

Guidance Document

G186 Assurance of Fractured Rolling Stock Components

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1. Purpose

The purpose of this document is to provide guidance and support to the process of managing fracture defects (cracks) discovered in rolling stock components. Dealing with cracks should be seen as a 'business as usual' activity. Rolling stock, in common with aircraft and any other (relatively) non-mass produced technology which also has a long design life, will suffer cracking in some of its components at some time. The alternatives to this are 'over design' or lengthy testing and development such as is seen in the motor car industry which produces at least two orders of magnitude more 'units' to make this viable. Even then, the design life is only about ten years compared to forty years for rolling stock.

2. Scope

2.1 This Guidance applies to Rolling Stock components.

This document deals with the physics of crack behaviour to a level sufficient to inform non-engineering managers about the validity of decisions taken to manage and control cracks to allow continued safe running. A basic familiarity with London Underground rolling stock is assumed. This guidance document should be read as a supporting reference to such LUL and Partners procedures as fleet document "Case for Continued Safe Operation". There are a number of such procedures in existence and this document better informs their use when the sub-standard condition relates to fracture defects. The focus is on dealing with cracks after their discovery rather than on design for avoidance.



3. Guidance

3.1 Coping with Cracks

The document is organised into five sections:

How Cracks Start – Insights into the circumstances which allow cracks to start and so provide the possibility of large and damaging cracks growing.

How Cracks Grow – Insights into the mechanisms by which cracks extend and cause gross failures.

Assessing and Dealing With Cracks – Insights into how to investigate failures, draw conclusions about safe operating with cracks present, and into providing lasting solutions.

Rationale for Continued Safe Operation – Insights into creating a sound rationale to support a case for Continued Safe Operation

Assurance of Fractured Rolling Stock Components – (1) Definition of what constitutes adequate assurance supporting a Case for Continued Safe Operation, (2) A procedure to be applied to deliver an assured Case for Continued Safe Operation which builds on the preceding advice.

This document is intended for use by non-engineers. The management of cracked structures contains many subtleties and needs great care, but there are a small number of guiding principles which enable managers to be confident that their engineering colleagues have reached sound conclusions on a basis which can be simply communicated to stakeholders.

These principles are shown in the table below and form an essential managers' check-list which they should task their engineers with answering.

Principles of Fracture Defect Management	
Principle	Supporting information
A cracked structure is only safe to operate if (1) it is possible to inspect it frequently enough to ensure that a crack does not become unacceptably large between inspections, or (2) a modification or means of secondary security is applied rendering crack growth irrelevant.	Knowledge of what the maximum acceptable crack length is. Knowledge of the crack growth rate. An inspection technique able to detect the defect applied frequently enough
A modification or means of secondary security can only be effective if the root cause of failure is identified.	Secondary security has to be as effective as the failed primary security. Confidence in the secondary system depends on knowing why the primary system failed.
It is only possible to create a permanent solution if the root cause of failure is identified	It is not possible to design for a given duty if that duty is not known.
A proposal to manage cracked structures by inspection only (rather than repair and/or modification) is unlikely to be sustainable indefinitely.	The resource intensiveness implied is unlikely to be sustainable and the lack of root cause knowledge implied represents an unquantified risk.



This document provides guidance for managers on all the supporting features, but it is also useful to know what 'good' management of fracture defects looks like. It includes:

- a) Knowledge of why the cracks started.
- b) Knowledge of how fast the cracks are growing and why.
- c) Knowledge of how to detect crack growth effectively.
- d) Knowledge of what the maximum acceptable size of defect is.
- e) Good management of inspection data.
- f) Competent personnel employed on all tasks
- g) Use of inspection and/or modifications as interim measures to allow safe service operation before provision of a permanent repair.
- h) Provision of a permanent solution which is based on knowledge of the root cause of failure and does not rely upon repeated inspection for its effectiveness.
- i) The ability to communicate to stakeholders in their own terms throughout to ensure confidence in the action taken.

Before dealing with any detail there are also three important concepts to define – stiffness, strength and toughness. The terms “stiffness, strength and toughness” are often used interchangeably to indicate a material which can resist high forces in some way. Colloquially this usage presents no problems, but it is a positive hindrance in understanding how to deal with cracks. Some definitions follow.

Stiffness – How much a structure moves, or bends, when a load is applied.

Strength – How much load a structure can take before it breaks.

Toughness – How resistant to impact and cracking a structure is.

These three features are independent, with either high or low values, and able to exist in any combination in a structure. These terms will be used later.

3.2 How Cracks Start

Any physical component subject to loading is liable to crack. The question of whether or not it does, or what happens subsequently, is a function of:

- a) How well it has been designed to withstand the intended loading.
- b) The degree to which the actual loading differs from the intended loading (either because of poor understanding or because of different service duty).
- c) The degree to which any manufacturing or service induced defects are present.
- d) The degree to which intended maintenance attention is correctly applied.

These items can be thought of as the underlying or root causes of failure. The immediate causes that they give rise to are explained in this section.

In deciding on a course of action for dealing with cracked components it is important to understand the immediate and root causes to ensure that the problem does not repeat itself or that if it does, it happens in a timescale which is acceptable.

Most load bearing rolling stock components are metallic, and of those, most are made of steel of some type, with aluminium alloys being the next most common choice. Unless cracks grow to great length quickly (catastrophic failure) the mechanism of initiation is usually 'fatigue' and is caused by cyclical loading applied first in one direction and then the opposite direction. Catastrophic failures are the result of unintended high loading applied suddenly, and it is their gross nature which generally makes their analysis and rectification simple – they are often true 'one-offs'.

Fatigue failure is the more insidious and common of the failure mechanisms and is the main focus of this document. Fatigue failure, which is caused by reversed, or cyclic loading, can be described as 'insidious' because it can cause a material to fail at loading levels much lower than can be supported under simple static loading. The form of failure is usually steady and accelerating crack growth followed by catastrophic failure as the remaining material cross section is unable to support service loads. Without the foresight to realise this at the design stage a structure will appear to perform adequately in the early part of its service history only to fail later.

An understanding of how cracks start is the first step in dealing with their management.

3.2.1 Static loading

If the loading applied to structures is purely static (i.e. constantly applied in one direction) then the only real consideration is that the applied stress allows the material to remain 'elastic'. The term is well chosen as it refers to the behaviour of most materials under modest loading – they act like springs. If the load is applied they stretch, and if the load is then removed they relax back to their original position. For many materials, and particularly ferrous materials (i.e. materials containing iron, such as steel), there is a natural and sharply defined limit to this behaviour, called the 'yield point'. This is the point at which the applied stress causes the material to stretch permanently (i.e. deform plastically). Once this point is reached physical damage is caused to the material and micro cracks will initiate.

3.2.2 Stress concentrations

The presence of a small defect in a material, or a design feature which puts a sharp corner or notch into a material, has the effect of 'concentrating' the stress at the tip of the crack. The picture below illustrates this at the molecular level as the load taken by the molecular bonds which have been broken is all transferred to the remaining bonds,

which now take a much higher load than previously until they too break. Clearly this behaviour will accelerate as long as the load is applied.

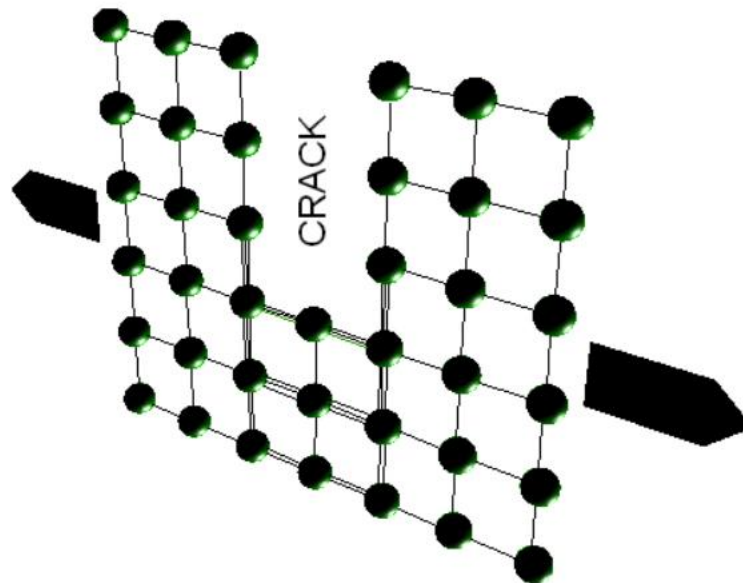


Figure - 1

At the macro, or real-world level, the same applies: Each of the 'designs' below will concentrate the stress as indicated. Stress can be thought of as a flow of liquid – if it has to pass through a constriction it flows faster and with higher pressure.

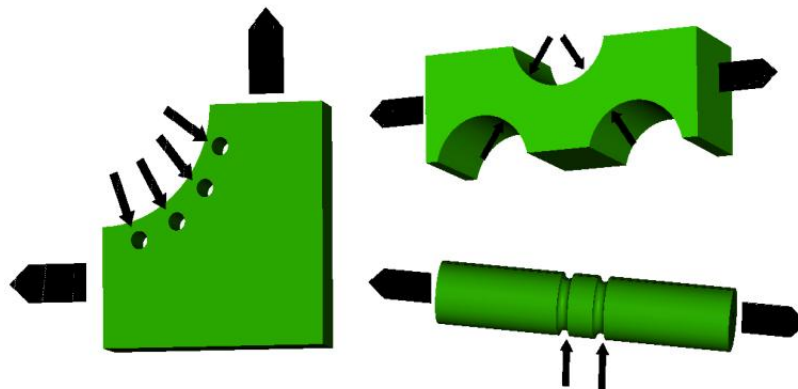


Figure - 2

Each of these sources of stress concentration is also a source of potential crack initiation and failure.

3.2.3 Fatigue

It has long been demonstrated by experiment that materials subjected to cyclic loading (i.e. loading which is reversed repeatedly) will exhibit micro-cracks (i.e. very small cracks visible only with a microscope will initiate and then grow). The name 'fatigue' was chosen originally to represent the apparent 'tiredness' of a material which fails under repeated loading.

It is not necessary to understand in detail what happens to materials at the crystal, molecular, atomic or sub-atomic levels to understand how cracks start, and then grow.

It is enough to know that materials are formed of molecules (which are themselves collections of atoms – the smallest unit of matter) and that when cracks are formed and grow the bonds between the molecules are broken. Materials of the type discussed here have their molecules organised into crystals and cracks are the result of slippage between crystal edges. It requires energy to be applied to break the bonds, and when the bonds break they release energy themselves (which manifests as cracking noises and heat).

Cyclic loading is likely to initiate a crack at loads lower than static loading. The small imperfections present in real materials act as stress concentrations which, very locally to them, cause slipping between adjacent crystals. Repeatedly reversing the load aids further slippage by momentarily removing local compressive stresses which would otherwise lock the boundaries together. Load applied in a single direction would not have this effect at such low loads.

The picture below illustrates the start of such a micro-crack as several crystals slip past each other under the influence of a load with the crack site marked with an arrow. Once formed this crack then extends under the influence of the loading and the concentration of stress at the crack tip.

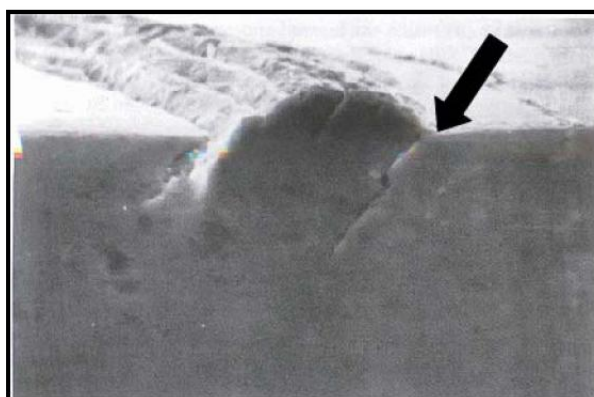


Figure - 3

The lower the stress level the greater number of cycles of loading that can be resisted. The characteristics of ferrous materials (iron based, such as steel) and non-ferrous materials are different as shown in Fig 4.

The term 'stress' refers to 'load per unit area' to which the material is subjected, first in one direction and then the other (this is one cycle). The most notable difference is that ferrous materials have a threshold of applied stress below which no cracking will be initiated. This is not true of non-ferrous materials such as aluminium and its alloys.

As most rolling stock components are ferrous, a good design principle is to ensure that loading stresses do not exceed the threshold stress to give at least 10^6 cycles life (i.e. practically infinite). This threshold is usually given the name 'endurance limit'. National and International standards¹ for design of steel structures recognise this fact and have embedded it in their design parameters. Structures may be designed for a lower life when this is adequate for the service duty.

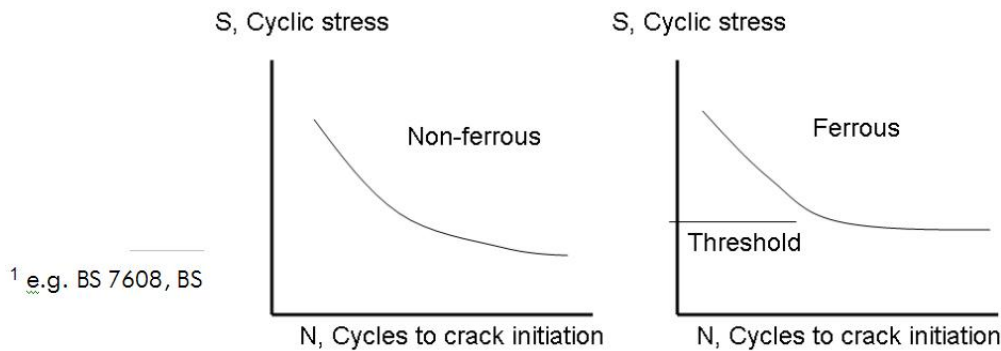


Figure - 4

One of the most important factors for steel structures is the relationship between the applied reversed stress level, S , and the life (measured in number of cycles, N) as shown in Fig 4.

A small reduction in the level of stress gives a dramatic increase in the life. The number of cycles, N , is inversely proportional to S^3 for a given design detail, e.g. halving the stress will give 8 times the life (since $2^3 = 8$). This is a very real incentive to keep stress levels low.

Most of the standards which are designed to aid estimation of fatigue life in real structures have experimental data at their heart originally produced by Det Norske Veritas (the Norwegian equivalent of BSI) for the design of sea-based structures subjected to fatigue loading and they helpfully categorise what happens in the case of loading on structures in different configurations of parent metal and welding.

Different details of design (termed 'Classes') have different characteristics when presented in the form of Fig 4 above. Some of the examples illustrated in Fig 5 show straightforwardly that loading along a weld gives a longer life than loading across a weld.

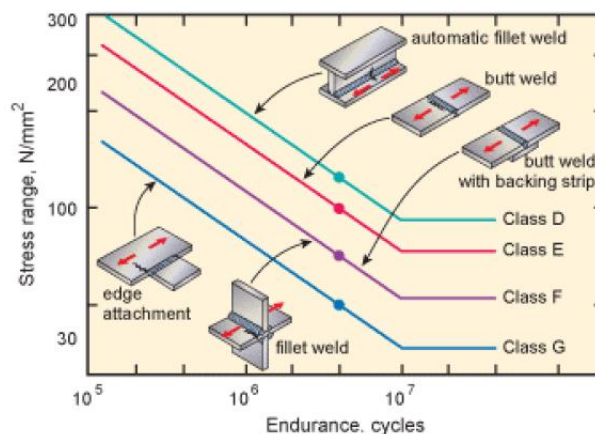


Figure - 5

The data may be presented in a probabilistic format, i.e. for a given design detail a curve can be derived connecting the proportion of a population of components likely to be cracked after a given number of cycles of loading. It is a classic 'S' curve based on the cumulative normal distribution. A typical example is shown in Fig 6

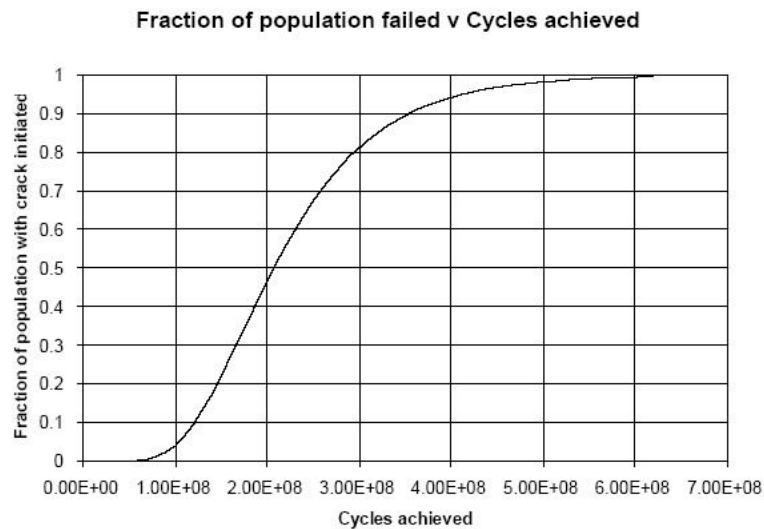


Figure - 6

Fatigue 'damage' is cumulative, i.e. once damage has been incurred, operating at a lower load will not 'cure' it - it remains to be added to by the next instance of high loading. This is reasonable as the 'damage' is the breaking of molecular bonds, or breaks across crystal boundaries which, cumulatively, eventually provide a defect large enough to be termed a 'crack'.

3.2.4 Static and Cyclic loading

In the real world, structures do not always have stresses applied which are 'reversed' in the true sense. Most have a mean level of stress applied about which there is variation. The more that this mean stress is compressive the less will be the propensity to crack – because the material is 'held together' by the applied compressive stress.

The characteristics shown in Fig 4 are modified by the addition of a static stress around which the alternating stress varies. The more compressive mean stress there is, the greater level of alternating stress that can be withstood.

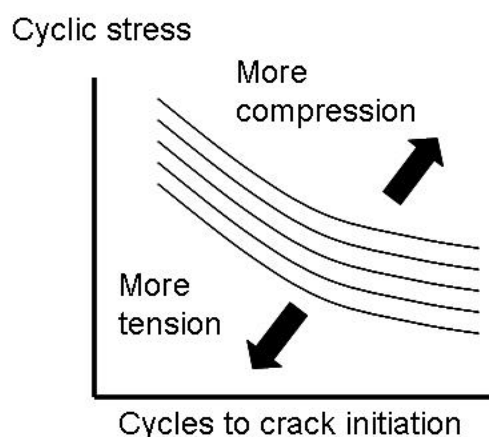


Figure - 7

3.2.5 Welding

Welding is the most common form of construction in use for complex structures. Because it consists of raising the metal to its melting temperature, and because of its application in often less than perfect conditions, it is prone to a variety of faults.

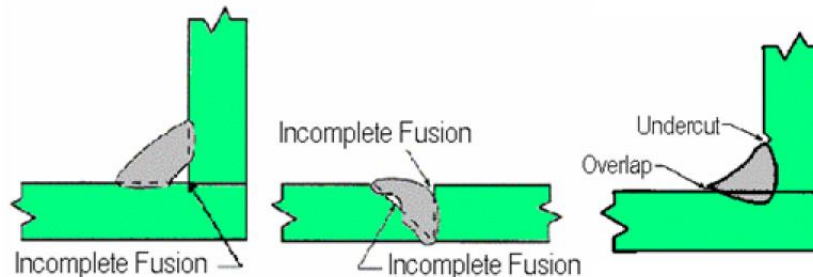


Figure - 8

Each one of these examples is a source of stress concentration (see above) and so a source of potential failure. However, there is another source of potential problem with welds. Even a perfectly made weld will have locked into it stresses (referred to as 'residual stresses') caused by the fact that the molten weld material has cooled, and so contracted. This contraction causes residual stresses up to the yield point of the material (see static loading above) and so may induce a micro-crack to start even before any load has been applied. It is possible to 'anneal' the weld (heat it and let it cool slowly to allow these stresses to relax) and then grind it (to remove any small cracks), but this is not usually done. For this reason welds are always 'weaker' in resisting fatigue loading than unwelded material as they have a high mean tensile stress level.

3.2.6 Bolts

Bolts are a very common method of joining components. There are two sources of potential trouble with bolts – (1) the holes through which they pass are a source of stress concentration and (2), if they become loose they are unlikely to withstand cyclic loading applied to them and will fail through a fatigue mechanism. The reason for the first issue, stress concentration, is self-evident, but the second less so.

Two flat plates held together by a bolt and nut will be in compression to an amount determined by how much the nut and bolt have been tightened. This is termed 'preload'. If a load applied to the plates attempts to pull them apart it is important to understand that most of the load applied will go in reducing the compression between the surfaces of the plates – it will not increase tension in the bolt by much. At first sight this is a counter-intuitive result; the plates are being pulled apart so the tension in the bolt must increase. It does, but only by about 15% of the applied load.

In pulling the plates apart the external load is doing two things simultaneously. It is increasing the tension in the bolt and it is reducing the compression between the plates. There are two load paths. Load paths attract load based on their stiffness. Take the case of two springs side by side, both the same length, one very stiff, one very flexible, and constrained to move together. As they are compressed or stretched, the stiff spring will offer most resistance and the flexible one very little resistance. In this case the stiff spring is the two plates and the flexible spring is the bolt (which is flexible compared to the plates). The two paths attract load in proportion to their stiffness which is usually about 85% and 15%, for plate and bolt respectively.

This is an important result. For a correctly tightened bolt, with external load which does not separate the plates, the bolt will only experience 15% of the applied load. If the plates separate the bolt will experience 100% of the load, and most likely break,



either instantly by brittle fracture as a result of experiencing more than 6 times its normal load, or if not, by fatigue.

Keeping bolts tight is important.

3.2.7 Residual stresses from the manufacturing process

Sometimes items are bent straight, or to some other form, while they are at normal operating temperature (i.e. not heated to make them plastic). This takes the material past its yield point so it may be plastically deformed. This also locks in tensile stresses which will reduce resistance to fatigue (see Fig 6). This is a very common manufacturing technique.

Summary

A crack can start through any of these mechanisms, alone or in combination:

- a) Poor design or service damage (scratches, notches) which create stress concentrations.
- b) Cyclic loading, especially if it is greater than the 'endurance limit'.
- c) A single application of (static) load which is high enough to reach the yield point.
- d) Welds. Poorly executed welds will certainly give stress concentrations but all welds can give high residual stress even if well executed.
- e) Loose bolts.
- f) Residual stress due to manufacturing processes.

Other features of importance are:

- a) Cyclic loading is more likely to start a crack than static loading
- b) Propensity to cracking is very sensitive to stress levels (a cubic relationship)
- c) Fatigue damage is cumulative. Once incurred it cannot be undone and the component remains weakened.

3.3 How Cracks Grow

There is a large body of research on this subject, all grouped under the generic heading 'Fracture Mechanics'. This document is not intended to be a treatise on the subject and so will summarise the main findings. These are grouped under two headings, Fundamentals (or physical laws) and Consequences and Mitigations (or what the Fundamentals give rise to).

If the energy released in growing a crack exceeds what was required to extend it, the crack runs uncontrollably without further application of load and brittle fracture results – the classic case of breaking glass. This can apply to some surprisingly soft materials too. A block of gelatine will exhibit the same behaviour if a spoon is inserted into it. If it requires more energy to grow the crack than is released then the cracking is controlled and can be stopped by releasing the load.

3.3.1 Fundamentals

3.3.1.1 *Thin materials (usually < 3mm) have a better resistance to crack growth than thick materials*

Thick materials offer support and constraint at the tip of the crack so keeping it 'sharp' and able to grow. Thin materials cannot offer this support and so allow the crack tip to deform plastically and become 'blunt' slowing its growth. This is why armour plating against artillery consists of layers of thin material rather than one thick slab, and why First World War tanks (which had single thick plating) would shed shrapnel splinters from the inside surface of the tank after a shell strike outside.

3.3.1.2 *The rate at which cracks grow (mm length per cycle of loading) is related to the alternating stress cubed*

This 'law' is of the same form as shown in Fig 4. This should not be surprising as the underlying physics is the same for micro and macro cracks. The term 'related to' actually refers to something called the Stress Intensity Factor (which is not the same as 'stress concentration' above). The Stress Intensity Factor is a function of the alternating stress applied and factors describing the geometry of the component.

Each material has a fixed property known as the Critical Stress Intensity Factor which is related to one of three main cracking modes – given the symbols K_{IC} , K_{IIC} and K_{IIIC} – illustrated below in Fig 9.

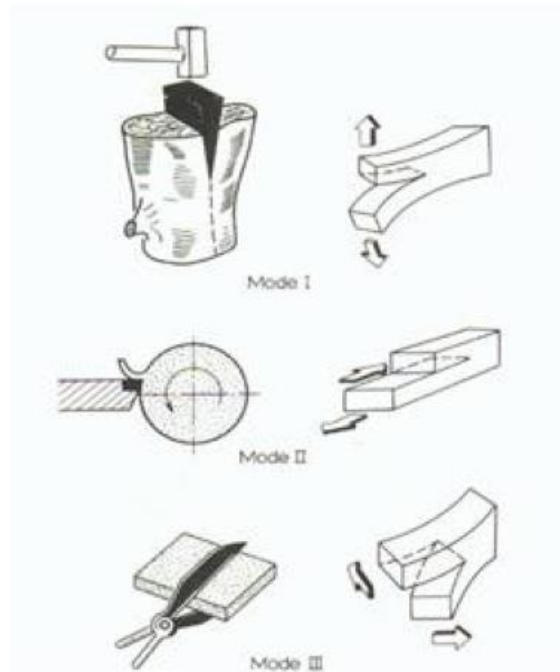


Figure - 9

If the applied Stress Intensity Factor (which is related to the applied stress) is less than each K_{IC} value a crack will not grow. These K_{IC} values are associated with high material thickness – see 3.3.1.1. This is an important tool for engineering analysts, who can estimate values for the Stress Intensity Factor applied.

As a crack grows it often leaves behind evidence at the micro-level of the fatigue mechanism at work. This is in the form of a series of small jumps, or striations, on the fracture surface as it moves incrementally under the influence of cyclic stress – Fig 10. By knowing what the applied frequency of loading is (e.g. an escalator rotational speed) and by counting striations over a given length, it is possible to estimate how much time it took for a crack to grow. This can be useful when seeking to understand the failure characteristics to prevent recurrence.



Figure - 10

3.3.1.3 *Some cracks will be stable and not grow beyond a certain limit. Others will be unstable and grow catastrophically. It is possible in each case to make judgements about which applies.*

When cracks grow the fracture surface releases energy stored there. In order to grow the crack in the first place energy has to be applied from some external source. There

are two cases to consider. (1) If the energy applied to grow a crack is greater than that released the crack will stop growing if the external load is removed. (2), otherwise, it will grow catastrophically (like cracking glass). In practice, analysis of the rate of cracking with knowledge of the loading and the structure is enough to estimate which circumstance applies. Essentially this relates to the applied K being less than the K_C values in item 3.3.1.2.

One of the most famous instances of catastrophic crack growth concerns the WWII Liberty ships. These were of all welded construction and designed using simple beam theory before a time when stress concentrations (which start cracks) and crack growth criteria were well understood. The picture below shows the result – a ship with a broken back in harbour. The crack started at a stress raising feature (the curved superstructure at the top of the crack).



Figure - 11

3.3.1.4 *Cracks which grow beyond a certain length (the critical crack length) in a particular case will be unstable.*

This arises because as the crack grows it releases strain energy stored in the structure as a whole which then becomes available to grow the crack, supplementing that from the external source. As this released energy grows the crack, yet more energy is released to grow the crack even further... a classic positive feedback situation. It represents the transition between case (1) and case (2) in item 3.3.1.3 above.

3.3.2 Consequences and Mitigations

3.3.2.1 *Drilling a hole at the end of a crack will often not stop it*

This is often a direct consequence of the issue in item 3.3.1.4 above. The theory behind using a hole to stop a crack is based on exchanging a sharp crack tip for a blunt hole. However, once the critical crack length has been reached the hole is simply an extension of the crack, and if the hole is large enough it may actually cause the critical crack length to be reached sooner thus guaranteeing the crack will grow. Essentially the large crack has altered the geometry of the component to the point where the stresses at the hole edge are now large enough to initiate a 'new' crack which continues to extend the path of the old.