"Two Steps from Disaster" – The Science and Engineering of Structural Integrity

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Abstract

The paper, which is a somewhat up-dated version of the author's 1999 Royal Society/Royal Academy of Engineering Lecture of the same title, presents an overview of the issues involved in the initial design of structures and machines, in material selection and guarantees of quality, in erection and fabrication, in non-destructive examination and through-life "health-monitoring", and in assessment of the threats to integrity posed by the presence of defects. Attention is drawn to the R6 Failure Assessment Diagram and to the characterisation of fatigue-crack growth. Finally, the issues are set in terms of a risk-based probabilistic approach to the occurrence of failure and to the consequences of such failure. The 1999 Lecture was given to an audience having a non-specialist, general science/engineering background and so was put in more popular form than would be the norm for a specialist audience. This form has been retained in the present paper, but it is hoped that no "integrity of message" has been lost by so doing.

"Dicing with Death" - Disasters and Risk-taking

1998 was billed as the *Year of Disaster*. Natural forces, generated by snow-storms, hurricanes, floods and earthquakes, wreaked havoc on engineering structures all over the world: disabling electricity supplies, claiming lives, making people homeless. 1998 was also the year in which *Titanic* won eleven Oscars. We are eternally thankful that we do not have to share the plight of the victims of real disasters, but, ambiguously, we flock to disaster movies; to shudder at the dangers portrayed on the screen, to quake at risks to life and limb.

In everyday life, we engage, to a greater or lesser extent, in activities which bear the risk of a disastrous outcome: contact sport, the ski-slopes, driving on race-tracks or on public roads. Some delight in hang-gliding or in "death-defying" fairground rides on *Oblivion* or *Nemesis*, regarding such experiences as the spice-of-life. Others are more circumspect, trying to minimise personal risk, perhaps being unnecessarily overcautious. Our language contains everyday phrases which continually remind us of risk and potential disaster: *Sailing Close to the Wind*; *Walking on a Tightrope*; *Skating on Thin Ice*; *Treading on Eggshells*; *Playing with Fire*. "*Dicing with Death*" aptly represents *hazard* in terms of *probabilities*. For most of our everyday concerns, we have a working perception of the risks involved. We form views on the dangers of cigarette smoking, on eating beef-on-the-bone, on riding a bicycle without a crash-helmet. Insurance companies quantify day-to-day risks quite precisely when they set their premiums.

What, however, do we know of the risks involved with large-scale engineering enterprises? How can society judge what level of risk is acceptable? The chemical plant which might explode (*Flixborough* 1974); the offshore platform which might capsize (*Alexander L. Kielland* 1980) or catch on fire (*Piper Alpha* 1988); the super-tanker which might founder and saturate beaches with oil-spillage (*Torrey Canyon* 1967, *Amoco Cadiz* 1978); the nuclear power plant which might release cancer-producing radiation (*Chernobyl* 1986); the aeroplane which might crash as a result of metal fatigue (*Sioux City* 1989); not forgetting the *Titanic*, the *Derbyshire* and a host of other examples.

Many disasters are attributed to the fault of whoever was in the "driving seat" at the time, but, in this paper will concentrate on technical, "engineering" failures, on the factors which affect *structural integrity*: those which may cause the structure or component to fail to continue to do what it was designed to do and, through such failure, lead to a disastrous outcome. The term *Structural Integrity* embraces contributions from design codes, materials science and engineering, fabrication technology, non-destructive inspection, through-service monitoring, fracture mechanics, probabilistic assessment of failure, safety-management procedures and, inevitably, an important measure of "human factors".

"The Reason Why" **- Function**

We start with *function* - what is the final engineering construction supposed to do? *Failure* can then be defined as *loss-of-function*, which *may* lead to disaster. There are two main types of engineering structure. One, such as a bridge crossing a river, is *functionally static*. It deflects in response to traffic loads, winds or waves, it expands or contracts as the temperature fluctuates, but its prime function is to span the river and bear traffic. The second, such as a ship's hull or an aircraft body, is *transported* from place to place, but must maintain a measure of *rigidity* with respect to the payload and external forces.

Machines, in contrast, are *functionally dynamic*: assemblages of gears, crankshafts, pistons and the like, which move relative to each other, often at high speed; producing power-drives for transportation, turbine systems for the generation of electrical power, machine-tools for manufacturing industry. There is not always a sharp distinction between structures and machines. As part of its function, *Tower Bridge* has a roadway which is raised and lowered to allow shipping to ply up and down the *Thames*. An aeroplane wing incorporates "flaps" which are essential features during take-off and landing,

It is of interest to note three specialised functions. In "death-defying" *Fairground Rides*, the function is to provide the *thrills* of perceived danger, *without* any unintentional *spills*. In *Musical Instruments*, the function is to *amplify* an initial *vibration*, quite contrary to normal engineering practice. The third could be termed an *Architectural Statement*. Here, the function is to *create something quite different* from what has been done before: whether a *Building* (such as the *Guggenheim Museum* in Bilbao) a *Sculpture* (the *Angel of the North*) or one of the *Millennial Mirabilia* (the *Dome*, *London Eye*).

Designers have to respond to *societal pressures*: views on aesthetics, environment, emissions, pollution, waste-disposal, use of recyclable materials. The looming carbon tax is forcing car manufacturers to reduce bodyweights. *Cost* is a major factor in any design, related to a need for *high performance*. *Defence* and *Sport* spend rather more than most to obtain this, but the "acceptable lifetime" of a fighter-plane or a racing-car is very much less than that of its civil counterpart.

The cost factor does not *always* reduce to the use of more "cheap and cheerful" materials and manufacturing processes. Consider air-travel. Passengers do not want to pay more for their air-fares than they need, but they also want to be safe. *Cheaper fares* require more *efficient* use of aviation fuel; hence, *higher thrust/weight engines*, *higher stresses*, *higher temperatures*. In turn, this entails *sophisticated* aero-engine design and the use of *expensive*, high-performance *materials*. The passengers insist on high safety: the airlines want engines that will run for long periods without need for replacements. *The conflicting aims of designing simultaneously for high efficiency and high assurance of safety throughout an economically viable lifetime pose the fundamental problem for any designer of high-performance systems*. How far from potential disaster can one afford to be? An important feature of *Structural Integrity* analysis is that it provides quantitative input to the formulation of an appropriately balanced response to the problem.

"The Daily Round" - Duty

Associated with any function is the service *duty*: what does it have to stand up to? Structures and machines are a bit like human beings in this respect. They have to endure the stresses and strains of everyday life, suffer a few unexpected blows and generally experience wear and tear, developing "rusty joints" as they grow older. *Duty* includes non-varying *"dead" loads* (the weight of a structure, constant pressure in a vessel) and a variety of fluctuating *"live" loads*, varying with time: *a loading spectrum*. An example is the flight cycle of an aircraft: take-off; in-flight manoeuvring; running into turbulence; landing; operating reverse thrust. A North Sea drilling platform experiences gusting winds, pounding waves, and occasional impacts from vessels. Such forces produce response from all parts of the structure. Structural Integrity analysis treats the design, the materials used, features of how components are joined together and the service duty to try to answer the question: "*For how long can the construction withstand the service duty before it fails, i.e. suffers loss-of-function?"* This is the *Design Life*. The supplementary, *$64,000 (or sixty-four billion dollar), question* is: "If it fails, what are the *consequences of failure*: will they lead to *disaster*?"

The saying has it that "A chain is only as strong as its weakest link". In many structures, *redundancy* can be designed-in: if one link fails, alternative load-bearing paths exist and the structure as a whole is not at risk. This is not usually the case for simple linked chains, boilers, pressure-vessels or pipelines. Cables, for cranes, lift-shafts or nautical applications, normally consist of bundles of strands of fine wires, tightly bound together: then, if a single wire fails, the load is transferred to neighbours in the bundle. In aero-engines, where weight is at a premium, it is difficult to include much redundancy and some *components* have to be regarded as *critical*: if one of them fails, the engine is lost and, possibly, the aircraft.

In principle, the route to ensuring that a critical component will not fail is straightforward. The through-life spectrum of stresses to which it will be subjected is derived from the service duty and is compared with materials test data. The component's *dimensions* are then adjusted to *maintain the stresses* at a level which will *guarantee the design lifetime* within an acceptable margin of safety. "Acceptable" here implies some probability of failure, even if this is very low. The dimensions must, of course, be consistent with the overall function, including minimisation of weight, if this is important, and any cost penalty will be examined with intense interest. There are usually well-established *Design Codes*, including *Safety Factors* on stress, and *Data-bases for Materials Properties* to which designers can refer. Modern structures and machines possess a high degree of reliability, particularly when they are developments of "tried and trusted" forerunners. Problems have, however, occurred in the past and it is useful to describe some of these to illustrate the sort of issues that may arise.

"Slings and Arrows" **- Unanticipated Duty**

Just as human beings do not anticipate all the blows that they will encounter in life, so the designer may underestimate the severity of the service duty. The *safety factor*, based on past experience, may not be sufficient. In the North Sea, the so-called "100-year wave" seemed to occur every few months! Some twenty-five years ago, the *axle loads on lorries* were allowed to rise from 32 tons to 38 tons. This greatly *increased the high-load duty* on road-bridges. Now, the loads are increasing further, to 44 tons.

In design scenarios, it is important to *consider all factors*, so far as the mind is able. Mr. Butler, in his 1995 Royal Society/Royal Academy of Engineering Lecture, referred to 4000 scenarios when considering how to evacuate an offshore platform if it caught fire. The unexpected can still occur. Perhaps the builders of *Pompeii* should have realised that they were "playing with fire", but the reported cause of the destruction of *Jericho* was less predictable. A coloratura soprano may be able to shatter a wine glass by producing such a sustained, pure note that resonance generates high elastic stresses, but Joshua had a limited number of rams' horns and the walls of Jericho were very thick. Bronowski notes that Jericho sits on an earthquake fault-line. Despite the fact that Japan is known to be particularly prone to earthquakes, the magnitude of the earthquake which devastated *Kobe* in 1995 appears to have been greatly underestimated, in that the resistance of buildings and elevated roadways to the shock was quite inadequate. Acts of War or terrorism can apply loads to structures well above those anticipated in the original design. The horrors of "9/11" remain fresh in our memory, but the bombing in the Second World War, culminating in the devastation of Hiroshima and Nagasaki, wrecked many an office block, row of houses or church. Centuries earlier, churches and castles in England had suffered, through "the dissolution of the monasteries" and the Civil War –producing many more than just "one of the ruins that Cromwell knocked about a bit!" Perhaps one of the most bizarre examples of an unexpected overload is that which was experienced by the *Erskine Bridge* in August 1996, when it was *run into* by a 6200 tons, 170 ft high *oil rig*, being towed down the river. It is difficult to assign a probability to the occurrence of such an event.

A major factor is the possible onset of *resonance*, amplifying vibrations: splendid in a musical instrument or the larynx of a coloratura soprano; potentially disastrous in a structure or machine. Following the spectacular failure in 1940 of the *Tacoma Narrows Bridge*

("*Galloping Gertie*") it has become the practice to test models of bridges in wind-tunnels as part of the design process. Car suspension systems and aero-engine components and sub-assemblies are subjected to representative vibrational loading spectra as a matter of course. The experimental testing is needed because the stress distributions in a vibrating system may not be the same as those predicted by a static analysis. It is important to locate any *hot spots.* Given all this understanding, it is still possible to make mistakes, as in the example of the "Blade of Light" pedestrian bridge across the Thames, which suffered excessive vibrations until dampers were fitted. This was probably due less to human "error" than to the "architectural concept" being allowed to dominate the engineering assessment.

Other unknowns may arise because something new is being attempted, either in function or material. The newer *"death-defying" Fairground Rides* introduce concepts such as fearsome vertical descents and 360° rolls. New *Architectural Statements* bring new challenges: what are the aerodynamic loadings on the *Angel of the North* or *London Eye* really going to be? What would happen if they were to ice-up very badly in a severe winter? Composite materials and magnesium alloys are being considered increasingly by aerospace and automotive industries, in attempts to reduce weight. What is known of their properties for long-term operation under stress? Engineering design is sometimes perceived to be unadventurous, because safety issues are taken so seriously. Too many steps into the unknown at one time can lead to disaster: even *Brunel's Great Eastern* exploded on her maiden voyage.

"Many a Slip" **- Erection and Repair**

Between the designer's virtual-reality simulation on the computer-screen and the finished work, structures have to be erected, materials processed, components manufactured and joined together. *It is vital that the analysis and control of these processes are carried-out with the same degree of care as that which goes into the original design* in the "stress-office". *Lack of attention* to detail can lead to *premature failure*, either during the erection stage itself, or after service duty of *much shorter duration than anticipated*, because the manufacturing and assembly stages have introduced *fatal flaws*.

An example of the erection problem is given by the collapse of a box-girder bridge at *Milford Haven* in 1970. At the time, the box-girder was a new concept. Other failures occurred at *Koblenz* (1971), *Vienna* (1970) and *Melbourne* (*Westgate Bridge* 1970). All were associated with a lack of understanding of the buckling behaviour of the trapezoidal "boxes" fabricated from thin plate. In one manner or another, *excessive forces* were applied *during erection*. The *original designers* were *not aware* of the abuses that might occur at the erection stage. The *bending moments* that were generated at Milford Haven were *very much larger* than any that would have been encountered once the bridge was up and built. *It is clearly vital to involve the construction team in the total design process*.

A second cause of trouble in the construction of bridges and buildings in the 1970s was the failure of *falsework* (temporary scaffolding, wooden planks and props) needed to support concrete whilst it is poured and is setting over its reinforcement. The *design* of the falsework as a *structure* was *not* subjected to rigorous analysis and a number of *falsework failures* occurred which led to the collapse of the partially-built edifices.

Lack of rigorously-analysed design was also the reason for the disaster, thirty years ago, of the (cyclo-hexane) chemical plant at *Flixborough*. A leaking reactor in a cascade of six was removed from its position and replaced by a *jury-rig* of (undersized) stainless steel pipe and bellows, supported by scaffolding. Some time after re-start, the bellows squirmed, creased and split, allowing contact between hot cyclo-hexane and the air outside. The explosion was "equivalent to that of 15-45 tons of TNT". The Enquiry castigated the lack of professional engineering design input to the "quick fix". There are, however, other theatres in which comparable "initiative" to rescue a "mission" would be regarded as admirable. The use of a genuine "jury-rig" to bring home an otherwise disabled vessel would certainly be applauded. The context is different, but how is that difference perceived by the individual at the time: how robust is the supposed culture of "safety at all costs"?

***"Achilles Heels*" - Materials and Manufacture**

Structures and machines are created from an assemblage of smaller components joined together, using welds, brazes, solders, adhesives or mechanical fasteners. *Failure* of the whole is often associated with *features of the joints* rather than with those of an individual component. Small *cracks around rivet-holes* near the square corners of window cut-outs led to the premature failure of *Comet* aircraft in the 1950s. A *poor-quality weld*, fixing a hydrophone to a leg of the *Alexander L.Kielland* offshore platform, triggered off crack growth that led to the platform capsizing in 1980. In both cases, the stresses associated with service duty caused the initial cracks (*fatal flaws*) to grow with time, primarily by mechanical *fatigue* mechanisms, assisted, perhaps, by some environmental interactions. Eventually, they reached a critical length, at which failure occurred: ripping the *Comet's* fuselage apart; collapsing one of the *Kielland's* supporting legs.

Fatal flaws may also be introduced during material processing and component manufacture. Improperly poured *casting*s may contain *shrinkage cavities* or *entrained non-metallic particles*, which can serve as initiating sites for crack growth. This is recognised in design codes: the safety factors that have to be applied to castings under fatigue loading are much greater than are those for wrought material. Yet castings are used successfully under very arduous conditions in aero-engines and cast steel "nodes" for offshore usage exhibit better fatigue performance than do all-welded nodes. The critical point is the extent of the initial defect content: what *fatal flaws* may be present?

Quite small material defects can give cause for concern in aero-engine components. As engine temperatures rise, in the search for greater efficiency, alloys more resistant to high temperature deformation are required: these are, naturally, more difficult to forge. For nickel alloy turbine discs, the traditional "cast and wrought" production route is being replaced by the consolidation of *powder, produced by gas-atomisation* of liquid droplets. Small particles of refractory can end up in the disc and, if one of these is located, by chance, in a region of high stress, premature failure can occur. Powder-formed discs have failed in flight: they are *critical components* and engines have been lost as a result. At the stress levels employed, the size of an initial *fatal flaw* may be only 0.05 - 0.2 mm. The failure of a titanium alloy fan disc on *United Airlines 232* (*Sioux City* 1989) was attributed to a hard, brittle micro-structural defect, of unspecified, but less than 2mm, size.

Initiation sites can usually be observed by examination of a failed fracture surface, using *scanning electron microscopy*. For *fatigue failures*, it may be possible to recognise a characteristic *striation "footprint"* as the crack progresses cycle-by-cycle; even, to measure the local crack growth-rate from the striation-spacing and "count back" to determine the *crack-propagation life*. The *size* of the initiating defect can be measured and it can be analysed chemically, using *X-ray Micro-analysis. Auger* analysis or *Electron back-scattered diffraction* can be used to obtain further information. Since the part has come to end-of-life, such examination might be called *Forensic Fractography*, searching for the *fatal flaw* that *shortened life*. This is virtually identical to the work of a pathologist.

"Needles in Haystacks" **– Detection and Control of Defects**

Defects of *some* size are present in all structures and machines. What needs to be assessed is whether the *defect present in the finished product* is sufficiently large to cause the lifetime to be shorter than that assumed in design calculations. Three strategies are employed.

The first is that of *non-destructive inspection*, NDI. This includes surface-sensitive techniques and (X-ray or γ-ray) radiography, but I will concentrate here on *ultrasonics*(U/S) inspection, which is the best for detecting crack-like defects in thick sections. The problem is much worse than that of looking for needles in a haystack: arguably, the needles could be removed by the use of sufficiently strong electromagnets. The U/S techniques employed are rather like those in underwater sonar: certainly, an advance on wheel-tapping. Use is made of a piezo-electric *transceiver*, emitting ultrasound at a frequency in the range 1-10 (often 2) MHz and operating in *pulse-echo* mode. The *depth* of a defect is determined from the time taken to receive the echo and its *lateral dimensions* from the disappearance of the defect's "echo" to a threshold level as the probe is rastered across the surface. The limit of resolution on size is of the order of the wavelength, which, for 2MHz, corresponds to approx. 3mm in steel. Some design codes insist that, if a "crack" is detected by NDI, the surrounding volume must be removed and a weld repair effected. If the sensitivity of U/S detection were significantly improved, the consequence would be that smaller and smaller, progressively innocuous, defects might have to be removed and costly, possibly deleterious, repairs made. It is therefore critically important to *assess* the *significance* of any defect found.

The second strategy is to subject the component to a "proof-test" employing an over-pressure or over-speed some 20% higher than the maximum service design stress. This both ensures that the component *does not contain* a defect of size able to lead to failure under the overload and *generates compressive stresses* around the tips of defects after unloading, which help to retard crack growth in service. Defects may "open up" and become more reflective to ultrasound after proof-testing and it is usual, in modern practice, to carry out a U/S scan at this stage to provide a *fingerprint* for the component entering service. The effectiveness of such scans can be improved by attaching passive piezo-electric probes to the component during the proof-test to locate the sources of any *acoustic emission* during over-stress: U/S scans can then be concentrated in these regions.

The final strategy applies mainly to machine components, which often bear high stresses. The *fatal flaws* are very small, well below conventional NDI resolution. In such cases, integrity can be assured only by a combination of quality control during material processing and exhaustive testing of both testpieces and real components. For a successful product, details of the *processing sequence* are set in *tablets of stone* to ensure *consistency and reliability*. Moving to a new material is a major decision, because, not only do new processing variables have to be established, but a large new properties data-base has to be generated to cover low-probability failure events.

"The Crack of Doom " - **Fracture Mechanics**

It is necessary to assess the significance of defects in two sets of circumstances: *either* for a steadily increasing load leading directly to failure; *or* with respect to crack growth under cyclic loading (when environmental interaction may also be significant). The field is referred to as *Fracture Mechanics* and the starting point is to determine the distribution of local stresses just ahead of a crack tip. An elastically stressed body can be regarded as a set of elastic strings (the atomic bonds within the material) transferring force from one end of the body to another. For a uniform, applied tensile stress, the strings would appear as a uniformly spaced set of straight lines. Introducing a crack (which can bear no stress across its faces) normal to the applied stress *perturbs* the stress field in the region of the crack. The elastic strings have to bend to pass around the crack and they crowd together at the crack tip, indicating that high stress is produced locally. The effect can be seen as a decrease in the spacing of photo-elastic fringes in a stressed, pre-cracked polymer specimen viewed under cross-polars.

Continuum mechanics calculations show that, for an elastic solid, containing a crack, and subjected to a variety of external loadings, the *local stress field* varies as the *inverse square–root of distance* ahead of the crack tip. The *strength* of this field is denoted by K (the *stress-intensity factor*) which is a linear function of applied stress and a more complicated function of geometry: crack length, *a*, and component width, *W*: $K = f(a/W)$. For an infinite body, K varies more simply with the square-root of *a*.

In engineering alloys, a region of plastic deformation is produced around a crack tip when load is applied, but, provided that this is small compared with other geometrical dimensions, K still *characterises* the *extent of yielding* and the *crack-tip opening*. It is found experimentally in testpieces of different geometries that catastrophic, *fast*, fracture occurs at a critical value of K. This is called the material's *fracture toughness*. It is now possible to assess the *significance of defects* vis-à-vis *fast fracture*. First, a pre-cracked testpiece of standard geometry is fractured and the applied stress at fracture, together with the known geometrical function $f_1(a_1/W_1)$ is used to determine the fracture toughness. This value is then used in combination with the design stress applied to a component and a second geometrical function $f_2(a_2/W_2)$ to determine the size of the *critical defect*..

For materials of high fracture toughness, different characterising parameters are used to characterise the amount of crack-tip deformation before fracture, but the methodology followed is similar. The failure condition relates to fast fractures. It is clearly beneficial to use materials of high fracture toughness, so that high stresses need to be applied to cause failure by fracture. As the applied stress is raised, so the stress on the uncracked ligament increases and the likelihood of failure by *plastic collapse* of the ligament assumes increasing importance. A *two-criteria* failure condition underlies the basis of the *Failure Assessment Diagram* (FAD) which plots as abscissa the ratio of applied load to collapse load L_r and as ordinate the ratio of applied "K" value to the fracture toughness, K_r. A point is located by its values of L_r and K_r. Within the *failure locus* all is well (SAFE): outside the locus, failure is predicted (FAIL). The failure locus is supported by a substantial amount of analysis and validation.

"Half a League Onward" - Sub-critical Crack Growth

In previous sections, we have seen that *fatal flaws*, initially too small to produce fast fracture, increase their lengths as a function of time until they reach the critical size. This growth is termed *subcritical crack growth* and its treatment by *Fracture Mechanics* analysis relies on the fact that the region of plastic deformation ahead of a crack tip is characterised by K. Plastic deformation creates slip steps (clean surface) ready for chemical interaction with an external environment or for the adsorption of gas molecules from the air. It is possible, for chemically-driven crack growth under steady loading *(stress-corrosion)* or high-temperature crack growth *(creep)* to relate the rate of growth to the maximum value of K, K_{max}. For crack-growth under cyclic loading *(fatigue)*, the crack growth-"rate", per cycle, is related to the range of stress intensity factor $\Delta K = K_{max} - K_{min}$. For most cases, and certainly for uniform applied stresses, the crack growth rate (per second or per cycle) increases with crack length, so that *catastrophe is approached ever more rapidly*. Charging into the "Valley of Death" is an appealing analogy, although the distance that has to be travelled is usually quite small.

If the dependence of crack growth rate on K_{max} or ΔK is known, it is possible to determine the *lifetime* by *integrating the growth-rate* between a known size of any initial defect present, to the size at failure, based on the onset of fast fracture or plastic collapse. The analysis helps to provide *quantitative underpinning* for experimentally-derived *fatigue design curves*, such as those for welded features. Alternatively, a knowledge of the service duty, the material's fracture toughness and the desired lifetime enables a calculation to be made of the size of the initial *fatal flaw*. This can then be used to rationalise NDI or other defect-control strategy.

The *Fracture Mechanics* approach to treat cracking is *powerful*. It has been used to good effect in the *aerospace* industry, mainly for lifetime calculations and for specification of material properties. Aerospace, however, tends to use high-strength alloys of comparatively low fracture toughness. *Fracture Mechanics* is also used extensively to treat fracture in medium-strength, welded *steel structures*, particularly nuclear pressure vessels. Here, due attention has to be paid, not only to the use of alternative characterising parameters, but also to the way in which the toughness of steel assumes different values under different test conditions.

"Steels Behaving Badly" – **Brittle Fracture**

Structural steels comprise a fine-scale mixture of *ferrite* (almost pure iron) *grains*, having diameters typically in the range 5-100μm, and fine-scale carbide distributions, at the boundaries between the grains (thicknesses up to ~10μm) or distributed within the grains as very small platelets or spheroids. The steels are joined together most usually by *fusion welding* which deposits a weld metal of generally similar composition, but with somewhat lower carbon content, and containing small oxide or silicate inclusions, usually less than ~3μm in diameter. The yield strengths generally lie in the range 300-500 MPa at room temperature, but may be as high as 1000 MPa for some applications. Yield strength is generated by a fine ferrite grain size, alloying elements in solid solution in the ferrite and a fine carbide dispersion. Fine-scale microstructures can be obtained by *controlled-rolling* (CR) schedules or by *quenching-and-tempering* (QT), but it is not easy to obtain very fine grains in thick sections because cooling-rates are slow. The regions of plate next to the fusion boundary of the weld (the *heat-affected-zone*, HAZ) receive a further heating-and cooling cycle and in many cases, particularly for pressure vessels, post-weld heat-treatment is applied.

At room temperature, the fracture toughness of CR or QT structural steel is high. If a pre-cracked sample is tested, extensive plastic flow occurs at the crack tip and the testpiece absorbs a large amount of energy before the crack advances by a *ductile* fracture mode: small voids forming around second-phase particles and the material pulling apart as would plasticine containing a distribution of small steel balls. At low temperatures, however, the fracture toughness decreases dramatically and the fracture mode changes to one of *transgranular cleavage*, in which cracks run rapidly across the {100} cube planes in the ferrite grains. This is referred to as the *Ductile/Brittle Transition* and the reason for it is that the yield strength increases markedly with decrease in temperature. At low temperatures, high *tensile stresses* are generated ahead of the main pre-crack tip. These can *propagate micro-cracks* formed in brittle *carbides,* or brittle *inclusions* in welds, following fracture mechanics principles applied at the microstructural scale. The yield strength is also increased by pre-straining the material (with or without subsequent ageing), by increasing the strain-rate, and, significantly, by *hardening* mechanisms induced by *neutron irradiation*.

There have been many catastrophic brittle fractures throughout this century. There was a spectacular example in 1919 when a *molasses tank in Boston* shattered, drowning twelve people and many horses in molasses, injuring forty others and causing much damage to property. Between 1942 and 1952, *233 US Liberty ships* and *tankers* suffered fractures of such severity that they were lost or left in a dangerous condition: *nineteen broke in half.* Two similar failures which have occurred since are the *World Concord*(1954) and the *MV Kurdistan*(1979). There have also been major brittle fractures in *bridges*: *seventeen in Belgium* between 1938 and 1950, the *Kings Bridge* in *Melbourne*(1962). and in boilers and pressure vessels. There is some interest in the fracture of a *boiler drum* at *Sizewell* 'A' in 1963. The broken plates were replaced, re-welded into the drum, and operated without incident for over 30 years. Inspection, during an "outage" nine years ago, revealed the presence of quite large cracks, which apparently had been *present throughout life*, but *not subjected to any significant tensile stress*. Nevertheless, the cracked regions were removed and the drum has now been re-welded and returned to service. The need for repair was driven more by public opinion than by the technical case. In 1965, a pressure-vessel fabricated from 149mm thick steel, and intended to be used in an ammonia plant at *Immingham*, shattered during the proof test. A *two-ton piece* was *thrown* to a distance of *over 45m*.

"Ear to the Ground" - Condition Monitoring

A critical part of any safety justification is that *operational procedures* and *maintenance schedules* must be adhered to, slavishly. The procedures/schedules may include advice on *condition monitoring*. A motorist knows that if the engine begins to "run rough" it is time to have it checked-over. Similar indicators in engineering plant are often not given the full attention that they deserve, perhaps because there are no instructions in written form, or because the company's safety culture is not sufficiently well engrained at all levels. It may be necessary to offer *positive* (financial) *rewards* for the *reporting* of "faults": too often, such reporting is tacitly discouraged. Excessive vibrations or clear evidence of leaks indicate that not all is well with plant and *carefully considered* remedial action should be taken. The *Flixborough* disaster occurred, following the observation of a leak in one of the reaction vessels. The action taken was not to explore the cause of the leak, but to remove the vessel and replace it with the "jury rig" that failed. The vibrations on *Galloping Gertie* (the *Tacoma Narrows* bridge) in the months before final failure were so spectacular that it became a tourist attraction. In the light of such occurrences, the action taken to close the "Blade of Light" bridge across the Thames in order to fit stiffeners and dampers must be viewed as prudent.

As sensor technology and signal processing improve, there is opportunity to provide "on-line" automatic *condition monitoring* throughout service life. This is a separate exercise from that of periodic non-destructive testing, although, as experience is gained, it could help provide a more rational basis for the setting of inspection periods. Through-life sensor/actuator combinations are used, at present, to provide *operational* response to changes in conditions: whether a simple bimetallic strip to control temperature or a combination of accelerometers and actuators to trim an aircraft's wing when "flying-by-wire". Pressure sensors in the heavily glazed *John Hancock* building in Boston (Mass) are coupled to a floor of servo-hydraulic actuators, which are able to respond to damp down any effects of vibrations induced by wind forces. Such examples are focused on continued *operation*, rather than on the *prediction of failure* or *remanent life*, but there is no reason, in principle, why they should not feed back also into condition monitoring. Passive monitoring of elastic waves in pressure vessels (*acoustic emission*) is achieved using an array of piezo-electric transducers attached to the vessel's wall. Embedded f*ibre-optics* containing *Bragg gratings* are used to measure service strains in civil engineering structures and in composites in e.g. the masts of racing yachts. The action taken in response to detected signals varies. Sensor feed-back in the Hancock building is used to provide active control *via* actuators. If too large a load on a bridge is detected, traffic restrictions can be applied: too high a strain in a mast can be alleviated by relaxing the main-sheet or taking-in the sail; too high a level of acoustic emission in a pressure-vessel can be addressed by coming off load. In this last case, the method of alleviation may have consequences with respect to plant economics and the question that is raised is "what is the level (amplitude) of emission that gives cause for concern?" In the ideal case, this can be related to models for the growth of sub-critical cracks, or to the closeness of approach to fast fracture, but, even for reasonably well-controlled tests in the laboratory, the underpinning science is, at best, semi-quantitative.

The Rolls-Royce approach to engine health monitoring and diagnostics (EHM&D) includes temperature monitoring, gas-path monitoring, oil systems diagnostics and vibration monitoring. Taking the last of these and using the analogy of the car engine, the questions are: a). how is it determined that a part is "running rough"? b). how "rough" does the part have to run before mandatory remedial action is required? These questions define what an automated system has to do. The human ear can detect features of a noisy spectrum which indicate that an engine is not running as smoothly as it should be. An owner-driver becomes so used to the sounds of the engine running smoothly (over a range of r.p.m.), that the slightest deviation "sets the alarm bells ringing". For automated systems, it is important to ensure that the vibration sensors themselves do not add *variable* confusion to the noise spectrum, i.e. that they do not resonate at specific frequencies or saturate at different amplitudes at different frequencies. Given consistent sensor response, the first question could be addressed by making use of neural network analysis: "training" a set of sensors on a smoothly-running system and then subjecting the same set of sensors to the system running in a more "ragged" fashion. The sensors are then required to detect differences between the two sets of input vibration spectra, in terms of amplitudes, frequencies, spatial differences in source location etc. Once the "running rough" anomaly has been detected, its significance can, at present, be assessed only experimentally: monitoring a component and gradually increasing the severity of duty, whilst continuing to monitor output, noting that the noise spectrum associated even with a smoothly-running part will change its amplitude/frequency characteristics as the part is forced to run under higher duty. The eventual aim is to provide models to relate changes in vibration spectra to specific types of events,

"A Chancy Business" – Probabilities of Failure

The probability of failure by fast fracture at a given stress level in a body containing a crack is addressed by examining the *overlap* between *two probability density functions (pdf)* derived from histograms of data. *One pdf* is that of the *critical defect size* required to produce fracture: this is obtained from the fixed value of stress and the *distribution of fracture toughness values* for the material being assessed. The *second pdf* is, *in principle*, that of the probability of the *existence of a crack of given size* in the component. The *overlap* then represents the *probability* that there is a *crack present* that is able to *produce fast fracture* at the set stress level. A similar analysis can be carried out with respect to failure by plastic collapse and the combination of probabilities can be visualised as *sets of contours* on the *Failure Analysis Diagram*.

Low failure probabilities relate to the overlap of the *tails of distributions*, often where data points are lacking. Reliance is placed on *functional forms* for the pdf, fitted to such data as do exist. Extrapolation of such functions can mislead, if not backed by physical models. Usually, the *actual defect distribution* in the component is *not known*, and what is compared with the critical defect size pdf is the probability distribution of the *capability of the ultrasonics NDI technique* (or other method employed) to detect and measure defects of different sizes. The U/S beam may possibly fail to detect defects of particular tilt or skew. In this context, *Fracture Mechanics* can be used to *assist inspections*, by analysing the sensitivity of the failure calculations to particular defect locations and attitude to the beam. The *probe angles* and *rasters* can then be *optimised* for the more critical defects, leading to more effective inspection. This is termed *Risk-based Inspection*.

In machines, operating at high stresses, the *fatal flaws* are initially well *below* the NDI detection limit. The concern is that the fatigue life will be shorter than that assumed in design. The *life* depends *strongly* on the *initial defect size*, emphasising the *extreme importance* of *good process control*. At constant stress-amplitude, the *probabilistic distribution of fatigue life reflects that of the distribution of initial fatal flaw sizes*. Through-life monitoring to detect cracks must be set at intervals such that the inspection interval is shorter than the period between the ability to detect a crack and failure. This period decreases rapidly at high stresses because the crack growth-rate is a function of stress raised to a power of order 3-4.

In nuclear pressure-vessels, it is necessary to *monitor* both *crack growth* and *changes in yield strength and fracture toughness* produced by neutron irradiation. For the *Sizewell 'B' PWR*, NDI was exhaustive and all procedures, personnel and equipment were vetted by an independent *Inspection Validation Centre*. Not only was the vessel inspected: *the inspectors were inspected.* For *Magnox* stations facing life-extension issues, changes in materials properties are obtained by the use of *surveillance specimens* located in the reactor core to receive accelerated irradiation. These results have been supported by measurements on cut-outs from the decommissioned *Trawsfynydd* reactor. The material *hardens* as a result of point-defect clusters and fine-scale precipitation of copper. There is also some *segregation of phosphorus* to grain-boundaries, which may produce *embrittlement*. Both effects *increase the Ductile/Brittle Transition Temperature*. We might think that, as the vessel has grown older, it suffers from both *sclerosis* and *gouty joints*. The plant operators have to *treat it more gently* and ensure that it is *always warm* before it is subjected to any significant stress.

Much can be done by plant-operators to minimise risk and enhance structural integrity. Initial *training* and *testing* of *personnel* is vital, and it is important to instil a *safety culture* which permeates the whole organisation. Regular *maintenance* and *health-monitoring* of plant are also vital. The initial cause of the serious "incident" at Three-Mile Island in 1979 was a sticking valve. Fortunately, the pressure vessel did what it was designed to do: it just stood there and contained all the mayhem breaking loose inside.

"Two Steps From Disaster" - **Concluding Remarks**

The paper has concentrated on the technical aspects of structural integrity, illustrating the processes involved in going from the functional design to an engineered endpoint which is *efficient* and *economic*, but one that will remain *safe* throughout the *design life*. The tensions are expressed clearly in the conflicting aims relating to cheaper airfares, economically viable lifetimes for aero-engines and a high degree of safety. There are examples of unanticipated duty and other steps into the unknown:

- increased axle weights on lorries *re* loads on road-bridges
- new design ventures: fairground rides, architectural statements
- increased use of new materials, with limited property data
- life-extension of engineering plant, ageing aircraft.

The descriptions of failures during erection emphasise the need for a "seamless product and process model" (words from Mr. Butler's 1995 Lecture): *both* construction *and* mid-term modifications (e.g. Flixborough) must be treated as seriously as the original design.

The comments above will be familiar to all design engineers, but the paper lays emphasis also on the importance of *crack-like defects* (*fatal flaws*) which can lead to premature failure. It describes ways in which they are introduced and how they can be detected, measured and controlled. In particular, *Fracture Mechanics* analysis plays a vital role in assessing the *significance of defects* with respect to both fast fracture and to the insidious growth of fatal flaws. There should be strong interaction with initial inspection and through-life monitoring of any defect growth. It is highly relevant that Rolls-Royce has a *Key System* for *Fan Discs*, which incorporates not just the "seamless product and process model" but also a *Lifing Model*.

The *Ductile/Brittle Transition* in steel has been described, and, for nuclear pressure vessels, attention has been drawn to the need to monitor *property changes in the material*, in addition to the measurement of any sub-critical crack growth. Finally, there is mention of the ways in which the overall *Probability of Failure* is determined, with *caveats* regarding the tails of distributions and a plea for more physically-based modelling.

The treatment of *Risk* involves both the *Probability of Failure* and the *Consequences of Failure*. There is also a large measure of *societal concern*. The HSE reported on *The Tolerability of Risk from Nuclear Power Stations* in 1988 (revised 1992), a Royal Society Study Group reported on *Risk: Analysis*, *Perception and Management* in 1992 and the HSE produced the final version of *Reducing Risks, Protecting People ("R2P2")* in 2001. A starting-point is the FN-Curve (the frequency at which an event might kill N people plotted *vs* N). Although this is not explicitly given in *R2P2* para. 136 clearly states "Where societal concerns arise because of the risk of multiple fatalities occurring in one event from a single major industrial activity, HSE proposes ..... that the *risk* of an accident causing the *death of fifty people* or more in a single event should be *less than one in five thousand per annum*".

Why *Two Steps from Disaster*? Can we contemplate even *two* step*s* in a *critical component*, where the fatal flaw is smaller than the NDI detection limit? *What could the two steps be*? Careful, conventional design with all players as part of the team should eliminate most of the sorts of problem that have occurred in the past. This leaves the *Fatal Flaws*.

- STEP ONE is to *minimise the initial flaw content* through high-quality **process-control**, including joining. *Fracture Mechanics analysis helps* to indicate what initial content is acceptable.

- STEP TWO is **through-life monitoring** to detect any *defect growth in service*. *Fracture Mechanics analysis helps* to set appropriate inspection periods.

Control and *Monitoring* involve *cost* and Society will ultimately be the decider of what is an *acceptable risk of disaster*. Society's views can be better informed by quantitative input from those working in *Structural Integrity*, the initials of which, *SI*, happily tie together the *Science* of scientists and the *Ingenuity* of engineers.

"A Good Read" - References

In an overview of this sort, detailed references are not appropriate, but the following provide some informative "extra reading".

Why Buildings Stand Up – The Strength of Architecture Mario Salvadori Norton 1990 ISBN 0-393-30676-3
Why Buildings Fall Down Mario Salvadori Norton 1994 ISBN 0-393-31152-X
Structures or Why Things Don't Fall Down J.E.Gordon Pelican 1968 ISBN 0-14-02-1961-7
Engineering Progress Through Trouble R.R.White I.Mech.E 1975 ISBN 0-85298-183-X
Brittle Fractures in Steel Structures G.M.Boyd Butterworths 1970 ISBN 0-408-70042-4
Aviation Disasters David Gero Patrick Stephens Ltd 1993 ISBN 1-85260-379-8

No Highway Nevil Shute William Heinemann Ltd 1948
Airframe Michael Crichton Arrow 1997 ISBN 0-09-955631-6

The Wheel Extended Toyota Quarterly Review Nos.92-95 (Kobe Earthquake) ISSN 0049-755X
The Flixborough Disaster Department of Employment 1975 ISBN 011-361075-0
Report on *Falsework* HSE 1976 ISBN 0-11-880347-6
Boiler Shell Weld Repair IMech 1999 ISBN 1-86058-244-3

Fig. 1 “Dicing with Death”. *Hazard* was an old gambling game, played with dice. The analogy here is that it is now common to treat catastrophic outcomes in terms of probabilities (see fig. 7)

Fig. 2 The “Balancing Act” between Efficiency, Economic Lifetime and Safety

Fig. 3 Schematic diagram of the failure of the box-girder bridge at Milford Haven. As (the trapezoidal) section 40 was being cantilevered out over sections 43, 42, 41, the bending moment increased and caused a catastrophic buckle to occur in (the trapezoidal) section 43

Fig.4 Schematic R6 Failure Assessment Diagram

Fig. 5 Schematic diagram showing increase of fatigue-crack length with number of cycles and indicating safety margins between first detection of a crack and failure for different stress levels

Fig.6 Schematic diagram indicating the way in which the probabilities of the presence of a defect and the critical size of defect are combined to derive the overall probability of failure

Fig.7 The “F/N” curve given in “R2P2” 1999, but not in “R2P2” 2001, relating the frequency of fatalities to the number of people involved in the fatality. The <1 in 5000 figure for 50 or more fatalities is referred to in “R2P2” (see text).