Chapter 20
Designing against Fatigue of Structures

... convince your manager about designing against fatigue ... ?
... first convince yourself ...
... next your colleagues ...
...

20.1 Introduction

The present chapter is a kind of a reflection on previous chapters. It starts with a brief survey of different types of structures and related prediction problems in Section 20.2, followed by a repetition of design tools in Section 20.3. Uncertainties of predictions and safety factors are addressed in Section 20.4. Some illustrative case histories of structural fatigue problems are presented in Section 20.5. The chapter is completed with summarizing conclusions.

20.2 Different types of structural fatigue problems

The question about how to define problems of designing a structure against fatigue is obviously associated with the goals to be achieved. In principle it implies that satisfactory fatigue properties of a structure should be obtained, but it depends on the type of structures which fatigue properties should be explored. For the present discussion three categories are considered:

1. *Structures for which fatigue failures are unacceptable.*
2. *Structures in which fatigue cracks may occur after a sufficient lifetime but without the risk of a complete failure.*
3. *Structures for which crack initiation and crack growth until a complete failure are acceptable, but for which a reasonable lifetime is still desirable.*

Rotating blades of turboprop engines, wind turbines and compressors are examples in the first category. Many components of various engines are also in this category with a crankshaft as a well-known case. A fatigue failure in such components would be a kind of a disaster. The fatigue limit of the structure is the important fatigue property and high-cycle fatigue is an important issue. However, fatigue failures may also be unacceptable in pressure vessels for which the number of pressurization cycles is not very large, e.g. not exceeding 10^5. If all cycles have practically the same load range, the relevant fatigue property is the crack initiation life under CA loading.

A variety of structures can also occur in the second category. Obviously the crack initiation life is again of interest, and it should be large enough for a satisfactory lifetime in service. If a complete failure is unacceptable, a reliable inspection procedure is indispensable. This applies to aircraft structures, and it can also be applicable to several welded structures. As a consequence both the crack initiation life and the crack growth life are of interest. Moreover, fatigue under VA amplitude loading may also be a relevant condition.

The third category includes various utilities for which final failure simply implies that it must be replaced by a new one. Various housekeeping articles are in this category, e.g. washing-machines, vacuum cleaners, but not stairs. Bicycles are another typical example in which fatigue failures do occur. The fatigue property is the fatigue life until failure with lifetime as an economical criterion. Data on crack initiation life and crack growth properties are not required, but again both CA and VA load histories can be significant.

The three categories of structure have been defined because within each category similar fatigue properties should be predicted. The literature on fatigue prediction problems is quite diverse. The world of building steel bridges and the world of manufacturing wind turbines are two different cultures, but still with similar fatigue problems. As an example, in both worlds load spectra are consisting of a combination of deterministic loads and random loads.

In practice the designer who is faced with fatigue endurance problems, must also consider other durability issues, such as: maintenance, inspections, repairs, replacements, service conditions with implications for corrosion, wear and tear. They are all a matter of concern dealing with the structure as an object that should be in function for a long time. Anyway, the possibility of fatigue crack initiation is a relevant problem because it can have a large economic impact. Designing against fatigue crack initiation is one of the responsibilities of the designer of the structure. Figure 1.2 of Chapter 1 is reproduced here in a slightly different layout. It shows that predictions require:

(i) information about the structure,
(ii) analysis and fatigue data, and
(iii) last but not least, the load spectrum.

In the literature it is sometimes suggested that our fatigue problems are solved if an accurate prediction model would be available. This is misleading. The present physical understanding about fatigue damage accumulation is reasonably well developed in a qualitative sense. And just because of this understanding, it must be accepted that accurate quantitative predictions on fatigue lives are illusory.

Problems of fatigue life and crack growth prediction were discussed in Chapters 7, 8, 10 and 11 for notched elements, and in Chapters 18 and 19 for joints. It was indicated how estimates of the fatigue limit of notched elements could be obtained. Unfortunately, similar prediction procedures are not applicable to fatigue of joints. Empirical data of joints must be available to arrive at estimated of the fatigue limit. Predictions on the fatigue life under VA loading is even more complicated. The Miner rule is physically rather primitive. The rule starts from the idea that damage can be characterized by a single damage parameter which essentially disagrees with the present knowledge about fatigue damage accumulation. At best, the Miner rule gives some weighted indication of the load spectrum, but not of the severity of the load spectrum. The Miner rule fully breaks down in comparisons of load spectra severities. When the Miner rule is used to obtain some rough indication of the fatigue life under VA loading, one should realize that the prediction is an extrapolation of S-N data which by itself have already a limited reliability.

The situation appears to be more convenient for predictions of fatigue crack growth. Crack growth prediction for CA loading based on the well-known fracture mechanics methodology can be reasonably reliable. But the situation is less satisfactory for fatigue crack growth under VA loading, see the discussion in Chapter 11. A major problem is to account for interaction effects of cycles with different amplitudes. If the interaction effects are ignored, predictions will probably be conservative, but it can lead to significant under-predictions for crack growth under steep load spectra.

In general terms, it must be accepted that fatigue predictions are speculative in a way that the order of magnitude may be instructive, but the predictions should be evaluated with appreciable judgement. In cases of doubt, the design variables should be reconsidered to see where weak links are present. Estimates of fatigue properties can be improved by experiments. Whether this is really necessary depends on safety margins and costs involved. Detailed stress analysis, fatigue experiments and load spectrum measurements can improve the significance of predictions. It is possible that a simple fatigue analysis shows that the occurrence of a fatigue failure problem is very unlikely, and no further design improvements are necessary. It is also possible that fatigue failures in service are acceptable because a simple replacement of the failed element is not expensive and safety is not involved. In such cases, a cost-benefit analysis can show that efforts to improve the fatigue prediction are not really worthwhile. But it is also possible that a simple prediction indicates that structural improvements must be considered, i.e. designing against fatigue. It then is useful to have some idea about the accuracy of preliminary fatigue life predictions. Several sources of uncertainties in the prediction technology should be considered, including the strategy of applying safety factors.

20.3 Designing against fatigue

The fatigue life as discussed in Chapter 2 is divided into two periods with final failure at the end of the life:

crack initiation period → *crack growth life* → final failure

The practical significance of recognizing the differences between the two periods has been emphasized in several chapters. *A designer should know*

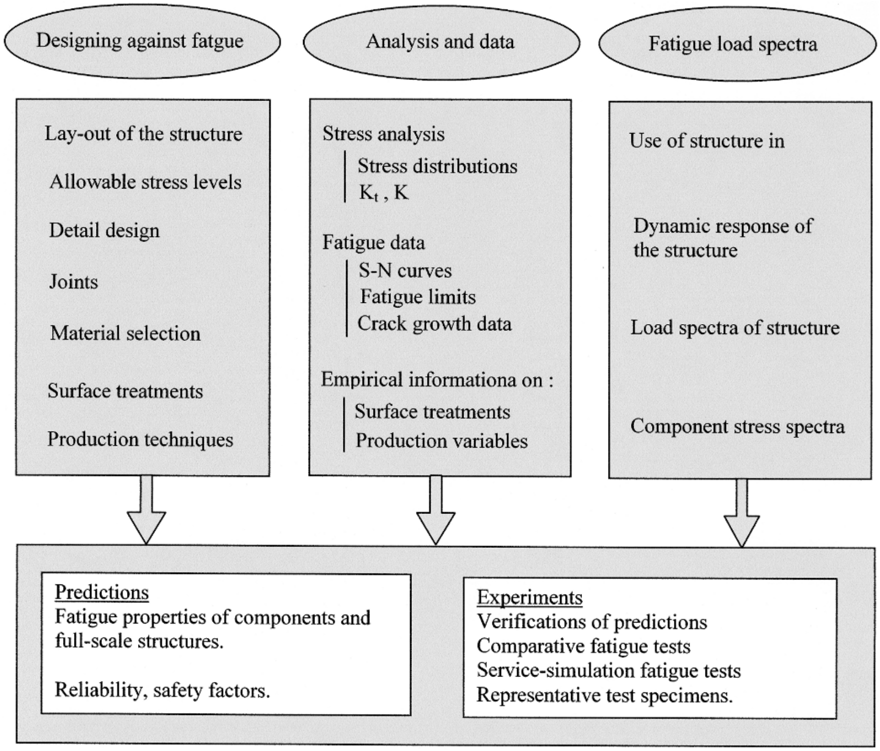


Fig. 20.1 Survey of topics associated with designing against fatigue.

whether he is designing against crack initiation, or for an acceptable crack growth behavior, or for both. Moreover, he also should be aware of the question whether his problem is associated with high-cycle fatigue or low-cycle fatigue.

The initiation period is basically a material surface phenomenon, whereas crack growth is a matter of crack growth resistance of the material as a bulk property. As a consequence, fatigue related influences are essentially different for the two periods. The crack initiation period and the fatigue limit are heavily depending on material surface conditions, whereas most of these conditions are practically irrelevant for the crack growth period. Understanding of the effects of these variables is essential for designing against fatigue.

The crack initiation aspect

It is easily understood from Figure 20.1 that designing against fatigue crack initiation is concerned with the general layout of a structure, detail design, material selection and surface treatments. The layout of a structure depends on the purpose of the structure. But there are various possibilities to obtain an improved load distribution in a structure, e.g. by changing local dimensions such as a locally increased thickness to reduce the stress level around a fatigue critical detail. Another example is associated with eccentricities which are causing unfavorable secondary bending. An illustrative example will be discussed later in Section 20.5.2.

Material selection

The selection of the material depends on many circumstances, such as static properties, workshop properties, corrosion resistance, thermal properties, costs, etc. It may be recalled that a material with a higher $S_{0.2}$ may have a higher S_f for unnotched specimens, but also an increased notch sensitivity, see the discussion in Chapter 7. Similarly, welded joints of a higher strength material usually do not necessarily have an improved fatigue strength.

If a new material is considered for a structural application, it should be supported by results of service-simulation fatigue tests on specimens which are representative for fatigue critical details of the structure under consideration. A different question arises when advanced fiber-metal laminates and composites materials are considered as an alternative for the more classical materials. Especially for the black composites it implies an entirely different design and production discipline, and thus another technological culture. Fatigue aspects of fiber-metal laminates are briefly discussed in Chapter 21.

Surface treatments

The designer can specify the quality of the material surface, and also certain surface treatments. Several options for surface improvements and preventing unfavorable surface effects were discussed in Chapters 14 to 16. Some typical examples of surface treatments are: fine machining, nitriding of steel, shot peening, surface rolling, prevention of fretting and corrosion protection. It has been pointed out that surface treatments are carried out for various purposes: improvement of fatigue properties, protection against corrosion, improved wear resistance, restoring poor surface quality, and cosmetic reasons. Surface treatments can increase the hardness of a surface layer, and thus hamper cyclic microplasticity. At the same time, residual compressive stresses restrain the opening of microcracks in the surface layer and thus will reduce or even arrest the growth of these cracks. As a result, the major benefit of surface treatments is on the crack initiation period. They are important for high-cycle fatigue, and in particular for the fatigue limit.

Detail design for an improved stress distribution

An essentially different approach is associated with the reduction of stress concentrations. For fatigue critical notches it generally boils down to increasing root radii or applying stress relieving grooves if that is possible. Non-circular fillets are rarely considered. Recently K_t-values were calculated for elliptical fillets which are not covered in the book by Peterson [1]. Results have shown significant reductions of the K_t-value to be discussed in Section 20.5.1. It may be repeated here that various K_t-values in the book by Peterson are instructive but not always very accurate as a result of older techniques used to determine the various graphs in the book. By now FE analysis can produce more accurate K_t-values as well as stress gradients.

Large-scale design issues

Detail design as discussed previously, is associated with dimensions which are significant for local stress concentration, e.g. a hole diameter or notch root radii. On a larger scale, the designer is considering the general concept of the structure. As an example, although perhaps a somewhat curious one, rather different concepts can be contemplated for designing a bridge. Another noteworthy example, in various structures joints are present, but the variety of different joint concepts is also large. Decisions to be made on the type of structure are generally depending on experience of the industry, and in the industry on economic implications.

20.4 Uncertainties, scatter and safety margins

The purpose of designing against fatigue is to prevent disasters, and also to avoid non-fatal incidents in view of unwanted economic consequences. Unfortunately, uncertainties about the fatigue performance of a structure cannot be solved by accurate and rational arguments. It implies that some philosophy about safety factors or other measures should be considered. A solid rational frame work to arrive at safety factors cannot be formulated. Statistical distribution function are unknown. Information about scatter of fatigue properties is largely coming from laboratory test series (see Chapter 12), and not from service experience. The choice of reasonable safety factors is a matter of experience and engineering judgement. Both economic and safety consequences of the occurrence of a premature fatigue failure must be considered. In view of limited accuracies of quantitative fatigue predictions, it must be asked how this situation should be carried on. The variety of sources for uncertainties is fairly large. They will be briefly discussed.

20.4.1 Uncertainties

Three reasons for uncertainties about the prediction of the fatigue performance of a structure are easily recognized:

(i) Uncertainties about the load spectrum.
(ii) Uncertainties about the fatigue properties of the structure.
(iii) Uncertainties about the reliability of predictions.

Not all these uncertainties can be associated with scatter of some properties. Variations of the load spectrum were discussed in Chapter 9 including differences between deterministic loads (applied by the operator) and stochastic loads (random type loads depending on environmental conditions). With respect to the deterministic loads, all structures of the same type are not used in exactly the same way. The designer must consider the variability of loads which should be taken into account (functional loads, maneuvers). But another part of the variability of the load spectrum does not depend so much on the operator. Stochastic loads are relevant to structures operating under a variety of weather conditions (aircraft, boats, drilling platforms) or moving over various roads (passenger cars, trucks, coaches). Statistical distribution functions and power density spectra can be involved for air turbulence, sea-waves and road roughness. Several types of structures will see a combination of deterministic and stochastic loads. Cranes, bridges and buildings offer interesting combinations of both types of loads.

The second reason for uncertainties is associated with fatigue properties of the structure. These uncertainties are of an entirely different nature. Statistical variations are related with material properties and production quality. The fatigue properties of a material with a standardized composition may be obtained from data banks, but it cannot be guaranteed that these properties are always the same. Scatter may occur as a result of batch to batch differences, but even in a single plate statistical variations are possible. Moreover, the crack initiation fatigue life is depending on the quality of the production of components. There are sufficient reasons why components produced during a number of years cannot be considered to be samples of the same statistical population.

Finally, the third source of uncertainties is associated with the reliability and accuracy of a prediction model. As discussed in several chapters, estimates can be obtained for S-N curves, fatigue limits and crack growth. But is was also explained why accurate predictions are problematic, especially for the crack initiation life, while VA loading is an additional problem.

20.4.2 Scatter and safety factors

The fatigue limit and the safety factor

As discussed earlier, an important category of problems of designing against fatigue is associated with high-cycle fatigue and a flat load spectrum. If fatigue failures are unacceptable, the criterion is that all load cycles should be below the fatigue limit of the structure. The variables involved are the maximum load cycles occurring in service load spectra and the fatigue limit of the structure. They are both affected by uncertainties. It can be tried to obtain an estimated value of the fatigue limit of the structure, but even if the analysis would be supported by experiments, some unknown scatter must be expected. With respect to the load spectrum uncertainties are involved, not so much as a consequence of scatter, but due to different utilizations. Under these twofold conditions, a safety factor cannot be defined with rational arguments. If a fatigue failure of the structure would cause a fatal accident, relevant experimental efforts should be considered. A full-scale fatigue test

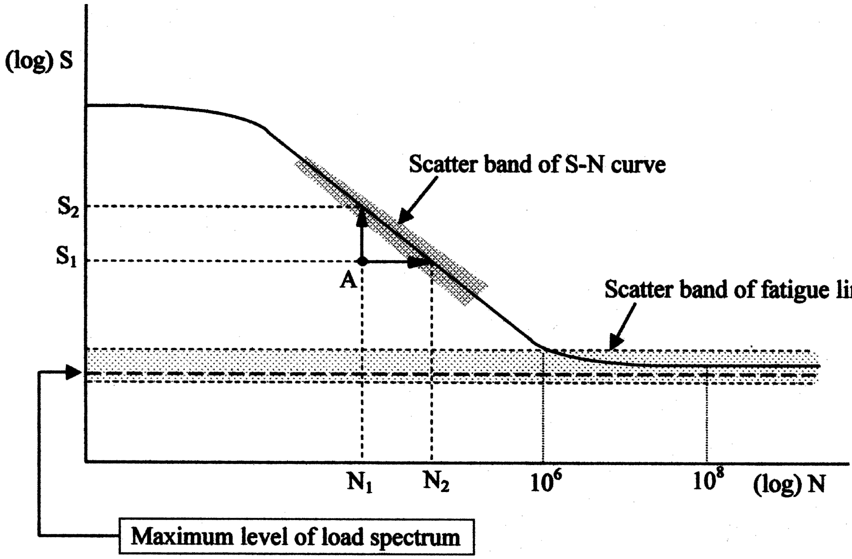


Fig. 20.2 Safety margin on load level S_1 for required life time N_1. A similar margin for the fatigue limit is unrealistic.

on a representative part of the structure with the step by step increasing load (see Figure 13.2) can give useful information about the fatigue limit.

A full-scale CA load tests at the estimated load level of the load spectrum cannot be recommended. The test should be continued to a very high number of cycles, say $> 10^8$. However, if the load level is just below the unknown fatigue limit, see Figure 20.2, then failure will not occur. In view of the scatter band of the fatigue limit, an other similar structure can fail at a fatigue life between 10^6 and 10^7 cycles, just above the average fatigue limit. It implies that information about the safety level remains unknown. In the high-cycle fatigue regime and for the fatigue limit, scatter of fatigue lives is not the relevant issue. Scatter of the fatigue strength, and in this case of the fatigue limit, is crucial. For this reason the step by step increasing test of Figure 13.2 should be preferred. Of course the number of cycles in each step (ΔN) should be large enough in order to be in the high-cycle fatigue regime, for instance $\Delta N = 10^6$ or 2×10^6 cycles.

The fatigue limit S_f obtained with the step-by-step method and also the load spectrum in service are not free from uncertainties. A safety factor should be adopted. Since quantitative indications on scatter are lacking, an intelligent guess must be made. Possible consequences of fatigue failures in service have to be considered. It is believed that a safety factor of 1.5 can be sufficient in many cases. However, if more confidence is desirable, more fatigue tests should be carried out. Another approach is to carry out load history measurements in service to have more information about the load spectrum.

Safety factors for finite fatigue life problems under CA loading

Crack initiation cannot be avoided if stress amplitudes above the fatigue limit occur in the service load spectrum. As a consequence, fatigue crack initiation is possible and a finite life should be considered. A typical example is represented by a pressure vessel. A safe approximation of the load spectrum is that the pressure vessel is always loaded to the same maximum operational pressure. Load spectra of other structures with a flat load spectrum can be approximated in the same way. A safety factor can now be defined in two different ways. The factor can be applied to the fatigue life or to the fatigue strength. If a finite life is envisaged, the natural approach is to think in terms of endurances which guarantee a sufficient lifetime. If N_1 is the required lifetime and N_2 the estimated fatigue life, see Figure 20.2, then the safety factor is $f_N = N_2/N_1$. However, in terms of the fatigue strength, if S_1 is the required fatigue strength and S_2 is the estimated fatigue strength, then the safety factor $f_S = S_2/S_1$. Adopting the Basquin relation ($S_k \cdot N =$ constant), the relation between the two safety factors is $f_N = (f_S)^k$. If loads exceeding S_1 should not be expected or even be impossible, then the safety factor for the fatigue life should be considered. However, if required lifetimes larger that N_1 are of little interest then the safety factor for the stress level is more appropriate. The size of these safety factors to be adopted depend on the consequences of a fatigue failure. Obviously larger factors are necessary if fatal accidents are possible, say 1.5 on the stress level or 6.0 on lifetimes. In such a case, a realistic experimental verification test must be advised. If the consequence of a final failure are not serious, a smaller safety factor can be adopted, say 1.2 on the stress level, or 2.5 on the fatigue life. If the quality of the stress raisers is poor (e.g. in low-quality welds), larger values may be worthwhile. Engineering judgement and experience from previous structures should be practiced.

Safety factors for finite fatigue life problems under VA loading

The VA load case offers an additional uncertainty if compared to the CA load case. Predictions for a VA load history are affected by the unreliability of the Miner rule. It is difficult to understand how this might be accounted for by a safety factor. As said in Sections 10.4.2, when using the Miner rule, it appears to be wise to extrapolate S-N data below the fatigue limit. In cases of doubt, some exploratory service-simulation fatigue tests are much recommended.

Safety factors and fatigue crack growth

Safety factors on fatigue crack growth have to be considered if the crack growth period covers an essential part of the lifetime in service. This can occur when cracks are initiated at material defects, corrosion pits, or sharp corners with a high stress concentration. It can also start from unintentional surface damage caused in-service (nicks, dents, scratches, impact damage, etc.). In welded structures, crack initiation is possible from weld defects, but also at the edge of the weld toe due to a locally unfavorable profile. All these situations are undesirable, but they cannot always be avoided. In view of safety, it may be necessary to consider fatigue lives with a practically zero crack initiation period. It is kind of a worst case analysis which should be made if complete failure is unacceptable.

Two different cases can be defined:

1. Crack growth is accepted, but the occurrence of a complete failure must be prevented by periodic inspections.
2. The crack growth period until failure should be larger than the design lifetime of the structure because inspections for cracks in service are undesirable or not feasible.

The first case is well-known for aircraft structures for which so-called damage tolerance requirements are laid down in official airworthiness regulations. It can also be applicable to nuclear pressure vessels or other structures if fatigue failures are inadmissable and periodic inspections must be done to detect fatigue cracks before failure occurs. The problem setting is illustrated in Figure 20.3 by a schematic crack growth curve and a corresponding curve of the decreasing static strength of the structure caused by the growing fatigue crack. Failure of the structure is supposed to occur at a critical crack length, a_c. Cracks can be detected at the crack length denoted

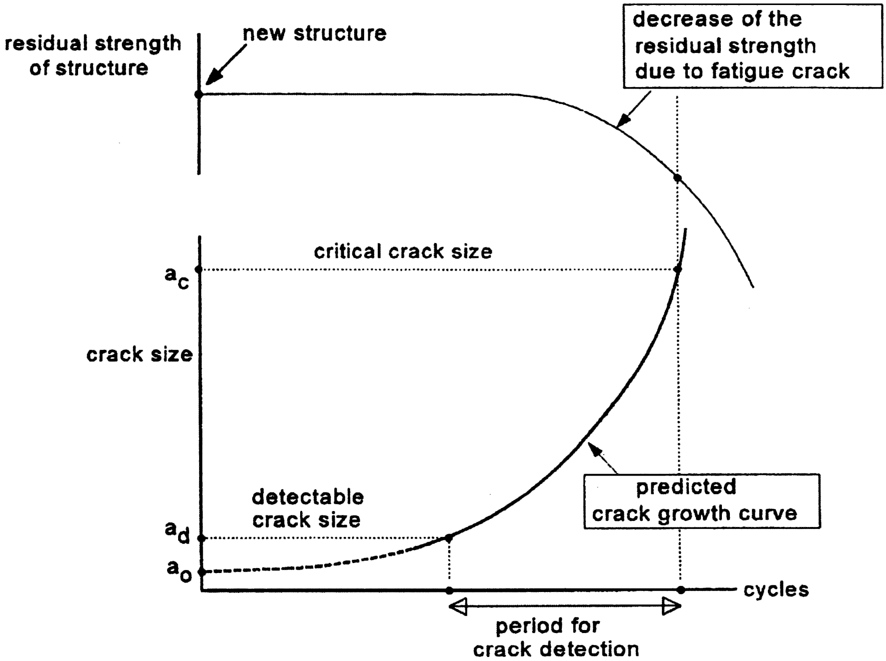


Fig. 20.3 Principle of safe crack growth by period inspections.

as a_d. The period for crack detection covers crack growth from a_d to a_c, see Figure 20.3. The number of uncertainties is fairly large: (i) the initial crack length a_0, (ii) the final crack length a_c, (iii) the crack growth data of the material, (iv) the load spectrum, (v) the crack growth prediction model, and (vi) the probability of detecting a fatigue crack.

All uncertain topics are quite obvious. They are addressed here with a some comments only. Limitations of crack growth predictions have been discussed in Chapters 8 and 11. The probability of crack detection depends on the non-destructive techniques adopted. Questions can be raised whether a surface crack with a length of a few millimeters can be detected. In general, very small cracks, say 1 mm (0.04 inches) cannot be detected reliably. Crack detection of invisible cracks, e.g. in joints, must be done with special inspection techniques.

Secondly, it must also be established how far the crack may grow before the risk of a large failure is present. The crack must be found within the crack growth range between the detectable crack size (a_d) and the critical crack size (a_c), see Figure 20.3. A safety factor should then be applied to this period to assess the inspection period. In the past, a factor 3 has been used for transport aircraft, but more recently, the tendency is to use a factor 2. Obviously, the choice of the safety factor is a matter of judgement, which requires that all sources of uncertainties are recognized and understood. It should also include the human factor of the inspection procedure. If a large number of structures must be inspected, most of which will be free from cracks, an occasionally occurring small crack might escape detection. Situations of finding cracks in order to prevent dangerous situations are not confined to aircraft. It also applies to other types of structures if a fatigue failure cannot be accepted, e.g. for pressure vessels. Operators of large structures try to combine inspections with periodic maintenance for economic reasons. Actually, operators prefer structures which do not require inspections.

The size of the initial crack length (a_0) must be associated with the size of some initial defect. This is a difficult issue because the crack growth rate of initially small cracks is very low. As a consequence, the predicted crack growth life will significantly increase for a smaller value of a_0 as discussed in Chapter 8 (see Table 8.2). It is more conservative to select a larger a_0-value, but which size? The final crack length, a_c, is reached at the moment of failure. It requires that the reduction of the residual strength of the structure is calculated as a function of the increasing crack length, which is not a simple calculation because macroplasticity will occur. However, the crack growth rate in the last part of the crack growth period is relatively high, and assuming a lower a_c will have a small effect on the crack growth period, see again Table 8.2.

The crack growth prediction model is less problematic for a CA load spectrum than for a VA load spectrum. In case of CA loading, predictions may give reasonably reliable results provided that K solutions are available. Quite often, K solutions are not available, even for structural elements with a simple geometry. Small cracks are usually part through cracks at the material surface. If K-values are not available, they can be calculated with FE techniques, but it requires expertise on this topic.

Predictions on crack growth during VA loading offer problems due to interaction effects discussed in Chapter 11. Ignoring these effects should be expected to give a conservative prediction for most load spectra. The basic CA crack growth data used in the prediction are also subjected to uncertainties. Variations can occur between nominally similar materials from different producers. Even differences between batches from the same producer have been found, see Figure 8.16. It may be recalled from Chapter 11 that small cycles with $\Delta K < \Delta K_{th}$ can still contribute to crack growth. It was proposed to extrapolate the $\mathrm{d}a/\mathrm{d}N - \Delta K$ function in the Paris regime to low $\Delta K < \Delta K_{\mathrm{th}}$.

Safety aspects associated with a corrosive environment and low frequency fatigue

The previous discussion did not include possible effects of a corrosive environment and load cycles with a very low frequency. The problem of corrosion fatigue was discussed in Chapter 16, where it was pointed out that the effect of corrosion on fatigue depends on the material/environment system. Unfortunately, most types of steel and aluminium alloys are sensitive to corrosion. It can imply that these materials are also sensitive to the frequency and wave shape of the load cycles. Unfortunately, the effect of corrosion fatigue cannot simply be described by a quantitative model. Experience should indicate how to deal with safety issues introduced by a corrosive environment.

In Chapter 16, it was pointed out that corrosion can affect both crack initiation and crack growth. The fatigue limit case was discussed in the present chapter as being relevant to problems where crack initiation is not allowed (flat load spectra with all cycles below the fatigue limit). Obviously, the application of safety factors does not preclude the occurrence of corrosion. Pitting and other local corrosion phenomena can occur in a corrosive environment, and subsequent crack growth will be activated. It might be hoped that cracks should not grow at low stress amplitudes, but it would require a high safety factor (see Figure 2.29 for mild steel). The best solution is to prevent corrosion at the material surface. Sometimes this is done by preventing the access of the aggressive environment to a fatigue critical element of a structure. Corrosion resistant surface layers can be considered also, but experience should indicate whether this will be successful. Another solution is shotpeening of the material surface. This would not prevent corrosion at the material surface, but the residual compressive stresses may prevent crack opening and further crack growth. An example of this application is shotpeening of springs used in cars.

If water is trapped in the structure, the consequences of a stagnant water environment may be disastrous. An example was discussed in Chapter 16.4. Trapping of water should be avoided, either by design or sealing of critical locations.

Corrosion fatigue can be problematic for structures used in the open air or in the sea, e.g. for bridges, cranes, ships, offshore structures, but also for many other structures. In the open air, rain and fog are causing a moist environment of usually polluted water, which is an aggressive environment. After fatigue cracks have been initiated, the corrosive environment can enhance crack growth. As discussed in Section 19.6 on welded joints, accelerated crack growth has been observed in comparative tests carried out in air and salt water. In salt water, crack growth could be about three times faster. A safety factor of three applied on the crack growth life may be reasonable. If fatigue failures in the environment of the structure would have serious consequences, it might be necessary to support the fatigue analysis by relevant experimental work. The problem is how a service-simulation fatigue test should then be carried out in view of corrosion being a time dependent phenomenon. The frequency of the cyclic loads in service may be low and an exact simulation can imply an unacceptably long duration of the test. A compromise should be considered. Certain parts of the load-time history can be simulated faster than the history in service, while the more damaging load cycles can be applied with the loading rates relevant for the service load-history. It then should be recognized that the increasing load part of a cycle is the most important part for fatigue crack increments, see the saw tooth effect discussed in Section 16.2.2.

Another interesting alternative to service-simulation tests is to build a few prototypes of the structure and to test these prototypes in a realistic but severe application in service. This has been done for cars and trucks, which were tested by severe driving along selected tracks with rough road conditions. Actually, such tests are not done for fatigue only. It should show a satisfactory functioning of all parts of a structure under severe conditions. However, it also can reveal insufficient fatigue properties.

20.5 Some case histories

Four case histories are presented in this section as illustrations of design aspects discussed previously. It has been repeated that accurate predictions of fatigue properties are illusory. At best, a reasonable estimate can be made, and it requires a good deal of understanding and experience about fatigue problems in order to evaluate the significance of calculated results. It has been pointed out that a verification with realistic experiments should be considered in cases of doubt. The case histories to discussed are associated with:

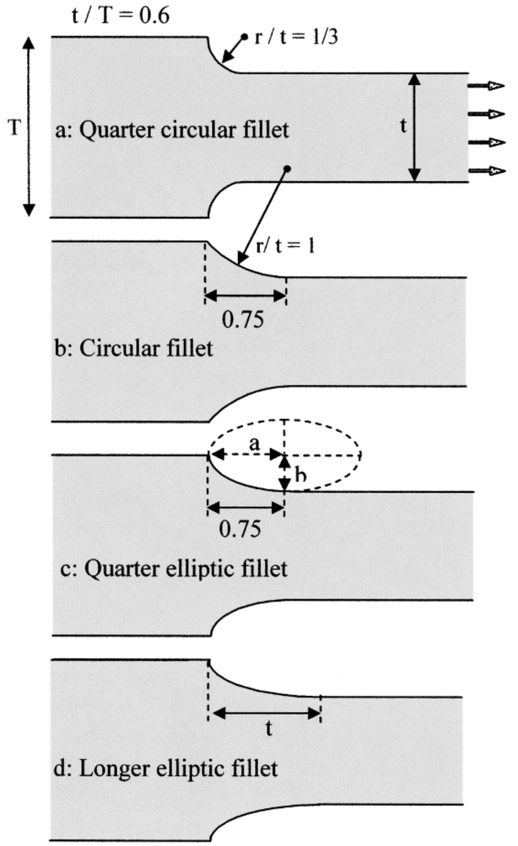
1. Improved shoulder fillets.

2. Secondary bending introduced by non-symmetric hole reinforcements.
3. Cracked aircraft wing panel repaired with a poorly designed patch.
4. Online structural health monitoring of the Tsing Ma Bridge.

20.5.1 Improved shoulder fillets

Peterson, in his book *Stress Concentration Factors* [1, 2], presents graphs with K_t-values for shoulder fillets, both for flat plates and round bars. Shoulder fillets occur in various structures. They are also important for laboratory specimens in order to avoid fatigue failures near the clamping of the specimens. It is well known that large fillet radii will give lower K_t-values, but in a structure that is not always possible. Quarter circular fillet are still frequently applied. Recently FE calculations were made for circular fillets, and in addition for quarter elliptical fillets [3]. It was expected that elliptical fillets would be superior to circular fillets, but K_t-values for these fillets are not in the book by Peterson. Results are presented in Figure 20.4 for both flat plates and circular bars. Increasing the root radius from $r/t = 1$ (quarter circular) to $r/t = 3$ gives a substantial reduction of the K_t-value. However, with the quarter elliptical fillets another interesting reduction is obtained.

It is of some interest to compare the K_t-values of the circular fillets obtained with the FE calculations with results obtained from graphs in the book by Peterson. For the shoulder fillet in a plate K_t-values for the dimensions in Figure 20.4 are not in his book. But values can be obtained with interpolation between the graphs for a stepped flat bar which may be considered as consisting of two mirrored shoulder fillets. The agreement with the present FE results is fully satisfactory. For the quarter circular shoulder fillets in a round bar Peterson shows K_t-values up to $r/t = 0.3$. With a small extrapolation and interpolation it suggests $K_t = 1.43$ to be compared with $K_t = 1.388$ of the FE calculations. Peterson warns that the data in his book for this case are approximations. In conclusion, with simple FE calculations accurate stress concentration factors can be obtained where as a lot of published data on K_t-values were obtained with photo-elastic techniques or with Neuber interpolation techniques applied to analytical solutions.



K_t - values	
Plate	Round bar
1.519	1.388
1.245	1.165
1.151	1.106
1.094	1.056

Fig. 20.4 Circular and elliptical shoulder fillets of a flat and a round bar tensile specimen.

20.5.2 Secondary bending introduced by non-symmetric hole reinforcements

Open holes in a structure may be fatigue critical because a significant stress concentration can be involved. Without any reinforcement around the hole a stress concentration with a K_t-value slightly below 3.0 will be present. Several decades ago a drain hole was machined in a plate of the tension skin of the wing of a large aircraft. The plate thickness around the edge of the hole was increased as shown in Figure 20.5. The purpose was to reduce the stress concentration. The aluminium alloy plate was produced by

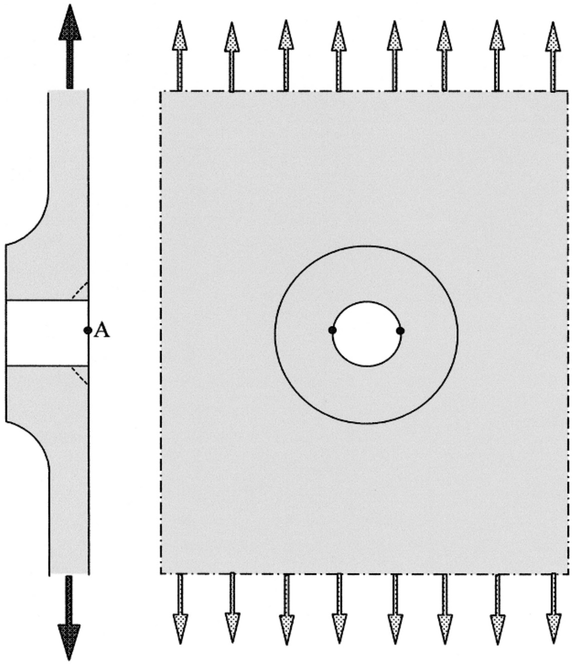


Fig. 20.5 Reinforcement of the hole edge introduces an eccentricity and thus secondary bending. Crack initiation occurred at point A.

computer controlled machining. However, it was overlooked that the thicker hole edge introduces an eccentricity which will cause secondary bending (see Section 18.5). Moreover, the reinforcement is adding locally increased stiffness to the plate around the hole which can attract load to the hole. Because of the additional bending stress, crack nucleation occurred at point A. The crack was found in a full-scale tests. A number of aircraft was already in service. A provisional solution was adopted consisting of tapering the hole (dashed lines) and shot peening of the tapered area.

The stress distribution including the secondary bending can be analyzed with FE calculations. Recently such calculations were made [3]. Selected results are presented in Figure 20.6. The maximum stress for the unreinforced hole agrees with the result obtained with the K_t-value in the book by Peterson. Secondary bending is still avoided if the thickness is increased at both sides of the plate, which is the second case in Figure 20.6. The maximum stress of the unreinforced hole is decreased from 303 to 229 MPa, a reduction with 25%.

In practical situations it is often required that one side of the plate remains flat and the increased thickness occurs at one side of the plate only. It implies

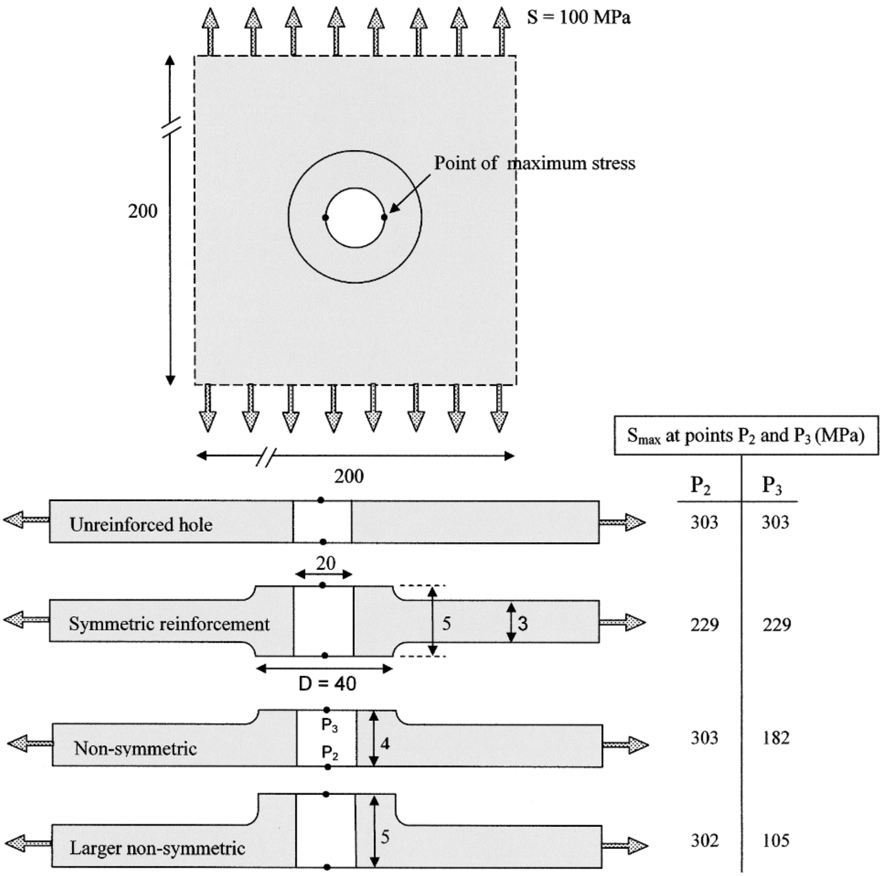


Fig. 20.6 Effect of secondary bending on the maximum stress at the edge of a reinforced hole.

that an eccentricity is introduced because the plate is no longer symmetric around the midthickness plane of the plate. Due to the secondary bending the maximum stress is larger at point P_2 than at point P_3 and even more so for the larger non-symmetry in the last case in Figure 20.6, as should be expected. But it is a striking result that the maximum stress at point P_2 is practically the same as for the unreinforced hole. Another surprising result was obtained by carrying out the same calculations for a larger diameter D of the reinforcing ring around the hole, i.e. for $D = 60$ mm instead of $D = 40$ in Figure 20.6. Actually, this is a rather heavy reinforcement, but it turned out that the maximum stress at point P_2 changed by a few percent only. The lesson to be learned is that adding or removing material around notches in a structure can satisfactorily be investigated with FE calculations. It can show instructive results for decisions on detail design questions.

20.5.3 Cracked aircraft wing panel repaired with a poorly designed patch

A fatigue crack was observed in the lower wing skin of a transport aircraft with four turbo prop engines. The tension skin of the wing box between the front and rear spar consisted of five planks with integral blade stiffeners. Figure 20.7 shows a single plank. A fatigue crack was found at the edge of a fuel access hole in middle plank after about 17000 flying hours [4]. The repair of this crack was done by a fairly large external patch and two angle sections nested inside the wing box against the skin and blade stiffeners. After some 11000 additional flying hours the repaired plank failed, but the failure was stopped at the edges of the adjacent planks which did not fail and the aircraft made a safe landing. Apparently, the fail safety feature of the five parallel planks was effective. It is now of interest to see why the repaired central plank failed. Fatigue cracks were initiated at fasteners A and B below the patch, and these fatigue cracks became unstable during a flight in severe turbulent air. The cracks occurred in the last critical end row of the repair as should be expected, see the discussion in Section 18.5. The patch and two angle sections considerably increase the local stiffness of the plank, which is good for the original fatigue crack but bad for the end row of fasteners A and B. Because of the significantly increased stiffness, load is attracted to the repair which is unfavorable for the four fasteners in the end row. As a result of the end row effect and eccentric loading on the fasteners of the end row, new fatigue cracks could easily be initiated. Note that fatigue cracks at the other end row (at the bottom in Figure 20.7) were also initiated. A better solution would be a lower stiffness repair, and a thickness tapered patch instead of a width tapered patch. A much better repair can be designed with a better understanding of the load transmission in and around the repair. A further optimization can be obtained with FE analysis.

20.5.4 Online structural health monitoring of the Tsing Ma Bridge

The Tsing Ma Bridge in Hong Kong was opened in 1997 (Figure 20.8) [5]. At that moment it was the longest suspension bridge in the world. The span

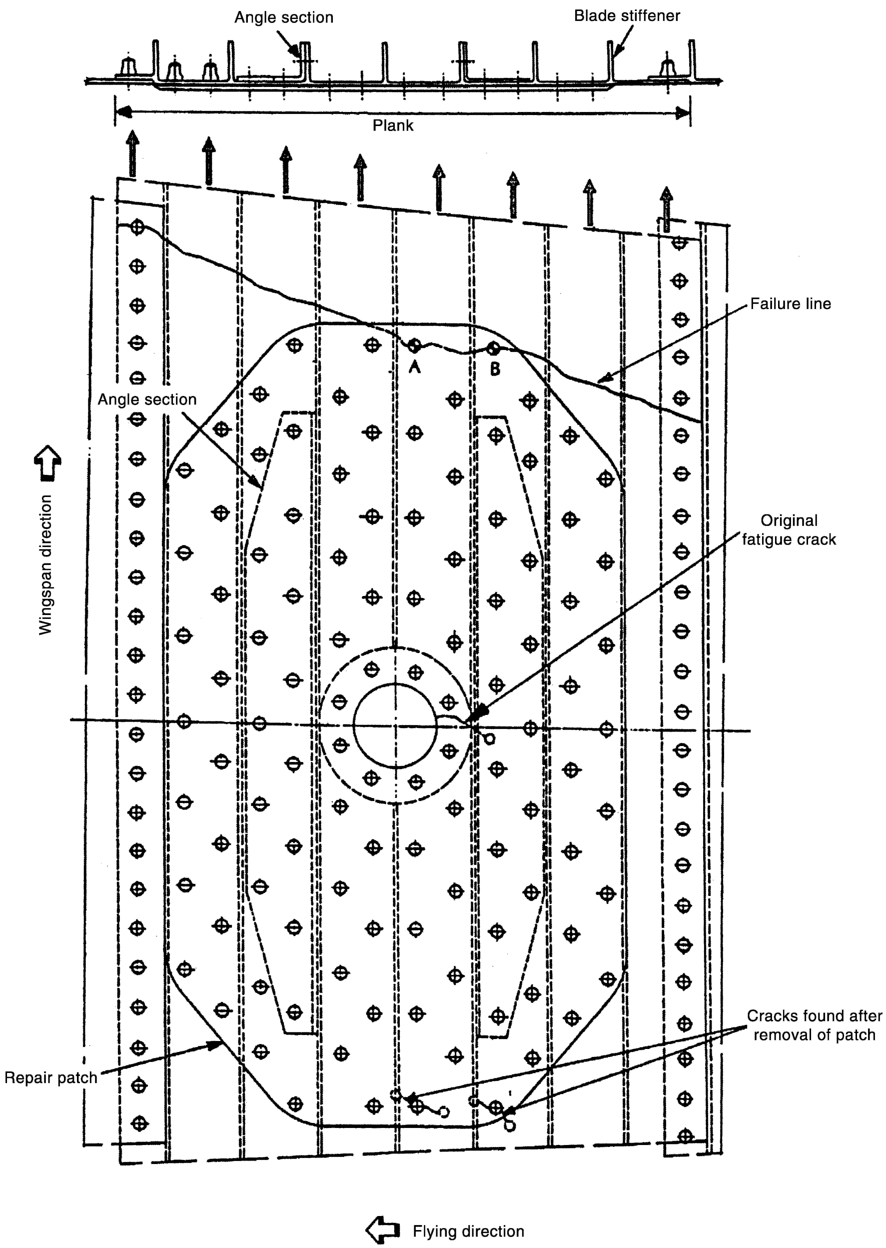


Fig. 20.7 Repair of a fatigue crack in an aircraft tension skin.

of the major part was 1377 meters, see Figure 20.9a. Details of the bridge are shown in Figures 20.9b and 20.9c. Several carriage ways and two railways

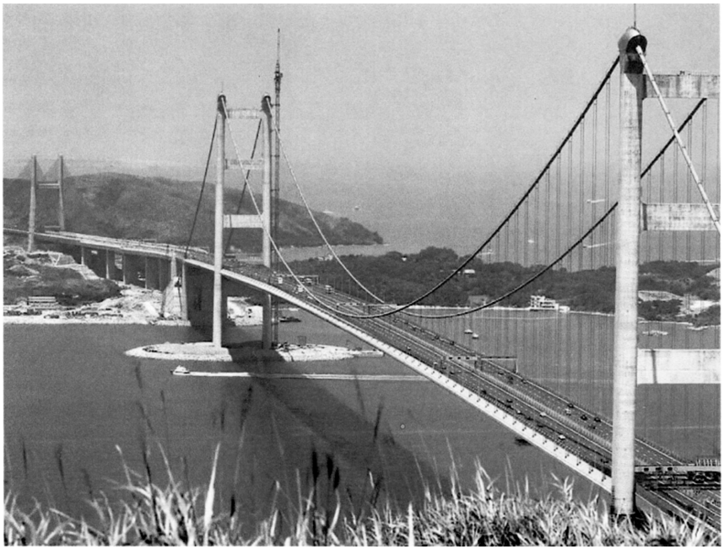


Fig. 20.8 The Tsing Ma suspension bridge in Hong Kong.

are available to take care of busy traffic. The deck section was built up as a welded framework of steel beams. It was realized that fatigue could be one of the major lifetime issues. A large number of strain gages was bonded near fatigue critical locations. A number of these gages are used for a continuous online recording. A record during 24 hours is shown in Figure 20.10a with samples in Figures 20.10b and 20.10c. Similar records were obtained on other days. Some systematic trends are easily observed. The record shows straight lines between successive maxima and minima. Little traffic between 2 and 6 o'clock (night-time), and a systematic mean stress variation with a period of one day (probably a night and day cycle, not discussed in [5]). Furthermore, a random character of the fatigue loads with a few large loads, and non-symmetric loads with respect to the average load.

A computer program was developed for a statistical analysis of the records. The results were then translated into fatigue damage for which a modified Miner rule was adopted. The procedure is known as online structural health monitoring. The approach implies that the load spectrum is continuously obtained and translated in a fatigue damage parameter. Structural health monitoring is not a design tool, but it substantially reduces uncertainties about the load history encountered by the structure in service. Actually, the message is simple. If you do not know what happens to the structure in service, just measure it. Of course, the question remains how much of the lifetime has been consumed by the measured load history.

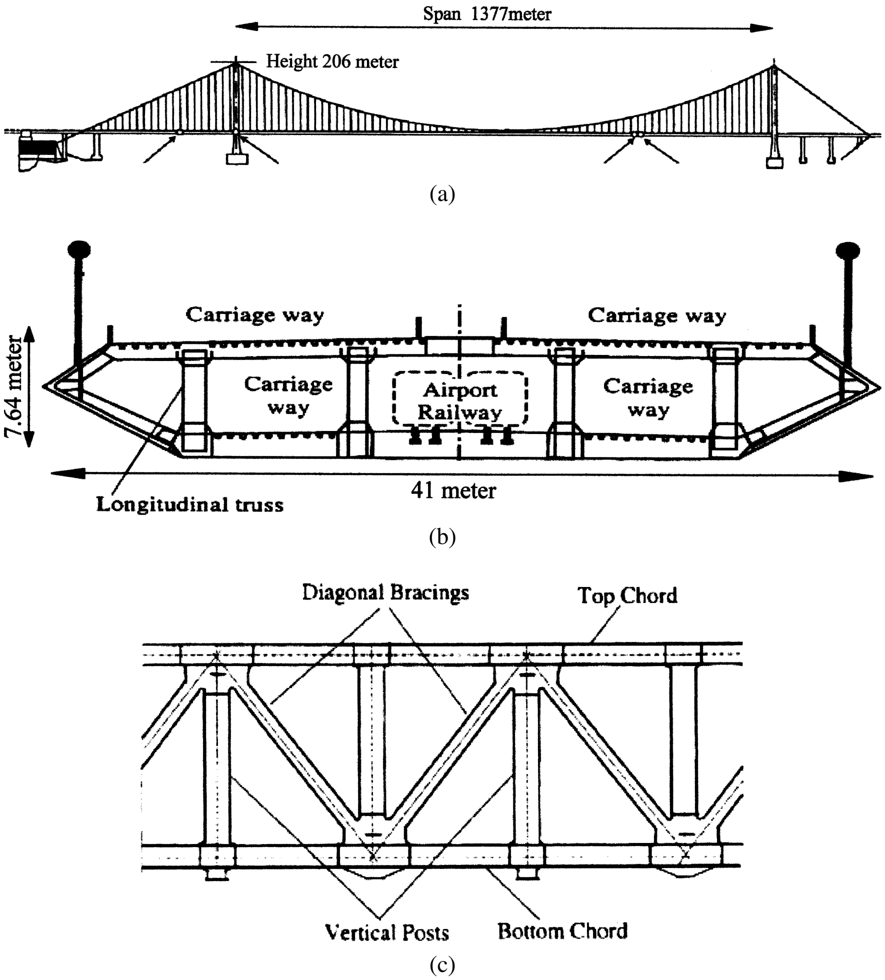


Fig. 20.9 Structure of the Tsing Ma Bridge [5]. (a) Span and height of the bridge. Arrows indicate locations of straingage. (b) Desk section of the bridge. (c) Typical longitudinal truss.

Structural health monitoring is also applied to military aircraft. The advantage then is that the load spectra from different aircraft can be compared. Because structural health monitoring requires a significant investment, it will only be done if thorough and risky conditions are applicable. But under such conditions it may well be recommended.

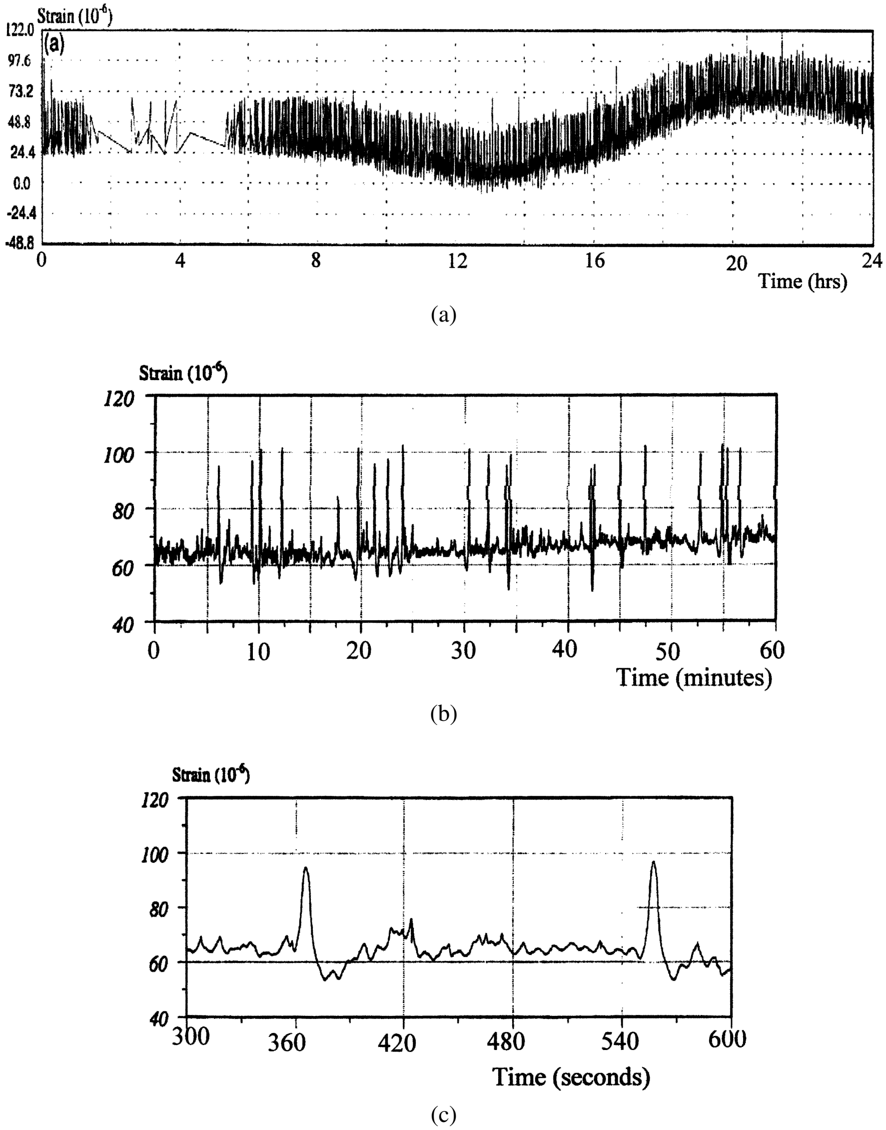


Fig. 20.10 (a) Strain-time history at May 20th, 1999. (b) Record during 1 hour. (c) Record during 5 minutes.

20.6 Summarizing conclusions

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.

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