Fracture-Safe and Fatigue-Reliable Structures

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ABSTRACT. Learning from history is, by popular account, something at which human beings are not particularly good; George Bernard Shaw having stated that "we learn from history that we learn nothing from history", while the Spanish philosopher George Santayana apparently claimed that "those who cannot learn from history are doomed to repeat it".[1] This is certainly true in the field of structural integrity where, some 150 years after the first full-scale structural fatigue tests were carried out, fracture-safe and fatigue-reliable design can be achieved to a statistical probability in complex and sophisticated structures, such as aircraft. Alongside this, however, failures of large, and expensive, welded structures can still occur from such simple causes as inadequate communication, and lack of awareness of the importance of the design of structural details to the overall fatigue life and failure. This paper considers several examples of such difficulties in the context of the development of fatigue design philosophies and the success or otherwise of learning from the history of failures.

KEYWORDS. Structural failure; Fatigue-reliable; Fracture-safe; Fatigue design; Design failure.

INTRODUCTION

Some 170 years after the term fatigue[2] was first coined and 150 years after the first full-scale structural fatigue tests were carried out, many large and expensive structures still experience very early fracture compared with their design fatigue lives. This paper will explore some of the reasons why this can occur with nominally well-designed and fabricated structures and draws some conclusions regarding the lessons to be learnt and how these might be disseminated to working engineers. This will be done using, as the main example, two large rotating shells with a replacement capital cost of some $20M, which should have been designed to provide a service fatigue life of 20 years, and which experienced severe shell fracture within 5-7 months of commencing service.

This example is instructive, as at first sight it seems a fairly straightforward case of inadequate fatigue design, while on closer inspection it became clear that a number of interacting factors were involved which made a replace/repair decision

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[1] At least according to the web site age-of-the-sage.org, see the web page
- http://www.age-of-the-sage.org/philosophy/history/learning_from_history.html

[2] The origin of the term 'fatigue' is uncertain; some papers have ascribed the first use of the term fatigue to J. V. Poncelet in his book *Introduction à la mécanique industrielle: physique ou expérimentale* published in Paris in 1839 (or to lectures given by him around that time). This volume appears to rather discuss the work and fatigue of 'living motors', i.e. horses and human beings, rather than mechanical components under cyclic loads. Neither do the seminal papers by C. Hood [1] or W. J. M. Rankine [2] appear to use the term.

rather difficult and which complicated the design of a replacement. These factors mainly derived from inadequate communication between the various parties, and included:

- Imprecise specification of the operating conditions and design codes by the owner of the process technology;
- Internal fixtures in high stress areas that caused high local stress concentrations and which were, in the main, eventually found to be superfluous;
- Inadequate consideration of the variable amplitude and biaxial stresses arising from ovality induced in the shell during rotation;
- Lack of a detailed finite element analysis of the internal fixtures;
- Unauthorised alloy substitution for some parts of the internal design fixtures that led to an increased chance of weld defects, especially hydrogen cracking;
- Poor weld documentation and poorly controlled preheat, which led to increased residual stresses and weld defects;
- Inadequate consideration of the maintenance requirements in terms of the duty cycle of the composters, which led to excessive erosion of the shell occurring.

The ultimate outcome from these interacting aspects of the failure was the instigation of legal proceedings that continued for some 5 years and cost a similar amount to the original capital cost, by which time repair of the structures had been made impossible through shell erosion. All of these issues could have been easily avoided had the various parties understood and shared more information regarding the requirements of the process for which the structures were designed, fatigue cracking, weld design and the influences of a corrosive environment.

The paper will also discuss the historical background to the development of fracture-safe and fatigue-reliable structures to set in context the main tenet of the paper, namely that learning from history is extremely good in certain industrial sectors and surprisingly poor in others.

HISTORICAL BACKGROUND TO FATIGUE

Failure of components and structures under varying or cyclic loading patterns has been discussed in the literature since at least 1843, when Rankine delivered a paper to the Institution of Civil Engineers in London entitled "On the causes of the unexpected breakage of the journals of railway axles; and on the means of preventing such accidents by observing the law of continuity in their construction" [2]. This was one of the first recorded papers which used the term "gradual deterioration" to describe failures of rotating or reciprocating components that occurred under cyclic loading after a period of time in service. Subsequently, in a series of papers between 1858 and 1870 Wöhler established several fundamental principles of the safe-life, or S-N, approach to fatigue design [e.g. 3, 4]. These included acquiring S-N data from full-scale tests of railway axles (reference 3, whose title translates as "Report about the experiments, which have been carried out with instruments to measure the tension and the torsion of the axles of carriages of the Koeniglichen Niederschlesischen-Maerkischen railway during travel"), and determining the effect of a notch on fatigue life (reference 4, whose title is "About experiments concerning the cohesiveness of iron and steel"). Wöhler observed the occurrence of a fatigue limit stress for steels at lives $> 5 \times 10^5$ cycles of loading and also explored the effect of a notch on the S-N curve.

The S-N philosophy is still widely used today for component fatigue design, albeit with a much more sophisticated understanding of interactions among the service environment (temperature, chemistry, loads and displacements), materials (composition, processing and microstructure), and their static and dynamic performance. Fig. 1 shows some of the fatigue data reported by Wöhler in reference [4].

Early examples of failure by fatigue and fracture were strongly influenced by the low metallurgical quality of cast iron and puddled or wrought steel [5]; the puddling furnace was an open-hearth metal-making technology used to create wrought iron or steel from the pig iron produced in a blast furnace. The major advantage of a puddling furnace was in keeping the impurities of the fuel separated from the pig iron charge. Puddled steel still contained, however, a high level of elongated manganese sulphide (MnS) inclusions (which are then crack-like defects) as shown below in Fig. 2 and 3. Early steels also exhibited low notched toughness and a high ductile-to-brittle transition temperature, meaning that failure occurred in an apparently brittle (rock candy) fashion in the presence of relatively small fatigue cracks or crack-like defects even at moderate temperatures (e.g. as illustrated in Fig. 4). This observation of apparently brittle fracture in an alloy that showed ductile tensile behaviour led to a longstanding controversy over the mechanism of fatigue cracking; the erroneous crystallinity theory advanced by Hood [1] (the concept that after a certain number of load repetitions the material became 'tired' of carrying the load and became crystalline in nature) versus the correct progressive fissuring mechanism proposed by Rankine [2]. The notion of the material having 'tired' of carrying the load led to the term 'fatigue' being coined to describe failures under cyclic loading. The Charpy notched bar impact test was subsequently developed as a simple means of assessing the notched toughness of steels.

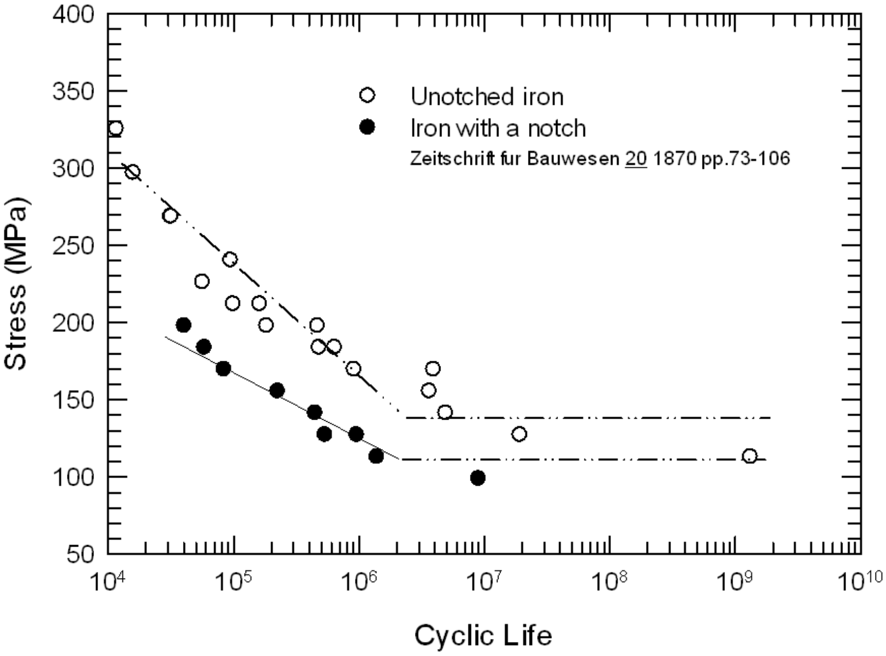

Figure 1: Fatigue data reported by Wöhler in 1870 [4] from S-N tests on notched and unnotched iron specimens.

Whilst the crystallinity theory was completely discredited by 1903 (through microscopic observations of crack initiation and growth via 'persistent' slip band cracking made by Humphreys and Ewing [6]) the term 'fatigue' has remained in use to the present day to describe the process of crack initiation and/or growth under cyclic loading.

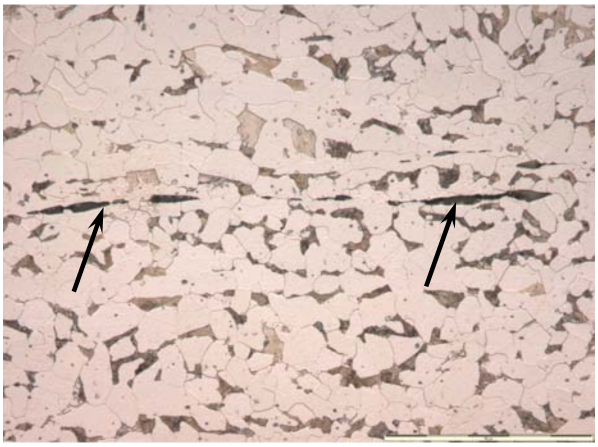

Figure 2: Micrograph of puddled steel circa 1880 showing sharp elongated MnS inclusions.

The two phenomena of fatigue and fracture remain of prime concern in ensuring structural integrity and reliability, even though the last 150 years have seen an enormous world-wide effort devoted to understanding, explaining and predicting failure from crack growth and fracture. A strong focus on fracture-safe and fatigue-reliable design is required by the sophistication and complexity of modern engineering components and structures, and their increasingly arduous service requirements. The term 'fracture-safe and fatigue-reliable design' was apparently first used by Pellini in guidelines intended for steel structures [7].

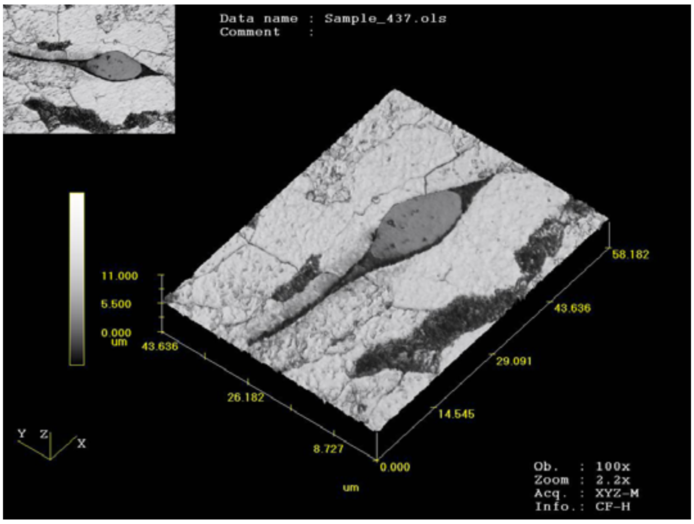

Figure 3: Confocal laser scanning microscope image of a sharp crack-like MnS inclusion in puddled steel.

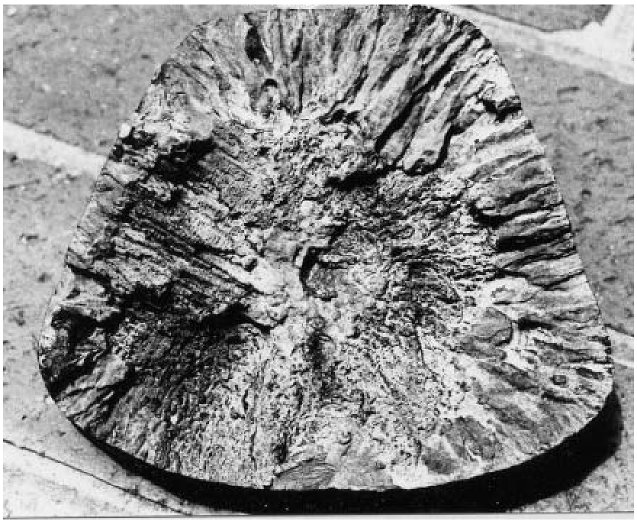

Figure 4: Example of brittle intergranular (rock candy) fracture during fatigue loading in cast steel. The particular example shown is due to aluminium nitride embrittlement.

FRACTURE CONTROL AND FATIGUE DESIGN STRATEGIES

Fatigue is a process of crack initiation and growth by microplasticity in metallic alloys or, more generally, a nonlinear constitutive stress-strain (σ-ε) response leading to hysteresis in the cyclic σ-ε curve and an associated input of energy into the material via damage mechanisms (in the case of metallic alloys this is the movement and interaction of dislocations in the crystal lattice).

Fracture is sudden, catastrophic collapse under either an applied static load (certain cases), a steadily increasing load or as the final stage in the fatigue process. The defining characteristics of these two phenomena are often that:

- Applied loads are much less than general yield (i.e. plasticity is highly localised to cracks or sharp defects)
- There is little prior evidence of imminent failure, i.e. the overall structure is still behaving in a linear elastic fashion.

In this context, however, it should be noted that there are now standardised processes for structural design which explicitly consider the possibility of failure by the conjoint mechanisms of plastic collapse and fast fracture [e.g. 8]. This two-parameter approach to fracture control uses a Failure Assessment Diagram (FAD), and has been driven by the use of high toughness metallic alloys often operating at high temperatures. It has been made possible through a detailed understanding of the response of materials to loading and by the development of fracture mechanics, which is the branch of applied mechanics dealing the behaviour of cracked bodies.

Fracture control and fatigue design strategies have developed alongside greatly enhanced analytical, numerical and experimental techniques to understand and characterise the response and behaviour of components and structures subject to applied loads and displacements. A brief outline of the historical development of these fracture control strategies is also given, as a precursor to considering the successes and failures in "learning from history".

Safe-life design

This philosophy is underpinned firstly, by experimental testing to establish the stress-life or strain-life (S-N) curve for the material under conditions that match those anticipated in service. As noted above, the first data of this type was reported by Wöhler who was the Locomotive Superintendent of the Royal Lower Silesian Railways in the second half of the 19th century [3, 4]. The second important requirement is the application of a so-called 'factor of safety' to ensure that the design level of stress or strain experienced by the component or structure is significantly less than the value from the S-N curve corresponding to the required cyclic fatigue life. This parameter is actually a 'factor of uncertainty' reflecting imprecise data on:

- Material properties and condition (e.g. heat treatment, notches, surface damage)
- Service environment and conditions
- Applied loads and displacements

Early structural testing of fatigue loaded structures often relied on simply factoring the measured yield, proof or tensile strength of the material, e.g. by loading the wings of wooden framed aircraft with bags of lead shot until fracture occurred. Interestingly, this technique is still widely applied to the wings of homebuilt aircraft, and it is worth noting that this simple approach works best with composite structural materials, such as wood, where the fatigue strength can be a high percentage (≈70-80%) of the tensile strength at lives $\sim 10^6$ cycles [9].

Ferritic alloys tend to show a 'fatigue limit' stress where the sustainable stress becomes asymptotic with the *x*-axis for lives typically greater than about 2×10^6 cycles. This is related to pinning of dislocations in the crystal lattice by interstitial atoms, such as carbon, nitrogen or boron. Nonferrous alloys do not exhibit this fatigue limit behaviour and it is usual to refer to an 'endurance limit' stress for these alloys that is applicable to a specific cyclic life.

The S-N approach is still widely and successfully used on such important components as crankshafts and connecting rods. The key requirement is that the conditions used in fatigue testing closely match those of the component in service. It is now routine practice in several industries to use computer-controlled testing applying a load spectrum that replicates the measured service load spectrum.

Failures can still occur when there has been:

- Incorrect assessment of:
  - Service loads (including incorrect assessment of different load state contributions)
  - Environment
  - Vibration or resonant frequency problems
- Implementation of new materials/technology with *a priori* unforeseen or unknowable consequences
- Unanticipated changes in:
  - Usage (loads or type of service duty)
  - Environment (corrosion and temperature)
  - Surface condition (including inadvertent damage)
- Human error
  - Inadequate communication amongst relevant parties
  - Inadequate fabrication/machining
  - Inadequate inspection/maintenance

Fail-safe design

This uses the same basic philosophy as safe-life design but takes account of the possibility of cracking of critical components. These are defined as parts whose failure would lead to catastrophic loss of the structure, e.g. wing or tail plane spars in an aircraft. Widespread manufacture and operation of aircraft with metallic structures, and a consequent relatively high number of failures was the main driving force behind this advance. The new developments included:

- Redundant load paths in critical areas which can redistribute the load in the event of a partial failure of the structure and/or act as crack arrestors

- Explicit consideration of inspection intervals at the design stage
- Identification of critical areas in the structure via full-scale testing
- Feed-back into design from failure analysis
- Codified design procedures

The success of this type of approach, when coupled with the use of fracture mechanics and defect-tolerance, can be illustrated by contrasting the consequences of fatigue cracking and subsequent structural damage in two famous aircraft failures:

- De Havilland Comet 1 in 1954, where growth of a fatigue crack led to rupture of the fuselage and complete break-up of the aircraft in the air through explosive decompression at an altitude of about 35,000 feet [10, 11, 12].
- Aloha Airlines Boeing 737 in 1988, in which a fatigue crack caused an explosive decompression and structural failure at an altitude of 24,000 feet [11]. According to the official US National Transportation Safety Board report [13], approximately 5.5 m of the pressure cabin skin and structure aft of the cabin entrance door and above the passenger floor line separated from the aircraft during flight. The flight crew made an emergency descent and landed the aeroplane safely.

The fail-safe approach is attempting to design 'defect-tolerant' structures, although prior to the development of fracture mechanics it was not possible to predict crack growth rates or remnant life in the presence of a defect.

Fracture mechanics and the quantification of defect-tolerance

The development of fracture mechanics was spurred by some notable failures that occurred over the period 1940 to 1980. These ranged across ships, aircraft, bridges and pressure vessels. Several useful reviews of the development of defect tolerant methodologies in these various industries are available, including the US Air Force Handbook for Damage Tolerant Design [14] and a review of strategies to combat aircraft structural failures by Brot [15].

The basic concepts in fracture mechanics are that:

- Crack tip stresses, strains or displacements reach a critical value (which under a specific set of conditions is represented by a material constant value of resistance to crack growth, the fracture toughness).
- The rate of energy absorption in incremental crack advance is < the rate of energy supplied by release through crack growth of the stored strain energy in the structure.

A critical factor in fast fracture is that the presence of a crack or sharp crack-like defect induces a triaxial stress field near the crack tip. This makes plastic deformation more difficult and increases the constraint on plastic flow, particularly in thicker sections of material. Extensive work in the period between 1950-1975 led to the definition of parameters to characterise crack tip fields, and to the development of standardised fracture toughness tests which give 'material constant' values (under specified conditions) for the resistance to crack growth of a material [16].

The three usual characterising parameters are the stress intensity factor K, the crack tip opening displacement COD, and the J-integral. K is an elastic parameter which characterises critical and subcritical crack growth under conditions of macroscopically elastic behaviour in a cracked body, i.e. constrained and limited plasticity. The J-integral is a nonlinear elastic parameter based on energy integration along a path around the crack tip, which has been shown to characterise macroscopically elastic-plastic behaviour. COD is a parameter which explicitly considers the existence of extensive plasticity at the crack tip. Current codes for the engineering assessment of criticality of defects in structures [8] allow for use of any of the three, depending on the level of plasticity experienced during fracture. The codes also consider a two-parameter failure mode where the possibilities of fracture and plastic collapse are assessed independently and the probability of failure is then plotted on a failure assessment diagram (FAD).

Work in the 1960's established that, in a similar manner that K characterises the onset of fracture in the presence of a 'critical' crack, the range of the applied stress intensity factor ΔK characterised the growth of stable cracks under cyclic loading, i.e. 'subcritical' cracks. For the first time, quantitative predictions of remnant life were possible once a crack was detected.

Thus defect-tolerant design involves living with defects and an explicit acceptance that manufacturing and fabrication processes introduce cracks or crack-like defects so that a structure enters service in a 'flawed' state. The steps in the procedure generally include:

- Size the initial defect population on service entry via NDT (perhaps coupled with proof testing to establish a possible maximum size of defect that could be present but has not been detected)
- Perform a fracture mechanics based life assessment
- Set inspection intervals and the level of inspection required

- This procedure requires fracture mechanics based crack growth rate data and a K-calibration for the region of interest in the structure or component, plus knowledge of an appropriate fracture toughness parameter. FEA may be necessary to establish the stresses present in the region of interest
- Extensive full-scale structural testing as well as specimen testing may be necessary to assure structural integrity assessment procedures

This type of assessment may represent around 5-12% of the capital cost of a sophisticated structure, which is likely to be cost-effective when considering that the percentage of failures associated with crack or fracture problems remains rather high in both engineering structures and in aircraft [17]. Table 1 presents information from reference 17 on frequency of occurrence of these failure mechanisms.

	Percentage of Failures	
	Structures	Aircraft
Corrosion	29	16
Fatigue	25	55
Brittle fracture	16	-
Overload	11	14
High temperature corrosion	7	2
SCC/corrosion fatigue/HE	6	7
Creep	3	-
Wear/abrasion/erosion	3	6

Table 1: Frequency of failure mechanisms in structures and aircraft [17]. In this table, HE represents hydrogen embrittlement and SCC stands for stress corrosion cracking.

The complexity of structural testing on a modern airliner is indicated in data provided in the Boeing Airliner magazine [18] which indicates that one hundred hydraulic actuators simultaneously apply flight spectrum loads, measured via 4,300 strain gauges, to a complete 777 airframe. The effectiveness of defect-tolerant design, coupled with this type of testing programme, in reducing the maintenance costs of aircraft has been discussed in a paper by Goranson [19] in terms of labour hours expended on maintenance as a function of aircraft type and manufacturing production line position. 'Maintenance labour hours per aircraft' is a measure of the effectiveness of design improvements resulting from the development and application of durability standards [19]. Reference 19 demonstrates significant order of magnitude improvements in maintenance labour costs between first and second generation wide and standard body aircraft.

LEARNING FROM HISTORY: SUCCESS AND FAILURE

An enormous amount of literature has been published on fatigue design, the application of fracture mechanics to structural design and on failure analysis, and the reliability achieved in the key industrial sectors of transport, energy extraction and generation, and pressure vessels is truly outstanding. The 2011 edition of Injury Facts published by the US National Safety Council [20] indicates the average death rate over the ten year period from 1999 to 2008 was 0.01 per 100,000,000 passenger miles for scheduled airlines and 0.05 for rail and buses.

In other industrial sectors, particularly where structures are fabricated by welding, there remains a greater potential for cracking problems to occur through fatigue or fracture. Reasons for this higher incidence of cracking-related problems include:

- Insufficient attention to environmental influences
- Lack of awareness of the importance of detail design to the fatigue performance of major structures (geometry and fabrication practice)
- Inadequate communication between the various parties involved in major design projects (end user, fabricator, design team and process owner)
- Insufficient knowledge of the requirements of, and limitations inherent in, current fatigue design codes

The remainder of this paper will briefly present some case study examples of the type of problems that occur and their underlying root causes which, very often, include lack of communication and/or inadequate knowledge of the interactions amongst materials, welding fabrication and fatigue and fracture. Such difficulties may also include misinterpretation of the requirements and constraints imposed by fatigue design codes.

Failure case studies

The main example of such problems in the present paper centres on two large horizontal rotating cylindrical shells in which author was recently involved as an expert witness. Each cylindrical shell rotates at 1 rpm, and is around 65 m long and 4.5 m in diameter. There is a significant corrosive distributed load inside the shell at any time as well as a substantial self-weight. The capital cost of the installation was around $24M and the design life was specified to be 20 years against fatigue and corrosion. A large through-shell crack was discovered in one cylinder within 5 months from the date of practical completion whilst the second cylinder experienced similar cracking within a further 2 months.

The initial cause of the failure was identified as fatigue cracking from internal detail attachment welds associated with two process-related features: firstly knife features designed to assist the internal process taking place in the cylinders. Forty of these features were arranged in an array inside the shell from low stress entry positions to high stress positions further along the cylinder. Secondly, wear bars in the form of channel sections were stitch welded to the inside of the shell as the internal process was known to be abrasive. The problem was ascribed to inadequate fatigue design, as the stress concentrating effect of these features, in particular the knives whose geometry created large stiffness transitions at their attachment points, had not been considered in the original stress calculations done for the shells. Further design issues were identified as:

- Transition tapers between shell segments of different thickness (25 mm to 40 mm to 70 mm) that did not meet the requirements for the weld class used in the fatigue life calculations of the circumferential butt welds between cylindrical strakes. There was high concern at this point as further fatigue life calculations indicated that in a free corrosion environment, cracks of the size found (in a very limited survey undertaken of the large number of internal welds) would very quickly lead to further through-shell cracks.
- There was a 35 m unsupported span of 25 mm shell in the central region of each cylinder, which a strain gauging and FE analysis showed became oval during rotation and that therefore led to two biaxial stress cycles occurring during each revolution of a shell.

Short-term remedial measures were accordingly implemented which included removing all the knives except those in low stress areas of the shell along with associated repair work, and a long-term re-design process was commenced along with a court case by the operators. It was interesting that the removal of the bulk of the knives had no discernible effect on the efficacy of the internal process inside the cylinders. This raises the interesting question as to why they had been specified as part of the original design. It was a point of note that the original design specification from the process owners made no mention of a highly corrosive internal environment, although it was clear from operational measurements that such an environment was present in at least some parts of the cylinder.

Further investigation demonstrated that additional problems had also contributed to the very short observed fatigue life. These included alloy substitution for the knife backing plates, which were fillet welded to the shell, from Grade 250 steel (yield strength around 250 MPa) which had been specified for all knives except those in low stress positions, to abrasion resistant steel with typical yield strength of 1,200 MPa. The backing plates of knives in low stress positions had been specified by the designers to be fabricated from abrasion resistant steel with a 0.2% proof strength of around 1,070 MPa. This alloy substitution meant that tightly controlled welding procedures should have been followed by the fabricator in terms of consumables, pre-heat and interpass temperatures. In the event, the procedures followed were not fully documented, while the hardness values and their variation across the weld zone implied that hydrogen cracking was a distinct possibility (this was supported by the observed positions of some cracks at the attachment welds). In addition, solidification cracks were present at some of the detail attachment welds.

The final issue of relevance to the ongoing legal argument regarding responsibility, replacement or repair, emerged from semi-annual non-destructive monitoring of sections of the shells, using automated ultrasonic inspection. It became apparent that significant shell abrasion was occurring between the wear bars, although the process design was supposed to lead to an adherent abrasion-resistant coating being deposited on the inner surface of the cylindrical shell between the wear bars. It is interesting to note that annual maintenance of these shells was supposed to occur in a very short shut-down period of about a week.

These difficulties could have been avoided through better communication amongst process owner, designers, fabricators and operator and by better familiarity with the requirements of weld design and fabrication for fatigue. The legal argument and associated preparation of reports from a variety of experts eventually pushed the settlement costs of the case to perhaps $40M and extended the time taken for achieving a long-term solution to more than 5 years, by which point the only option was total replacement.

The second example of a large structure that failed because of deficient communication concerns a 40 tonne portal crane operating in a harbour. Portal cranes are a form of crane where a large rectangular framework forms a flat-topped arch with a gantry across the top. This whole portal frame can move on tracks via a railway bogie attached under each end. The lifting gear itself is on a small trolley that can move crossways along the horizontal gantry. A driver's cabin was also positioned under the gantry. In common with many other shipyard gantry cranes, the design consisted of twin overhead box girders rigidly fixed to rectangular box section legs at one end and hinged at the other end to an A-frame structure. The crane failed during service whilst lifting a shipping container, and the mode of failure of the crane was by fracture through a welded joint between the bottom plate and the vertical members of the gantry box girder; this allowed collapse of the horizontal beams to occur over the fixed legs causing the other set of hinged legs to pivot outwards. The net result was that the driver's cabin was crushed in the collapse.

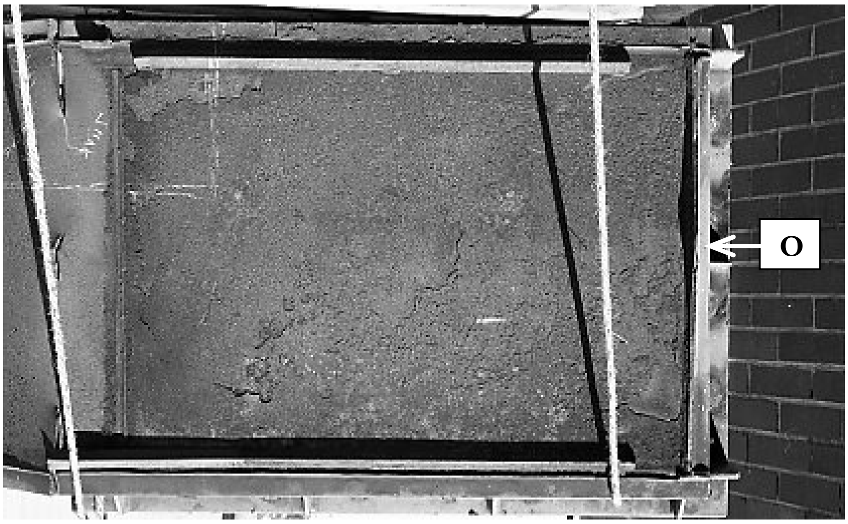

Figure 5: Fracture surface of the failed box section which led to collapse of the portal crane. The letter 'O' indicates the outer edge of the section, where the cracking started.

The fracture surface is shown in Fig. 5 where the symbol 'O' marks the outer side of the leg. The bottom plate of the gantry box girder was 17 mm thick, with the end plate at position 'O' being 8 mm thick and the side plates 6.5 mm thick. Examination of the failed joint indicated that final fracture had occurred from a pre-existing fatigue crack that had a length of the order of 1 metre at the time of failure. Heavy corrosion on the fracture surface indicated that the crack had been growing for a considerable period of time before the final fracture occurred. No unusual defects could be observed at the presumed initiation site for the fatigue cracking. The crane had been in operation for about 7.5 years and had last been inspected by an authorised inspection agency some 2 months before the failure. It was designed as a Class 2 crane for medium material handling duty, supposedly intended to work 2,000 hours per annum with a design lifetime of 20 years, i.e. 40,000 hours. At the time of failure the crane had been operating for some 22,515 hours, well inside the design life but with a greater number of hours, pro-rata, for the 7.5 year service life.

There were two main points of interest regarding this failure, firstly, that the design should have been done to Class 3 for heavy material handling duty, based on the operational service conditions and, secondly, that the inspection methodology had not taken account of the likely mechanism of failure of this portal crane. With respect to the first point, the manufacturer was aware that this crane was intended for harbour operation, moving shipping containers and should have queried the operator's specification of a Class 2 crane for this duty. It is worth noting that more recent designations of crane classes indicate that Class 2 equates to 100,000 to 500,000 load cycles while Class 3 equates to 500,000 to 2,000,000 load cycles. This crane was definitely in a Class 3 environment. Lack of clear and full communication between operator and designer regarding the duty cycle and crane class was therefore a prime cause in this failure.

With respect to inspection, the existence of a crack around a metre in length at the time of the failure should have implied that it would have been detected at the last inspection which took place 2 months before the failure. Speaking with the person who carried out the inspection of the crane, he stated that this critical joint (in terms of structural integrity) had been visually inspected from the ground level. It was also clear that the paint coating on this crane structure was flexible and of high quality; thus it was detached from the steel structure at this positon on other parts of the structure but was uncracked. In summary, despite the existence of a metre long fatigue crack at the time of the inspection, the paintwork would have been uncracked and the problem would not have been detected except by detailed inspection of the joint itself.

CONCLUSIONS

Learning from failure remains highly relevant to achieving fracture-safe and fatigue-reliable design, particularly as the cost-driven requirements for life extension and lower design margins are, to some extent, mutually exclusive. Failure analysis therefore forms an important part of the repertoire of successful design and inspection, and should be included in the education and training of engineering students, as well as forming part of the requirement for continuing professional development of practising engineers. Further advances in achieving fatigue-reliable and fracture-safe design is, at least in part, contingent on closing the loop between failure analysis and engineering design. This is turn appears likely to require some changes to current undergraduate engineering curricula which focus more on materials as ideal homogeneous, isotropic continua, rather than the reality of polycrystalline media joined by 'defective' processes. In such 'real' media fatigue and fracture properties reflect the crystal- and micro-structure, and hence their heat treatment and manufacturing/fabrication processes, as well as their defect population, surface condition and environment.

Nonetheless, the advances in engineering capability in reliable probabilistic fatigue and fracture design for complex structures, made over the last 40 years, is a tribute to the combined input from metallurgists and materials scientists, and mechanical and welding engineers.

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