Rail Safety & Standards Board

Research Programme

Engineering

Rolling contact fatigue of rail: Review of current understanding

Railway Safety's response to the report by Prof. Rod Smith, Imperial College, entitled 'Rolling Contact Fatigue of rail: Review of current understanding'

1. Purpose

1.1 The purpose of this paper is to outline Railway Safety's response to the attached report, and to summarise the actions being taken by Railway Safety.

1.2 The report was commissioned under the Railway Safety Research Programme (RSRP), and prepared by Professor Smith. The research was designed to provide a review of the issues surrounding rolling contact fatigue (RCF) and suggest areas for further work.

2 Railway Safety response

2.1 The report provides a sound summary and review of the background to rolling contact fatigue. It provides a good introduction to the issues associated with the interface between the wheel and rail, and the consequent structural fatigue of the rail.

2.2 Recommendation

The report identifies several areas of potential research. These include the effects of lubrication and the need for improved and automated inspection techniques.

2.3 Response

2.4 The areas identified are being incorporated into the future work of the RSRP in this area.

2.5 Two current research projects taking this work forward are:

- Rolling contact fatigue (RCF) risk model. This work is to better understand the different factors and consequences of RCF in order to enable the industry to better prioritise control measures and manage the risks.
- Rolling contact fatigue (RCF) physical model. To develop a model(s) to describe the physical processes that lead to the initiation and propagation of RCF cracks and to better understand the likelihood of RCF developing into rail breaks.

2.6 Both of these projects are planned to be completed towards the end of 2003.

2.7 There is also research and development into the various causes, effects and mitigations of RCF, including consideration of wheel/rail lubrication processes, the acoustic monitoring of rail conditions and wheel impact measurement. These projects will complete at different times but should all be available by the middle of 2003.

3. Contact

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Rolling Contact Fatigue of Rail:

Suggestions for Further Work

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Summary
This report considers some general features of our knowledge of fatigue which are particularly relevant to rolling contact fatigue (RCF) of rails.

Some gaps in our knowledge are identified. Caution is expressed about the likely accuracy of quantitative predictions of the interactions between wear and fatigue processes.

The effects of lubrication and the need for improved and automated inspection techniques are amongst the topics requiring further work.

It is argued that the industry should generate a more extensive database of the occurrence of RCF, that existing knowledge be catalogued and that international exchanges of experience of RCF be encouraged.

Report for Railway Safety

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INTRODUCTION

The Hatfield derailment of 17 October 2000, has prompted many studies to be undertaken on the phenomenon known as rolling contact fatigue (RCF) of rails.

We should recognise from the outset that this is not a new problem nor is it confined to the UK. In fact, it is a well known problem common to railway authorities throughout the world. The management and control of RCF has generally been achieved through programmes of inspection and grinding. The widespread extent of the problem which was discovered across the UK network subsequent to Hatfield was probably due to the relatively low use, in recent years, of grinding and the lack of utilisation of automated inspection techniques for the detection of rail cracks.

Knowledge of rolling contact fatigue in rails has been publicly available in books, papers and conference reports for the last 20 years. The great attention given to this problem over the last year has rediscovered some (but not all!) of this information. It has also served to advance our knowledge of some of the practical details of railway operation in the UK which affect the problem. Much of this knowledge has been generated from studies on cracked rails removed from service, but it is a matter of regret that, after inadvertently conducting the largest experiment of rolling contact fatigue in history, not enough efforts were directed to capturing more of the information generated: from the greater than 2000 crack sites discovered, only 138 samples of cracked rails were recovered and subsequently examined. A huge opportunity has therefore been insufficiently exploited.

Several major reports have been issued describing the reason why the conditions which arose on the UK network arose, the basic known facts about rolling contact fatigue, including the particular manifestation know as gauge corner cracking, and what might be done to contain, manage and possibly eliminate the problem.

It is not the purpose of this brief report to repeat all this detail. Instead it aims to highlight those areas of the problem which require further attention, both in a fundamental sense and in practical aspects.

Nearly all the material produced during the last year has discussed the special case of the fatigue of rail. It is worth stepping back from this position to first consider fatigue in general, because the principal observations which arise are equally applicable to the particular case of the fatigue of rails.

FATIGUE IN GENERAL

Fatigue was first recognised as a problem with failures associated with railways from the 1840s. Axles in particular caused problems and much early work was directed to failures of these in particular. Rails, of course, fractured: largely because of lack of resistance to impact load of the brittle iron materials used and because of excessive wear. Both problems were eased by the introduction of steel to replace wrought and cast irons from the 1860s on.

Much of the detailed experimental work was conducted in Germany, by Wöhler in particular. His work elucidated some of the key facts of fatigue:

- That cyclic, rather than static, loads lead to failure
- A fatigue limit(ing) stress existed for steels. That is, lives greater than 10^6 or 10^7 cycles could be achieved if cyclic stresses were kept below a experimentally determined fatigue limit. (This limit was about 1/3 of the static strength of the steel.)
- That finite fatigue lives at cyclic stress levels above the fatigue limit were very sensitive to stress levels.
- There is considerable scatter on life for a given stress range. Typically larger than an order of magnitude in life for a given cyclic stress level applied under nominally identical conditions to samples of the same steel. This has important repercussions for the prediction of fatigue lives.
- Mean stress affects the life: compressive mean stresses around which the cyclic stresses are superimposed, retard or suppress fatigue: conversely high positive mean stresses shorten fatigue lives.

All this early work was phenomenological and ignored study of the internal mechanisms which caused fatigue. This knowledge was slowly unravelled during the twentieth century, particularly in the post World War II years after failures in ships and the Comet jet aircraft.
It is now common knowledge that fatigue is the result of the progressive initiation and subsequent propagation of cracks.

Initiation	is typically accepted to involve crack development up to μm
Microcacks	are up to mm in size
Macrocracks	are greater than mm, and up to as long as sizeable fractions of a metre.

Quantification leading to so-called “laws” of crack development is relatively recent.
As cracks get longer, this quantification becomes more reliable, through the use of a branch of mechanics known as Fracture Mechanics.
The rate of crack growth increases strongly with crack size, over many orders of magnitude. It is then possible to get what appear to be instantaneous failures.

In general crack detection and sizing techniques (non-destructive testing, NDT) have great difficulty with small cracks. In practical applications, defects of surface length several to ten mm are the smallest we can reliably detect, although much smaller cracks can be sized under ideal laboratory conditions.

The really important crack dimension which determines fatigue life is penetration into the load bearing area. The ability of NDT techniques to penetrate below the surface is both very limited and limiting. The depth of defect which can be detected is therefore larger than the minimum length and this remains the Achilles heel of the practical monitoring and containment of growing fatigue cracks.

Quantification of initiation is extremely poor, almost impossible, in real circumstances. Although lab based tests are claimed to confirm good correlations, extrapolation to service conditions is generally difficult.
Real service loads, particularly those arising from dynamic effects, are often unknown and therefore achieving similitude between test and application is very difficult.

Fatigue is often only one of several simultaneous failure mechanisms, for example, corrosion, creep (at high temperatures) and wear, are often present at the same time. Conjoint action is often not merely by linear superposition, as there are sometimes complicated interactions.

Initiation is dependent on slip processes, governed by cyclic shear stresses.
Propagation is generally governed by cyclic tensile stresses, and is caused by repeated plastic stretching and blunting at the crack tip. The classic explanation is that when a flat crack is opened by a tensile stress, stretching occurs normal to the existing crack tip, thus creating new surface at the now blunted crack tip. When the stress is then reduced back to zero, this new surface folds back on itself, ahead of the crack tip, thereby advancing its position. It is generally difficult to produce sustained crack growth by shear, the crack usually attempts to change direction in response to tensile stresses and to develop normal to the local principal stress. However, in a generally compressive field, such as that under a contact, early growth by shear is the only possible mechanism available to advance the crack. Only later, under the influence of bulk bending stresses in the body of the rail, does the crack grow by tensile opening and closing.

Most experimental data is generated for constant amplitude loading: many applications have variable amplitude or even random loading. Superposition of the effects of different amplitudes is not trivial; there can be interaction effects which depend on the sequence in which the stresses are applied.

If tests are carried out on nominally smooth specimens, life is dominated by the initiation phase.

But in real situations fatigue is initiated at some form of stress concentration feature. As the stress concentration becomes more severe, the initiation

phase becomes less important and propagation becomes the life determining mechanism. An important technological example is that of fatigue at welds, the toe region of which contains crack-like defects which immediately grow as micro or even macro cracks.

Defects can range from microscopic metallurgical discontinuities to macroscopic holes. An example of initiation from a large internal defect is the “tache ovale” type of rail failure, now largely eliminated by improving the purity of steels via continuous casting etc.

An important fact has been elucidated by studies on cracks growing from sharp notches. It has been recognised that conditions can be so severe in the vicinity of the notch that, although early growth is easy, when the crack emerges from the influence of the notch into the bulk stress field, the bulk stresses can be insufficient to “**handshake**” with the first notch phase of growth and the crack arrests. This so-called **non-propagating crack** will later be shown to be an important feature of cracks growing in rails.

Appendix 1 is a paper, published more than two years ago, which reviews fatigue in a wide range of transport applications, Attention is particularly directed to the discussion on pages 218-219 on the problems associated with the fatigue of rails.

Rolling Contact Fatigue (RCF) in Rails

There are some particular features of fatigue in rails that distinguish it from general fatigue considerations.

The stress concentration feature which causes the initiation of RCF cracks is not a geometric notch, but is the high stress field produced locally by the contact between the wheel and the rail.

The stresses which result are complex and governed by the detail of the wheel/rail geometry near the contact patch, the position of which is governed by, inter alia, curving behaviour, vehicle suspension characteristics, existing conditions of wheel and rail.

The contact stresses are short range, intense and largely compressive, but produce cyclic shear stress ranges in the contact zone.

These stresses are so high that every passage of every wheel over the rail causes irreversible damage either through the production of wear or the development of a crack. It is worth adding that these loads are transmitted down to the support and foundation of the rail in which they also cause damage which needs correction by maintenance in order to prevent increases in the dynamic component of load at the rail head.

The extremely high contact stresses and the enormous power density (ie. the power passing through per unit) concentrated at the contact under the vertical loads are enhanced by lateral (curving) and longitudinal (traction and braking) loads. In these circumstances, the initiation of cracks is almost inevitable.

The contact conditions are conveniently represented on a so-called "shakedown map", see Figure 1 as an example. It should be remembered that these maps only refer to conditions at the rail running surface and thus are used to describe the possibility of the initiation of cracks, but are not applicable to questions of subsequent deeper crack propagation.

These contact stresses govern both the initiation and early growth and they differ in detail from "ordinary" fatigue, in that they are predominately compressive, but have reversed shear components during the passage of the load over the surface of the rail.

Quantification of their effect is very difficult (impossible??) to obtain from lab experiments. A little progress has been made over the last decade, but similitude with actual conditions in the railhead has proved elusive.
Large scale tests have been performed (Nippon Steel) at great expense, but to little practical effect. New equipment has recently been commissioned in Germany and Austria, and results from these sources are awaited.

A major component of information which is lacking is reliable field data for load distributions on the railhead and their variation throughout the life of the rail.

A correlation with tonnage and vehicle type for the initiation and shallow propagation phases is key to managing this process. It should be noted that local features of track geometry can enhance stresses by dynamic effects and can therefore be instrumental in initiating fatigue cracks at particular locations along the track.

The conjoint action we are concerned with is that of wear and fatigue, corrosion is secondary. (Corrosion at the head of the rail is removed with every passage of the wheel and in this sense is indistinguishable from wear. Gross corrosion at the foot of the rail is, of course, a separate matter.)

If we can quantify the simultaneous actions of these two processes, we can rationally manage the maintenance of the railhead (profile).

The change over from contact stress control to the control of the progress of the turned down crack by the bulk stresses is very important as far as safety is concerned. It is difficult to predict or indeed to observe by NDT when and where this will happen.

There can be sufficient residual life after turndown to enable the rail to remain in service until replacement can happen. To quantify how much service life is left, we need to know about service loads (again), what bending stresses they produce and residual stresses from manufacture and laying. Although our

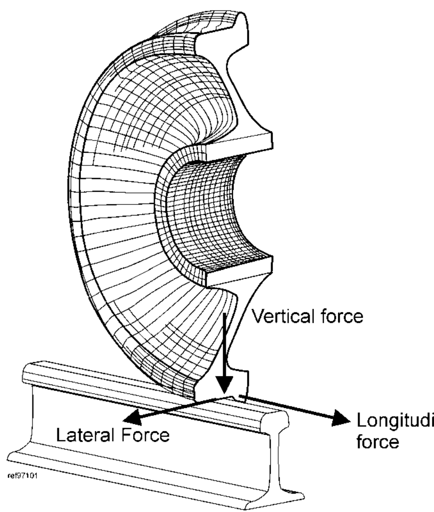

Fig 1. On this simplified typical "Shakedown Map", the vertical axis is the maximum contact stress divided by the appropriate shear yield stress of the rail steel. The horizontal axis is vector sum of the lateral and longitudinal forces acting in the plane of the top of the rail, normalised by the vertical wheel load.
As the traction coefficient increases, less contact stress is needed to initiate plastic flow and therefore the initiation of cracks by gross plastic deformation or ratchetting. Some operational factors which increase the severity of loading are indicated.

Sub surface flow

Contact Stress Ratio **P_o/K**

Surface flow

Higher CD
Heavier loads
Smaller wheels
Poor profile

Lack of lubrication
Stiff suspension
More traction

Traction coefficient, Q/P

knowledge of bending stresses due to the regular passage of the wheel is high, the effects of irregularities on both the wheel tread, for example flats or out of roundness, and on the rail head, are difficult to predict with the same certainty. The values of residual stresses both from manufacture, straightening on laying and continuous welding, are, in general, not well known.

Many of these questions can be answered empirically and practically, by observations taken in rails removed from service, coupled with knowledge of their service load histories. Indeed, was potentially the greatest value output item from this whole episode, and as has been previously mentioned, it is a matter of regret that this opportunity has not been comprehensively grasped.

It is worth summarising the three stages of initiation and growth of fatigue cracks in rails.

1. Cracks are initiated by severe plastic flow at and just below the surface of the head of the rail. The initially high growth rate is rapidly attenuated as the crack deepens into the rail. These cracks are inclined at a very shallow angle, about 15 degrees, to the head of the rail and in the same direction as the direction of the passage of wheels. The severe plastic strains in this region locally modify the metallurgical structure of the rail.
2. Continued propagation in the same inclined direction occurs under the influence of the stress field produced by the wheel rail contact. The reversed shear stresses which cause the growth, first increase with depth causing an acceleration, but then decease with distance from the contact causing a slowing down. Typically the effect of the contact stress field extends some 10 to 15mm below the surface.
3. The interaction between the contact stress field and the bulk stresses in the rail causes, by an imperfectly understood criterion, a branching, either up or down. Upward branching leads to a flake of material becoming detached. Downward branching, at an angle of about 70 degrees inclination, can cause continued propagation until a fracture of the rail occurs.

The sequence of growth rates of cracks is therefore initially high, followed by a dip before “handshaking” with the increasing rates of stage 2, which then decrease to a further handshake with stage 3. *It is important to realise that the handshake between each stage is not automatic and crack arrest is possible. Not all initiated cracks inevitably lead to failure*. For example we might envisage very low bending stresses which are insufficient to couple stage 2 with stage 3. Furthermore, there are interactions with the prevailing wear rates at the head of the rail (discussed later).

There are parallels here to the sequence of events in fretting fatigue (in the failure of axles under the press fit between wheel and axle) and in thermal fatigue (in the failure of brake discs). Study of these parallels may serve to inform the rail fatigue problem.

Interaction with wear

The service life of a rail is determined by the conjoint action of wear and fatigue. As a physical deterioration process, wear has been much studied but remains very difficult to predict over the wide variety of situations in which rail is used. Of particular importance to rails is the corrosive influence of the atmosphere (for example wear in tunnels is, in general, much greater than in open air, probably due to poor dispersion of corrosive fumes etc.). In general, wear rates are empirically related to particular circumstances by only order of magnitude correlations.

Since for a given stress level, the life for both the fatigue and wear mechanisms can rarely be estimated to better than an order of magnitude, we should not expect any improvement of this in the case of rail fatigue, particularly when it is born in mind that the loads (stresses) cannot be defined accurately at a given location.

The interaction of fatigue and wear is important because at its simplest level, if the wear rate at the head of the rail is high, then cracks will be worn away faster than they can form.

More subtly, the three stages of growth of crack previously discussed, need to "handshake" as stage 1 changes to 2 and 2 becomes 3. This changeover occurs at a minimum growth rate, which might be higher or lower than the wear rate at the head of the rail. Crack arrest is therefore possible if the handshake growth rate is lower than the wear rate. The details of these interactions are currently being studied in the AEATechnology Whole Life Model supported by theoretical work from Dr. A Kapoor of the University of Sheffield.

SCIENTIFIC RESEARCH NEEDED TO UNDERSTAND RAIL FAILURE

Although considerable information of RCF in rail exists as a result of many studies conducted in various countries over the last two decades, some key gaps in our knowledge still exist. The following appear to be the main background scientific gaps:

Crack initiation and wear

The thin surface layer immediately under the wheel/rail contact is subjected to severe loading conditions. The initial stages of wear and fatigue are essentially identical. The material accumulates damage and fails locally. The rate at which material detaches as wear debris, must be greater than the deepening of cracks if fatigue is to be avoided. Currently the quantification of wear is order-of-magnitude, as is our ability to quantify initial crack

development. Research is needed on parameters such as initial roughness of both wheel and rail, the role of hydrostatic compression on extending ductility and on the detailed mechanics of the stresses arising from combinations of new and worn wheel and rail profiles, and the effect of longitudinal and tangential stresses.

Crack propagation by contact stresses

As cracks deepen and grow away from the severely stressed surface region, the sub-surface contact stresses control their development. More detailed 3-dimensional models need to be developed and combined with fatigue crack growth properties of materials subjected to equivalent complex stresses. Some particular features, which need further understanding, include:

- the effect of the crack surface roughness on the developing cracks. It is reasonable to assume that over part of the loading cycle, the rough crack faces interlock and reduce sliding motion along the direction of the crack. Continued cycling may smooth the crack surfaces, wear debris may become detached and act as rollers to facilitate crack movement. This problem is connected with the theories of enhanced crack growth due to fluid entrapment. Despite much previous research, it is not clear if fluid pressurises the crack, thus enhancing growth rates, although order-of-magnitude calculations suggest it may.

- the residual stresses in the rail are vital in determining around what mean stress the cyclic fatigue stress operates.

- the residual stresses locked into the rail head during manufacture need to be measured. Investigations on the modification of these stresses by the severe surface stresses need to be made. Thus detailed examinations need to be made of rails of various grades at various stages of their service lives.

Crack propagation controlled by bending stresses

At a later stage of RCF crack growth a transition is made from control by contact stresses to control by bending stresses. The exact criterion governing the changeover from cracks propagating at a shallow angle to cracks turning down and propagating into the body of the rail is as yet unclear. Furthermore, what causes some cracks to turn upwards leading to the detachment of large flakes of material needs elucidation. Models need be developed to quantify the turned-down growth phase. These models need to understand, inter alia, the effects of manufacturing residual stresses, continuously welded rail (CWR) stress and its variations with temperature, rail section shape and size, sleeper spacing and dynamic loading due to wheel flats, out-of-round wheels and surface irregularities on the rail head. Any steps that can be taken to reduce the bulk bending stresses and lower the mean stress around which they operate will reduce the possibilities of turned-down cracks propagating to failure.

All the phases of the development of RCF cracks are currently being brought together in a so-called Whole Life Model. The above work will serve to enhance the credibility of this model and make it a more realistic tool for the guidance of maintenance.

Similitude between laboratory and field conditions

In common with all areas of fatigue, great care needs to be taken in establishing similitude between conditions applied to sample specimens in the laboratory and what is actually happening in real rails in service. A major problem here is the appropriateness of the size scale to which non-linear plastic deformation effects are applied to a small crack near the head of the rail. The crack is effectively surrounded by a sea of plasticity: a condition which is often not matched in the laboratory. Thus the values of material properties such as crack growth rates and thresholds may be changed because of these effects.

Furthermore, laboratory tests often fail to match the dynamic stresses to which real rails are subjected. These dynamic effects are, of course, amplified by speed and the magnitude of enhancement for various kinds of irregularities needs clear elucidation.

It would therefore be valuable to establish a monitored section of mainline, which would provide, over a number of years, detailed data on the development of RCF over a range of rail geometry and condition.

PRACTICAL ASPECTS AND MAINTENANCE STRATEGIES

Despite a huge volume of work over the last few decades, clearly catalogued field observations of the extent, development and rate of fatigue development and/or wear are still sparse. The data collected after the Hatfield accident will contribute much useful information. But there still exists the need for the collection of much more information from the field for many types of operating conditions. It is important that such information is disseminated as widely as possible throughout the world's railway industry.

It is clear that a competition exists between wear and the development of rolling fatigue cracks in rails. Historical trends towards decreasing wear rates coincide with increasing rail break problems. Only by better quantification of both wear and fatigue, can rational choices be made of lowest economic wear rates which will eliminate rail failures. In situations where crack initiation is unavoidable, the progress of cracking can be checked by appropriate rail grinding: but again, rational and economic strategy needs quantitative understanding.

Lubrication, applied to reduce flange wear, needs to be properly understood, otherwise fatigue problems may increase. The balance here is between reducing wear and reducing the tangential stresses which enhance crack initiation, and the possible enhancement of crack growth away from the surface by the presence of the lubricant*. In simple terms, where lubrication is*

used to reduce severe wear of either rail or wheel flange on, for example, small radii curves, care must be taken to ensure that the reduced wear does not allow fatigue cracks to deepen.

The inspection of rails for cracking is expensive, but necessary. Automated techniques, coupled with locational identification have been developed and are being improved. But surface measurement alone may not give sufficient information. Accurate sizing of the extent of cracks below the surface continues to pose problems. In particular, any methods which reliably and unambiguously identify cracks, which have started to turn down, would be extremely useful. Although this happens at the later stages of the fatigue life of the rail, knowledge and confidence of the likely life remaining after this event would help to avoid the necessity for imposing the kind of speed restrictions which were deemed to be vital after the Hatfield accident.

Recent reports have emphasised the containment and management of the RCF problem, but little has been said of the need to make judgements on safety and remaining life of rails when cracks are discovered. A particular problem is that the visible surface development of cracks is an unreliable guide to the depth of penetration of cracks below the surface and hence their potential for causing fracture. In many cases what appears to be extensive surface cracking need not cause concern about the imminence of failure. If a "proof test" method could be found, a period of safe operation could be guaranteed. A "proof test" involves the application of stresses in excess of the service stresses. If the component survives, a life equal to that corresponding to the crack growing from the smaller critical crack size due to the proof load to the larger crack size corresponding to the working stresses, can be guaranteed. The beauty and strength of this technique, which is well known in the pressure vessel industry, is that the test cannot fail to identify a crack greater than that set by the proof test level – such a crack would cause failure and enforced retirement! Such a technique would require more detailed information about the propagation of cracks in the deep bulk zone.

The use of grinding to contain the development of RCF cracks is well established. However, its practical application needs a clear strategy on the balance to be struck between removing cracks and the control of head profile and longitudinal rail profile. An established rule of grinding is "little and often". Work needs to be undertaken to establish practical limits of depth of cut, heat input and shape control in order to better quantify this empirical rule.

Although much is known about the interactions of wheel profile and rail head shapes, detailed work on particular combinations is still needed. The rapid establishing of conformal contact conditions is desirable, but not always possible on mixed traffic routes.

Further general considerations

Despite all the recent efforts, a comprehensive catalogue of published work has not yet been produced. This should include a detailed survey of books, journals, papers, project reports and conference proceedings. Such a gathering could form the basis of an international effort of information exchange.

Within the UK, a great deal of work was performed and published by the former BR Research. The results of this work, the present author understands, remain in the public domain (at least as far as the ex-BR railway industry is concerned). At the moment access to this material is difficult, ways need to be found to catalogue what is available and to improve access (perhaps the custodians should be changed?).

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FATIGUE IN TRANSPORT:
Problems, Solutions and Future Threats†

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INTRODUCTION

I am privileged to have been invited to give this the Tenth Vernon Clancey Memorial Lecture. Vernon Clancey achieved a world-wide reputation as an investigator of incidents including fires and explosions. He was involved in the investigation of aircraft sabotage cases in the 1950s and 60s. Although my talk is only partly concerned with aircraft, the painstaking forensic skills developed by scientists like Clancey have been used to unravel the mysteries of fatigue failures. I am somewhat apprehensive because my invitation came from the Vice Chancellor, Professor Raoul Franklin. I last saw him, but doubtless he only saw me in a sea of faces, when he lectured to Engineering undergraduates at the University of Oxford in the late 1960s. Faults in my lecture today are, of course, due to my own inadequacies, and no blame should be attached to my former lecturers, whom I fear were dealing with unwilling material. In the years in question, students were revolting, O tempora! O mores!, and Engineering Science was not at the top of my priorities. I have spent the last 30 years trying to catch up. I aim in this lecture to give a broad overview of the problems of fatigue in all modes of transport. Given the huge scope of my canvas, the brush strokes will be thin to those members of the audience who are knowledgeable about fatigue. To assist the audience who are unaware of the basic facts of fatigue, I will give brief explanations of salient facts at appropriate points in the lecture, but in the interests of continuity, will relegate these to an Appendix in the written version of the paper.

I intend to review transport on land, sea and air, and to begin with trains, not only because they are my current research interest but historically, the introduction of railways led to the first recognition of the fatigue problem.

LAND TRANSPORT

Railways: Vehicles

The Industrial Revolution was powered by steam engines. In order to provide the strength necessary for high speeds of moving parts and high pressures in boilers, iron components were rapidly substituted for the wooden parts of earlier machines. The stresses to which these metals were subjected were much higher than stresses induced in earlier, slower machines. As the railways developed from 1830 on, so reports of breakages of key parts became more common. The first railway accident involving major loss of life occurred on the line from Paris to Versailles in 1842. About 70 people were killed, including the French circumnavigator Admiral D'Urville, the discoverer of the statue of Venus de Milo. The cause of this accident, which was a sensational event widely reported throughout Europe, was the breaking of the axle of one of the two engines hauling the train. The engines and flimsy wooden carriages fell into a smashed heap and were set alight by the spilt hot coals from the locomotives' fires. The carriages were locked, thus blocking the escape for the unfortunate passengers.

The investigations into the causes of this axle failure mark the beginnings of the investigation of fatigue failures. It was noted that fracture surface was smooth and the idea that the metal had suddenly tired (hence the term 'fatigue') and changed its internal structure causing immediate failure was a common view. Many other failures followed—of wheels, more axles, connecting rods, boilers, rails and bridges. The latter failures caused a Commission of Enquiry to be held in Britain, investigating the suitability of iron as a structural material. Famous experiments on a heroic scale were conducted by engineers such as Fairbairn and Hodgkinson, who discovered that a weight of one third that which was necessary to cause failure of a large beam on a single application, could eventually cause failure of the beam if applied on and off many times. This is the empirical manifestation of fatigue: the failure of a material due to the repeated application of cyclic loads at levels less than the static failure load. Originally investigations were confined to metals, indeed the words 'metal' and 'fatigue' are intimately linked, but non-metals also suffer fatigue fracture and this must be allowed for when, for example, plastics, composites and rubbers are used in designs.

The first systematic research into fatigue was conducted by Wöhler, working for the German State Railways in the 1860s. He used small samples of axle material and devised a machine which would reproduce on these samples the stresses caused by the rotation of the full-sized railway axles. He established an experimental relationship between the size of the applied stress cycles and the number of repetitions the material could withstand (the so-called S/N curve, see the Appendix); he drew attention to the importance of local areas of high stress, that is regions of stress concentration (for example, between the axle and the press fitted wheel) and he identified a cyclic stress level below which the material could apparently resist an infinite number of repetitions, the 'fatigue limit'. Thus emerged the first rule of design to avoid fatigue failure: keep the cyclic

† The text of this paper was first presented at the Tenth Vernon Clancey Memorial Lecture given at City University, London, UK, on 6 May 1998. This year's lecturer was Professor R. A. Smith, Royal Academy of Engineering/British Rail Research Professor and Chairman of the Advanced Railway Research Centre at the University of Sheffield.

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Table 1. Mechanical failures on UK railways—now and 100 years ago. (Rates are per 10^6 train kilometres: various sources.)

	1992–94	1881–90
Wheel or tyre	0.04	2.0
Axles	0.04	0.8
Rails	1.5	0.7

stresses below the fatigue limit. (After years of careful study, we now know that fatigue is a highly localized phenomenon involving the growth of a crack from a region of high stress. The initiation, or birth, of the crack can be influenced by very small-scale features such as a scratch or surface finish and is therefore particularly difficult to predict. Once the crack has developed in length through a micro to a macro crack, prediction of its rate of growth is relatively much more straightforward.)

Over the years, experience has been accumulated which has allowed trains to be designed in a robust way and, in general, rail vehicles have proved capable of operating safely for many years: 30 years is a nominal design life, but 50 or even 60 years usage has been common. This means that reserves of strength have been built into the design and fatigue problems have been rare and are hardly ever generic. Axles still break (see Table 1), bearings occasionally fail, but generally the fatigue problem can be said to have been contained. However, modern design pressures have led to the concept of light-weighting, which is particularly important for high speed trains, now travelling at around 300 km/h. Changes from steel to aluminium and even composite materials, has led to some cracking problems. The airtight cars of the Japanese Skinkansen provide an interesting example. These cars must be pressure-tight to avoid uncomfortable pressure pulses as trains pass at high speeds in tunnels: the major cause of retirement of the vehicle is loss of airtightness due to fatigue cracking from fastener holes. In high speed systems, great care is taken to inspect wheels or axles for growing cracks (a technique in principle, similar to, but in practice more sophisticated than the wheel-tapping which will be remembered by older readers!). Inspection intervals of say 400,000 km are common, after which the wheelset is dismantled and inspected by magnetic or ultrasonic methods. One company's records indicate that out of 15,000 such inspections annually, no fatigue cracks were found, but 1.4% of the axles examined had to be scrapped because of damage caused by the dismantling. This 'inspection after a service interval' is expensive and largely inefficient. It is a current aim to inspect and maintain based on knowledge of actual condition, so in many branches of engineering the development of appropriate sensors by which plant condition can be continuously monitored is a top priority.

Railways: Infrastructure

Railway vehicles contact the infrastructure through their wheels and at current collection points for electric locomotives, a third rail or via overhead wires. All contacts lead to locally high stresses and potential failures by fatigue and/or wear. In the case of rails, fatigue failure remains a rather difficult problem.

Heavy freight traffic causes rapid rail wear; a particular problem in the USA where freight movement is more important than passenger traffic. Table 1 illustrates that rail failures are still numerous. The data is from the UK and is subject to some causes of uncertainty, particularly definition and reporting standards over the hundred plus years of the time span. However, it is clear that whilst failures of wheels and axles have reduced by a factor of 20 over the last century, failures of rails per train kilometre have actually increased by a factor of more than 2. Heavier axle loads, more axles/train and the move to all-welded track have all contributed to these figures. Because the consequences of failure can be severe, much effort and cost is expended in detecting, monitoring and repairing cracks in railway lines. A quantitative understanding of the mechanisms and mechanics of fatigue failure of cracks in regions away from joints in rails is still lacking. The problem is important and the subject of active research in many countries. There are now many examples of the organizational separation of the infrastructure and train operations. The quantification of damage caused by particular vehicles, and therefore the appropriate level of costing for track access which should be applied, has assumed even greater importance because of these changes. The deterioration of bridges with the passage of both trains and time, has for many years been recognized as an important problem. Many of the iron (and later steel) bridges now in use were built more than 100 years ago. Corrosion can be contained by painting (the famous stories of the Forth Bridge indicate how time-consuming and expensive this can be), but often a coat of paint is cosmetic, and in crevices and corners of the structures, the joint effects of corrosion and fatigue eat away into the structure. The use of structural frequency response changes for the whole structure, in order to detect cracks, is often not sensitive enough to identify cracks in an early stage of life, and because of accelerating growth rates as cracks become longer, vital cracks can be missed on inspection, yet grow to failure before the next inspection becomes due. Although major failures of railway bridges due to fatigue have not occurred for many years, the costs of inspections are high and are becoming even higher as the age of our bridge stock increases.

Automobiles

That the automobile has liberated and enriched the opportunities which stem from the ability of the common man to travel easily is a glorious achievement of this century's engineering and production technology. However, its very success in multiplying in an exponential fashion, and concerns at the level of pollution produced by the internal combustion engine, have led many people to realize that the unbridled expansion of road transport cannot continue.

The fact that cars are produced in such large numbers has led to several important characteristics of their fatigue design. Large amounts of money are available for research, development and testing programmes. The car is a mature product which has developed steadily in an evolutionary way; new modifications can be tested in prototypes and operated well ahead of actual service. As a result, one might suggest that fatigue is not a major constraint to the automobile industry—major components in engines,

transmissions and suspensions rarely fail. Nevertheless, considerable attention is paid to fatigue design and many practical advances in general areas such as cumulative damage due to random loadings, have stemmed from the work of automobile manufacturers. The average motorist is unlikely to experience fatigue failure of any major parts, but may be unaware that the irritating failures of knobs, springs and hinges, particularly those made from non-metallic materials, are most likely due to fatigue. Pressures to reduce the weight of cars have been a recent challenge—partly met by the introduction of lighter materials (high-strength low-alloy steels, plastics and composites), but also by the use of increasingly sophisticated finite element stress analysis which has allowed excess lightly stressed mass to be shaved from components made from established materials. Since the lifetime of cars is relatively short, corrosion has been a limiting factor, but recent improvements have helped to overcome this limitation.

The levels of maintenance required for modern cars are astonishingly low compared with even 25 years ago—a lesson which could be learned and applied to other areas of the transport industry. An element of concern, however, is the increasing electronic sophistication of modern vehicles which in many cases defeats simple diagnosis and repair when faults occur. Although solid state and 'chip' based electronics are generally reliable, a major source of failure is the thermal fatigue of soldered connections; an area which is now the subject of active research worldwide and a problem generic to equipment used in fields of transport.

Infrastructure Damage Caused by Heavy Road Vehicles

Vehicles cause damage to the surface of the road on which they pass. Continual passage of traffic causes cyclic loading, the damage accumulates and eventually the road surface breaks up and needs to be repaired. The repair costs, and the costs associated with delays to traffic whilst repairs are made are huge. The UK spent 1.17% of its GNP on roads in 1990, of which 46% was spent on maintenance. Despite the obvious economic consequences, the fatigue relationships between traffic quantity, axle loads and road surface lifetime are little understood. A recent extensive review suggested a fourth power law between axle load and damage as a rule of thumb; the relationship may be an even higher power law, but in any case illustrates the high sensitivity of damage to the axle load. In recent years the overall weights and axle loads of heavy lorries have increased considerably. 44 tonne lorries are commonplace throughout Europe, as are the sections of highway under repair caused by their passage.

Bridges too are subject to cyclic loadings from traffic—on longer bridges the total weight of the vehicle is clearly more important than the axle load. The severity of this problem can be illustrated by a simple calculation. If a bridge was designed for lorries of 10 tonnes and a 50 year life, then for the same number of lorries of 44 tonnes, the life will be reduced to 1.6 months if the fourth power law holds! The UK is only halfway through what is a 15 year £1.3 billion programme to assess and strengthen the nation's 100,000 bridges in preparation for the arrival, under a EU directive, of 40 tonne trucks in 1999.

SEA TRANSPORT

Ships: The Unsolved Fatigue Problem

Recently, there has been a steep rise in the number of large cargo ships lost at sea. In 1994, 15 of these massive ships sank, killing 141 crew members. Over the last 12 years, 906 people have been lost when bulk carriers sank. The scale of losses prompted the International Maritime Organization (IMO), the United Nations agency that administers international conventions on safety at sea, to hold a conference in London during May 1995, to consider measures to improve safety at sea. The costs involved, apart from loss of ships, cargo and lives, are huge. The Exxon Valdez accident cost $1b in clean-up charges, a large routine repair costs about 100,000 ECU and delays cost up to 30,000 ECU/day. The costs of frequent inspections are high, and often the inspections are by necessity superficial. The world's trade depends on cheap transport by sea; the vessels used are often old and suffer from corrosion and fatigue cracking, the value of the ship is often less than the value of the cargo and, as always, time is money so that loading and unloading operations are sometimes conducted with undue haste and can induce damage into the ships' hulls.

Why are losses of large ships so prevalent? Basically, ships are large but extremely fragile welded structures. A typical Very Large Crude Carrier (VLCC) is some 330 m long and 56 m wide. The side plates are 18 to 20 mm thick. An egg is about 48 mm wide and its shell some 0.35 mm thick—that is, the thickness to width is of the order 1/140, relatively some 20 times thicker than the corresponding VLCC ratio of 1/2800. Given the huge mass of a loaded VLCC, it can easily be imagined that a 'gentle' impact with a dock side can cause severe indentation damage. A ship is often divided into six huge holds: if the cargo is loaded unevenly into the holds, large bending stresses can result. In recent years some ships have been instrumented to assist the Master to control the stresses induced by loading. However, many owners cut costs to a minimum. A driver or walker can now be equipped with a Global Positioning Satellite navigation system for a few hundred pounds, but many ships do not carry such equipment! Modern ships are constructed by welding large plates and girders into a structure. The total length of weld in a VLCC runs into several hundred kilometres, often originally made in the shipyard under difficult conditions leading to misalignment and poor quality control. Inspection in service is difficult because of the size of the structures involved and hampered by poor accessibility. In addition, and vitally important, ships' hulls have traditionally been designed to Codes based on static loads and without consideration of fatigue loadings of either the high cycle type caused by wave action or the low cycle type caused by uneven loadings. When the hostile corrosion conditions in which ships work are then taken into account, it should come as no surprise to learn that ships suffer structural deterioration with age—deterioration which often goes unnoticed until a large-scale failure occurs.

The largest British ship lost at sea was the MV *Derbyshire*, a bulk carrier 294 m long and 44 m wide, with a displacement of 192,000 tonnes. In 1980 the *Derbyshire* disappeared without sending a distress call in a storm in the Philippine sea. Many theories have been put forward to account for the sudden loss, but several centre round sudden catastrophic failure caused by fractures running from

fatigue cracks in the area just ahead of the stern superstructure. A somewhat inconclusive inquiry was held, which prompted a report which discussed the unpredictability of fatigue cracking in large ships, included the comments:
'We despair of ever estimating the fatigue life of a ship with any accuracy. Our reasons for pessimism include:
(1) Uncertainty about material.
(2) Impossible to predict fatigue properties.
(3) Corrosion.
(4) Welding not perfect.
(5) Residual stress in hull.
(6) Stress concentrations.
(7) Mean stress effects not fully understood.
(8) Stress states at all points impossible to predict.
(9) Impossible to determine entire stress history at every point.
(10) Crack detection very difficult.
(11) Brittle fracture during lifetime.
The truth is that ships do crack and cracks grow'.

In August 1996, it was announced that the wreckage of the *Derbyshire* had been located at a depth of 4200 m some 1000 miles south-east of Japan. A later expedition secured some remarkable photographs of the wreckage and early in 1998, the Government announced that the public inquiry in the ship's loss would be re-opened later this year.

This comprehensive list serves to indicate the large number of 'unknowns' still associated with fatigue in ships' structures. However, the author's attention has recently been drawn to fatigue design standards for ships produced by Lloyd's Register together with a Fatigue Design Assessment procedure, which appears to be considerably in advance of any previous proposals.

This review would be incomplete without a mention of losses of passenger ships. In general, the problems here arise not from structural failures: the ships are smaller, better maintained and generally newer. At the time this paper was originally written, news broke of a ferry loss on Lake Victoria, Tanzania with 500 feared drowned, probably caused, as many other accidents have been, by overcrowding. Even in heavily regulated European waters, tragedies have occurred. In 1987 the *Herald of Free Enterprise* capsized in Zeebrugge harbour, most probably because of sloppy operating practices induced by cost-cutting management policies. But the loss of the *Estonia* in the Baltic sea, in 1994, may have been due to excessive sea loadings on fatigue-cracked bolts securing the bow door, used to allow vehicles to enter the loading decks. Both cases have prompted discussions of the poor stability of roll-on/roll-off ferries when water enters the vehicle decks.

Of all the transport industries, shipping is probably the 'lowest tech', but it is interesting to recall that two of the most significant theoretical advances in fatigue and fracture arose out of studies of ships. In 1913 a famous paper on stress concentrations was published in the *Transactions of Naval Architects* by Inglis; he was studying the stress round cut-outs and portholes in ships hulls. This work was used later in 1921 by Griffith to formulate his famous energy balance approach to fracture instability. The numerous brittle fractures of Liberty ships during World War II led to the intensive study of the effect of welding and low temperatures on the fracture of mild steel plates and arguably to increased interest in fracture research and the development of sharp crack fracture mechanics.

AIR TRANSPORT

Aircraft: Keeping Fatigue at Bay by Inspection

Aircraft are designed in such a way as to minimize their structural mass. The consequences of failure are usually severe. The failures of the pressure hulls of the early *Comet* aircraft in the 1950s prompted much research which contributed to the development of quantitative understanding of fatigue crack growth, particularly in aluminium alloys. A modern aircraft is a complex system and failure of apparently insignificant parts can lead to catastrophic loss: a classic case was the crash of a DC-10 on take-off from Chicago on 25 May 1979. A bolt in the engine pylon/wing attachment bracket failed by fatigue. During the subsequent investigation the world's fleet of DC-10 aircraft was grounded, to await changes in maintenance techniques which overcame the problem, which was caused by loads generated by incorrect fitting of the engine pods to the wings. At the time of this accident about one fifth of the world's jet passengers was being carried by aircraft of this type.

It would be wrong, however, to suggest that fatigue is a major limitation on the safe operation of aircraft. A recent survey indicated that:
- Only 2% of plane crashes are caused by structural failure;
- 7% by deficiencies in maintenance;
- 11% by terrorism or military action;
- 12% by weather—thunder and lightning, ice, fog, wind shear, etc;

and a vast proportion, 67%, are caused by human error—by pilots, aircrew and air traffic controllers.

A further report suggested the following figures for the relative frequency of occurrence of different types of failure mechanisms in structural failures in civil aircraft. Fatigue, (47%) predominated, but stress corrosion (16%), corrosion (27%) and corrosion fatigue (10%) failures often occurred. It was suggested that the rectification of corrosion damage in military and civil aircraft consumed more effort than the repair of fatigue cracking. (The statistics for helicopters give a rather different picture. Failures in the highly stressed mechanical transmission system lead to sudden loss of airworthiness and accident rates are greater on a passenger kilometre basis.)

Why then, despite the obvious difficulties, do fatigue failures contribute so little to the loss of aircraft? The industry is subjected to very tight regulation which is, in the main, strictly enforced. Aircraft are subject to a range of inspections designed to detect cracks before they grow to dangerous sizes. Repair and replacement techniques have been defined and in critical parts such as engines, strip-down inspection and replacement is performed which has reduced failures to low levels. The situation is different for military aircraft where operational lives are much shorter than for civil aircraft, flight loadings more severe and performance criteria are more stringent. Expensive research programmes to reduce fatigue damage in military aircraft have had obvious spin-offs in the civil field. Until recently many national governments funded civil research in support of their national aircraft industries. The trend has now turned to international collaboration—the European Airbus is a good example.

Overall therefore, resources have been available in the aircraft industry to allow it to lead other branches of transport in fatigue and fracture design. Economic pressures

are beginning to force extensions to design lives for existing aircraft and the weight problems associated with long-haul fuel loads in large capacity aircraft are forcing the margins of structural design to be lowered. Only by strict compliance to high standards of safety-related regulation will the aircraft industries' impressive record in suppressing structural failures be kept or even enhanced in the future.

THE RISK OF TRAVEL

The risk of travel has commonly been assessed in terms of accidental deaths per 10^9 km travelled—see, for example, Table 2. For rail travel it will be noted that there is an increase in the most recent figures, which reflects two major accidents in that period: the King's Cross Underground fire and the Clapham Junction railway accident. For road travel the risk will vary with many conditions (e.g., class of road, experience of driver, weather, lighting, wearing a seat belt or crash helmet, as well as type of vehicle). The reduction of risk for car travel noted in Table 2 reflects the introduction of compulsory wearing of seat belts, greater enforcement of drink-driving laws and the public attitudes to drink-driving, improvements in car design, a greater mileage on motorways, which have lower accident and casualty rates, and slower traffic in towns due to increasing congestion. For air travel the risk per flight (or per sector of a flight) is arguably more significant than per 10^9 km travelled, as a substantial proportion of all fatal accidents occur during take-off or landing. The reduction in risk of air travel noted in Table 2 reflects the improvement in reliability of aircraft and the extensive use of automatic landing of aircraft with a reduction of accidents due to pilot error.

Much work has been performed on aspects of the quantification of risk in recent years. In the field of transport, risks on public modes (rail, coach and aircraft) are significantly lower than in private modes (walking, cycling and the automobile). The public expects to be safer 'when in someone else's care'. Nevertheless, there remains much to be done in educating the public of the link between safety and cost: further improvements from current acceptable levels of safety are generally costly (the gradient of the safety level/cost curve is very shallow at the top end). A major challenge of the public transport industry, particularly acute in aircraft, is the need to at least sustain, or better improve, safety and risk levels whilst at the same time operating under more stringent economic conditions.

Table 2. Deaths per 10^9 km travelled. UK.

	1967–71	1972–76	1986–90
Railway Passengers	0.65	0.45	1.1
Passengers in scheduled air services on UK airlines	2.3	1.4	0.23
Bus or coach drivers and passengers	1.2	1.2	0.45
Car or taxi drivers and passengers	9.0	7.5	4.4
Two-wheeled motor vehicle driver	163.0	165.0 }	104.0
Two-wheeled motor vehicle passengers	375.0	359.0 }	
Pedal cyclists	88.0	85.0	50.0
Pedestrians *	110.0	105.0	70.0

* Based on a National Travel Survey (1985/86) figure of 8.7 km per person per week.
Source: Department of Transport.

FUTURE THREATS

The main future threats which will increase the pressure on designing against fatigue can be summarized as follows:

- The need for lighter structures which are more efficient at higher speeds and have lower life-cycle costs because of reduced maintenance levels;
- The need, for economic reasons, to squeeze more out of existing plant by extending original design lives;
- Increasing complexity of engineering products which are becoming 'mechatronic' systems—that is, mixtures of mechanical, electronic and computer components.

The first pressure may require the introduction of new materials or composite mixtures for which the fatigue properties and failure mechanisms will have to be determined. Advances in computational power are already assisting in the design of lighter, more stress-efficient components made from more traditional materials. The prolongation of the lives of structures and machines, together with the elimination of reduction of maintenance periods, can only be safely achieved if all the modern tools of fracture mechanics and crack growth behaviour are understood and used at the design stage. The final threat, from the failure of electronic components, can and will, of course, be matched by increasing knowledge of fatigue failures on a size scale much smaller than that traditionally studied. The real danger comes from the knock-on effects of system failures and the need for robust fail-safe control systems. This lecture has indicated how fatigue failures have, in the main, been eliminated or controlled in various transport applications. Human errors have been identified as a much more potent cause of accidents than structured breakdown due to fatigue or other causes. The use of advanced electronic and computer control systems will reduce human error but, in the course of its introduction, must not be allowed to increase the risk from system failures.

APPENDIX—A BRIEF OVERVIEW OF FATIGUE

Fatigue is the phenomenon of the growth of cracks in materials. The essential feature is that the cracks are driven by stresses of variable amplitude, which are sometimes regular and cyclic, for example those due to the rotation of axles, or in other cases may be of a more random nature like the wave loading on a ship or the gusts of turbulence on an aircraft wing. Although individually the driving stresses may be small, if a sufficient number are applied the crack can grow to a large enough length to cause failure. The site of the birth or initiation of the crack is highly localized, in a region of stress concentration caused by a local change of shape or a defect such as a surface scratch. It is easy to produce, by experiment, a relationship between cyclic stress amplitude and a number of cycles to cause failure. It is however much more difficult to predict the location of the fatigue critical site in a large and complex machine or structure.

For many steels, it is found that a fatigue limit exists (see Figure A1), and stress below this limit can be applied

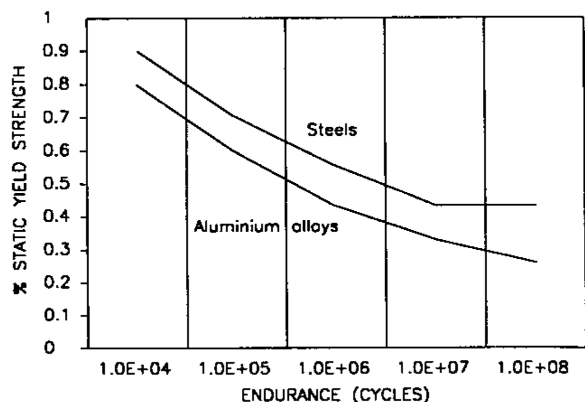

Figure A1. Typical stress/endurance curves.

indefinitely without failure. The simplest design technique to avoid failure is to ensure that the highest local stresses are below the fatigue limit. Unfortunately, aluminium alloys do not have a fatigue limit.

In the last 40 years, considerable understanding has been gained of the local internal mechanisms which drive cracks and many designs now acknowledge the existence of cracks and are based on quantifying how quickly cracks will grow under service loadings. The techniques of 'fracture mechanics' allow for inspection intervals to be set, based on the size of crack which might reasonably be detected and on how much it can grow between inspection intervals. Experimentally determined fatigue crack growth laws can be determined and their integration between critical and final crack sizes is a relatively straightforward task. Figure A2 is a generalized illustration of the importance of size-scale to the fatigue problem. In particular, it shows that in many cases a very high proportion of fatigue life is consumed before cracks can be detected by any practical means. This is the root of the mystery of fatigue failure: apparently perfect performance preceding an unexpected failure. The quantification of service loads is virtually important if fatigue assessments are to be made. The important fatigue loads might be applied relatively infrequently—for example, the pressurization of an aircraft hull once per flight. During a flight, the disc of the turbine in the aircraft's engine will have rotated millions of times and will be subjected to a very different design methodology

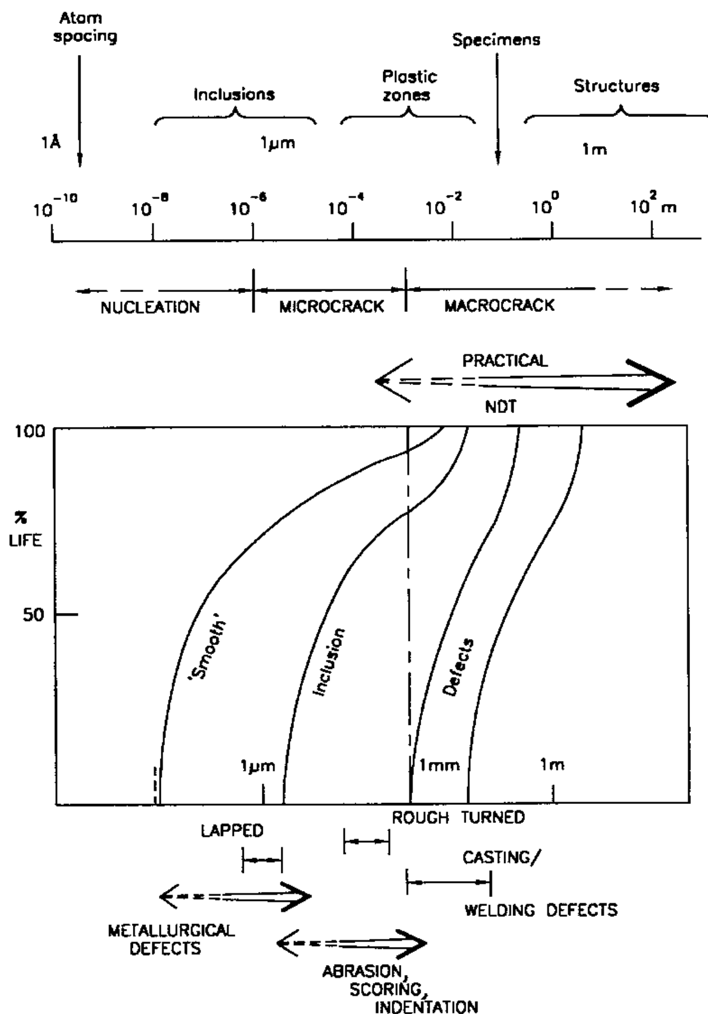

Figure A2. Size scales of fatigue and fracture.

than the pressure hull. Loadings of a mechanical nature are the primary causes of fatigue, but thermal stresses due to temperature changes can also be important. The turbine disc mentioned above will see an alternative of hot and cold conditions during the flight. Electronic components are susceptible to thermal stresses due to changing current flows and cracks can be formed on soldered joints or at the interfaces between wafers of material. Most electronic fails by fatigue and thus system integrity of modern machines and equipment depends on fatigue knowledge applied at the microscopic scale of the electronic component parts.

POSTSCRIPT

In the period between the delivery of this lecture and the return of the proofs from the publisher, two serious railway accidents occurred which may have been caused by metal fatigue problems and, at first sight, may appear to be in conflict with the opinions expressed in the paper.

On June 3, a German Inter City Express (ICE) travelling from München to Hamburg derailed from 200 km/h at Eschede and smashed into an overbridge which collapsed onto several telescoped carriages. In what proved to be Germany's worst rail accident in 50 years, 100 passengers were killed. On June 16, a London King's Cross to Newcastle express, travelling at about 160 km/h, partially derailed at Sandy in Bedfordshire, but fortunately stayed upright and came to a halt without major injuries to any passengers. In both cases faults with wheels were suspected of being the root causes, although investigations are still under way and official reports are being prepared. Preliminary statements point to cracks in the tyre of a resilient wheel in the ICE set, and to a star-shaped fatigue crack growing from a bolt hole holding a balance weight in the wheel of the British train. If this latter report is true, it emphasizes yet again the vast gulf in knowledge between researchers and practitioners. Both accidents point to the continuing difficulties of practical non-destructive examination methods aimed at detecting cracks in an early stage of their development.

The media coverage of the first accident was intense in the couple of days in the immediate aftermath. The author was contacted for a television interview on why the accident had happened before he had heard of the tragedy from any other sources. He declined. The second case merited only a few column inches in a couple of papers, but fate had been kind and there was no chain reaction to cause a major accident out of the initial failure, as had been the case in the German accident. Inevitably some politicians were quick to show their ignorance, coupled with their desire for publicity; by calling for mandatory passenger lists and seat belts. Even a supposedly sensible newspaper like *The Guardian*, ran a leader which said, '*trimming a few minutes off the journey time is simply not worth the extra risk. In the end, trains are not planes, and they should not pretend to be*'.

In fact, neither accident occurred at the highest speeds of which the trains were designed for and neither happened on special dedicated high-speed track. There is overwhelming evidence that the travelling public will switch from other transportation modes to high-speed trains, and thus reduce the death toll arising from automobile use. Although the number of fatalities in the German crash was high, it should be seen in the context of the 8000 or so deaths which occur on Germany's roads every year. High-speed trains on dedicated tracks in Japan, France, Germany, Spain and Italy, fitted with Automatic Train Control, having no level crossings and with the latest infrastructure technology, have carried billions of passengers and have not yet produced a single casualty.

ADDRESS

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