Chapter 13
Fatigue Tests

Experiments never lie,
but you should ask the right question!

13.1 Introduction

Fatigue tests are carried out for different purposes. The engineering objectives are the determination of fatigue properties of materials, joints, structural elements, etc., including comparisons of different design options. Research objectives of fatigue tests are concerned with understanding of the fatigue phenomenon and its variables. Research objectives and engineering objectives may be complementary.

The variety of fatigue test programs reported in the literature is large, and the number of publication is steadily growing. Different types of fatigue loads, specimens, environments, and test equipment are used. Fatigue tests generally require significant experimental effort and time, which implies that these tests are more expensive than simple tests of several other mechanical properties. Experiments on fatigue problems are supposed to answer questions, while empirical answers are assumed to be more convincing than a theoretical analysis. The saying is: “Experiments never lie”. But, if an experiment is not correctly planned to answer the question under consideration, the result can be a right answer to a wrong question.

In view of large investments in experimental fatigue programs, a careful planning of a test program, experimental procedures, and evaluation of the results is required. Planning should always start with an explicit definition of the problem to be investigated. Another saying is: “A fully detailed definition of the problem is already half the solution”.

The purpose of the present chapter is to summarize various aspects of planning fatigue test programs. Obviously, a program will be different for ad hoc problems of the industry and for general research on specific subjects. Different purposes of fatigue tests are indicated in Section 13.2 followed by separate sections on specimen selection, fatigue test procedures, and evaluation of test results (Sections 13.3 to 13.5 respectively). Crack growth experiments are considered in a separate section (Section 13.6). The major points of the chapter are again listed in a final section (Section 13.7).

13.2 Purposes of fatigue test programs

The extensive literature on fatigue problems illustrates the large variety of purposes of fatigue investigations. Some categories are:

- Collecting data on material fatigue properties for material selection by the designer.
- Investigations on effects of different surface finishes and production techniques.
- Investigations on joints and other structural elements.
- Investigations on environmental effects.
- Investigations on crack nucleation and crack propagation.
- Verification of fatigue prediction models.

Although other lists can be compiled, it is obvious that the choice of experimental variables will depend on the type of investigation to be carried out. Major variables to be selected are: (i) type of specimen, (ii) fatigue loads, and (iii) testing procedures.

The main purpose of an investigation can be to compare fatigue properties for different conditions, e.g. different surface conditions. It implies comparative fatigue tests. In other test series, the main objective is a determination of specific fatigue properties for a single condition, e.g. the determination of crack growth properties of a material. In this case, it is not a comparative investigation. Last, but not least, tests may have an ad-hoc nature because of questions of industrial applications.

Other investigations are carried out in view of a common interest to know more about the fatigue behavior of materials and structures under certain conditions. This category comprises many fatigue research programs published in the literature. Obviously, various circumstances can affect the choice of test specimen, fatigue load and testing procedures.

13.3 Specimens

Some elementary types of fatigue specimens are presented in Figure 13.1. The specimen with a central hole can be characteristic for radii occurring in a structure. Figure 13.1 also shows three simple types of joints, each having some special characteristic features. The lug joint specimen is representative for load transmission by a bolt or pin. Fretting corrosion can occur inside the hole. In the riveted lap joint, a tension load introduces bending, while fretting between the two sheets can also be important. The welded butt joint is the most simple type of a welded joint. Joints are discussed in more detail in a separate chapter (Chapters 18 and 19) because they are frequently the most fatigue critical elements of a structure.

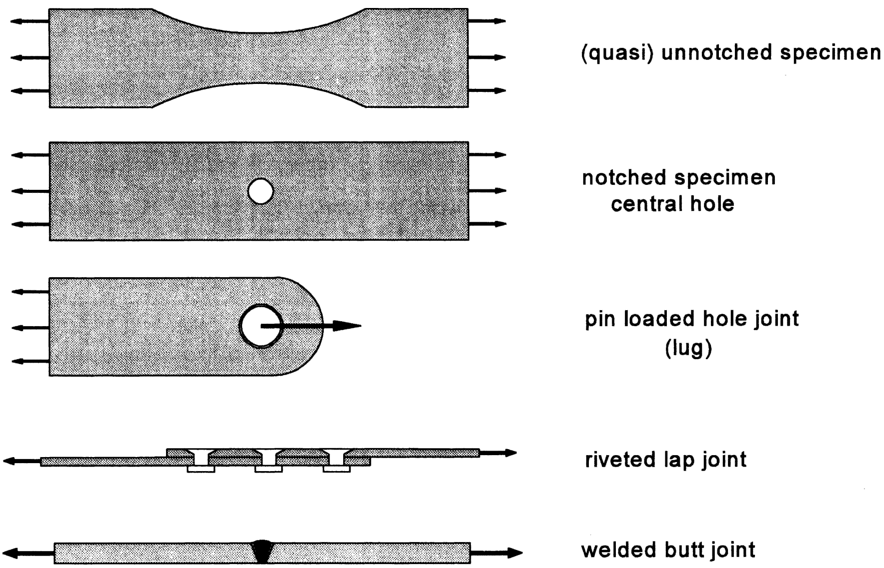

Fig. 13.1 Different types of simple fatigue specimens.

Unnotched specimens

Two aspects of unnotched specimens should be considered. First, fully unnotched specimens with $K_t = 1$ do not exist. Unnotched specimens still have an area where the material is carrying a slightly higher stress than the nominal stress, see the discussion on Figure 6.13. This area is important for size effects. If results of CA tests on unnotched specimens should be used for fatigue predictions or comparative experiments on certain different surface conditions, small specimens should be avoided. In view of possible size effects, these specimens can give misleading results, i.e. a higher fatigue strength or a longer fatigue life.

A second aspect of unnotched specimens is associated with the specimen cross section. The specimens shown in Figure 13.1 are usually manufactured from plate or sheet material. These specimens have a rectangular cross section with corners, but unnotched specimens can also have a cylindrical shape with a circular cross section without corners. Unnotched specimens produced from extrusions or rod material are easily manufactured with a circular cross section, while specimens of plate and sheet material are quite often made by contour milling without reducing the thickness. But even if the thickness is reduced, an unnotched specimen has machined edges with corners at the two specimen surfaces. These corners are a preferential site for fatigue crack nucleation. Theoretically, this should be expected because cyclic slip occurs more easily in grains at the corner. In addition, corners are machined by cutting, which can produce a different machining quality at the corners. Finally, 90° corners are easily damaged, and even minor scratches at the corner can promote local crack initiation. This is particularly true for high-strength alloys which are usually sensitive to the surface finish quality. The initiation of cracks at corners of cross sections can be prevented, or at least discouraged, by smoothing the corners with emery paper.

It is obvious that fatigue tests on unnotched specimens cannot give an indication of the material notch sensitivity, a property of relevant engineering significance. Three other specimens in Figure 13.1 are more informative for this purpose. However, unnotched specimens can be advantageous for problems related to the quality of the surface finish. The material surface is very important for fatigue crack nucleation as discussed in Chapter 2. It implies that a fatigue limit is particularly sensitive for the quality of the material surface as obtained by production techniques used in the industry. The same is true for special surface treatments such as nitriding of steel, see the list in Figure 2.21 and also Chapter 14. It was explained in Chapter 2 that surface effects are relatively small at high stress amplitudes, and much

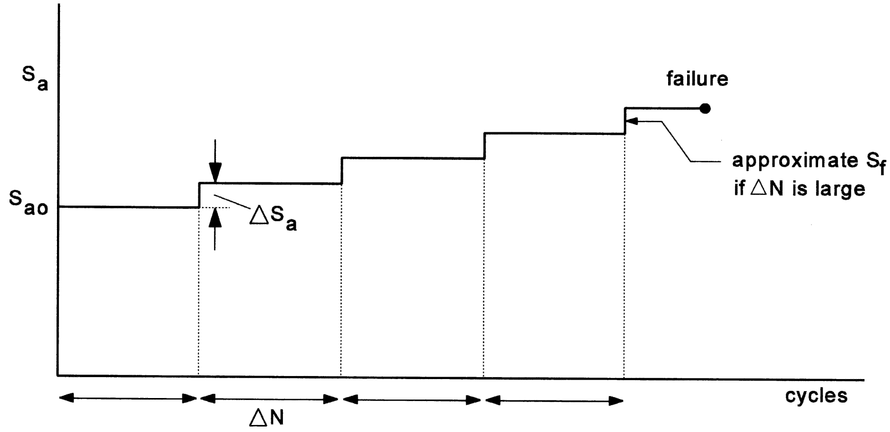

Fig. 13.2 Load history in a step test to obtain an approximate fatigue limit with a single specimen. A small ΔS_a and a large ΔN-value should be adopted.

more significant at low stress amplitudes, see Figure 2.23. Adverse effects can substantially reduce the fatigue limit, while other surface treatments can improve the fatigue limit. Such effects can be indicated by CA tests on unnotched specimens. If an important effect is expected, it is desirable to perform more comparative tests at stress levels close to the fatigue limit. In the previous chapter, it was discussed that many tests may then be necessary in view of scatter. Especially the determination of the fatigue limit requires a large number of specimens. An approximate determination of the fatigue limit can be done with less specimens in so-called step tests in which the stress amplitude is increased with small steps, ΔS_a in Figure 13.2 [1]. The initial S_{a0} should be below an expected fatigue limit. In each step of S_a, a large number of cycles should be applied, e.g. $\Delta N = 2 \times 10^7$ cycles. If failure does not occur at a certain S_a, the amplitude may be expected to be below the fatigue limit. If a specimen fails, the last S_a should be just above the fatigue limit and the previous S_a just below the fatigue limit. A comparison between different surface conditions is then based on the failure stress and number of cycles spent at the failure stress. The estimate of S_f is indicated in Figure 13.2.

Comparative tests to determine surface effects give qualitative indications on these effects. As an example, it can show the favorable effect of shot peening with different peening intensities. If such results give promising improvements for a certain peening intensity, the application to a specific structural element still needs a more realistic verification by experiments. This should preferably be done in service-simulation fatigue tests on notched specimens with a geometry representative for the structural element. It is possible that improvements in notched specimens are quantitatively smaller than in the experiments on unnotched specimens.

Notched specimens

Fatigue properties of candidate materials are considered by a designer for the purpose of selecting a suitable material for a dynamically loaded structure. The question is which fatigue properties must be considered? Fatigue properties provided by the material manufacturer are quite often limited to the fatigue limit of unnotched material for $S_m = 0$ without mentioning the type and size of the specimen used to determine this fatigue limit. Sometimes a broader evaluation of fatigue properties is made by determining S-N curves for $S_m = 0$ or $S_{\min} = 0$ ($R = 0$), generally on unnotched specimens. However, this information does not give indications on the notch sensitivity of a material. Fatigue tests on notched specimens should provide more relevant data. Comparative experiments on candidate materials should preferably be performed on notched specimens. Obviously, a service-simulation fatigue test on the real structural element is the best solution, but that is not easily done in a preliminary stage of a structural design. However, service-simulation fatigue tests on simple notched specimen shown in Figure 13.1 can provide useful information for material evaluations.

If the fatigue limit is a crucial property of a structural element in service, tests on notched specimens should be made with low stress amplitudes. Arguments presented earlier for unnotched specimens are applicable again.

If newly developed materials become commercially available for structural application, all kinds of material properties must be available. Various aspects of durability properties should be known. This includes fatigue properties of specimens with technically relevant notches loaded under various types of fatigue loads characteristic for service load spectra.

Structures

Tests on full size structures or structural elements are realistic tests with respect to the test item. Tests on small structural elements with relatively simple load transmissions to these elements can still be carried out in standard fatigue testing machines. Larger structures, e.g. an automobile, a

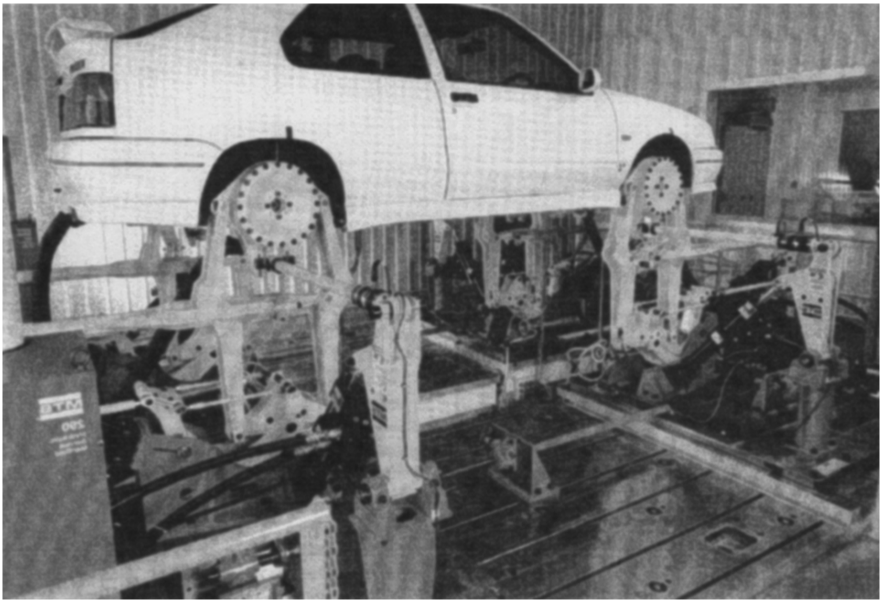

Fig. 13.3 Full-scale simulation test on the chassis and coach work of a motorcar with 12 electro-hydraulic actuators providing vertical, lateral and longitudinal inputs at four corners of the test vehicle. (Courtesy MTS)

truck, or an aircraft structure, require more specialized test equipment. In general, the structure is then loaded with a number of hydraulic cylinders with electro-hydraulic closed loop systems monitored by a computer. Depending on the size and the complexity of the loads on the structure, the number of hydraulic cylinders can vary from a small number, e.g. four cylinders, to large numbers in the order of 100 for full-scale fatigue tests on an aircraft structure. A test set-up for a motorcar is shown in Figure 13.3.

Obviously, it would be inconsistent to apply a simple load sequence on a realistic full-scale structure. The load history to be applied should also be realistic. Service-simulation load histories can be applied by computer controlled equipment. Equipment for such purposes can be built up, but it is also commercially available.

In the automotive industry, aircraft industry, and some other industries as well, complex tests are carried out on new designs. In general, the automotive industry is producing large numbers of vehicles, and in principle, fatigue failures in service are unacceptable. A full-scale test with a conservatively selected service-load history should reveal any weakness of the structure in order to modify the structure before it goes into mass production. In fact, such a test is primarily done to see whether all parts of the structure are properly functioning without any deterioration of any part of the structure after a long testing time. In the aircraft industry, full-scale tests are also carried out to prove the safety of the aircraft and to satisfy airworthiness regulations. The occurrence of fatigue cracks in aircraft structures can be accepted, provided that fail-safety is demonstrated. However, also in aerospace, a full-scale fatigue test is carried out to reveal deficiencies of the structure, which then require design modifications.

A noteworthy type of full-scale tests on parts of a car is done in the automotive industry. Many parts of a car are obtained from different sources, and also in different years. Checking the fatigue quality of delivered components is desirable. Variations of the properties of a product are possible, both with respect to material and production technique. These sources of variability and their effects on the fatigue endurance is checked by fatigue experiments in small tests systems. Such tests should run as fast as possible, while usually a simple but conservative load history is used. It is quality control by fatigue experiments.

13.4 Fatigue test procedures

Specimen production

In general, it should be tried to avoid scatter in fatigue test series as much as possible in order to accurately reveal experimental trends of the results. It starts with considerations about specimen production. All specimens for a test program must be made in exactly the same way. Schütz [2] once wanted to repeat fatigue tests on a riveted lap joint. New specimens were ordered from the same industry according to the same drawing. He obtained fatigue lives about three times longer than obtained in the previous test series. Schütz observed from the dimensions of the driven rivet heads that riveting of the second series of specimens was done with a significantly larger rivet squeeze force. It has a highly favorable effect on the fatigue life. This is an extreme example of large differences between nominally similar specimens. It should be recommended that investigators visit the workshop to ascertain that all specimens are made in the same way, rather than just sending a drawing to the shop. It is also advisable to prepare a substantial number of spare specimens, which later may turn out to be needed for additional tests in view of unexpected test results.

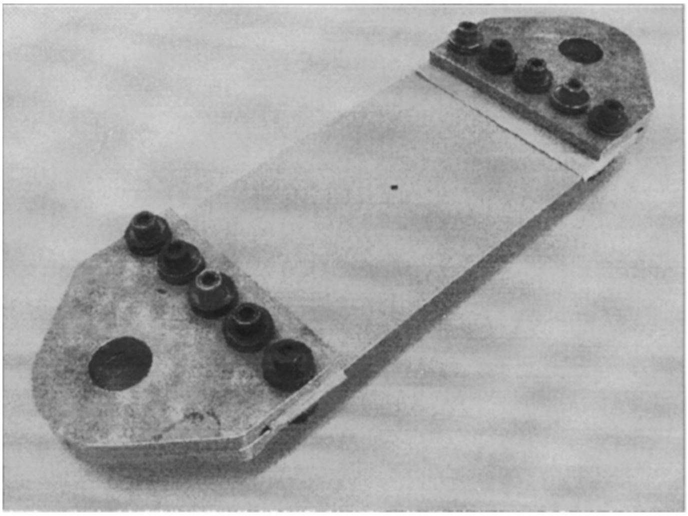

Fig. 13.4 Clamping of a sheet specimen with bolts to steel plates assembled outside the testing machine. Mounting in the machine occurs with a single pin at each end into a clevis.

Clamping of specimens

Modern fatigue testing machines are provided with standard grips which allow an easy installation of specimens in the machine if the specimens have flat ends. Due attention should be given to a correct alignment of the specimen in the testing machine to assure that the central axis of the specimen coincides with the loading axis of the machine [3]. It is recommended to check the alignment on each new type of specimen by strain gage measurements.

Several types of specimens cannot be loaded by the standard clamping method of the fatigue machine. This obviously applies to the lug type specimen in Figure 13.1, which requires a clevis to hold the pin to introduce the load on the hole of the lug. Sheet specimens are often clamped between steel plates with a row of bolts, see Figure 13.4. The bolts are sufficiently torqued to obtain a friction grip connection. The specimen with these plates can then easily be mounted in the fatigue testing machine with a pin-connection. A homogeneous load distribution on the specimen can thus be obtained. Because of the load transmission from the plates to the specimen, a significant stress concentration occurs at the edges op the clamping plates. Moreover, fretting corrosion between the plates and a metal specimen can occur near these edges. If no precautions are made, fatigue failures may be initiated at these edges. Fretting is avoided by preventing metallic contact between the specimen and the clamping plates. This can be done by placing a very thin layer between the specimen and the plates (e.g. wax paper). Also, bonding thin sheet layers (e.g. 0.5 mm thickness) on the clamping areas can be a good solution. Furthermore, the stress in the clamping area can be reduced by increasing the width of the clamping area of the specimen. This must be done for unnotched specimens anyhow, see the unnotched specimen in Figure 13.1, and also for the welded butt joint specimen in the same figure.

The problem of clamping failures is much less serious for notched specimens because the net section at the notch is smaller than the gross area, and thus the gross stress at the clamping is lower than the net stress. Moreover, the notch introduces a significant stress concentration. As a result, the net section with the notch will usually be more fatigue critical than the cross section at the clamping edges.

Sequence of tests of a test program

Fatigue test programs are usually defined in tables, indicating the number of specimens to be tested for each condition to be explored. The test program should start with a single test for each condition. It is possible that these first test results will indicate that the test program must be reconsidered.

Fatigue tests to determine an S-N curve should start with a test at a high stress amplitude. If the tests are started with a low amplitude, the amplitude may be below the fatigue limit. The specimen will not fail (run-out) after a long testing time. The only information gained is that the stress amplitude was below the fatigue limit without knowing how much.

If scatter at a high stress level appears to be low, which is usual, more specimens can be saved for later tests at low amplitudes. Such decisions require an immediate evaluation of the results of each test after it has been completed. Postponing the analysis until all tests have been completed is not a clever approach.

Service-simulation fatigue tests

Service-simulation fatigue tests and results of these test were discussed in Chapters 9 to 11. It was pointed out that load histories for such tests can be generated by computers, which are also regulating the load history in the test. A major problem is how to obtain a load spectrum for the problem to be investigated; and subsequently, how to compose a sequence of minima and maxima of the load spectrum. The approach is different for comparative tests and test associated with a specific design topic of a structure.

Comparative service-simulation fatigue tests can be used to investigate the effect of several variables (materials, surface conditions, production variables). As discussed before, some effects can be explored in CA tests on unnotched specimens. However, if fatigue problems are concerned with specific structural fatigue problems, quantitative indications on the effects are desirable. Service-simulation fatigue tests should then be used. The load history and type of specimen in such comparative tests should be representative for the structure under consideration. As an example, Schütz [4] mentions that the effect of coining (a Douglas technique to introduce favorable compressive residual stress around holes) increased the fatigue life ten times in CA tests. However, under a realistic flight-by-flight load history of the F-104 aircraft, the life increased by a factor of two only.

For several types of structures, service-simulation load histories have been designed which are characteristic for these structures. Standardized load histories are listed in Table 13.1.[18] The load histories are useful for general investigations related to these structures. However, verification of the fatigue performance of a specific structure should not be done with one of the standardized service-simulation load histories. Instead the spectrum and the load sequence must then be related to the real structure as used in service. As discussed in Chapter 9, it can be difficult to develop such a load history. Measurements under service conditions would be most useful, but that is possible only if the structure, or another similar structure is available. If full real-time load histories are recorded, the signal can be used in the fatigue machine. This is done in the automotive industry. Loads on a car are measured at several points with accelerometers or strain gages under realistic service conditions representative of intensive and practical use of the car. In a complex test set-up, the signals are simulated, but it can require a complex computer program to achieve exactly the same load history as measured. Such simulations should include the dynamic behavior of the car including the chassis. The purpose is not only to obtain fatigue lives, but also to observe the response of the structure and to find deficiencies if any.

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[18] The aerospace and wind turbine blade load histories are available on a CD from the National Aerospace Laboratory NLR, Amsterdam.

Table 13.1 Survey of the standardized service-simulation load histories [5, 6].

Year	Name	Load history for:
1973	TWIST	Transport aircraft lower wing skin
1976	FALSTAFF	Fighter lower wing skin
1977	GAUSSIAN	Random loading
1979	miniTWIST	Shortened TWIST
1983	HELIX/FELIX	Helicopter main rotor blades
1987	ENSTAFF	Tactical aircraft composite wing skin
1987	Cold TURBISTAN	Fighter aircraft engine, cold engine disks
1990	Hot TURBISTAN	Ditto, hot engine disks
1990	WASH	Offshore structures
1990	CARLOS	Car components
1991	WISPER/WISPERX	Horizontal axis wind turbine blades

13.5 Reporting about fatigue test results

The evaluation of results of a test program should include a description of the material, specimens, experiments and results. The material is characterized by its composition, heat treatment, material structure, and mechanical properties. Specimens are described by dimension, workshop practice, and surface finish. Experimental details include the testing machine, clamping of specimens, stress levels, numbers of specimens, test frequency and environment (temperature and humidity); and in addition, a description of special techniques used in the experiments. The environment is often labeled as lab air of room temperature (RT). However, the humidity of lab air can vary from very dry to rather humid. Systematic effects on fatigue crack growth in a aluminium alloys and high-strength steel have been reported, even with different results obtained in summer and winter time, which was attributed to a humidly effect [7]. Incomplete descriptions of test conditions can imply that significant information cannot be retrieved any more after some years when a re-evaluation of the test results appears to be desirable.

Fractographic analysis

The evaluation of the test results should reflect how much has been learned form the experiments. The minimum information of a fatigue test is to present the fatigue life until failure. However, a fatigue test until failure has produced a fatigue fracture surface. Fractographic analysis of a fracture can reveal valuable information contributing to understanding fatigue test results

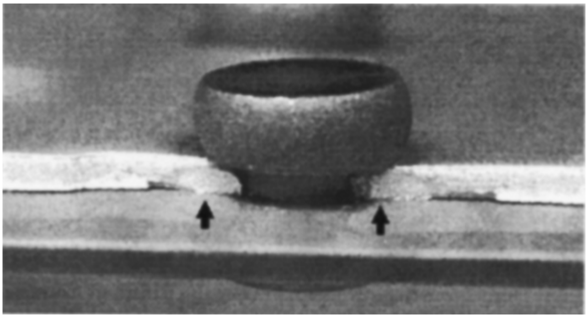

Fig. 13.5 Semi-elliptical surface cracks in a fatigue failure of a riveted lap joint of sheet material. Crack nucleation occurred away from the rivet hole, see arrows.

and their significance. It is strongly recommended to examine visually the fracture surface of each specimen with the unaided eye and a magnifying glass (six to eight times). Observations will reveal if crack nucleation occurred at the material surface or subsurface, and how many cracks were nucleated. It will also show if crack nucleation started at the most critical section of a notched specimen or away from this section. An example of the latter case is given in Figure 13.5. It shows the initial part of a fatigue failure in a riveted lap joint. Obviously, crack nucleation did not start at the rivet hole, but away from the hole. The question then is why this could happen in spite of a good fatigue performance. Such observations are essential for understanding the fatigue behavior of this type of joints. Another example, associated with an unexpectedly low fatigue test life, was discussed in the previous chapter (Figure 12.5). Fractographic observations can sometimes explain why a poor fatigue result occurred because unintentional surface damage was present.

Other useful information is related to the size of the fatigue crack at the moment of failure in comparison to the size of the quasi-static final fracture (see Figure 2.33). This gives an indication about the fatigue crack sensitivity of a material. The usefulness of fractographic observations was illustrated by several examples in Chapter 2 and the discussion in Section 2.6. Contributions of fractographic analysis, including electron microscopy, in order to analyze fatigue damage accumulation under VA loading, was discussed in Chapters 10 and 11.

An evaluation of the results of a fatigue test program without fractographic observations should be considered to be incomplete. Unfortunately, fractography is ignored too many times in publications in the open literature.

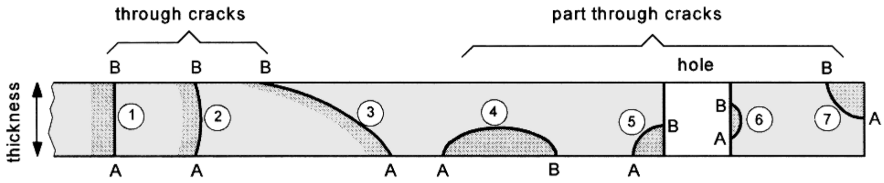

Fig. 13.6 Different shapes of crack fronts of AB through cracks and part through cracks. ① Straight crack front, ② slightly curved crack front, ③ oblique crack front, ④ surface crack, ⑤ corner crack at notch, ⑥ surface crack in notch, ⑦ edge corner crack.

13.6 Aspects of crack growth measurements

Crack growth records are data obtained by measuring the increasing size of a crack during a fatigue tests. Unfortunately, the crack front inside the material cannot be observed. Various crack front shapes are shown in Figure 13.6. Only the ends of the crack front at the free surface, points A and B, can be observed visually. Several measuring techniques have been developed for crack growth test programs. Some topics are discussed below:

1. Automation of crack length measurements to facilitate and speed up crack growth measurements. It also enables crack growth tests with a constant ΔK during a test.
2. Fracture surface analysis. It can provide information on crack front shapes, but also on local crack growth rates.
3. Crack closure measurements.

These subjects are briefly discussed, primarily for indicating experimental possibilities. More detailed information about the large variety of measurement techniques should be drawn from the literature.

Crack length measurements

In the early days, the crack length was only measured by visual observations, but this method is still frequently used. A kind of a ruler is attached to the specimen just below the crack path, see Figure 13.7. The location of the crack tip is then read from this ruler. The advantage of the visual observation method is that it is simple and does not require much preparation time. The accuracy is generally satisfactory.

Observations are improved by using a binocular microscope with a small magnification, e.g. 15 times, and a hair line system to locate the crack tip. Accuracies in the order of 0.1 to 0.2 mm can be achieved. Automatic

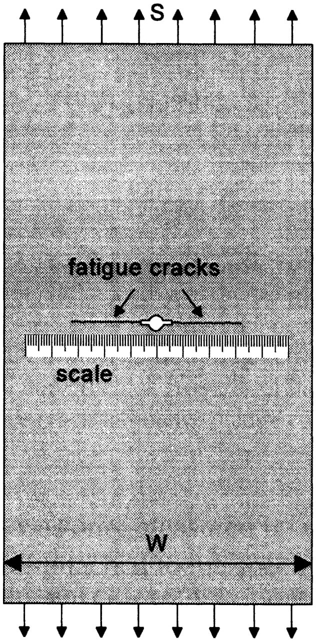

Fig. 13.7 Specimen with a simple scale for making visual crack growth records.

measurements can be performed by taking pictures at certain time intervals. A full crack growth record is obtained by video recording. Techniques have been developed to project such images on a monitor during an experiment. It is an interesting experience to see real-time opening and closing of the crack in each cycle.

Automated crack length measurements have been promoted by the introduction of the potential drop (PD) technique, see Figure 13.8. An electric current is passing through the specimen. The potential difference ($V_{1,2}$) is measured between two points at both sides of the fatigue crack (P_1 and P_2), and as a reference, also between two points (P_3 and P_4) in an undisturbed area of the specimen remote from the fatigue crack ($V_{3,4}$). The ratio $V_{1,2}/V_{3,4}$ is a measure for the crack length from which the length can be calculated. A theoretical function is available for this purpose [9], but it is advisable to determine the correlation also empirically by some calibration tests. Both DC and AC electrical currents are used in commercially available PD apparatus. With the DC option, the electric current is more uniform through the thickness of the material. It implies that the crack length of a slightly curved crack front, number 2 in Figure 13.6, is averaged. The AC method implies that the electric current occurs more along the material

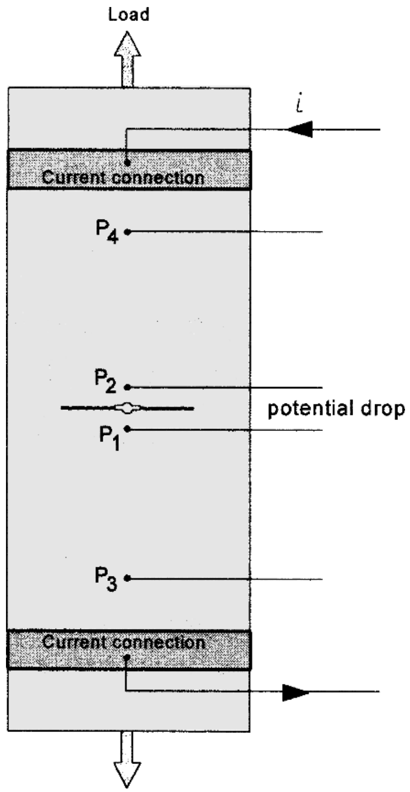

Fig. 13.8 Potential drop technique for crack length measurements.

surface, depending on the AC frequency. Both methods have advantages and disadvantages, see [10]. The potential drop measurement should be made at the maximum of the load cycle because the crack must be fully open. At lower stress levels, metallic contact between the upper and lower flank of a fatigue crack can occur which will conduct electrical current through the crack instead of around the crack. A false crack length indication is then obtained.

Results of crack length measurements consists of data pairs (a_i, N_i), i.e. the crack length a_i and the corresponding number of cycles N_i, with i as a rank number. A plot of a_i as a function of N_i gives the crack growth curve. The most simple procedure to calculate the crack growth rate as a function of the crack length is defined by

$$a = \frac{a_i + a_{i+1}}{2} \quad \text{and} \quad \frac{\mathrm{d}a}{\mathrm{d}N} = \frac{\Delta a}{\Delta N} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \tag{13.1}$$

This equation is a simple averaging method between successive data pairs. More sophisticated data fitting evaluations have been proposed [8], but the improvement of the data representation may be small.

The electrical signal of the PD crack length measurements can be directly processed in the computer to calculate the crack length and crack growth rate. The advantages is that crack growth tests can run without personal attendance. The computer can also automatically stop a test at a preselected value of the crack length.

In computer controlled crack growth tests, it is usual to adopt a constant ΔN-value between successive PD crack length measurements. The interval ΔN may not be too large in order to have enough data points when the crack is growing fast, i.e. in the last part of the test. However, this will produce a large number of data points in the beginning of the test when the crack is still growing slowly. The crack length increment Δa may then be of the same order of magnitude as the inaccuracy of the measurements, and artificial scatter will be introduced due to too many data.

An other important advantage of the PD method is the possibility to perform crack growth tests with a constant ΔK-value. If a crack is growing under CA loading, the ΔK-value increases. In order to keep ΔK constant, the load on the specimen must be reduced during crack growth. This is called load-shedding. The constant ΔK equation for a center cracked specimen is

$$\Delta K = \beta \cdot \Delta S\sqrt{\pi a} = \Delta S\sqrt{\pi a/\cos(\pi a/W)} = \text{constant} \qquad (13.2)$$

After measurements of small crack length increments, the increase of the square root function is calculated. The increase is then balanced by a small reduction of ΔS to keep ΔK constant. This can be automatically done by the load-control program of the computer by readjusting S_{max} and S_{min} applied to the specimen in order to maintain both ΔK and the stress ratio R ($= S_{min}/S_{max}$) at a constant value.

Techniques for crack length measurements, and also for crack closure measurements, are different for $M(T)$ specimens (specimens with a central crack) and $C(T)$ specimens. Advantages and disadvantages were discussed in Section 5.4. It appears that the results for $M(T)$ specimens are more reliable and relevant. A disadvantage of the $C(T)$ specimen was that cracks in this type of specimen are also opened by a significant bending moment on the specimen. In general, this does not occur with fatigue cracks in a structure.

Crack growth data published in the literature are frequently presented as a function of $\mathrm{d}a/\mathrm{d}N$ on the vertical axis and ΔK on the horizontal axis. It is hiding the size of the observed cracks. It must be advised that crack growth curves $a(n)$ should also be given, i.e. graphs with the crack length as a function of the applied load cycles.

Fracture surface analysis

Crack front shapes of oblique through cracks and part through cracks can be observed on the fatigue fracture surface with some special test procedures. A destructive method is to interrupt a fatigue test before final failure occurs. If the specimen is then pulled to failure by static loading, the fracture surface will reveal the size and shape of the crack. If the development of the crack shape is the purpose of the investigation, a number of similar notches in a single specimen can be profitable. Due to scatter of fatigue crack nucleation, cracks of different sizes will be present in the specimen and can thus be observed after opening of the cracks.

A different approach is to perform fatigue tests with VA loading. Depending on the VA load history, macroscopic growth bands will appear on the fracture surface. An example was shown in Chapter 2 (Figure 2.37). Cracks started from two side notches of a specimen loaded alternately by two different blocks of cycles. Crack front shapes are easily observed from the growth bands, and average crack growth rates in the bands can be deduced from band width measurements. The dark bands correspond to the high-amplitude cycles, and the light bands to the low-amplitude cycles.

So-called marker load cycles have also been used in CA tests. Marker load cycles are applied at a cyclic stress level which should leave some markings on the fracture surface, but the marker load cycles should give a negligible contribution to crack growth. Furthermore, the marker load cycles should not affect subsequent crack growth during the base-line cycles of the CA loading. Ichsan [11] used very small marker load cycles as shown in Figure 13.9. The faint bands of these cycles could be used for a reconstruction of the crack front shapes during crack growth of a semi-elliptical surface crack in a thick plate, see the results in the figure.

Fractographic analysis in SEM introduces another possibility based on striation observations. A marker load history, applied by Piascik and Willard [12] and later used by Fawaz [13] and De Rijck [14], is shown in Figure 13.10. The marker loads have the same Smin as the base-line cycles, but a lower S_{max}. During the period of marker load cycles, small blocks of

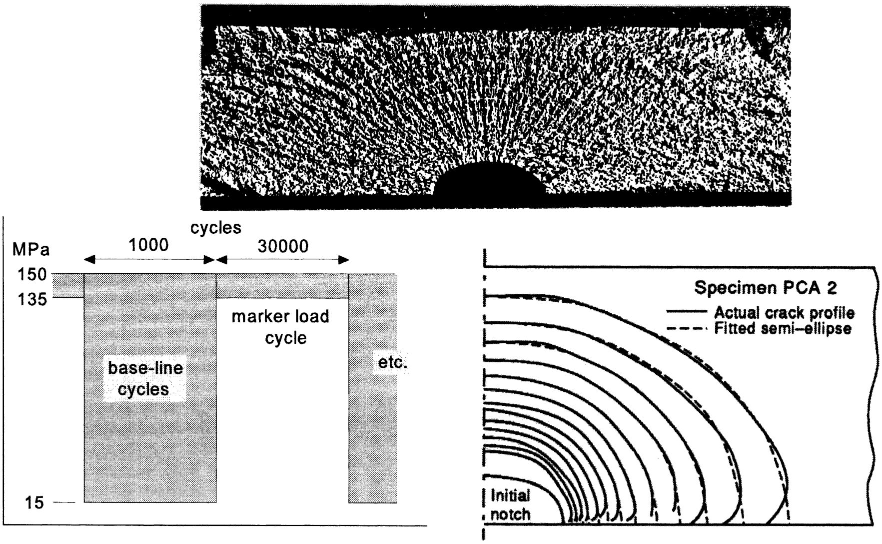

Fig. 13.9 Fractographic analysis of crack front shapes of a surface crack by using marker loads. Plate thickness 9.6 mm, Al-alloy 7075-T6, CA loading [11].

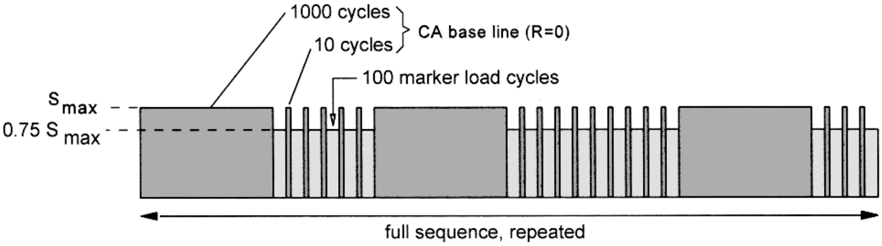

Fig. 13.10 Marker load history adopted by Piascik and Willard [12].

base-line cycles were inserted. These blocks could be seen as single lines in the SEM. The small blocks of 10 base-line cycles are applied in alternating numbers of 5, 9 and 3, see Figure 13.10. Counting these numbers in the SEM gives extra information for the correlation between the location on the fracture surface and the fatigue life in the test. A digital marking procedure was previously used by Sunder [15]. Careful fractography in the electron microscope can give valuable information, but it requires experience and a patient investigator.

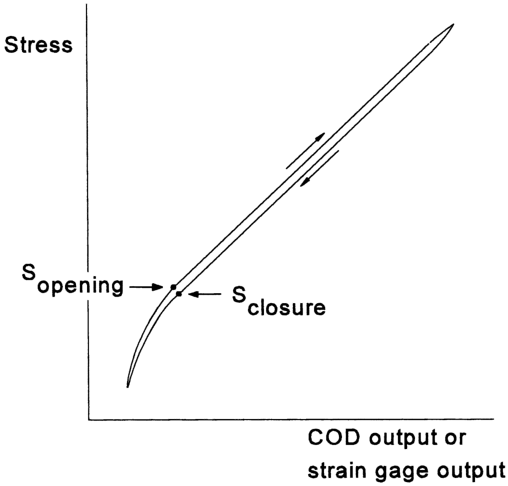

Fig. 13.11 Hysteresis of crack closure measurements. Differences between S_{op} and S_{cl}?

Crack closure measurements

Crack closure during fatigue crack growth was discussed in Section 8.4. The concept was used to describe the effect of the stress ratio R on crack growth under CA loading. In Chapter 11, the occurrence of plasticity induced crack closure was used again to explain several crack growth interaction effects under VA loading. Crack closure plays a major role in crack growth prediction models.

Since Elber detected crack closure in 1968, various methods have been developed to measure the stress level at which a crack is fully opened at the crack tip during loading, S_{op}, and the stress level at which closure starts at the crack tip, S_{cl}. A survey of methods was given in [16]. Some advanced techniques are based on optical observation of the crack tip with a microscope. In the more well known methods, a compliance technique is adopted, either by using a small displacement meter to measure crack opening displacement (COD), or strain gages bonded on a specimen close to the crack tip to measure the strain response as affected by crack closure. In both cases, a partly non-linear record is obtained as schematically shown in Figure 13.11. Some problems can be encountered. The record may show hysteresis. It may also suggest that crack opening and crack closure do not start at exactly the same stress level. These stress level are the transition points between the non-linear part and linear part of the record. It is not always fully clear at which stress level this occurs. Sometimes, the transition

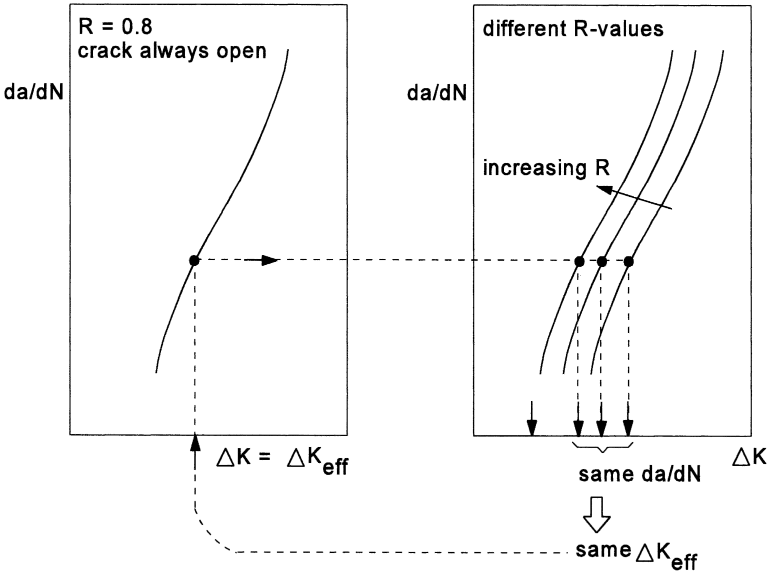

Fig. 13.12 Deviation of ΔK_{eff} in CA tests from da/dN results. Method adopted by Zhang et al. [18].

is more easily observed during unloading (S_{cl}) than during loading (S_{op}), while the latter one is theoretically of greater interest. Experience has shown that measurements close to the crack tip produce more well defined records than measurements taken at a distance of the crack tip. Anyhow, measurements confirm that crack closure occurs indeed, but it must be admitted that crack closure measurements offer problems with respect to reproducibility, accuracy and interpretation. It should be recalled from the discussion in Section 8.4.2 that crack closure stress levels under plane stress should be expected to be higher than under plane strain because of larger plastic zone sizes. As a consequence, the crack closure stress level will vary along a crack front with more crack closure at the material surface, and less crack closure away from the surface.

Measurements on crack closure along the crack front are difficult. Sunder and Dash developed a fractographic method [17], which was used by Ichsan [11] for semi-elliptical surface cracks as shown in Figure 13.9. The method, based on striation spacing measurements, confirmed that more crack closure occurred at the material surface, while crack closure along the major part of the crack front was more limited. Part-through cracks growing in the thickness direction will meet an approximate plane strain condition because of significant restraint on displacements along the crack front.

A method to obtain crack closure stress levels without crack closure measurements was adopted by Zhang et al. [18]. The method is illustrated in Figure 13.12. It starts from the assumption that crack closure is absent at high R ratios, i.e. stress cycles with S_{min} close to S_{max}. The crack is then fully open during the entire load cycle, and thus $\Delta K_{eff} = \Delta K$. Crack closure occurs at lower stress ratios. The value of ΔK_{eff} is now obtained by a cross plot as shown in Figure 13.12. The basic idea is that equal da/dN-values obtained at different R-values correspond to the same ΔK_{eff}-value. It thus can be studied how $U = \Delta K_{eff}/\Delta K$ depends on the stress ratio R. Zhang et al. [18] found an excellent agreement for crack growth data of an Al-alloy (7475-T7351). The method appears to be logical, but it should be recognized that the agreement is promoted by the ΔK_{eff} calibration procedure.

13.7 Main topics of this chapter

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.

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