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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.

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			
Two-wheeled motor	163.0	165.0 }	104.0
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

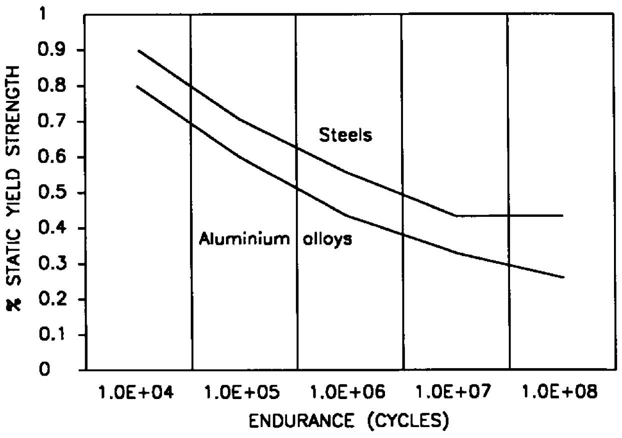

Figure A1. Typical stress/endurance curves.

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

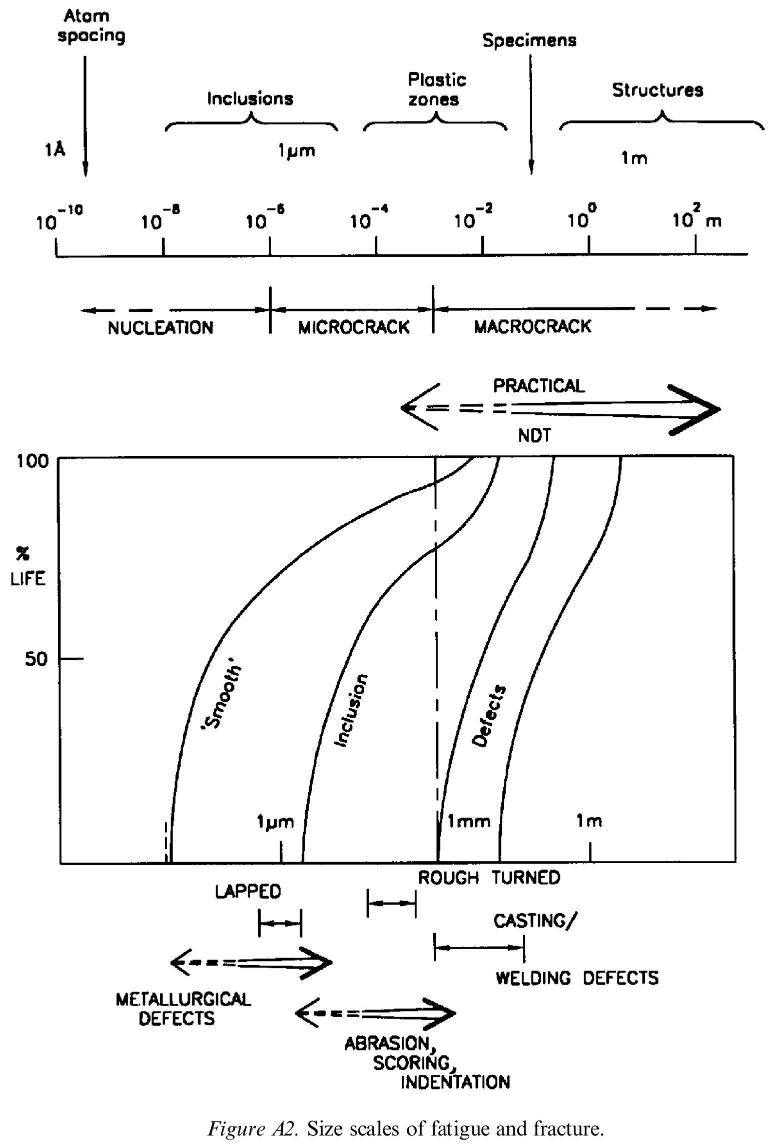

Figure A2. Size scales of fatigue and fracture.

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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