FATIGUE CRACK GROWTH UNDER CONTROLLED K

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ABSTRACT

This paper describes a simple experimental technique which enables fatigue crack growth tests to be performed at constant values of applied stress intensity factor. The system utilises the strain developed on the back face of a conventional compact tension (C.T.S.) test piece.

KEYWORDS

Fatigue crack growth, constant stress intensity factor.

INTRODUCTION

The use of stress intensity factor, K, to describe the mechanical environment near sharp crack tips, has given the designer a powerful similitude parameter which can be used to compare fracture and fatigue data obtained from small laboratory specimens with behaviour in large structural applications. The alternating stress intensity factor, ΔK, the difference between the maximum and minimum positive values of K in a cyclic loading, has been shown to have a dominant effect on fatigue crack growth. Consequently, the whole thrust of fatigue data collection has swung from stress/endurance testing to fatigue crack growth rate measurement.

The conventional crack growth test is conducted at constant load amplitudes on a specimen for which K and therefore the growth rate, da/dN, increases with crack length. Experimental records of crack length, a, against loading cycles, N, are differentiated to obtain da/dN. The da/dN data is then plotted as a function of ΔK on a log-log plot from which useful power laws can be obtained. However, the scatter in such tests is considerable, so inherent material variation can often be masked by the experimental errors in crack length determination or the errors in subsequent differentiation. An error of as great as a factor of between 2 and 10 on growth rate is not exceptional (see, for example, the data of Frost, Pook and Denton, 1971). Moreover, such errors are often swamped by the ability of logarithmic plots to hide such variations by compressing the scales. This means that the effects of secondary parameters on growth rate, such as stress ratio, overloads and environment are often difficult to quantify with certainty.

If, however, the crack tip loading can be controlled so that the cyclic K remains constant as the crack grows, then the growth rate will remain constant and can be measured with much greater accuracy than in a conventional test.

TECHNIQUES FOR CONSTANT ΔK

Various attempts have been made to achieve constant ΔK, without changing the load cycle, by special geometry specimens. The first such test piece was the tapered double cantilever beam, invented by Mostovoy (1967). However, it is expensive to manufacture and gives unstable crack growth direction (which is generally overcome by machining side grooves, but this leads to calibration uncertainties). A more recent idea employed the fact that for a centre crack in a finite sheet, K increases with the crack length if a constant load is applied at the ends of the sheet, but decreases if the load is applied at points on the crack surfaces midway between the crack tips. By applying point loads through pins a small distance from the crack plane, a balance is found between these two effects (Schijve & de Koning, 1977). However, this type of specimen has the disadvantage that, for many materials, only modest values of K are obtained for the maximum allowable pin loads or before crushing of the specimen at the loading points begins.

If a servo-hydraulic rig is used for applying the fatigue load and if there is some means of monitoring the length of the crack, the load can be reduced as the crack grows in such a way as to keep ΔK, and therefore the growth rate, constant. Monitoring may be done optically using a travelling microscope, in which case the load is shed manually (eg Bernard, Lindley and Richards, 1976), or using the electric P.D. method, in which case automatic control may be applied using a small computer (Pickard, Ritchie & Knott, 1975). A standard geometry may be employed, the most generally useful being the A.S.T.M. Compact Tension Specimen (C.T.S.), which is relatively inexpensive and permits high K values for relatively small machine loads. The disadvantage of manual load shedding is obvious: the electric potential method suffers considerable difficulties from stability and interference and, of course, can only be used for metals.

BACK FACE STRAIN GAUGE

An elegant means of monitoring crack length has been developed by Deans & Richards (1979, 1981, see also their paper at this conference). The compressive strain, in the same direction as a line joining the centres of the loading pins, measured at the centre of the back face of a C.T.S. specimen, is proportional to the applied load (and therefore at a given crack length to K). Also for a given K this strain is also an approximately linear function of the crack length.

If the load is known (this is a standard output on most servo-hydraulic machines) and also the back face strain which is easily measured using a standard resistance strain gauge, then two relationships with two unknowns enable the crack length and K to be deduced, and thus load shedding can, in principle, be achieved automatically. If microprocessor control is employed, this is most efficiently executed from the A.S.T.M. compliance relationship and the measurements of Richards et al.

ANALOGUE CONTROL

However, a happy relationship between the load and the back face strain at a given value of K enables a very simple and inexpensive analogue control system to be used for C.T.S. specimens. This is illustrated in Fig. 1. The reciprocal compliance decreases with increasing crack length: this indicates the load required to produce a given K. On the other hand, the (compressive) back face strain for a given K increases. It happens that both these lines are almost straight over the range of interest, but this is not in itself necessary for what follows. If these two relationships are summed in carefully chosen proportions, the result, i.e. $\alpha P + \varepsilon$ is a line approximately parallel to the abscissa. The additive constant, α, must be right in order to maintain linearity over a wide range of crack lengths: too much of the load leads to a sum which decreases with crack length, too much of back face strain the opposite. A change in proportion of 9% either side of the best value, α_0, leads to a variation of the signal as shown in Fig. 2. It can be seen that there is some tolerance in the choice of the ratio, indeed small differences in the ratio merely serve to alter the range of optimum linearity.

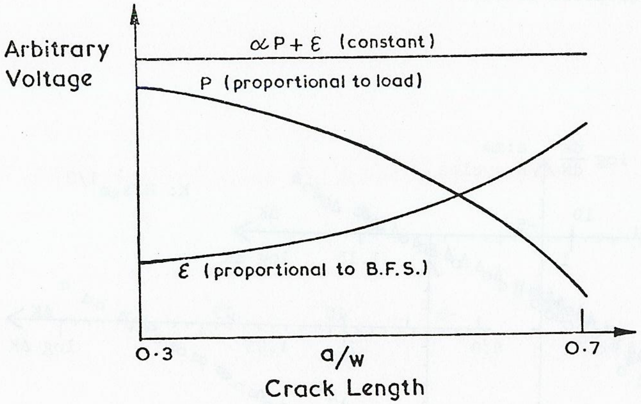

Fig. 1 Illustration of the principle of the constant feedback signal. The falling load and rising back face strain signals are summed with appropriate constant α to achieve a constant signal.

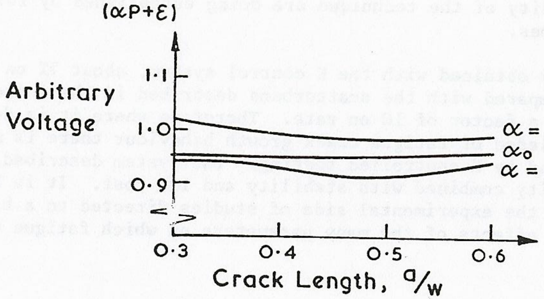

Fig. 2 The effect of varying the proportionality constant, α, from its optimum value for linearity, α_o.

A direct corollory of this result is that if the values of $\alpha P + \varepsilon$ is constant, then this corresponds to an approximately constant value of K, irrespective of the crack length. This is the basis of the analogue K control. A signal corresponding to $\alpha_o P + \varepsilon$ will thus give a direct measure of K at the crack tip, accurate to ±1% over a range of a/w of 0.3-0.6.

The principle of control in a servo-hydraulic test machine is the comparison of some feedback signal with the command signal by a servo amplifier. This operates the servo hydraulic valves so as to reduce the difference. If a K signal is used for the feedback in such a rig, then this will ensure that the stress intensity factor follows the command signal throughout the range of crack growth. For example, if the command signal is sinusoidal with constant amplitude, this should cause the crack to grow at constant K, and therefore at a constant growth rate.

CUMULATIVE PLASTIC STRAIN

The major problem with this technique is that as fatigue crack growth proceeds there is a cumulative strain on the back face resulting from plastic deformations. This is negligible in any single cycle, but over the large number of cycles in practical tests it can grow to be significant compared with the cyclic elastic strain. The effect of this in the K controlled system outlined above would be to cause the stress ratio to decrease. Therefore although ΔK might remain constant, the mean value of K would not, and in general this would affect the growth rate.

The cumulative plastic strain problem may be overcome by a separate unit designed to maintain a specified stress ratio, $R = \sigma_{min}/\sigma_{max}$. Servo-hydraulic rigs may have fitted as a standard option a peak monitor which indicates simultaneously a voltage proportional to the maximum (V^+) and minimum (V^-) of the load signal. It is therefore necessary to maintain $-RV^+ + V^- = 0$. The V^+ signal is thus amplified with a gain of $-R$, and added to the V^- signal. This signal is then amplified with an infinite D.C. gain but very long time constant, and the final output is fed with appropriate sign to the K control unit. This ensures full compensation for any departure from the desired stress ratio.

The peak monitor is designed to respond immediately to changes away from a previous mean level, but to return to the desired level slowly. For reasons of stability (consider a fluctuation which caused a higher value of V^+) the stress ratio discrepancy signal must have a time constant which is very long compared with the peak monitor.

EXPERIMENTAL PERFORMANCE

To prove itself the K controlled system must satisfy two separate requirements: first, the a against N plot for a given test must be straight for a substantial range of crack length, second, the growth rate under nominally identical conditions must be reproduceable.

A complete system has been incorporated into a servo-hydraulic testing machine. It consists of an unmodified strain gauge bridge and 3 potentiometers for setting α, gain and R, together with various switches and monitor facilities used for calibration and setting-up. Initial values depend on starting crack length and are read from calibration tables. A close-up of the specimen can be seen in Fig. 3, which shows the location of the back face strain gauge and a travelling microscope used for optical crack measurement.

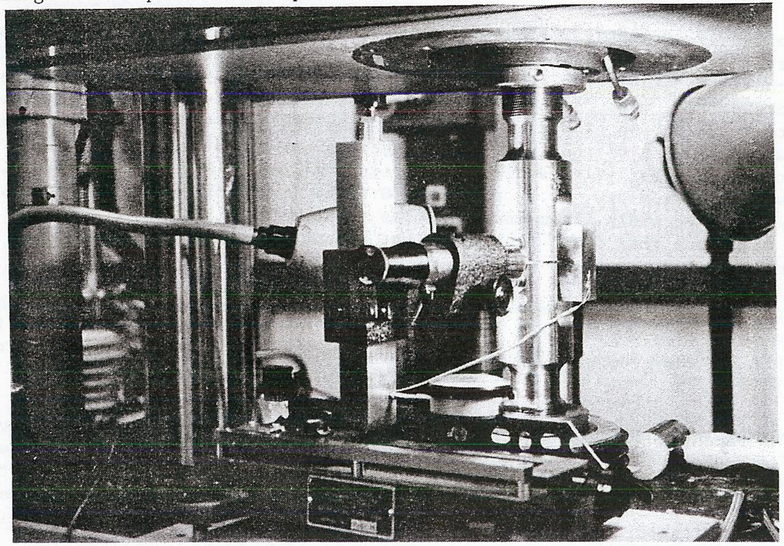

Fig. 3 Illustration of positioning of back face strain gauge on C.T.S. specimens.

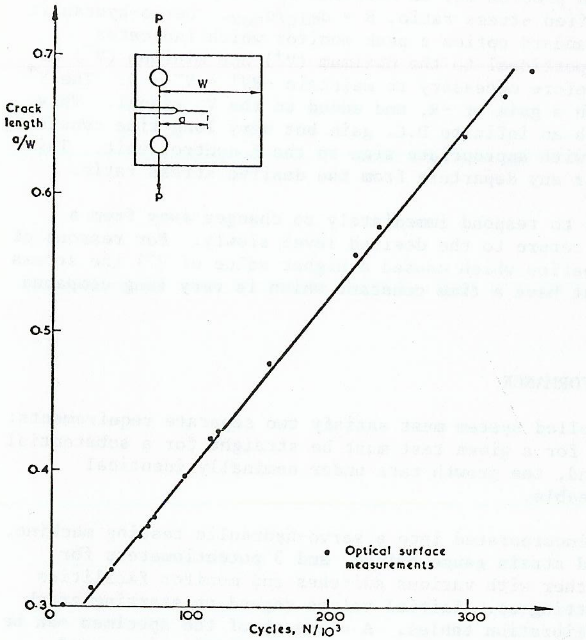

Fig. 4 Typical constant fatigue crack growth rate achieved by present control system.

Typical measurements are shown in Fig. 4. Initially the crack growth is slow, partly because it is growing from a notch of nominal radius 0.25 mm, and also because the crack grows faster in the centre of the plate than at the surface, where optical measurements are made. (The back face strain probably gives a better indication of mean crack length than the optical surface measurements). Towards the end of the life of the specimen the crack again slows down, here because the load is so small that strain dominates the feed back signal. However between a/w = 0.32 and a/w = 0.6 the growth is tolerably linear. (w is the specimen width, from loading holes to back face). For the material tested it was found that $da/dN \propto \Delta K^3$, so that a departure from linearity of 3% in the growth rate corresponds to 1% in ΔK.

Once the method has been established, fewer measurements need be made than are indicated by Fig. 4. This is an additional advantage over load controlled tests, where readings must be taken at frequent intervals, increasingly so as the test proceeds and the growth accelerates.

The test was repeated under nominally identical conditions including environment. The measurements were independently analysed, and the growth rate thus determined differed by less than 7% from that found previously. This would indicate less than 2½% error in K even if there were no other errors, but some do also arise from the optical measurements and subsequent analysis, and possible variation in the material itself.

THE USES OF K CONTROL

Two limitations must be mentioned. The crack tip plastic zone must not intercept the back face of the specimen causing net section yield. Clearly this would only occur for relatively high values of K, depending on the material in question. Secondly, if the mean level of the load signal is such that significant crack closure occurs then the system described will not maintain the constant desired ΔK. The exact limits of validity of the technique are being established by further experimental programmes.

However, the accuracy obtained with the K control system, about 7% on growth rate, may be favourably compared with the scatterband described in the introduction, which was as much as a factor of 10 on rate. Therefore where it is desirable to obtain detailed knowledge of fatigue crack growth behaviour there is much advantage to be gained by K controlled testing. The system described offers accuracy and simplicity combined with stability and low cost. It is hoped that this will facilitate the experimental side of studies directed to a better understanding of the effects of the many parameters on which fatigue crack growth depends.

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REFERENCES

Bernard, P.J., Lindley, T.C., and Richards, C.E. (1976) A.S.T.M., S.T.P. 595, 78-97.

Deans, W.F., and Richards, C.E. (1979) J. Testing and Evaluation, 7, 147-154.

Deans, W.F., and Richards, C.E. (1981) A technique for measuring crack length and load in compact fracture mechanics specimens using strain gauges, presented at this conference.

Frost, N.E., Pook, L.P., and Denton, K. (1971) Eng. Fract. Mechanics, 3, 109-126.

Mostovoy, S., Crosley, P.B., and Ripling, E.J. (1967), J. Materials, 2, 661-681.

Pickard, A.C., Ritchie, R.O., and Knott, J.F. (1975), Metals Technology 2, 253-263.

Richards, C.E., and Deans, W.F. (1980) The measurement of crack length and load using strain gauges, Proc Symposium Measurement of Crack Growth, Birmingham University April 1979, E.M.A.S., Birmingham.

Schijve, J., and de Koning, A.U. (1977), Eng. Fract. Mechanics, 9, 331-340.