DESIGN FOR CYCLIC LOADING IN TRANSPORT

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ABSTRACT

This paper is a broad overview of the current status of fatigue design capability applied to the major sectors of the transport industry; land (road and rail), sea and air. Infrastructure effects bridges, rails and roads are included.

KEYWORDS

Fatigue, transport, design.

INTRODUCTION

In 1981, the author prepared a brief review of the history of the development of fatigue and fracture problems. That review is summarised as Appendix 1. The conclusions were:

- many practical problems arise in transport applications
- stress concentrating features (notches and joints) are important in real problems
- there is a return from small specimen testing to full-scale structural testing, an increasing interest in low cycle fatigue, corrosion effects and realistic loading patterns
- crack propagation can be reasonably well quantified, but crack initiation is still difficult to deal with quantitatively
- there is a wide gulf between microscopic, mechanistic understanding and practical macroscopic engineering design
- weight saving will result in more fatigue/fracture problems in the future

With the benefit of now more than fifteen years hindsight, I would not significantly change those overall conclusions. Perhaps the most significant developments in this period have been first the advent of cheap, local computing capabilities of enormous power and the advent of useful software, particularly accessible finite element stress analysis programs with powerful graphical interfaces. Secondly, microelectronics have been introduced into many engineering applications, replacing mechanical parts, but introducing new kinds of maintenance problems.

With regard to the understanding of fatigue and fracture, my conclusions have hardly changed despite the large increase in the number of publications on these topics. The key problem seems to be the dissemination of existing knowledge from research to practical engineering design.

The purpose of this paper is to review fatigue and fracture problems in passenger and freight transport, excluding the bulk transport of material in pipelines. In all transport cyclic loadings occur in a variety of ways: from rotating parts e.g. wheels, axles, pistons and crankshafts, from contact with the environment e.g. bumpy roads, dips in rails, gusts in the air and from starting/shutdown operations e.g. pressurisation once per flight, thermal loads in engines. Additionally equipment operational on transport is subject to vibration and its own internal operation cycles. The increase in the application of electronic components has led to a generic class of a new kind of failure with attendant reliability problems.

Land based transport is, of course, particularly susceptible to loadings from the wheel/running surface interface and arguably, the biggest problems occur with deterioration of the infrastructure. Bridges and viaducts deteriorate with use and the prediction of remaining safe lines is an acute problem. Costs of road repairs include large sums attributable to delays caused to traffic. Broadly speaking, fatigue of the major components of automobiles is not a major problem because lives are generally short, about 200,000 km or 10 years and have been limited by corrosion until recent improvements. Particular components in braking or steering gear do occasionally fail and sometimes prompt expensive recalls. Trains have much longer lifetimes, but are generally over-designed. Axles and rails occasionally cause difficulties despite over 150 years of effort.

Ships are very large welded flexible structures subjected to the joint attack of corrosion and fatigue. The poor safety record of bulk carriers gave rise to international concern in the 1980's and led to a tightening of inspection standards. Over 118 large ships have been lost since 1990, with 587 crew deaths. The design of large cargo ships remains a problem.

Superficially, aircraft are 'fatigue machines' and the consequences of critical failure are severe. Nevertheless, much attention has been given to the problem and many advances in our understanding of fatigue design and maintenance have come from the aircraft industry, often from the study of failures. Structural fatigue is a much smaller cause of accidents than human error, but several well publicised accidents have occurred through the failure of minor components such as bolts, thus emphasising the local nature of fatigue.

The paper will conclude by summarising the issues raised by efforts to maximise the life of ageing equipment. Economic forces have emphasised the need for such activities and have raised many challenges to our knowledge of the effects of cyclic service loads.

FATIGUE KNOWLEDGE - CURRENT STATUS

It is not the purpose of this paper to review the current status of fatigue knowledge. Several authoritative reviews have been published in recent years: Miller (1991) discusses the central role of cracks, Nelson and Sheppard (1995) review life estimation methods, the proceedings of a recent conference, "Fatigue '96", (1996), contain many reports of current research problems.

It is sufficient for present purposes to understand that the fatigue life of a structure or component can be, somewhat arbitrarily, divided into various stages: the crack initiation period and the macro crack growth period, with the former divided into a nucleation and a micro growth phase.

The size scale over which these events occur is a central issue. Figure 1 identifies some key orders of magnitude: the range of size scales involved is high and shown in a logarithmic scale. A bridge might be several kilometres long, a large ship 1/3km long, an aeroplane say 50m and a car 3m. Vital components in these structures may only be millimetres long, but the initiation and growth phases of fatigue might occupy the majority of the fatigue life before any cracks are detectable. Defects introduced during manufacture can erode the nucleation and macro crack stages, such that the fatigue life of a large welded structure may be determined by macro crack growth from an initial defect of several mm length, but at the other end of the spectrum the life of a 'clean' steel ball bearing will be dominated by nucleation and micro crack growth.

The reality is that this range of sizes causes many practical problems and in any particular case, the identification of the dominant size of the problem should be carefully identified, so that the appropriate theoretical or experimental prediction technique can be identified.

It is worth recalling that in general, we make tests on laboratory samples of typically mm size scale and use data so generated to make predictions of internal events in our structures, perhaps of a metres size scale, which occur at a micron size scale or even less. It should come as no surprise to learn that such extrapolations are fraught with difficulties!

Overview of Design Methodologies

The design techniques for transport equipment with regard to fatigue can be divided into several categories, following the suggestion of Schijive (1996):

Cracks Should Not Occur
1a Fatigue Crack Nucleation Not Allowed. Infinite life required, so load cycles in service should not exceed the fatigue limit. Many parts of engines such as crankshafts fall into this category.

1b Defects Should Not Grow. Defects are often unavoidable, such as scratches from machining, nicks from impact damage, weld defects and corrosion pits. In many components there is a requirement that such defects should not grow into the macro-size range, e.g. railway axles.

Cracks Will Occur
2a Incidental Fatigue Failures Are Acceptable. A finite life of such parts can occur in service, economy and safety are not directly involved, but a sufficient economical life must be guaranteed. Many small parts fall into this group, e.g. small return springs on ashtrays, knobs, often made of plastics and switches in automobiles. Considerable customer irritation impacting on overall quality perception is generated by this type of failure.

2b Sufficient Fatigue Life Without Inspections Required. Inspections are sometimes undesirable for economic reasons, being time consuming, interrupt operation or impracticable by lack of accessibility. A *safe-life* philosophy is adopted and large safety factors are usually applied, e.g. the structures of cars or train bodies.

2c Sufficient Crack Growth Life Required for Crack Detection by Inspection. Inspections for fatigue cracks are generally acceptable if safety or large economic consequences of a fatigue fracture are involved, e.g. aircraft hulls.

LAND BASED TRANSPORT

The Automobile - a Tarnished Glory?

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 system, have led many people to realise 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 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, Bignonnet (1996). 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 is however 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 generic problem to equipment used in fields of transport.

Infrastructure Damage Caused by Heavier 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. Cebon (1993) in an extensive review, but concentrating on heavy vehicles, suggests a fourth power law between axle load and damage is essentially a rule of thumb, the relationship may be even higher, but in any case illustrates the high sensitivity of damage to the axle load. Now in recent years the overall weights and axle loads of heavy lorries have increased considerably. Forty four tonne lorries are common place through 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 seen for a simple calculation. If a bridge was designed for lorries of ten tonnes and a fifty year life, then for the same number of lorries of forty four tonnes, the life will be reduced to 1.6 months if the fourth power law holds! To meet a European Union directive to take heavier lorries from January 1999, some 700 bridges in the UK need strengthening at an estimated cost of £2.2 billion.

Trains - Due For Revival?

The development of railway systems since 1830, brought about an awareness of fatigue as a failure mechanism. The first railway accident involving major loss of life, at Versailles in 1842, Smith (1990), involved the failure of a locomotive axle by fatigue and instigated many studies into fatigue failures, including the classic work of Wöhler, and the establishing of the 'fatigue limit' concept.

Trains have traditionally been over designed and have proved to be capable of operating for many years (30 years is a nominal design life, but 50 or 60 years usage has been common). These reserved of strength have meant that fatigue problems have been rare and hardly ever generic. Axles have, and still, break, bearings fail but generally railway vehicles have been robust. Modern design pressures have led to lightweighting and changes from traditional steel to aluminium and even composite materials, have led to some cracking problems. An interesting example, is the airtight cars of the Japanese Shinkansen. The cars are pressure-tight to avoid uncomfortable pressure pulses as trains pass at high speed in tunnels: the major cause of retirement of the vehicles is loss of air-tightness due to fatigue cracking from fastener holes.

In parallel with road traffic, fatigue problems arise with the associated infrastructure, rails, bridges and overhead electrical equipment.

Broken Rails: a Remaining Problem for the Railway Industry

The passage of trains both wears the track and causes fatigue failure. Corrugations have been extensively studied for decades, but the exact mechanism of their formation remains a mystery. Heavy freight traffic causes rapid rail wear; a particular problem in the USA when freight movement is more important than passenger traffic. Table 1 illustrates that rail failure still remain a major problem. 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 crack 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.

SHIPS: THE UNSOLVED FATIGUE PROBLEM

Escalating losses of bulk carriers during the 1980's caused considerable concern in the shipping community and led to a tightening of inspection standards. The total number of large vessels lost since 1990 is 118. Thirty four of these accidents involved loss of life and a total of 587 crew members have lost their lives over this six year period. The costs involved, apart from loss of

ships, cargo and lives, are huge. The Exxon Waldez 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 fragile welded structures. A typical Very Large Crude Carrier (VLCC) is 330m long, and 56m wide. The side plates are 18 to 20mm thick. An egg is about 48mm wide and its shell some 0.35mm thick i.e. 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: 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 and still are 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 294m long 44m 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 paper by Bishop and co-workers (1990), discussed the unpredictability of fatigue cracking in large ships.

"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 detention very difficult.

11. Brittle fracture during lifetime.

The truth is that ships do crack and cracks grow".

This comprehensive list serves to indicate the large number of 'unknowns' still associated with fatigue in ships structures. On 1 August 1996, it was announced that the wreckage of the *Derbyshire* had been filmed at a depth of 4,200 m some 1,000 miles S-E of Japan. The stern section appeared to have detached, confirming the speculation of major structural collapse.

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. In May 1996 a ferry was lost 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. Inglis (1913) famous paper on stress concentrations was published in the Transactions of Naval Architects, because he was studying the stress round cut-out and portholes in ships hulls: this work was used by Griffith (1921) to formulate his 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.

AIRCRAFT: KEEPING FATIGUE AT BAY BY INSPECTION

Aircraft are designed in such a way as to minimise their structural mass. The consequences of failure are usually severe. The failures of the pressure hulls of the early *Comet* aircraft prompted much research which contributed to the development of quantitative understanding of fatigue crack growth, Smith (1986), particularly in aluminium alloys. A modern aircraft is a complex system and insignificant part can lead to catastrophic loss: a classic case was the crash of 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 overcome 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 maintenance defects
- 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.

Peel (1990) discussed the relative frequency of occurrence of different types of failure mechanisms in structural failures in 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 in 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 force 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.

CONCLUDING REMARKS

This brief review has described how fatigue related problems in the major branches of the transport industry have been addressed to allow 'safe' economic operation. Of the major branches discussed, only large ships have generic fatigue problems. In land transport more needs to be known about the interaction of vehicles with their infrastructure - roads and bridges for automobiles and lorries, rails in the case of trains. The public have an expectation of a continuance of enhanced safety standards.

It is worth quoting some figures for the risks associated with various modes of travel, and a brief explanation of the statistics, Anon. (1992), given in Table 2. The risk of travel has commonly been assessed in terms of accidental deaths per 10^9 km travelled, 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 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.

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 schedules 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

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 reflect 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 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, and better improve, safety and risk levels whilst at the same time operating under more stringent economic conditions.

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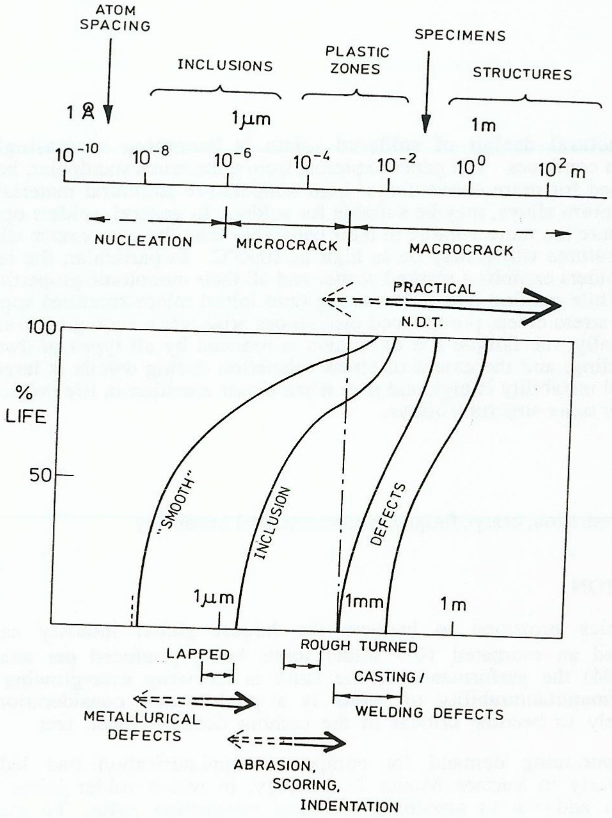

Fig 1. Size scales of fatigue and fracture

Appendix 1. A Brief Outline of Fatigue and Fracture History

Date	Experimental Techniques, Materials	Ideas	Theory	Important Names
1825 Railways Axles	Full scale tests 3 pt bending (wrought iron)		Empirical	Trevithick Albert 1830 Rankin 1840 Hodgkinson and Fairbairn 1840 - 65
1850		Crystalline metal?		I. Mech. Eng. discussions 1849 - 52
1850 Britannia Bridge		Importance of K_T		R Stephenson, President
1856	Steel			Bessemer
1879 Tay Bridge	Laboratory specimens, rotating bending	Importance of stress range	σ/N data Infinite life design, fatigue limit	Wöhler 1867
1900	Optical microscope	Slip bands and microcracks		Ewing 1902
		Mean stress effect	K_T for ellipse	Inglis 1913 Goodman 1914
1920	Bending and torsion	Multiaxial fatigue		Gough 1920
Axles, Springs in Automobiles		Importance of cracks in brittle fracture, energy balance	$\sigma\sqrt{a}$ = const.	Griffith 1921
1930		Residual stresses	Notch strain analysis	Haigh 1930
		Dislocations Elementary block concept	Notch strains	Taylor, Orowan 1934 Neuber 1937

Date	Experimental Techniques, Materials	Ideas	Theory	Important Names
1940 Brittle fracture in ships, welds				Tipper
		Cumulative damage	$\sum \frac{N_i}{N} = 1$	Miner 1945
			Stress analysis of crack, singularity	Sneddon 1946
1950 Comet	Closed-loop servohydraulic machines, Electron microscope, beginnings of computers, Strain gauges	Effect of plasticity on energy balance		Orowan 1955
			K-concept for cracks	Irwin 1957
1960 QEII turbine blades	Improved data collection and analysis	Low cycle fatigue, thermal strains	Finite element stress analysis	Zienkiewicz 1960
		Crack propagation	$\varepsilon_p N^\alpha$ = const	Manson/Coffin 1962
		Elastic/plastic fracture	da/dN = C(ΔK)^n	Paris 1963
1970			C.O.D.	Wells 1963
North Sea Oil Concord	Micro-chip technology	" "	J-integral	Rice 1968
Energy crisis, conservation		Fail safe, safe life and damage tolerant design		
1980		Only history will teach us the really important contributions of this recent era.		