AUTOMATED BATCH PROCESSING OF FATIGUE CRACK PROPAGATION TESTS

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ABSTRACT

Computer software was developed for automated evaluation of Fatigue Crack Propagation (FCP) properties of materials. The software permits "Batch Mode" execution of FCP test series under constant amplitude, programmed, random and other arbitrary load sequences with stress control as well with user definable variation of stress intensity. It includes modules for maintenance of an FCP Data Bank and processing of data with graphical output. The programs operate on foreground-background, time-sharing, reentrant code with provision for control of multiple testing machines. The software was designed for minimum operator interaction and maximum test data protection under conditions of prolonged unattended testing with restricted use of hydraulic power.

KEYWORDS

Fatigue crack propagation; automated testing; computer control; software; batch processing.

INTRODUCTION

The digital computer occupies a prominent place in current day-to-day activities. The fatigue laboratory is no exception (Mindlin and Landgraf, 1976). If the sixties heralded the entry and subsequently, the virtual monopoly of servohydraulic test systems, the seventies saw the appearance of mini and micro computers to control such systems. In the area of FCP testing, the computer generates the test load sequence, samples feedback to monitor machine performance, estimates crack length from unloading compliance, etc..It is also used for FCP data reduction and storage. The capacity of the computer to generate a load signal, representative of service load environment has direct practical applications. Online compliance and crack length measurements not only free the operator from a tedious task but also exclude a potential source of data errors. The computer can use the estimated crack length as a test control variable and adjust load levels to obtain any desired function of stress intensity.

The study described in this paper was devoted to the organization of high throughput "Batch Mode" FCP testing under a variety of loading conditions with minimal operator-machine interaction. The first section describes the test setup at NAL. Requirements for Batch Mode testing are formulated in the second section. This is followed by a description of the procedures implemented for Batch Mode testing. Certain hardware and software elements along with typical test results are also presented.

TEST SETUP

The computer controlled fatigue laboratory at NAL is schematically described in Fig. 1. It is based on a 25-ton servohydraulic testing machine linked to a PDP 11/23 computer through an analogue/digital interface. All the software related to realtime test control and data processing were developed at NAL. It is proposed to link two more load frames to the same computer. A dual (30+6) lpm hydraulic powerpack is used with the system. Aircooling for the powerpack makes it independent of the water supply. The PDP 11/23 is linked to a HP9825B desktop computer which is part of an Aircraft Flight Data Analysis System. This linkage provides for transfer of aircraft load spectra directly to the PDP. A wide variety of peripherals on the two systems are accessible to both computers. A multiprogrammer hooked onto the HP9825B has the capability to control low speed (static/LCF) tests on upto two load frames, providing for some redundancy in the event of a breakdown of the PDP. The serial data link also allows the use of the HP9825B as an intelligent terminal of the PDP, with the capability for local processing of FCP test results, preparation of test report, word processing (including the preparation of this manuscript), etc..

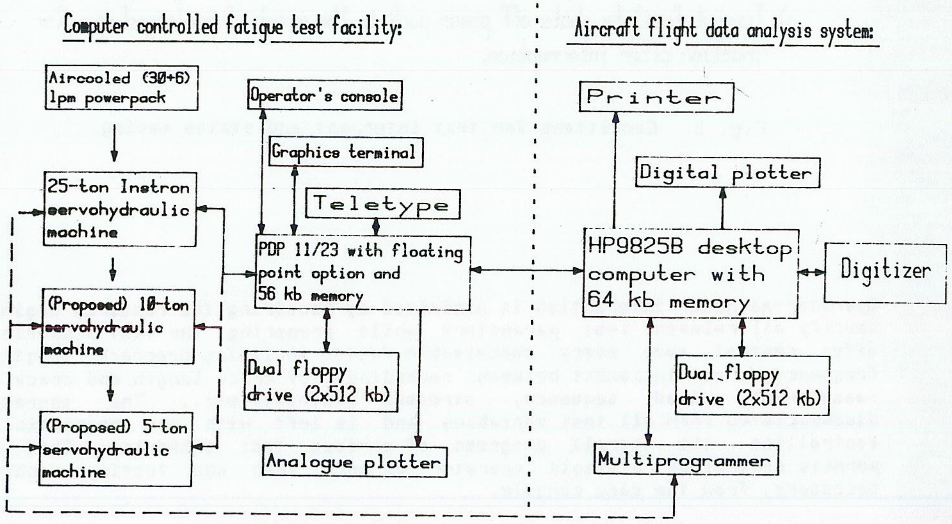

Fig. 1. Schematic of fatigue test system at NAL.

REQUIREMENTS FOR AUTOMATED FCP TESTING

In terms of test system usage, FCP tests may be classified into two categories:

1. Material characterization with reference to crack propagation under various load and environmental conditions. This calls for a test schedule which may cover more than a hundred specimens and require many months of testing. Studies by Schijve and de Rijk (1966) and by Schijve, Jacobs and Tromp (1968) may well fall into this category.
2. "Single shot" or limited tests to study the influence of specific factors on the FCP process. Tests by von Euw, Hertzberg and Roberts (1972) and by Katcher and Kaplan (1974) serve as examples of this category.

FCP test software described in the literature largely caters to the second category of testing. Being highly interactive, it provides for (and demands) a lot of attention from the operator. Obviously this requires the constant presence at the testing machine of a qualified, "fatigue educated" person (perhaps the interested scientist himself) to enter test variables at the console. During data entry at the console, the test machine itself is idle. Another drawback of available software for testing lies in the restricted choice of load sequences / control modes. These two problems can introduce considerable overheads on the test process, especially when a large volume of testing is involved.

The computer controlled tesing machine at NAL is a general facility catering to the requirements of the entire laboratory. To ensure efficient usage of the system, the following organizational requirements were formulated for the FCP test software and hardware:

1. Multiuser access to the facility with batch processed "queues" of test jobs.
2. Integrated software for FCP tests on specimens of different geometries under constant amplitude, programmed, pseudo-random and user defined arbitrary load sequences with stress control as well as with user definable variation of stress intensity.
3. Maximum test automation with minimum operator interaction.
4. Provision for unattended testing outside office hours.
5. Test status saving to protect intermediate test results in the event of power failure / breakdowns.
6. Provision for interruption of prolonged tests to permit priority execution of urgent short duration test schedules.
7. Maintenance of an FCP Data Bank with mandatory storage and protection of all test results.
8. Parallel (background) processing of test results with graphical output in standard formats.
9. Restricted energy consumption by way of hydraulic power.
10. Capacity for system expansion through additional load frames with no increase in computer capacity or manpower.

Some of these features (e.g. 4,8,10) are incorporated in available FCP test software developed at various laboratories and offered by manufacturers of test systems. The software described in the following sections includes all these features.

BATCH MODE TESTING

The operational schematic of Batch Mode FCP testing appears in Fig. 2. In this mode the testing machine is never made directly "available" to a specific user. Rather, system users prepare computer based schedules of test series and submit them for execution. A number of such "queues" are handled by the operator in a manner, conducive to effective and continuous system utilization. The research engineer whilst not having direct access to the testing machine does enjoy access to the FCP data bank on disc storage. This allows him to scan existing FCP data and his own test results to obtain plots of FCP characteristics. This activity proceeds on a time-sharing basis on the same computer system. A major problem in Batch Mode FCP testing is the interaction of multiple users with the system, management of individual test schedules, interruption (without loss of data) of prolonged tests (e.g. near threshold studies) to execute higher priority tests and the protection of FCP test results, both intermediate as well as final. In the Indian environment an additional problem is posed by the rather frequent power supply failures. An important feature of the test software is test status saving in the event of interruptions. The conditions which force status saving are illustrated in Fig. 3. Some interruptions (e.g. low hydraulic pressure) require operator intervention. To conserve energy during unattended testing, a timeout routine shuts off the powerpack if operator attention is sought but is not immediately available. The status saving feature requires the capability to maintain adequate information on individual projects to enable their continuation after interruptions. A

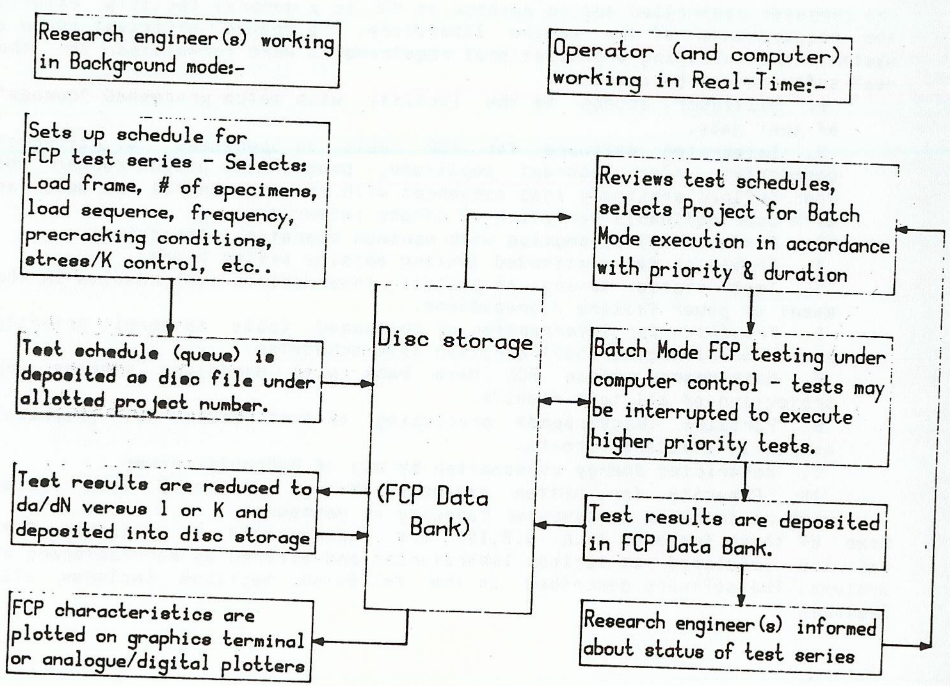

Fig. 2. Schematic of Batch Mode FCP testing.

streamlined filename structure was evolved to assist in the management of test schedules and maintenance of the FCP data bank on disc storage. The computer generates unique filenames based on Project, Material and Specimen code. At the conclusion of each test, a mandatory record of test results is made in the FCP data bank. Storage of status files enables swapping of tests in progress. With a number of test queues awaiting processing, minimal downtime results from unforeseen problems holding up a specific test.

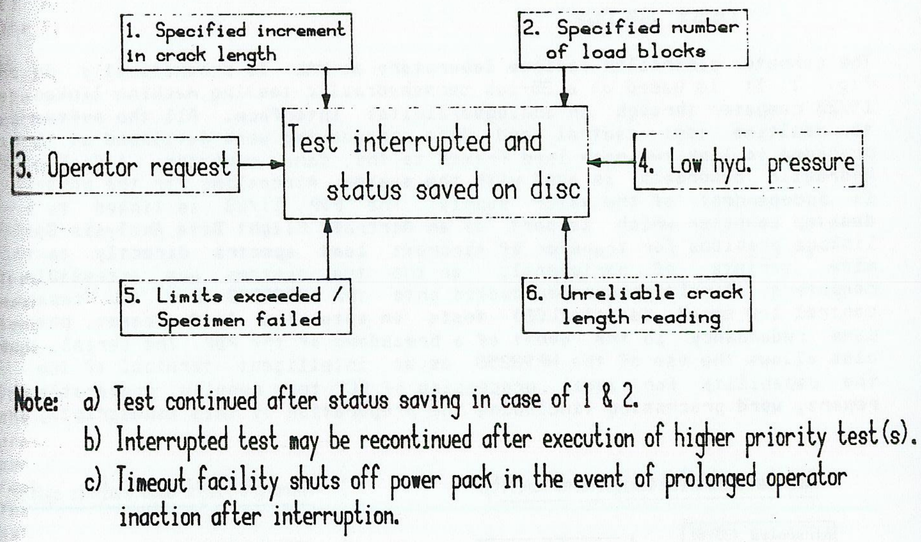

Fig. 3. Conditions for test interrupt and status saving.

Operator-machine interaction is minimized by requiring the research engineer to specify all relevant test parameters while preparing the test schedule. These offer control over every conceivable factor including precrack length, load frequency, crack increment between recordings of crack length and crack closure measurement, load sequence, stress/K control, etc.. The operator is disassociated from all test variables and is left with the responsibility of controlling the overall progress of various test schedules. This feature permits control by a single operator of more than one testing machine, if necessary, from the same console.

Loading hardware features also contribute to reducing the time between tests. Hydraulic grips enable rapid change of the test specimen. A sturdy COD gage with fully protected sensitive element was specially developed for easy friction mounting onto SENT specimens. Finally, all the FCP test software and online data storage use only one of the two available floppy disc drives. This frees the other drive for Background jobs and provides for redundancy in case of failure of one of the drives.

REALTIME FCP TEST CONTROL

All programs related to test control as well as background data processing run on a time-sharing basis under the INTRAN operating system (developed by Instron Ltd., U.K.). The operating system supports execution of multiple jobs, each consisting of one or more tasks. Tasks within a single job can share data areas and thus interact. All programs reside as reentrant code - only a single copy of code is resident irrespective of the number of tasks using it.

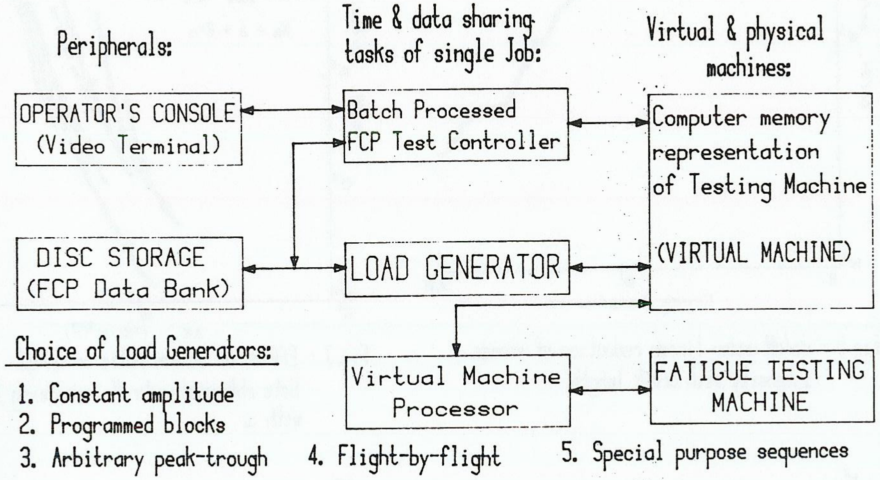

Fig. 4. FCP test control job environment.

The FCP test control job environment is described in Fig. 4. An FCP test control job consists of three tasks:

1. Batch Processed FCP Test Controller - the main controlling task of the job. It communicates with the operator and controls the overall progress of the test including the load generation process (by the Load Generator task) and interacts with the Virtual Machine Processor to control and monitor test machine status, crack length, etc..
2. Load Generator - is entrusted with the task of generating the test load sequence following a strict handshake protocol with the Test Controller. Load generators were developed to provide a wide choice of load sequences.
3. Virtual Machine Processor - drives and monitors hardware interfaces and maintains a computer memory representation of the testing machine.

Functional breakup of the three tasks offers considerable flexibility and power for computer controlled testing:

The Virtual Machine Processor code is interface hardware dependent but test control software independent. Thus, to implement the Batch Mode test software package on a different make of testing machine, only this module has to be

modified. On the other hand, the same module being "blind" to the type of test, is functional for all types of tests (tensile, fracture toughness, LCF, etc.) on the same type of machine.

The Load Generator is a "switchable" module, offering the possibility of conducting FCP tests under any conceivable load sequence. Special purpose load generators can be developed within a short time. They must ensure of course, that a strict protocol of communication with the Test Controller is followed. It may be noted that use of a particular load generator is not restricted to the FCP test. The same modules may be used for other fatigue tests (e.g. LCF).

An important feature of Test Controller - Load Generator interaction is that the latter generates nondimensionalised load peaks and frequencies. High speed machine code routines are employed during the demand signal generation process to scale the load level as well as frequency. This capability allows the Test Controller to:

1. vary overall load level to achieve required K-variation with crack length,
2. adjust load frequency with half-cycle range and crack length to account for deterioration in machine response.

Irrespective of the test load sequence, the user can specify either a constant mean stress or a third order polynomial describing K-mean variation with crack length. He can also use a special purpose load generator to introduce time dependent variation in K-mean.

The performance of a servohydraulic machine is linked to the flow capacity of the servovalve and powerpack. The latter must be viewed in the context of present day energy crisis. Essentially, there are three regions in the machine performance envelope. In the region of surplus flow capacity, the demand and feedback signals can be made to coincide (with suitable loop-gain adjustment). The second region permits accurate duplication of the demand signal waveform - but with a certain time lag. The third region corresponds to inadequate flow, leading to drop in hydraulic pressure. From the viewpoint of loading accuracy, the second region appears acceptable for FCP tests. As a rule however, manufacturers of test systems specify powerpacks to ensure operation in the first region of the performance envelope. Our experience shows that a powerpack of lower capacity is adequate for FCP tests, provided online load frequency adjustments are made to account for drop in specimen stiffness with crack extension as well as for load half-cycle range (in variable amplitude sequences). The test system at NAL is equipped with a dual (30+6) lpm powerpack. Currently, all FCP testing on SENT and CCT specimens is carried out at frequencies upto 25 Hz with the 6 lpm pack, i.e., using about 4 KVA of power instead of upwards of 30 KVA for recommended oil flow. Considering that in Batch Mode testing, the system is in operation round the clock, the associated energy conservation is appreciable. The question remains as to the influence of frequency adjustments on the FCP process itself. Experience shows that frequency variation during a test does not exceed a factor of 2 to 5. Frequency variations in this range in a nonaggressive environment are not expected to introduce a noticeable effect on the FCP process. This view is supported by test results obtained on the system.

Measurement of crack length and crack opening stress. A COD gage was specially developed for 1 to 5 mm thick SENT specimens. The gage is friction mounted onto the specimen. It contains a single sensitive cantilever element which is deflected by a screw mounted on a pin block. The tip of the screw deflects the cantilever during loading. A 1mm range of deflection was selected. The output of the gage is proportional to the displacement at a point about 5mm away from the edge of the specimen. No direct calibration function is therefore available for crack length estimates. A standard SENT specimen configuration was evolved for all FCP tests on plate material. These specimens are 75 mm wide to match the hydraulic grips. A 2.5 mm crack initiator is milled at the specimen edge, first with a coarse, then with a fine V-edged cutting wheel. The milling process allows for bulk preparation of test specimens at low cost. A calibration curve was empirically derived for crack length versus compliance. This curve was nondimensionalised with respect to specimen width, thickness and Young's modulus. Such curves can be obtained and stored as part of the FCP data bank for other geometries as well. Crack length during the test is estimated from unloading compliance. When crack length measurement is sought, the load generator holds the load at a relatively high level. The test controller then partially unloads the specimen (over not more than 25% of maximum stress) using a low frequency ramp signal. During this process, about 100 intermediate values of COD and load are sampled. A machine code routine then least square fits a straight line through these points and compliance is estimated as the slope of this line. The crack length is computed from a calibration polynomial as a function of compliance. A crack length estimation cycle is completed within one second. The algorithm for crack length estimation includes logical elements to detect obviously incorrect or unreliable data. Resolution of this technique was found to be about 0.05 mm. In low stress ratio and variable amplitude loading tests, the unloading cycle was found to have no effect on the FCP process. In high stress ratio tests, this load cycle is included in the baseline history for purpose of analysis.

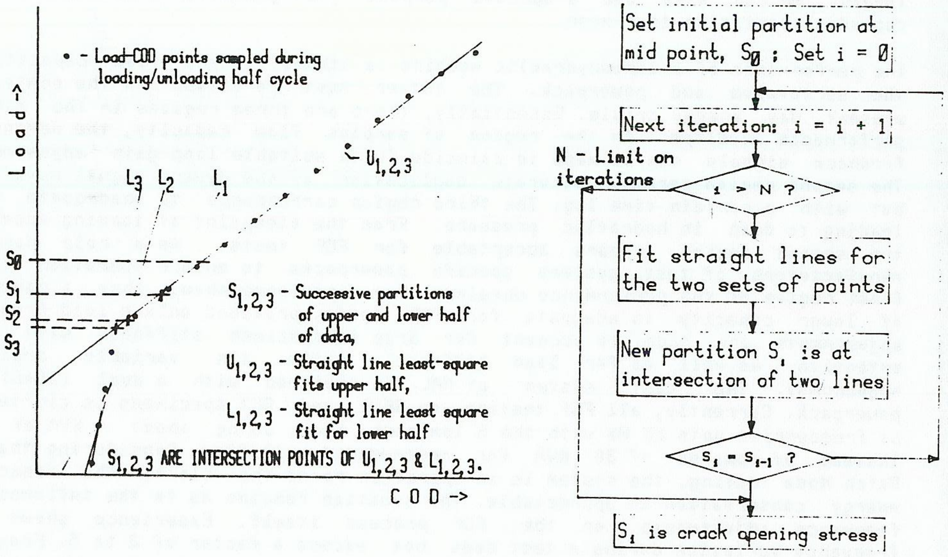

Fig. 5. Iterative technique for crack closure stress measurement.

A technique was developed for automatic crack opening stress level estimates. The same COD gage is used to estimate crack opening stress level at specified intervals of crack length (usually every 0.5mm). The procedure for this measurement appears in Fig. 5. Crack opening stress level is usually estimated within the first 10 iterations. Both crack closing stress (during unloading half cycle) and crack opening stress (during the loading half cycle) are

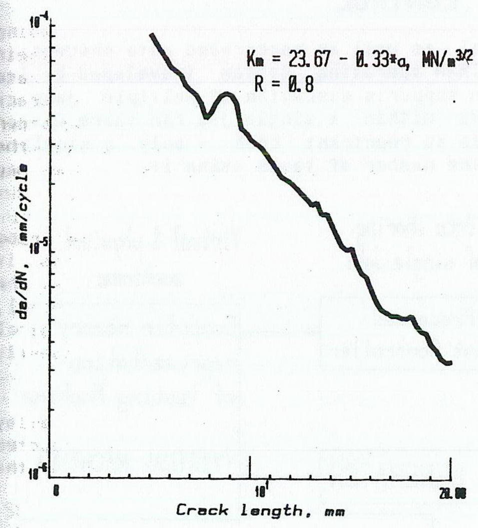

Fig. 6 - da/dN under linear reduction of stress intensity with crack length

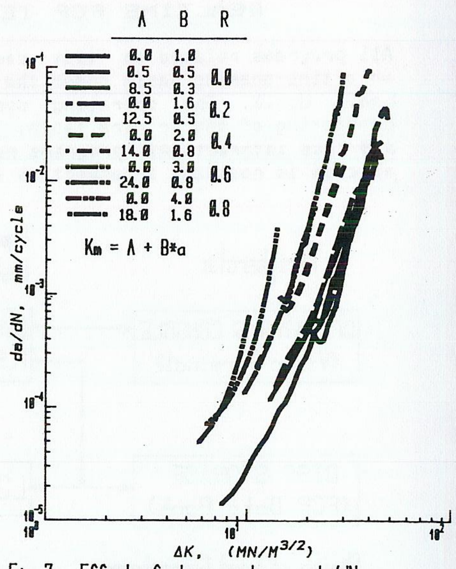

Fig. 7 - Effect of stress ratio on da/dN. Data obtained under K increasing linearly with a.

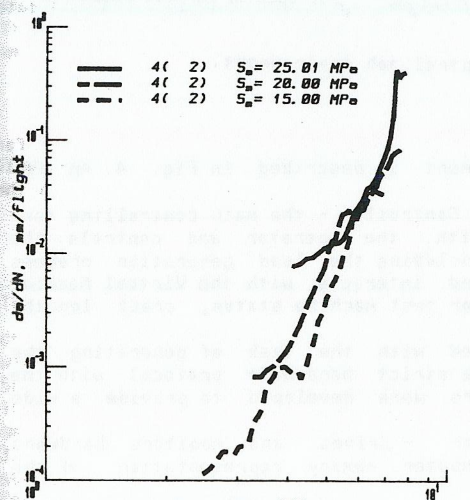

Fig. 8 - da/dN under pseudo-random combat aircraft spectrum loading - effect of mean (1g) stress.

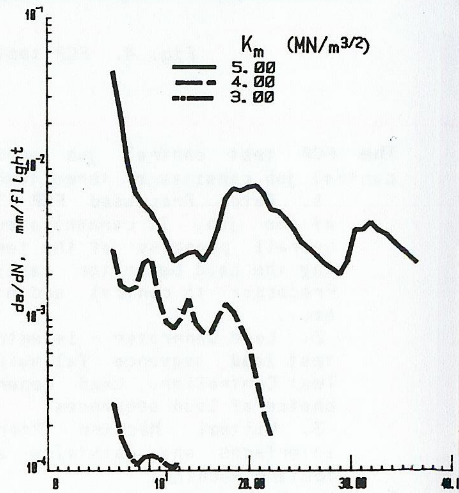

Fig. 9 - da/dN under aircraft spectrum loading at constant mean (1g) stress intensity

estimated. The routine includes logic to discard obviously incorrect estimates.

Processing of FCP test results. A package of data processing programs including graphics routines was developed for reduction of FCP test results and their presentation in a variety of formats. The choice includes crack growth rate versus crack length, stress intensity range and mean stress intensity. Crack growth rate is estimated using the incremental polynomial technique. The order of the polynomial as well as the number of points are left to the choice of the user. In case of multiple tests under similar loading, crack growth rates may be averaged.

Data processing tasks are executed in the background mode on a timesharing basis. They access the FCP data bank. Graphical output from these tasks is available as self contained figures, complete with captions and notations. The user has the option of first examining the results on the graphics terminal, then getting a hard copy of desired enlargement on the analogue or digital plotter. The figures are also stored on disc storage and can be subsequently recalled without repetitive data processing.

A series of FCP tests were recently completed on 1mm thick D16AT Al-Cu alloy sheet SENT specimens under various loading conditions. The tests were conducted in Batch Mode with the test set up in operation round the clock. Some of the test results appear in Figs. 6-9.

Utilization of computer resources. Time-sharing and code reentrancy provide for efficient utilization of computer resources. The system base period is 10ms with 10 slots of 1ms each. This permits random load tests at upto 25 Hz. The Batch Mode FCP test job requires 3 slots (one each for the three tasks). Unutilized time slots are alloted to background jobs on a round-robin basis. Code reentrancy ensures that 56 kb memory would be adequate for control of three testing machines as well as the running of at least one background data processing job.

CONCLUSION

Computer software was developed for fully automated Batch Mode testing for fatigue crack growth under a variety of load sequences with both stress as well as stress intensity control. It allows for efficient multiuser access to the computer controlled fatigue testing machine.

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