COMPUTER CONTROLLED MONITORING OF THE FATIGUE CRACK SHAPE

W.D. Dover
University College London, United Kingdom

INTRODUCTION

The current interest in Structural Integrity has arisen from both safety and economic considerations. It is now unacceptable to adopt the use of a general safety factor, instead a detailed fracture mechanics analysis is often required and this must be based on knowledge of crack/defect size, applied loading and component geometry. This type of analysis involves the assessment of sub-critical crack growth and in many cases this means the growth of surface breaking fatigue cracks. In order to meet this demand techniques have been developed for surface crack detection and sizing and these have been used to provide experimental information on crack shape evolution for a wide variety of situations. These measurements are needed to confirm theoretical predictions of sub-critical crack growth and hence validate calculations on Structural Integrity.

The most important development in these crack measurement techniques has been the improvement of the previously used a.c. potential drop method to the point where it is now possible to measure accurately the a.c. field distribution and to interpret the field perturbation around a crack in terms of the crack size and shape [1],[2]. This improved technique, more properly described as a.c. field measurement (a.c.f.m.), became possible through developments in electronics which lead to the introduction of an instrument capable of accurately measuring the true surface field voltage. This system is now available commercially for N.D.T. work [3] and laboratory studies [4]. The ability to measure the true surface voltage at any point in the a.c. field encouraged the development of theoretical solutions linking crack shape to field perturbation. The successful link between theory and practice, for this technique, has led to it being applied in a wide range of situations not previously considered possible. This paper will describe the application of a.c.f.m. to crack shape measurement in threads, tubular welded connections and laboratory fatigue specimens.

A.C. FIELD MEASUREMENTS

When an a.c. is passed through a metal body the current is carried in only a thin layer at the metal surface. The existence of this 'skin effect' means that the effective section carrying the current is quite small. Thus, even on a large structure, currents of only a few amperes are required to give a measurable potential difference.

The skin depth, δ, is defined so that calculations for a.c. resistance and voltage drop are similar to those for d.c. The usual form of this definition is as follows:-

$$\delta = (\mu_r \mu_o \pi \sigma f)^{-\frac{1}{2}} \qquad (1)$$

where

μ_r = Relative permeability of conductor

μ_o = Permeability of free space = 4 x 10^{-7} H/m

σ = Conductivity of conductor, S/m

f = Frequency of a.c., Hz

In attempting to use this skin effect for crack measurement it is necessary to appreciate how the electrical field is distributed over the surface of the structure under examination.

The simplest field that could be produced would be one where the electrical field was uniform in the region of interest i.e. around the crack. Under these circumstances the measured potential difference, V_1, measured along any stream line, remote from the crack, would only be a function of the distance between the contact points (usually a fixed length known as the probe length Δ). If the probe was used to straddle the crack the measured potential difference, V_2, would include the effect of the probe length and the path length down the crack (2a). Thus taking the two readings V_1 and V_2 allows the determination of the crack depth from the following equation:

$$a = (V_2/V_1 - 1)\ \Delta/2 \qquad (2)$$

The interpretation of crack depth from these two readings, without any prior calibration, makes the technique far more accurate and reliable than earlier systems that were dependent on prior-calibration. However the accuracy of the crack estimates do rely on the interpretations of field values and hence the accuracy of the theoretical model of the electromagnetic field produced in the neighbourhood of the crack.

The theoretical electromagnetic field solution has been derived for several cases starting from Maxwell's equations [1], [2]. In all of these cases it has been determined that the field on the crack face is, in mathematical terms, the analytic continuation of the field in the surface plane. This means that the surface and the crack plane field may be assumed to behave as if they occupy a single plane with the crack plane 'unfolded' to be coincident with the surface plane. This reduces the field equation to a Laplace type equation for which several solutions have already been produced (principally the part circular crack [2] and the semi-elliptical crack [5]. If these field distortions, due to crack shape, are ignored the predicted crack depth can be in error especially for cases of short deep cracks. Typical examples of predicted crack size, for a semi-elliptical fatigue crack growing in a flat plate subjected to tension only loading, are shown in Fig. 1. Using equation (2) led to an error in most cases of approximately 30%. The true interpretation of the electromagnetic field (the solid points) reduced this error to only a few percent.

Initial attempts to utilise this system employed a hand held

probe and this proved to be very successful and is still used widely for N.D.T. in industry. More recently several special purpose systems have been developed either because greater accuracy was required or monitoring over a long time was needed. These two variants, periodic detailed inspection and continuous monitoring, required the use of computers for control and data logging and have been developed for many situations, some of which are described below.

CRACK SHAPE MEASUREMENT IN THREADS

Threaded fasteners are widely used in industry and several particular cases have been studied recently in terms of crack shape evolution. One detailed study has already been reported [6] and this concerned high strength Titanium and Inconel bolts, of 12, 14 and 28mm diameter, that were to be used in the aerospace industry. In this study the bolts were subjected to a variety of random and constant amplitude fatigue tests. These tests were interrupted periodically so that the bolts could be inspected. A special purpose jig was constructed so that a probe could be accurately positioned across adjacent thread crowns and could be moved along the entire length of the thread. In this way the potential difference across each thread root could be recorded as a function of the distance along the thread. A typical record is shown in Fig. 2 and reveals that the fatigue crack produces a characteristic trace in these materials that is easily recognised. The general feature is of an increase in the measured potential difference when the probe straddles the crack and a decrease at sites with the same orientation as the crack but at a distance of one or more complete revolutions. An example of this feature is shown in Fig.2a and can be interpreted in terms of the electromagnetic field disturbances (crack shape or 'skin' thickness) on either side of the crack. For the titanium and inconel bolts the field can be shown to be a thick 'skin' so that even though the crack often had a high aspect ratio these field distortions occurred. A theoretical solution for these thick 'skin' field distributions in threads has been produced and has allowed these records of potential difference to be interpreted in terms of crack depth and shape and also explained several other features. The characteristic p.d. trace shown in Fig.2a is so easily recognisable that the system could be used for crack detection and monitoring. Approximately fifty bolts have been tested and this revealed that cracks as small as 0.05mm could be detected and monitored until the depth reached about 1.5mm.

In addition, the theory provides the explanation for a feature noted in Fig. 2b i.e. that the measured troughs were sometimes not of equal value in symmetric sites about the crack plane. The theory predicts that for cracks located at the threaded root the troughs would decrease in value according to a simple series and the series would be the same on both sides of the crack. However for cracks not on the thread root, i.e. located on the thread flank, this symmetry is destroyed. Instead the value of these troughs can be used to locate the position of the crack on the thread flank. Figure 2b, therefore, shows a situation where the crack is on the thread flank rather than at the thread root. Figures 2a and 2b were recorded during crack detection surveys of the thread. Having located the crack the sensitivity of the displacement transducer (recording the distance along the thread) was modified so that details of the crack shape could be recorded. A typical trace showing this greater detail is given as Fig. 2c.

It became apparent during this work that the information available on crack shape obtained using a.c.f.m. was very detailed and that it would be far better to record this information in digital form i.e. under computer control. At the same time it became possible to rationalise the computer facilities within the fatigue laboratories at University College London to provide the possibility of real time computing at up to fourteen satellites which would be linked to a host computer. It was expected that the computer program required at these satellites would often be similar and consequently the opportunity was taken to standardise satellite display hardware and data collection/analysis software. A software package (FLAPS) has been written which is capable of signal generation, testing machine monitoring and control, and data logging of fatigue crack growth and strain gauge instrumentation. It is also capable of manipulating the resultant measurements to provide graphical and tubular output [7].

FLAPS comprises three main programs which have the functions, Design or Preprocess, Run, and Post process. These programs permit the user to interactively select his experimental set up using a menu of options as for example the fatigue test set of options shown below:

Design Programme

TO ENTER INITIAL PARAMETERS	TYPE 1
TO SELECT SIGNAL GENERATION	TYPE 2
TO SELECT REAL TIME CLOCK	TYPE 3
TO SELECT SAMPLING OPTIONS	TYPE 4
TO SAVE SELECTIONS ON FILE	TYPE 5
TO READ OLD CONTROL FILE	TYPE 6
TO RUN CONTROL PROGRAMME	TYPE 7
TO RUN GRAPHICS PROGRAMME	TYPE 8
TO REPRINT OPTION TABLE	TYPE 9
OR TO EXIT FMT1 (FINISHED)	TYPE 10

Selecting option 2 would give the new menu shown below:

Signal

IF EXTERNAL SIGNAL REQUIRED	TYPE 1
TO SELECT SQUAREWAVE SIGNAL	TYPE 2
TO SELECT RAMP SIGNAL	TYPE 3
TO SELECT SINEWAVE SIGNAL	TYPE 4
TO SELECT RANDOM SIGNAL	TYPE 5
TO SELECT BLOCK LOADING	TYPE 6
TO SELECT INSPECTION SIGNAL	TYPE 7

Option 7 here contains a further set of option all related to crack measurement with the following menu:

Inspection

TO SELECT CTS INSPECTION	TYPE 1
TO SELECT SEN INSPECTION	TYPE 2
TO SELECT TETHER INSPECTION	TYPE 3
TO SELECT DISC INSPECTION	TYPE 4
TO SELECT TUBULAR JOINT INSPECTION	TYPE 5
TO SELECT T-BUTT WELD INSPECTION	TYPE 6

Selecting option 3, for example, would give the program specially developed, to investigate fatigue crack growth in Tension Leg Offshore Platform (TLP) components. The TLP's currently envisaged are connected to the seabed via 'tethers' which are approximately 10m in length and have screw connectors at each end. The fatigue programme at UCL is investigating the Structural Integrity of these screw threads and part of this work involves fatigue crack growth tests on quarter scale models of the probable tether configuration. The inspection system for the particular type known as a casing joint is shown in Fig. 3. Here a stepping motor, under computer control is used, to rotate the threaded connector under a specially designed probe head. The probe is constructed as part of a nut that fits the thread form and positions contacts on adjacent thread crowns.

The probe is restrained from rotation, by a guide parallel to the axis of the thread, and consequently as the thread is rotated the probe is caused to move along the axis of the thread. The type of thread used in this application is a taper buttress thread and the material a high strength steel. The irregular geometry of the test piece led to a modification in the normal procedure for this inspection technique. Instead of injecting the electromagnetic field directly into the test specimen several field wire coils were made around the probe with the result that the field was induced into the region of interest. This method gives a constant p.d. reading for the probe, as it passes along the thread, unless a crack is present. These tests are still continuing and a trace recorded at an early stage in one test is shown in Fig. 4.

CRACK SHAPE MEASUREMENT IN TUBULAR WELDED JOINTS

Tubular welded joints are used in the fabrication of offshore structures and have been found to have relatively low fatigue resistance, due mainly to the presence of high stress concentration regions and small defects produced by the welding process. In practice, most of the fatigue life consists of crack growth and this has prompted studies into the possibility of establishing a fatigue life prediction method based on fracture mechanics. Such an analysis would have to predict fatigue crack shape evolution and one of the aims of the current fatigue programme at University College London is to provide experimental evidence on the nature of this crack growth.

Several servo-hydraulic test rigs have been constructed for this programme and one of these, built to test Y and K joints is shown in Fig. 4. The FLAPS program is used to run the tests on these tubular joints and this means using a variety of programs for stress analysis (strain gauge datalogging), signal generation (usually a random load test sequence), and crack growth monitoring. In earlier work on the tubular welded T joints a hand held probe was used but as the requirements for greater crack shape detail and for tests in seawater arose it became necessary to change to a system employing permanent spot welded connections and a computer controlled switch unit. The general layout of the test set-up is shown in Fig. 6 and it can be seen that both field and probe inputs are under computer controlled switching. The probe switch units currently in use at University College London have been purpose-built to suit the a.c.f.m. system and can monitor up to 64 channels.

The provision of a graphics facility within the FLAPS program means that this data can be automatically printed out in terms of crack shape evolution or averaged "a" versus "N" data. An example of a series of measurements taken during a random load fatigue test on a Y joint is shown in Fig. 7.

FATIGUE CRACK MONITOR FOR SIMPLE SPECIMENS

The main problems in applying a.c. field measurement to specimens lie in the finite size, complex geometry of the typical specimen. Appropriate choices for the experimental arrangement can minimise these effects however.

The incorrect positioning of current inputs and probe contacts can produce non-linear calibrations and large effects due to stress. Figure 8 shows the ideal arrangement where induced fields and stray pick-up has been minimised. Unfortunately a theoretical solution for the electromagnetic field distribution is not available yet and for small specimens or large amounts of crack growth the field distribution along the crack faces must be treated as non-linear. Conversely for large specimens and small crack growth (the threshold corrosion fatigue type test or stress corrosion cracking test), this non-linearity can be ignored and measurements of very small crack increments occurring over a period of days or weeks are measurable.

A further improvement for these long term tests can be obtained by spot welding permanent connections to test specimens. For thick specimens these connections should be made at mid thickness and be as close to the notch tip as possible. In addition it is desirable to use computer control switching of the field input and probe/reference values. This approach has been used on recent stress corrosion tests at University College London on high strength steels. A typical set of results from these tests is shown in Fig. 9. A further recent development of the system allows the possibility of automatically stopping the test after a certain crack length has been reached. A parallel development by the manufacturers [4] employs a similar method for providing an automatic specimen precracking facility.

CONCLUSIONS

Recent developments in the theory and practice of a.c. field measurements has made it possible to automatically monitor crack shape evolution in a wide variety of geometries and components. This in turn means that the evaluation of sub-critical crack growth and the measurement of surface defects is now possible. The application of these techniques to several important industrial problems has been successfully demonstrated.

REFERENCES

[1] Dover, W.D.,Charlesworth,F.D.W.,Taylor,K.A.,Collins,R. and Michael,D.H., A.C. Field Measurement: Theory and Practice, in 'The measurement of crack length and shape during fracture and fatigue', C.J.Beevers,ed.,Engineering Materials Advisory Service, Warley, 1980.

[2] Dover,W.D.,Charlesworth,F.D.W.,Taylor,K.A.,Collins,R. and Michael,D.H., The use of A.C. Field Measurements to determine the shape and size of a crack in a metal, in 'Eddy current characterisation of materials and structures', G.Birnbaum and G.Free, eds., American Society for Testing and Materials,Philadelphia, 1981.

[3] The Unit Inspection Company Ltd., Sketty Hall, Swansea, U.K.

[4] Instron Ltd., Coronation Road, High Wycombe, Bucks, U.K.

[5] Collins,R.,Michael,D.H. and Ranger,K.B., The A.C. Field around a plane semi-elliptical crack in a metal surface, in 'Proceedings of Thirteenth Symposium on Non-destructive Evaluation', San Antonio, Texas, 1981.

[6] Michael,D.H., Collins,R. and Dover,W.D., Detection and measurement of cracks in threaded bolts with an a.c. potential difference method., Proc. Roy. Soc. London, A 385, 145-168, 1983.

[7] Broome,D.R.,Dharmavasan,S.,Dover,W.D. and Godfrey,L.J., The use of digital techniques in the large scale fatigue testing of Tubular Joints., SEECO 83, The City University, U.K., 1983.

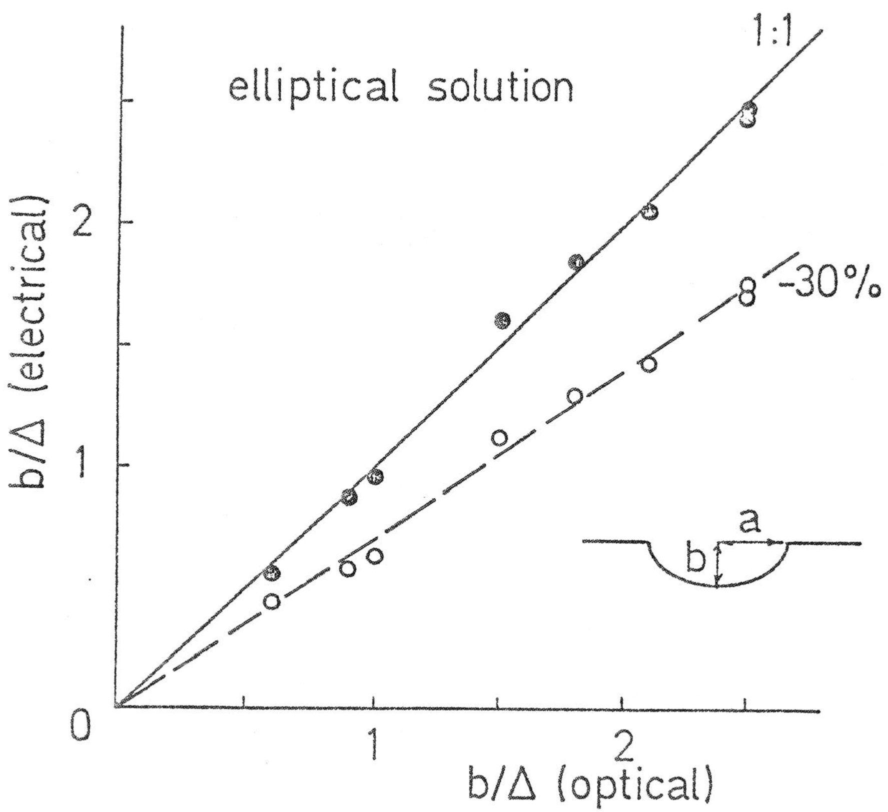


Fig. 1. One dimensional and two dimensional interpretation of voltage readings on the centre line of a semi-elliptical fatigue crack O one-dimensional ● semi-elliptical solution.

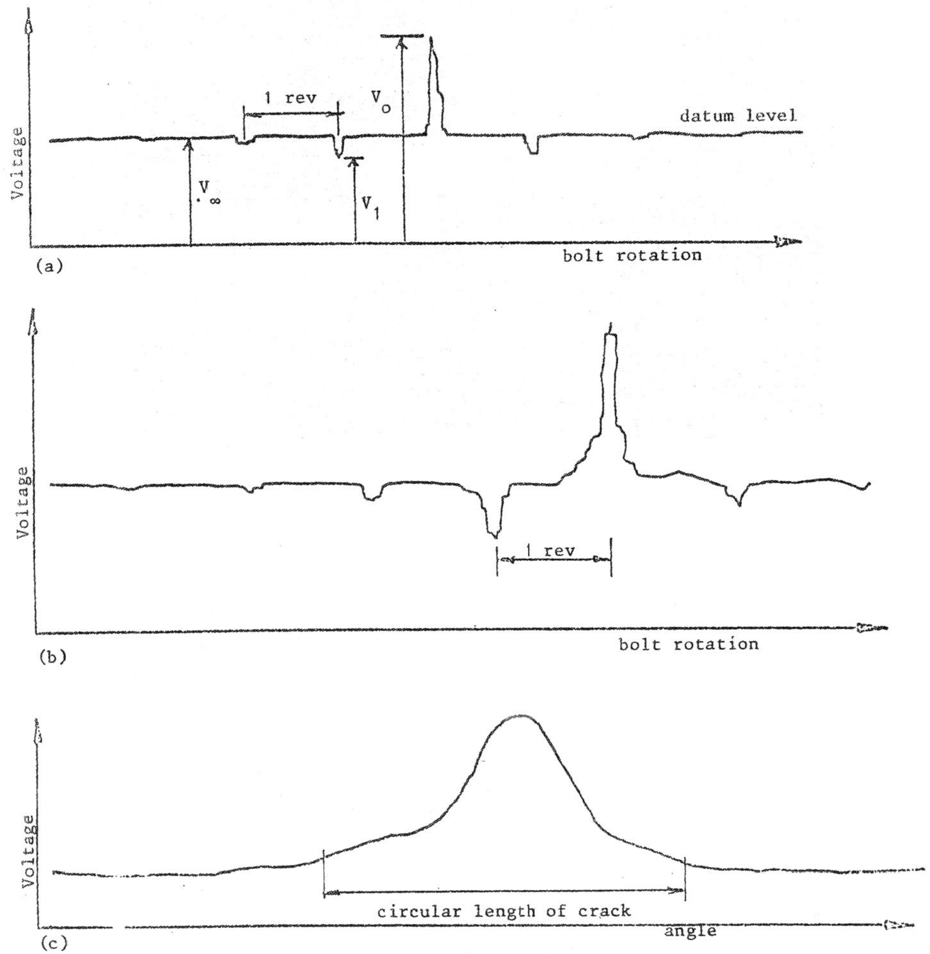


Fig. 2. a) Symmetric signal trace for a notch located at the thread root.
b) Asymmetric trace for a fatigue crack on the thread flank.
c) Fine scale trace of the crack region.

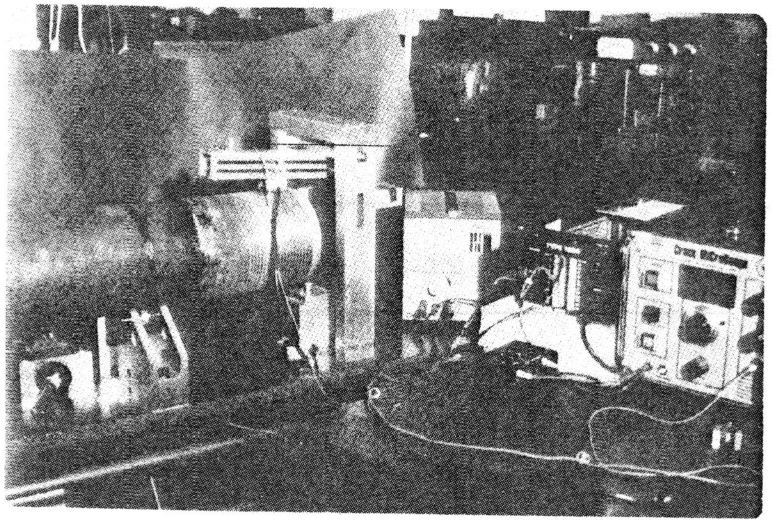


Fig. 3. Computer controlled inspection rig for crack detection and sizing in the threaded end of tubular steel components (tethers)

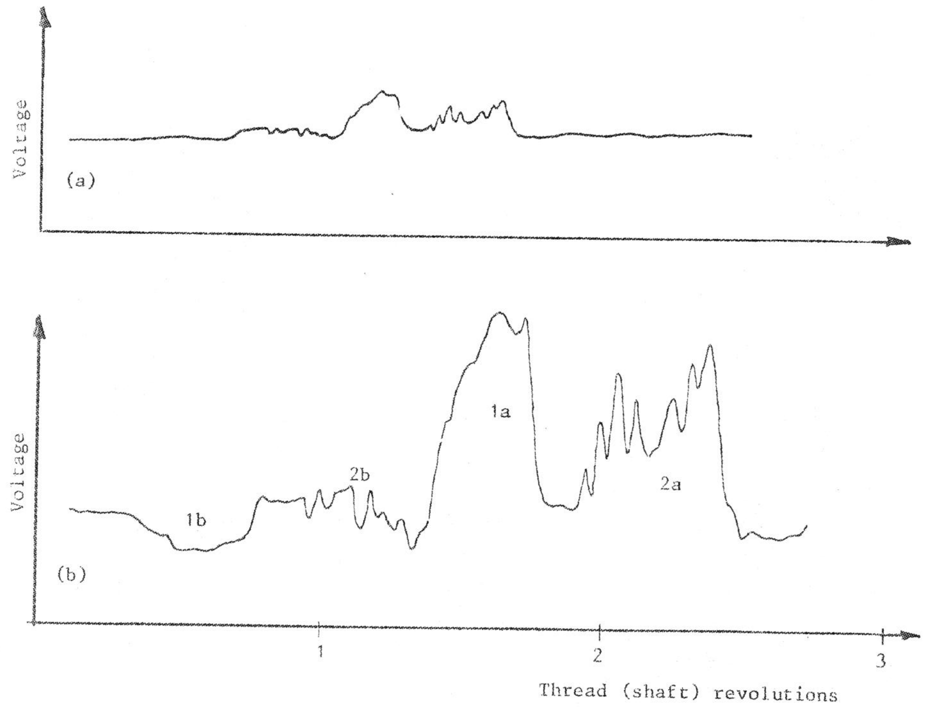


Fig. 4. 150mm dia steel shaft with tapered buttress thread possessing multiple fatigue cracks (a) coarse scale; (b) fine scale (1a and 1b are a crack and satellite pair, 2a and 2b are a second pair).

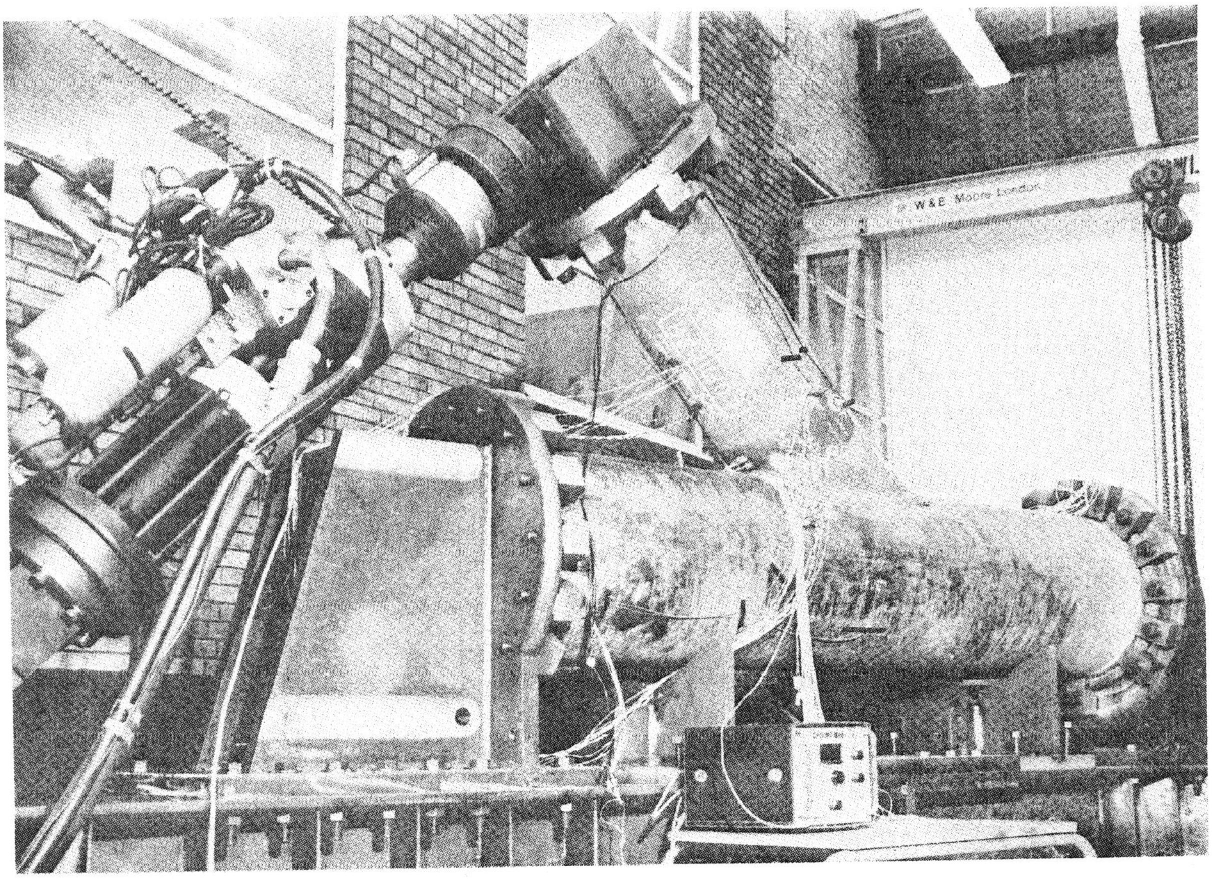


Fig. 5. Servohydraulic test rig for tubular welded Y joints.

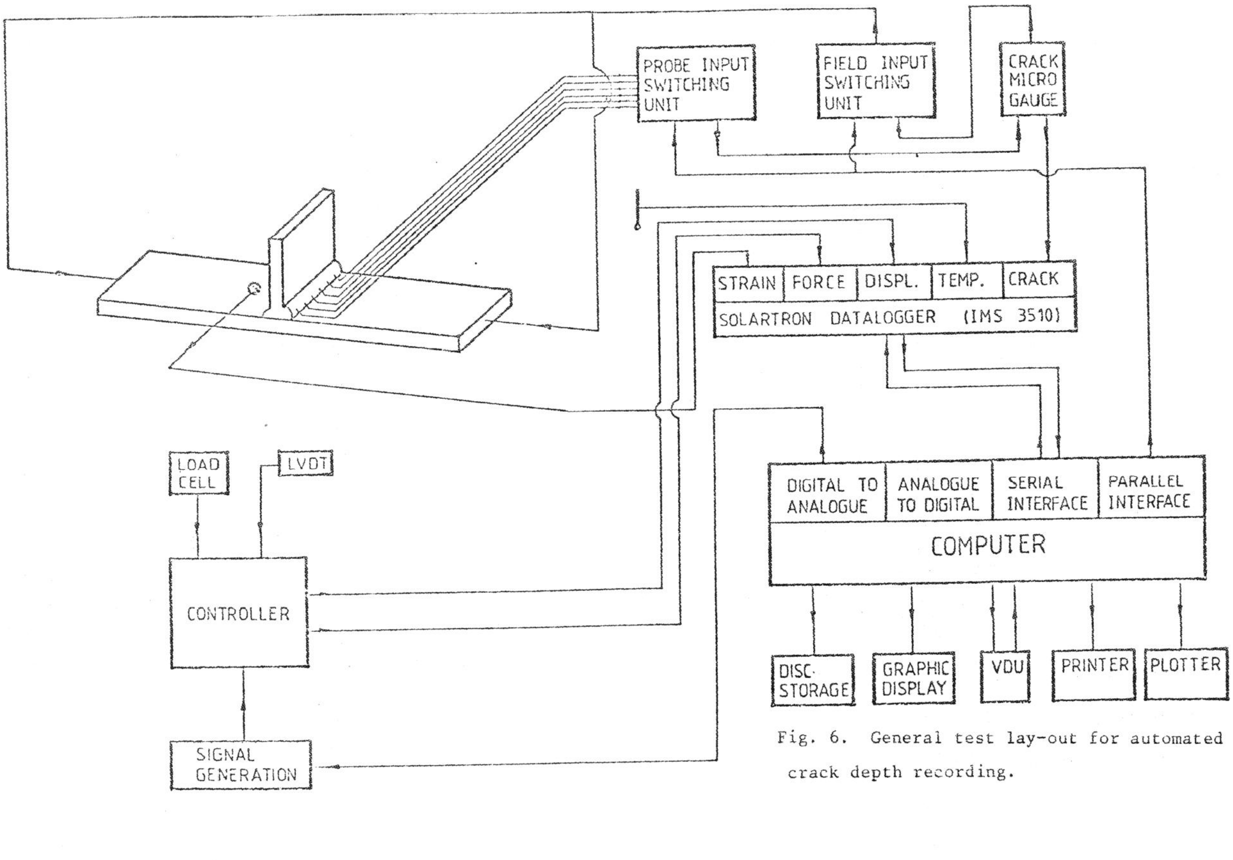
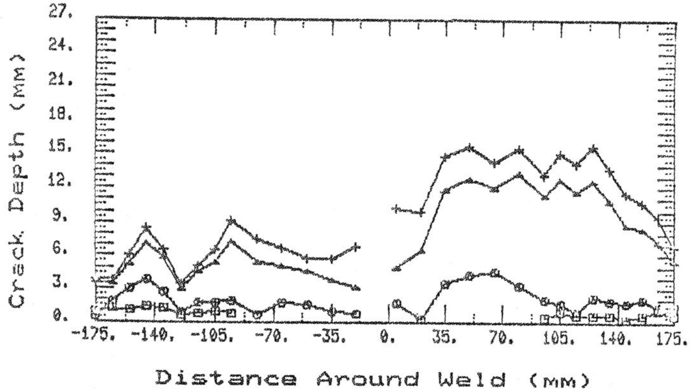
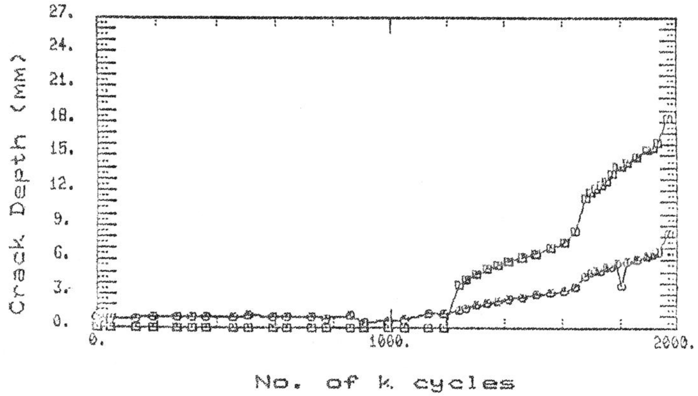


Fig. 6. General test lay-out for automated crack depth recording.



Key to Symbols

□ N= 365. K CYC
○ N= 1265. K CYC
△ N= 1751. K CYC
+ N= 1915. K CYC



(b)

Key to Symbols

□ X = 50. to 50. (MM)
○ X = -105. to -105. (MM)

Fig. 7. a) Measured crack shape around a tubular Y joint at various parts of the fatigue life.
b) Averaged crack depth versus N curves over various portions of the tubular intersection.

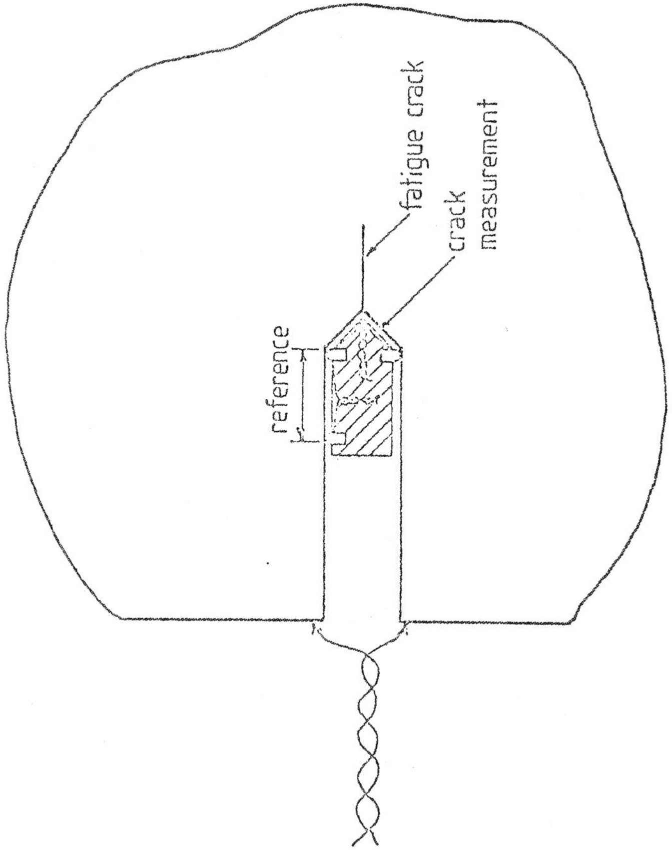


Fig. 8. Ideal layout for a C.T. specimen probe.

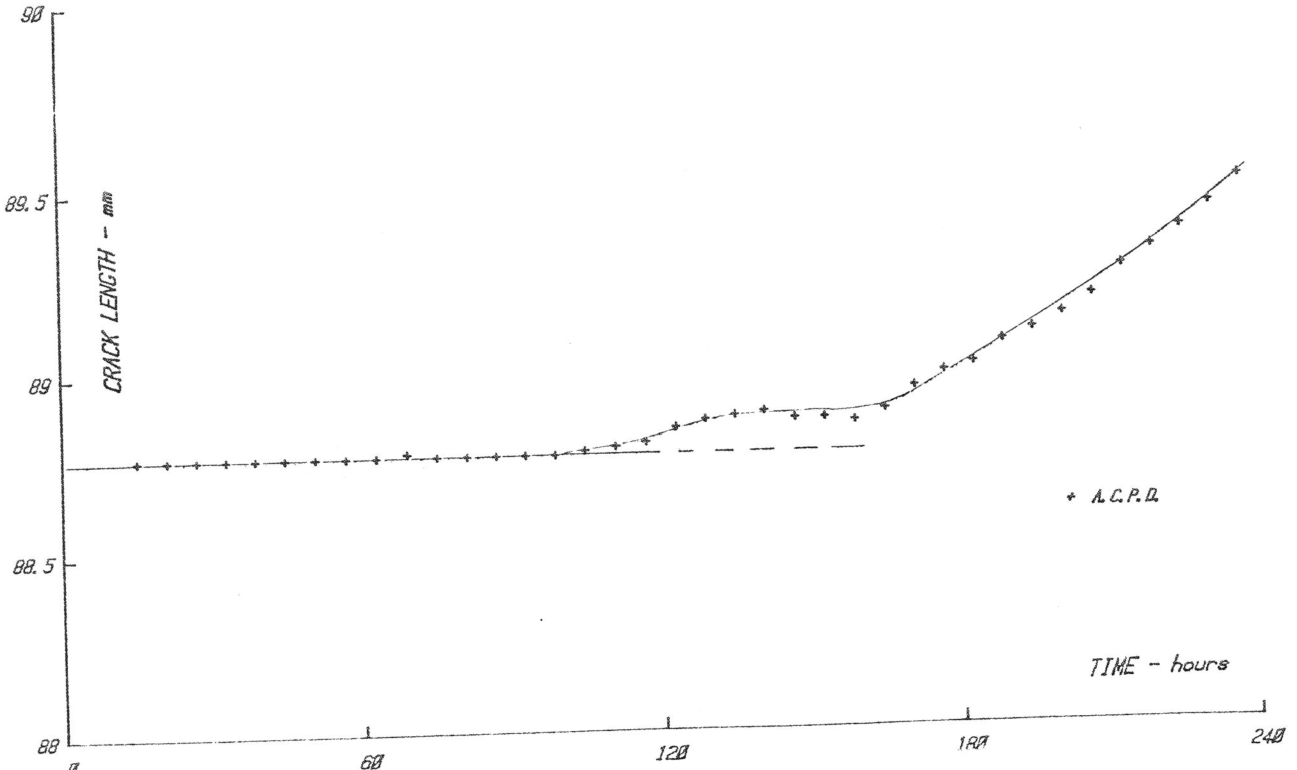


Fig. 9. Test results from an 80mm thick (SEN) Stress Corrosion test (crack measurements on mid-thickness).