Downloaded from rsta.royalsocietypublishing.org

The Application of Fracture Mechanics within the Central Electricity Generating Board [and Discussion]

H. D. Williams, G. J. Neate and P. J. E. Forsyth

Phil. Trans. R. Soc. Lond. A 1981 **299**, 169-177
doi: 10.1098/rsta.1981.0016

Email alerting service

Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1981 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Phil. Trans. R. Soc. Lond. A **299**, 169–177 (1981) [169]
Printed in Great Britain

OPERATING EXPERIENCE

The application of fracture mechanics within the Central Electricity Generating Board

By H. D. Williams and G. J. Neate
C.E.G.B. (Midlands Region), Scientific Services Department, Ratcliffe-on-Soar,
Nottingham NG11 0EE, U.K.

Fracture mechanics has been used extensively within the Central Electricity Generating Board to avoid failures and to permit plant containing cracks to continue in operation. A case history is presented, which describes a problem of fatigue cracking in the subconductors of large generator stators. The investigation of the failures is outlined together with the measures taken to allow operation in the short term while a replacement programme was effected.

The prime requirements when providing advice on the short-term integrity of defective plant are speed in diagnosing the cause of cracking and the availability of rapid fracture mechanics analyses. Developments in these areas are briefly reviewed. On-load condition monitoring is finding increasing application in assessing plant safety while complete solutions are effected: the techniques currently in use and under development are mentioned.

Introduction

The Central Electricity Generating Board (C.E.G.B.) has a duty to maintain and develop an efficient, coordinated and economical supply of electricity with due regard to the environment. The economic generation of electricity is in part dependent on the high availability of large, high-temperature plant, and over the last 10 years fracture mechanics has played a major role in enabling plant to remain in operation.

Although the cheapest electricity is generated by nuclear power stations, the bulk of the production comes from the large modern conventional sets of 500 MW capacity and greater, which operate at thermal efficiencies of up to 35.5%. In 1978–9 these 49 fossil fuel units generated 58% of the production; they form the main theme of this paper. If one of these high-merit units is not available for generation, the shortfall is made up by less efficient units with an increase in generating costs of typically £70000 per day.

The development of cracks in boiler or turbo-alternator components can lead to the loss of high-merit units, thereby incurring replacement generation costs as well as maintenance and possibly capital costs. Failure of a main component may be accompanied by costly damage to surrounding plant items. After a failure, there may be a need to mount an expensive non-destructive inspection programme on similar items at the next overhaul and, in the interim, to install on-load monitoring equipment. The discovery of cracking during an inspection towards the end of an overhaul period may require the extension of the period for remedial action with loss of availability or the return to service of the unit with restricted capability. The interval between planned overhauls is generally 30 months, and any strategy adopted to deal with a problem of cracking that requires the unit to be taken off load within this period may increase overall operating costs.

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

Against this economic background it is not surprising that the C.E.G.B. has a strong incentive to include fracture mechanics in its approach to avoiding failures and reducing costs in the repair and replacement of plant.

A case history is presented to illustrate the natural progression from a failure investigation through the provision of advice on operation and maintenance to strategic decisions on capital investment. The example chosen is that of cracking in the stators of some 500 MW generators.

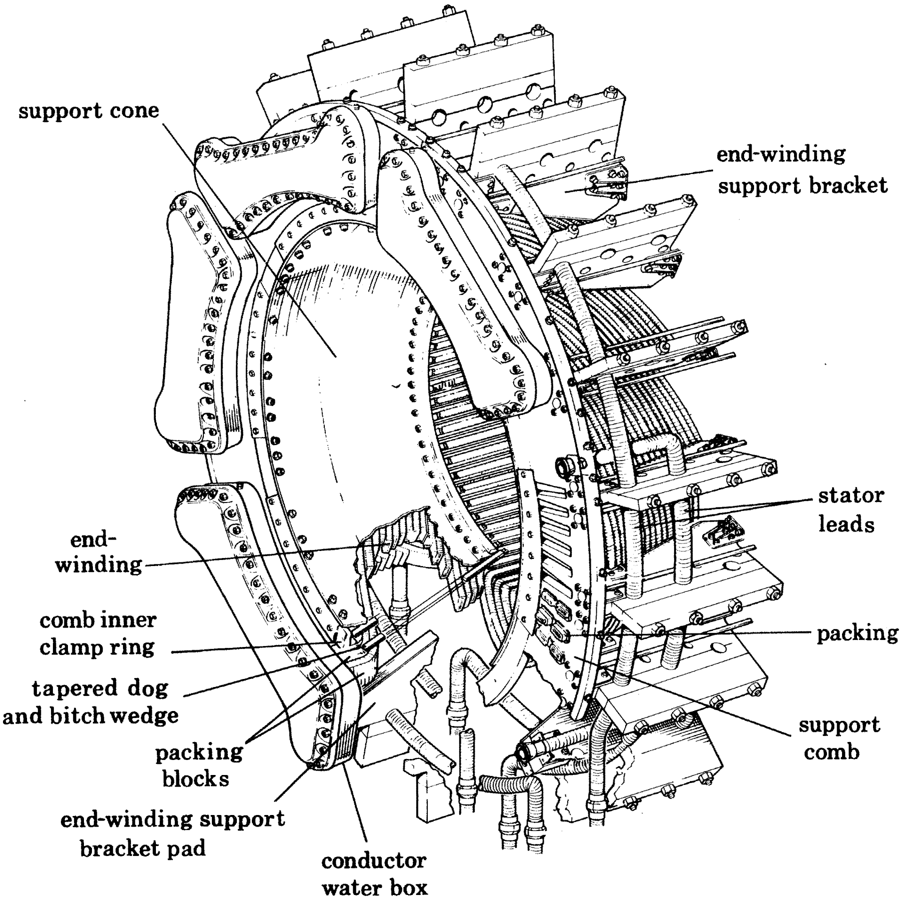

FIGURE 1. Stator winding.

CASE HISTORY

(*a*) *Description of the plant*

The basic features of an a.c. generator are a rotating magnetic field system (the rotor) and a stationary armature assembly composed of a winding and magnetic iron core (the stator). On energizing the rotor and rotating it within the stator, magnetic lines of force sweep across the stator conductors inducing a current in them. Vibrations are experienced in the end-windings of the stator due to the currents flowing in the conductor bars and the magnetic interaction between the iron core of the stator and the rotor poles. As the rotor has two poles, the excitation frequency is 100 Hz. To minimize vibration levels, the end-windings are supported by various means, which include the provision of wedges and conformable packing and heavy support cones fitting into each involute. A view of an end-winding is shown in figure 1.

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

In modern 500 MW generators, each stator conductor bar is made up of a number of hollow rectangular copper tubes (subconductors) arranged in two stacks. At each end of a bar these tubes are brazed into a ferrule, which is then screwed into a nozzle and sealed with solder (figure 2). During the brazing process, braze metal runs up between the subconductor tubes over a short distance (*ca.* 10 mm) by capillary action. The manufacturing process is then normally completed by applying layers of insulation to blend in with that over the remaining length of the bar. However, in bars intended to occupy the 'long outstand' positions at each end of each half-phase of the winding, additional layers of glass tape impregnated with epoxy resin are applied over a length of approximately 150 mm from the nozzle face to form a stiffening gaiter.

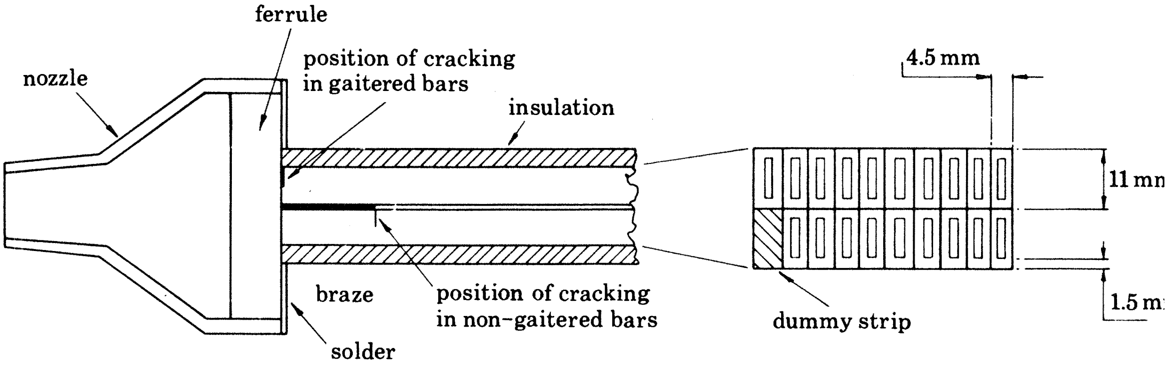

FIGURE 2. Schematic diagram of a nozzle–bar connection.

Water is passed through each conductor as a coolant, and hydrogen, which flows through the stator frame to cool the rotor, is maintained at a higher pressure, so that in the event of any failure within the bars, hydrogen will leak into the water and not vice versa. In the design of the stator of interest here, each half-phase of the stator winding terminated at each end in an epoxy-resin water box, which acts as a manifold (figure 1).

(*b*) *Failure investigation*

First indications of a problem with the operation of these stators came when a number of instances were recorded of stator hydrogen leaking into the conductor bar cooling water. Examination of the stators rapidly established the cause of leakage to be due to fatigue cracks that had developed in the subconductor tubes near to the ends of bars, the precise location depending on the bar type (figure 2).

Cracking in conductor bars is not acceptable because of the serious threat posed to the integrity and safe running of the generator. Thus, the continued growth of cracks could ultimately result in complete bar severance and thereby occasion a serious earth fault attended by extensive damage to the generator. Also, the ingress of hydrogen into the cooling water may itself lead to the undesirable consequences of accelerated degradation of the bar insulation due to overheating and to electrical flashover within a water box. To minimize the possibility of these latter types of failure occurring, a limit is set to the maximum acceptable hydrogen leakage rate.

Of the two types of cracking found (figure 2), that in gaitered bars was recognized as being potentially the most serious since, once initiated, a crack might be expected to propagate

Downloaded from rsta.royalsocietypublishing.org

unhindered through a bar and result in complete severance. In contrast, catastrophic failure of non-gaitered bars was considered to be much less likely, since in this case propagation of fatigue cracking through a bar is a discontinuous process requiring re-initiation in each successive tube. Consequently, all gaitered bars were replaced at convenient outages. As a result of this action, only one major instance of cracking in a gaitered bar has been found. In this case, all 19 subconductors were cracked through, with only a ligament of approximately 1.5 mm remaining along one of the longer edges of the bundle. From this it was deduced that the fatigue loading of bars was displacement-controlled. Similarly, displacement-controlled conditions were also indicated by the observation that the majority of subconductors found to be cracked in non-gaitered bars were only partly severed with the cracks being of a similar size.

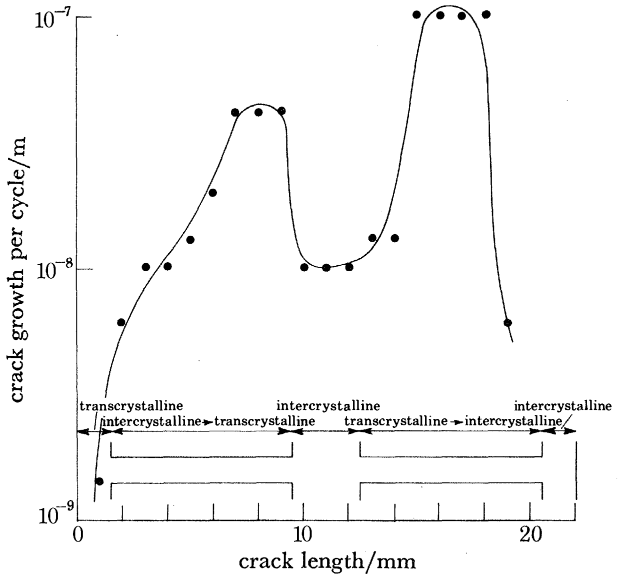

FIGURE 3. Crack growth rates deduced from fractographic examination of a crack in a gaitered bar.

Examination of the cracked gaitered bar revealed a variation in fracture mode across the bar as shown in figure 3. From laboratory studies of fatigue cracking in subconductor tube specimens, it was possible to deduce that the crack propagation rate had initially increased with depth towards the centre of the bundle, but had then diminished again to very low levels as the crack approached the far boundary of the bar (figure 3). A similar pattern of crack propagation behaviour was also revealed by examinations of cracked tubes from non-gaitered bars, with evidence for deceleration in growth rate in the later stages of propagation again being found.

(c) *Stress analysis*

The stress distributions in each type of conductor bar were determined by finite element techniques. In both cases, the position of maximum stress coincided with the observed location of cracking.

Finite element analysis was also used to determine the variation in the range of stress intensity factor, ΔK, and hence crack growth rate, with crack depth for both types of failure. For both non-gaitered and gaitered bars, ΔK was found to increase continuously with crack length under constant load conditions so that, once initiated, a fatigue crack would be expected to continue

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

to accelerate. However, for displacement-controlled conditions, ΔK was found to pass through a maximum before falling below the threshold value (ΔK_0) for crack propagation (figure 4): hence a propagating crack will begin to decelerate beyond a certain crack length and eventually arrest. It is noted that the form of the curves in figures 3 and 4*b* are similar and hence the hypothesis of displacement-controlled loading was taken as being confirmed.

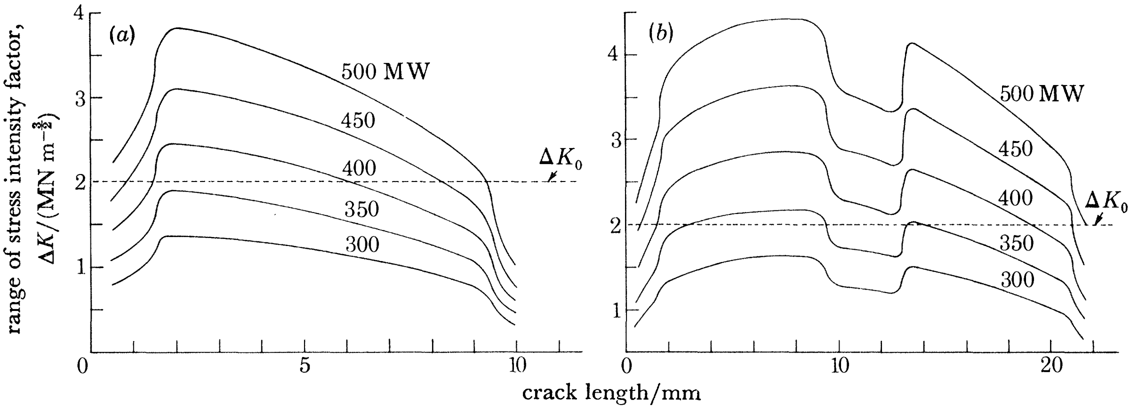

FIGURE 4. ΔK as a function of crack length and megawatt load for (*a*) a non-gaitered bar, and (*b*) a gaitered bar.

(*d*) *Bar leakage characteristics*

In a few instances, machines have been partly or completely assembled, and in one case returned to service, after bar repairs or replacements, only for bars to be found leaking that had previously been adjudged pressure tight. Experimental investigations on cracked bars removed from machines and on tubes containing laboratory-grown fatigue cracks demonstrated that subconductor tubes containing cracks over 70 % of the cross sectional area may not leak with no loading applied, but will do so on application of small static or cycle loads. The most likely explanation for this phenomenon was considered to be that cracks were held open by a mean force on the bars when loaded, with sealing when unloaded being aided by plasticity at the crack tip exerting a residual compression force on the crack, although simple sealing by corrosion products may also have contributed.

To ensure that all bars containing through-wall cracks were detected in machines taken out of service after developing leaks, the ends of all bars were subsequently mechanically manipulated before and during pressure testing. The use of this procedure was successful in that after its adoption no stators developed leaks immediately on return to service.

(*e*) *Operational and maintenance measures taken to improve plant integrity*

The principal conclusion drawn from the investigation of the failures was that the cracking in the conductor bars had been caused by fatigue stresses induced by vibration of the water boxes after slackening of the stator end-windings in service. The propensity for failures to occur only in bars terminating in the top two water boxes in the end-windings was deemed to be due to the non-uniformity of support provided by the cone as a result of its tending to move downwards under its own weight in service.

In addition to the previously mentioned measures taken to improve the integrity of machines, efforts were also made to tighten end-windings during overhauls in an attempt to reduce

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

subsequent vibration levels. This action was successful in the short term in that significant improvements in initial vibration levels were obtained, but slackening was generally found to develop after relatively short periods of further running.

Control of vibration levels was, on a few occasions, exercised by reductions in the megawatt output of machines when these rose to unacceptable limits. This procedure was, however, usually adopted only when a stator developed a leak. The effect of generator output on the range of stress intensity factor experienced by cracks in both non-gaitered and gaitered bars is shown in figure 4, where it can be seen that relatively modest load reductions would be expected to slow down or even arrest growing cracks. This analysis was vindicated in practice since, in one notable case, a machine that was subsequently found to contain a total of three cracked tubes was operated at a load of 420 MW over a critical 7 month winter period.

The only option available for securing a complete solution in the long term was to replace this type of stator with one of a modified design: this incorporated a flexible hose connection to each bar, thereby eliminating the source of fatigue stress. However, the number of machines in service was such that it was necessary to phase the replacement programme over a period of years to maintain an acceptable level of plant availability and to take account of limitations in manufacturing capacity.

Discussion

While the foregoing case history relates to one plant item, it illustrates the phases of development that are common to many problems of this type involving cracking. These are fourfold, namely the diagnosis of the mode of cracking, a fracture mechanics analysis of the body, the determination of the best advice to minimize the effects of the problem and finally consideration of the implications for other similar components. At the end of a decade of application of fracture mechanics to service problems within the Board, it is timely to review the progress made in these areas.

In view of the variety of plant in operation it is not surprising that all types of cracking (fatigue, stress corrosion and creep) have been experienced. An extensive programme of research has been mounted in response to these problems to provide both understanding of the phenomena involved and data on crack initiation and propagation. Operational conditions are rarely constant so that the complexity of problems is usually compounded by the cycling of temperature and environment during operation and by changes in the structure and properties of materials that occur over the long times of service (more than 10^5 h) at elevated temperatures.

The case history cited above demonstrates the potential benefit to be derived from the interpretation of morphological features on the surfaces of a crack. This aspect of failure investigations is receiving increasing attention and a further example that may be quoted that is of considerable interest is the interpretation of beach marks laid down at the tips of fatigue cracks as a result of changes in loading conditions. Such analysis has already provided vital information on rates of crack propagation in service in large shafts. In high temperature failures, topographical features on a fracture surface are often lost owing to oxidation, and information is now being derived from the morphology and thickness of the oxide itself ('oxide dating') that can be interpreted in terms of rates of crack growth. All of these techniques demand that a sample from the crack be made available, and considerable ingenuity is often required to obtain this without affecting the serviceability of the component. In the area of non-destructive examination, a successful development has been in the measurement of residual stresses on site

Downloaded from rsta.royalsocietypublishing.org

by using the centre-hole drilling technique (Beaney & Proctor 1974) and this is providing more complete information on the state of stress in components.

In the area of fracture mechanics analysis, the case history was provided with a valuable model through finite element stress analysis once the condition of displacement amplitude control had been recognized. Significant increases have been made in the speed with which finite element stress analyses can be made. However, it is still essential to have available very rapid approximate techniques of analysis to provide an early indication of the strategy most likely to be recommended, since £70000 may be lost each day that a decision is awaited. Such techniques are incorporated into computer programs for crack growth prediction and failure assessment, and also find use in the C.E.G.B. failure assessment route (Harrison & Milne, this symposium).

The development of on-load condition monitoring techniques in parallel with the developments in the application of fracture mechanics has provided important safeguards to the ultimate security of plant. The most significant of these techniques has been the expertise developed in monitoring and interpreting the vibration of large shafts containing cracks. Vibration monitoring afforded protection for about 50 low-pressure turbine rotors awaiting rehabilitation for suspected cracking at centre collar grooves (Jack & Paterson 1977). Another condition-monitoring technique employed is acoustic monitoring. This can be used in boilers to detect steam leaks from pipes before the onset of fast fracture, which is usually accompanied by extensive consequential damage. Other techniques with potential for future development include on-load ultrasonic inspection, acoustic emission from cracks and crack opening displacement monitors.

Since only four turbine manufacturers and five boiler makers were involved in the design and manufacture of the 49 modern conventional sets, a failure on one unit can be an early warning of a generic problem. With stator subconductor cracking, 18 sets were involved and strategies for containing the problem were devised within an Inter-regional Working Party. This group was also able to advise on priorities for a programme of stator replacements, using the data that it had collected on the histories of construction, operation, maintenance and leakage of stators. Although it occurred on smaller plant, the most extensive programme of rehabilitation within C.E.G.B. this decade was the securing of low-pressure disks in 60 MW non-reheat turbines, which were susceptible to stress corrosion cracking in their key-ways. This programme followed the catastrophic failure of a disk at Hinkley Point 'A' Power Station and involved the dismantling of 124 rotors of all designs (Hodge & Mogford 1979). The complexity of some of the problems encountered is such that simple models of the situations are inadequate and observations made on plant in service have to be incorporated into the analysis. This has been facilitated by the formation within the Board of the Component Integrity Centre, which draws together experience of operating cracked items of plant in all of the Regions to complement the fracture mechanics methods.

CONCLUSION

It is impracticable to quantify the total financial benefit that the application of fracture mechanics has brought to the C.E.G.B. since this now forms an integral part of a set of strategies for coping with defects as they arise in plant. However, taken individually, the savings are often substantial. Two examples that have recently been evaluated (Neate *et al.* 1979) can be cited. The benefit of being able to continue operating an extensively cracked alternator rotor (Stewart

Downloaded from rsta.royalsocietypublishing.org

et al. 1977) for a period of 2 years prevented a loss of £16M in replacement generation costs; similarly, the ability to accept for service cracks in welded joints in steam pipework which, without fracture mechanics appraisal, would have required repair, saved an estimated £3.75M in one Region alone where in excess of 2000 joints were thus accepted.

The next decade will undoubtedly see continued developments in fracture diagnostic techniques, further extension of analytical methods to more complex situations, additional means for monitoring the condition of plant, and a greater benefit derived from the analysis of the performance of cracked components in service. There will also continue to be considerable economic benefits to be gained from the careful application of fracture mechanics to the problems of cracking in C.E.G.B. plant.

This paper is published by permission of the Central Electricity Generating Board (Midlands Region).

The development and application of fracture mechanics has been pursued at all Regional Scientific Services Departments and Headquarters Laboratories: the contribution of colleagues at these establishments is gratefully acknowledged. We particularly wish to record the contribution of Dr B. L. Freeman and Dr A. T. Stewart to the investigation of the 500 MW generator stator failure described in this paper.

REFERENCES (Williams & Neate)

Beaney, E. M. & Proctor, E. 1974 *Strain* **10**, 7–14.
Hodge, J. M. & Mogford, I. L. 1979 *Proc. Instn mech. Engrs* **193**, 93–109.
Jack, A. R. & Paterson, A. N. 1977 In *Conference on the Influence of Environment on Fatigue*, pp. 75–83. London: Mechanical Engineering Publications.
Neate, G. J., Sparkes, G. M., Stewart, A. T. & Williams, H. D. 1979 In *Conference on Fracture Mechanics: Current Status, Future Prospects* (ed. R. A. Smith), pp. 69–90. Oxford: Pergamon.
Stewart, A. T., Haines, K. A. & Williams, H. D. 1977 In *Conference on Fracture Mechanics in Engineering Practice*, pp. 323–338. London: Applied Science Publishers.

Discussion

P. J. E. FORSYTH (*Materials Department, Royal Aircraft Establishment, Farnborough, U.K.*). I was interested to hear that Dr Williams could get an approximate indication of the age of his fatigue cracks from the nature of the oxide present on different positions on the fracture surfaces. It is particularly valuable to document all such aids to life determination, particularly for situations where the striations, normally used for estimating crack life are absent. In our experience with aircraft failures it frequently happens that the majority of the fatigue life is represented by a growth region of the fracture where individual striations cannot be resolved by any microscopical technique. Fortunately, the aircraft fatigue environment may provide a coarsely spaced flight-by-flight growth pattern that is resolvable even in these more difficult cases. It is regrettable that the scope and value of fractography has not been discussed at this meeting because we can now recognize fracture features, other than striations, that give a guide to the range of stress intensity and the degree of constraint that was present. It has also been possible, in a number of cases, to determine the stresses present and to decide whether the stress concentration factors assumed in the design have been enhanced in practice by the presence of manufacturing defects.

Downloaded from rsta.royalsocietypublishing.org

This approach has become an invaluable part of airworthiness considerations, and such fractographic studies are now considered routine adjuncts to the major structural fatigue tests, as well as the service failures of the Aircraft Industry. It would also be fair to say that the quality assessment methods that stem from the new airplane damage tolerance requirements of the U.S.A.F. are essentially dependent on fractographic analysis, and such requirements are bound to stimulate further interest in the micromechanics of fracture.