevant information about the load history can sometimes be obtained, but it leaves us with the problem of the prediction of fatigue properties. The situation can only be improved by developing more reliable prediction techniques for fatigue properties under variable-amplitude loading. As long as this problem is not yet solved, load-history measurements in service offer a kind of a black box which can tell us what has happened. At the same time, we can use the load history in service-simulation fatigue tests to discover what it means in terms of fatigue life.

IV.7 Research programs

Some comments about planning a program

The very first start of arriving at a proposal for research is defining the problem to be investigated. Creative ideas about research topics may be triggered in various ways. It may be associated with previous research with some open ends and thus some lack of knowledge. It may also result from ideas about innovation. Whatever it is, it implies that ideas for research must be defined in an explicit description. Writing up can also be instructive to verify your own view points, or in other words, to see whether you really know what you want to investigate. Written concepts of research proposals are necessary for discussions with colleagues and other people. It may lead to redefining the research target and to arrive at a more suitable description of the research. It is an old saying that a good definition of a problem covers half the solution of the problem. Indeed, a good definition is essential for running into a research program, but afterwards it can still be a long way of hard work to arrive at answers on questions of the research target. The first step then is to plan the investigation in sufficient detail which includes man hours, laboratory facilities, cost estimates, etc. This information is necessary if a research contract is required. In universities smart ideas should anyway have a chance to be explored also without a research contract.

Research contracts

In the present time many research programs can be carried out only when cost estimates have been made and a research contract has been granted. In previous centuries the purpose of university research was to increase scientific knowledge without economical profits as a prime motive. With respect to engineering problems the situation was changing already in the 19th century because of the “industrial revolution”. Technical developments were associated with production problems, durability, safety and economic aspects. And certainly in the previous century, it was thought to be necessary that we should have laboratories to deal with specific technical problems turning up in a modern society. This has significantly affected the motivation for research. By now, we can indicate three different parties for which engineering problems are a major topic for research:

- Universities
- Research institutes
- Laboratories of the industry

For the latter laboratories, the driving motivation of research is obvious. Research is focused on improving products, innovations, and in general for issues associated with the economic well-being of the industry.

Research institutes are supposed to develop solutions for various practical problems, and more specifically to support industries and other agencies which do not have their own laboratories.

Universities for a long time were expected to develop new theories and understanding of physical phenomena with the prime objective to increase scientific knowledge. As a kind of a persiflage, a university was sometimes labelled as being an ivory tower. Anyway profit motives were originally not essentially required, while scientific curiosity was a better motive for research activities.

At present we are facing drastically changed circumstances. Research frequently starts with obtaining a research contract in a competitive environment. Arguments about the usefulness for practical applications of the results of the research still to be carried out must be indicated in advance. It can lead to difficult situations because the success of the research cannot be guaranteed. The research is done because we do not yet know the results to be obtained. Research on fatigue offer an additional problem because time schedules depend on the fatigue properties to be elucidated.

Literature search

A literature search must be recommended for each investigation. It is possible that other people in the past have been equally clever to tackle the same problem. Some relevant research may have been done earlier.⁸ The available literature on fatigue problems is tremendous, and it is not always easy to trace older investigations. However, it is not correct to think that searching the literature with keywords published in the last 10 years is more than sufficient. Of course, older publications should be read with a critical mind, and it should not distract you from defining your own problem and starting your own research.

IV.8 Epilogue

I want to start this epilogue with the last conclusion of Chapter 20 of my textbook which reads: “Designing against fatigue requires imagination, understanding and experience”. I now want to add here: “Basic research is essential for successful designing against fatigue in the future”. We must know what happens during fatigue of a material, and because of this question, we must observe what happens in a material. Fatigue occurs on a microscale but the final result is a macroscopic fatigue fracture. It is obvious that fractography and other microscopic techniques are indispensable. But in addition, the observations must be linked up with concepts of metal physics including possible interactions with environmental influences. Because the fatigue phenomenon is not the same phenomenon for all materials, there is still ample room for research on fatigue in the future. At the same time, technical innovations (new materials, new jointing techniques) are also asking basic questions about the fatigue resistance. Although fatigue properties associated with innovations may be revealed by fatigue tests, the question remains whether we do understand the results obtained. Again questions which require observations on what happens. Hence: research.

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Delft, October 2008

⁸ In 1905, the philosopher Santayana said: “Those who do not remember the past are condemned to repeat it”.