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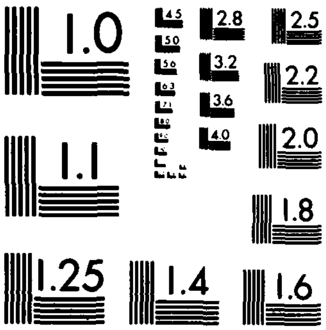

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USE OF SMALL CRACK DATA TO BRING ABOUT AND QUANTIFY IMPROVEMENTS TO AIRCRAFT STRUCTURAL INTEGRITY

J.M. Potter
B.G.W. Yee

Structural Integrity Branch
Structures and Dynamics Division

September 1983

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JOHN M. POTTER, Aero. Engr.
Project Engineer

DAVEY L. SMITH, Chief
Structural Integrity Branch
Structures & Dynamics Division

FOR THE COMMANDER

RALPH L. KUSTER, JR., Colonel, USAF
Chief, Structures & Dynamics Division
Flight Dynamics Laboratory

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Crack growth information has been used in many ways to quantitatively evaluate and predict damage tolerance and slow crack growth life limits of structures. Recent advances in the area of crack growth at small crack sizes (less than one millimeter) haveenabled increasingly quantitative studies into the specific mechanisms that affect initiation and growth at structural details. As an example, through the use of small crack data the USAF/General Dynamics study on "Fastener Hole Quality" was able to identify a manufacturing-related problem

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causing short structural lives, propose a modification to shop equipment, and quickly and specifically evaluate the resultant flaw growth improvement. This change to shop equipment has been subsequently adopted by several other major airframe manufacturers.

The purpose of this paper is to describe the general procedures used in the derivation of small crack data and to present growth data for different structural manufacturing methods. The data will be presented in terms of equivalent initial flaw size populations, crack growth rate, and initiation life to a specific length for fractographically measured cracks within the range of .01 to 1 millimeter in length. Procedures will be discussed to utilize the small crack data for developing and verifying changes in fastener systems and manufacturing methods for improving the fatigue performance of aircraft structures.

FOREWORD

This report describes a co-authored effort accomplished in both the AFWAL Flight Dynamics Laboratory and General Dynamics' Material Research Laboratory in preparation for a presentation to the AGARD Structures and Materials Panel Specialists Meeting on "Behavior of Short Cracks in Airframe Components." This paper appears as a part of AGARD-CP-328 dated April 1983. The US Air Force contribution was accomplished under project 2401, "Structures and Dynamics," Task 240101, "Structural Integrity for Military Aerospace Vehicles," Work Unit 24010179, "Life Analyses and Design Methods for Aerospace Structure."

The work was performed for the Structural Integrity Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/FIBE), Wright-Patterson Air Force Base, Ohio.

The completed report was submitted for publication as an AFWAL Technical report in August 1983.

Use of Small Crack Data to Bring About and Quantify Improvements to Aircraft Structural Integrity

by
J. M. Potter
Aerospace Engineer
Air Force Wright Aeronautical Laboratories(FIBE)
Wright-Patterson Air Force Base
Dayton, Ohio 45433 USA
and
B. G. W. Yee
Chief, Materials Research Laboratory
General Dynamics Corporation
P.O. Box 748
Fort Worth, Texas 76101 USA

SUMMARY

Crack growth information has been used in many ways to quantitatively evaluate and predict damage tolerance and slow crack growth life limits of structures. Recent advances in the area of crack growth at small crack sizes (less than one millimeter) has enabled increasingly quantitative studies into the specific mechanisms that affect initiation and growth at structural details. As an example, through the use of small crack data the USAF/General Dynamics study on "Fastener Hole Quality" was able to identify a manufacturing-related problem causing short structural lives, propose a modification to shop equipment, and quickly and specifically evaluate the resultant flaw growth improvement. This change to shop equipment has been subsequently adopted by several other major airframe manufacturers.

The purpose of this paper is to describe the general procedures used in the derivation of small crack data and to present growth data for different structural manufacturing methods. The data will be presented in terms of equivalent initial flaw size populations, crack growth rate, and initiation life to a specific length for fractographically measured cracks within the range of .01 to 1 millimeter in length. Procedures will be discussed to utilize the small crack data for developing and verifying changes in fastener systems and manufacturing methods for improving the fatigue performance of aircraft structures.

1. INTRODUCTION

A major application of fracture mechanics is in the design and verification of a structure's safe life assuming pre-existing flaws at highly stressed locations. In fact, pre-existing flaw sizes are mandated in some industries to insure safety and reliability, and to establish liability. For damage tolerance purposes, flaw sizes for initial damage assumptions are on the order of 1000 microns (0.04 inch). In damage tolerance, a relatively few locations in a structure are designed for a full service life with the presumption of this size initial flaw. Study of the behavior of the smaller crack sizes has not been emphasized but with the maturation of the damage tolerance discipline, the subject of durability and reliability has become of greater significance.

In structural durability and reliability, the study of crack growth at small sizes (10 to 1000 microns) is of primary importance since this level of cracking defines the structural life prior to generalized cracking problems (where the number of structural flaws is too great for economical repair). In order to define the onset of generalized cracking it is important to know the crack growth behavior of the flaw geometries of interest and a measure of the initial flaw sizes and their statistical variations.

For many structures, fastener holes serve as the major location of generalized cracking. These fastener holes provide a complex stress field that makes analysis difficult at crack lengths of 10 to 1000 microns. Because of this difficulty and the problems with obtaining crack growth at small flaws, there is virtually no data on crack growth in this regime.

A significant set of data on small cracks recently became available from the study of initial quality in fastener holes by Noronha, Henslee, Gordon, Wolanski, and Yee (ref.1). The data set contained statistically significant numbers of specimens with detailed fractographic crack length measurements. The crack length measurements generally range upward from ten microns (0.0004 inches) relative to the bore of a fastener hole. The purpose of the reference study was to characterize the quality of production fastener holes in terms of the equivalent initial flaw size. Fractographic crack length data and design flaw growth analysis were combined to determine an equivalent initial flaw size level and compare data from different hole preparation methods. This study produced excellent fracture-design-level data on hole quality, but did not address the reliability and definition of the measured crack growth data.

The purpose of this specialist's paper is to present the fractographic crack growth data obtained in reference 1 to better define crack growth behavior in the small crack regions and to discuss its application to the general improvement of structural integrity. While many individual observations and uses can be made with this data in parallel with the classical application of fracture mechanics, this will not be accomplished in this paper. The goal of this paper is to discuss the larger aspects of the unique definition (or resolution) of small crack data and its application to bringing about and quantifying significant improvements to the structural integrity. To accomplish this purpose, the fractographic data from a set of specimens made with conventional hole preparation methods were analyzed, first to evaluate repeatability, and then to define the actual behavior of flaws in the short crack length regimes. To do this, the fractographic crack length data were plotted to define the growth behavior. Following this comparison, the specific flaw origins in each specimen were identified, and means to eliminate the initial damage were proposed. The success of fatigue tests from another set of specimens where the initial damage was eliminated was verified through small crack techniques.

This specialist's paper is written as three separate chapters covering small crack measurements, interpretation of the measurements, and the applications of small crack data to structural integrity. The Rudd, Yang, Manning, and Yee(ref 2) paper in these proceedings is a companion paper which will further investigate the ref 1. and other data using a classical application of fracture mechanics to develop a durability based design methodology.

2. CHAPTER 1 -- SMALL CRACK MEASUREMENT

2.1 Introduction-Measurements

The majority of the reported studies of crack growth in the small crack regime have involved measurement of surface cracks by either direct observation or replication techniques(refs. 4 to 9). These approaches lead to significant information relating to crack growth in surface cracks. A more common situation in structural applications is the crack at fastener holes or other structural stress concentrations. These structural crack geometries often preclude the use of direct observation or periodic replication since a fastener is normally placed in its hole for the duration of life testing. Complicating the problem is the observation that many of the hole fastener cracks are embedded within the bore of the hole (ref. 10). This characteristic alone ensures that surface crack measurement of the data of interest (.1 to 1.0 mm) will not be possible since the head of virtually any fastener will cover this size crack. Thus, only means of measuring growth of embedded cracks are applicable in this regime. The available means are thus confined to either NDI/NDE during test or fractography following test completion. Unfortunately, NDE/NDI thresholds of detection are much larger than the size of fastener flaws of interest herein leaving only fractography as a means of measuring crack growth of small cracks at fastener holes.

The US Air Force completed a study in 1978 of equivalent initial flaw sizes at fastener holes. This program obtained large amounts of fractographic data on the growth of naturally occurring cracks in fastener holes for the purpose of comparing different methods of hole preparation. The data were obtained and documented (ref. 1,3) but not specifically presented as small crack data even though there were over 600 fastener cracks tracked to sizes of typically less than .05 mm. Therefore, this body of information will be presented and utilized here to demonstrate the type of data obtainable and to describe the potential application for the data.

2.2 Test and Analysis Procedure

Figure 1 shows the design of the 7475-T7651 aluminum alloy specimens used in the study. This specimen is similar to that used in the AGARD Critically Loaded Holes Program(ref. 11). The hole preparation equipment used was that specified for high quality production holes identified as fracture critical. None of the fastener holes were preflawed, or otherwise marked intentionally, during hole preparation and fastener installation; each was treated as a production fastener hole. Following hole preparation, each hole was inspected and a NAS-6204-7 straight shank, protruding head fastener was installed and tightened to 60 inch-pound torque in accordance with factory specifications. The fasteners had a maximum diameter of 0.250 inches. The specimens were fatigue tested to two lifetimes (16,000 design usage flight hours) of projected tactical fighter lower wing skin usage. The maximum gross section stress in the load history was 34 Ksi (235 MPa). Specimens that survived the 16,000 hour testing were broken apart. The load spectra applied was a blocked flight-by-flight history that was identically repeated every 400 equivalent flight hours. The exceedance curve is shown in Figure 2.

Following the completion of testing, the specimen failure surfaces were examined with a low power (10-30X) light microscope. In the case of these two piece specimens, each with two fastener holes, there were a maximum of eight possible failure surfaces to investigate. That is, two surfaces at each side of each hole multiplied by two holes in each plate and two plates. The microscopist was instructed to make observations of each potential failure surface but to fractographically follow and report only the flaw that grew to be the largest for each specimen. As a result, the data reported herein are relatively conservative in that they are from the fastest growing of eight possible failure sites in the fastened joint.

The test conditions dictated that the last fractographic striations correlated with a known failure block or with two lifetimes, thus giving a distinctive end point. The repeated markings associated with the 400 hour block spectra then allowed the microscopist to follow, or backtrack, the crack positions to the vicinity of their origin.

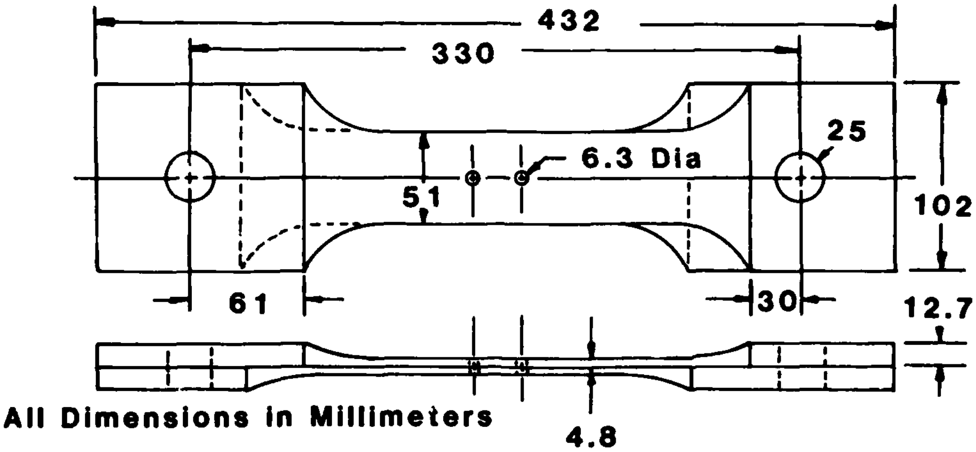

Fig. 1 TEST SPECIMEN GEOMETRY

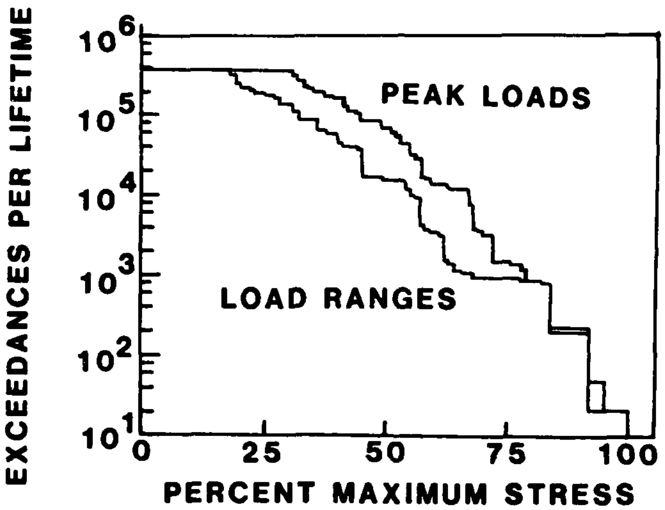

Fig. 2 LOAD HISTORY EXCEEDANCE PLOT

2.3 Results and Discussion-Measurements

Typical crack length measurements are shown in Figure 3 for specimen XWPF - 22. As seen from the data presented in the figure, it is possible to measure crack length to very small sizes with fractography provided that the load spectrum marked the surface distinctively.

Figure 4 shows the fractographic crack growth data from all 37 XWPF series specimens. This figure is made from 1204 individual fractographically derived crack length measurements. The XWPF series were low load transfer specimens. "W" stands for the Winslow Spacematic semi-automatic drill, "P" for proper drill speeds, feeds, and coolant, and "F" for fighter load history. This figure also indicates that all of the specimens could be read to small crack sizes using the fractographic approach. The data indicate a satisfying consistency; the crack length measurements appear to be parallel to each other. Primarily, this indicates that the crack behavior was uniform and that the fractography was accomplished correctly. If the fractography had been done inconsistently the data would have shown discontinuities with many curves crossing over each other. The crack lengths from Fig. 4 appear to be continuous and parallel without unusual behavior. Note that most specimens were fractographically tracked to cracks smaller than 0.05mm (0.002 inches).

Figure 5 shows the crack growth rate data determined by applying a seven point incremental polynomial method (ref. 12 and ASTM Standard E-647) to the data of Fig. 4. This figure contains 943 individual crack growth rate calculations. These data are plotted as a function of crack length rather than stress intensity factor since there is

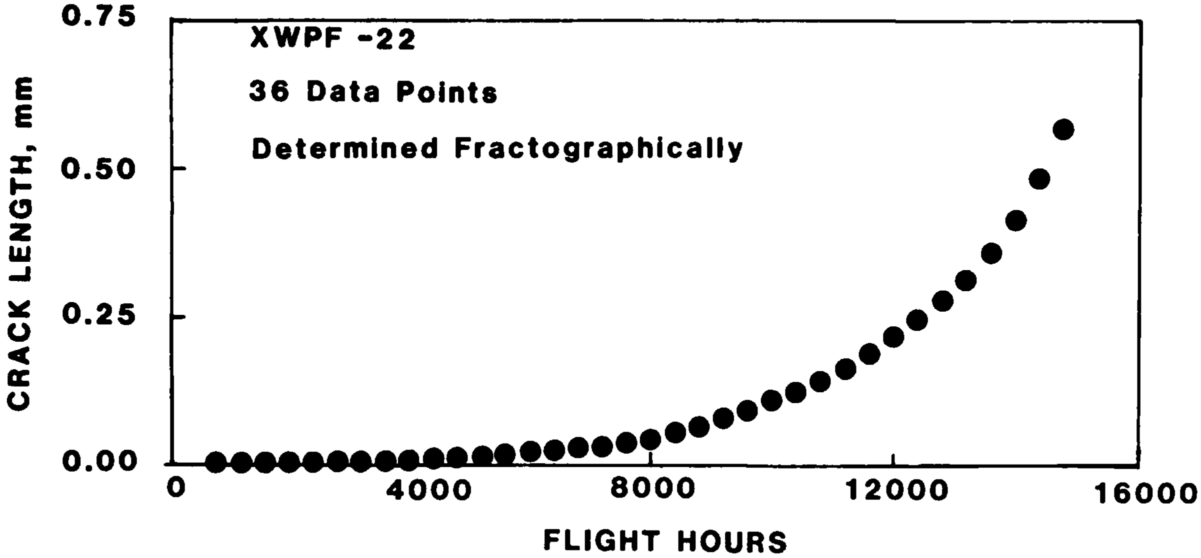

Fig. 3 FRACTOGRAPHIC CRACK GROWTH DATA FOR A TYPICAL SPECIMEN (XWPF-22)

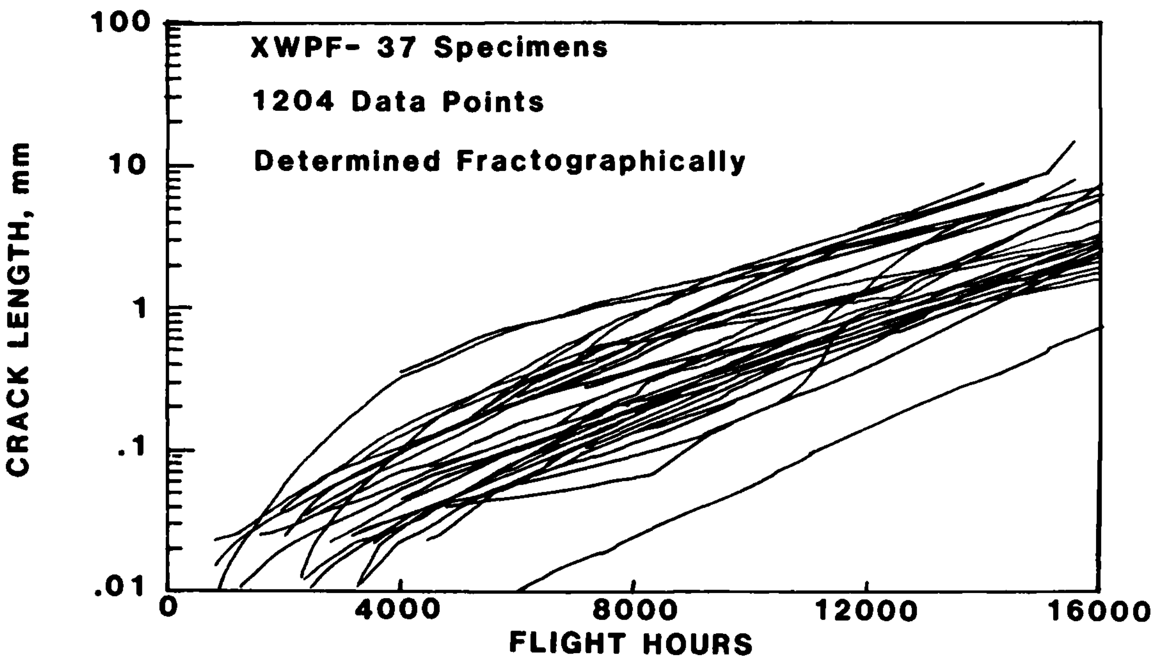

Fig. 4 FRACTOGRAPHIC CRACK GROWTH DATA FOR CONVENTIONAL QUALITY SPECIMENS

no generally recognized stress intensity solution for crack lengths of this small magnitude at a fastener hole. Again, the data show a well defined set of crack growth rate measurements which indicate that the growth process is continuous and repeatable.

Figure 6 shows the mean and one standard deviation for the crack growth rate data plotted as a function of crack length. The data has a standard deviation which averages 32% of the mean value. This variation in crack growth rate is consistent with that of the very careful surface crack measurements by Virkler, Hillberry, and Goel (ref. 13).

With the consistency in crack growth rate shown here it is possible to quantitatively identify the initiation life for these specimens. For instance, if the initiation crack sizes were assumed to be 0.2 mm(0.008 inches) then the initiation life from the XWPF data (Fig. 4) would be seen to vary from 3000 to 13,000 flight hours. This initiation crack size is significantly smaller than any the primary author has ever seen published. While other initiation flaw sizes can be used to determine a range of scatter in initiation life, the significance of this figure is that specific time-to-crack-initiation populations can be easily derived from this data because of the large number of measurements and the consistency of the crack growth data.

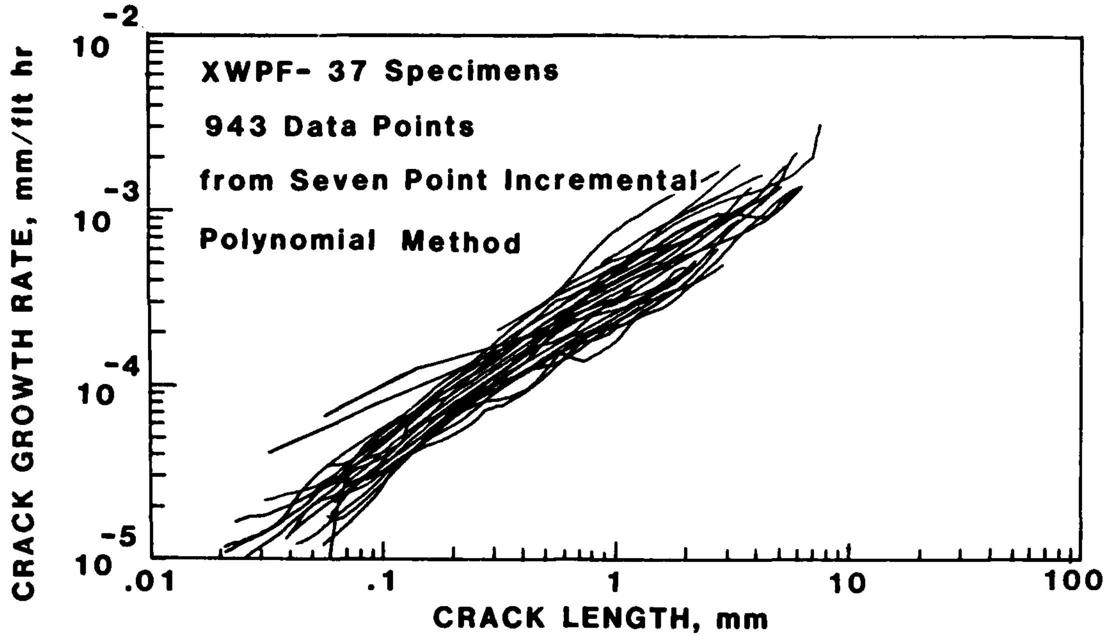

Fig. 5 CRACK GROWTH RATE DATA FOR CONVENTIONAL QUALITY SPECIMENS

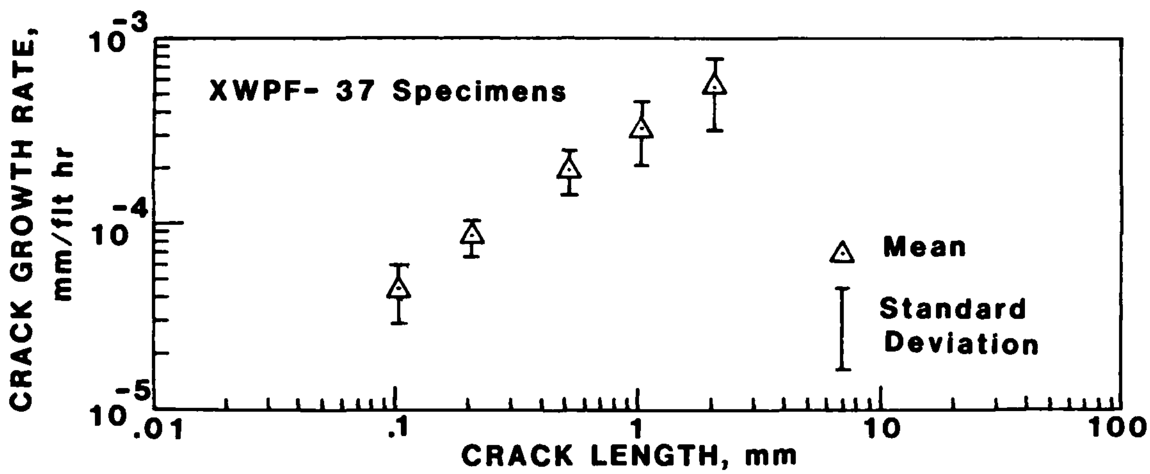

Fig. 6 MEAN AND ONE STANDARD DEVIATION OF CRACK GROWTH RATE

Many other comparisons can be made which are beyond the scope of this Chapter. The significance of this data is that information can be obtained on structures provided that the conditions are enhanced for fractographic examination. In the case of the tactical fighter load spectrum used herein, the history itself marked distinctively without changes to its content. Of primary importance is the repeated nature of the history which provided a clear pattern to the fractographic microscopist allowing him to track growth features to within 0.005 mm. The quantification of this approach made it possible to directly compare small crack growth data for different drilling techniques and quickly determine stress level and spectrum variation effects(ref. 1, 14, 15, 16, and 17).

As an added benefit, this approach saves considerable expense in testing and prospectively can save analysis costs as well. With reliance on fractographic data, there is no need for periodic crack length monitoring during the test. Thus, testing can go on unattended except for removal and replacement of broken specimens. After development of familiarity with the load spectrum marking patterns, the microscopist can fully track the flaw growth to its initiation in less than one hour per specimen. As a benchmark, the total cost of planning, manufacturing, testing, analyzing, fractographically back-tracking, and documenting the ref. 1 data was under $300. (US) per specimen. This value is extraordinary considering that each 16,000 flight hour specimen was subjected to over 750,000 cycles of load.

2.4 Summary-Measurements

The results of this study indicate that consistent and significant crack growth data can be obtained simply and inexpensively in the small crack regime. The type of fastener hole growth data obtained was possible by the application of a load spectrum that distinctively marked the front of the surface. This allowed detailed fractography to be accomplished to crack sizes of less than .1 mm in length. With the detailed crack growth data, it was possible to determine crack growth rates and time to crack initiation, as well as providing the ability to estimate the significance of initiation versus crack growth life.

3. CHAPTER 2 -- INTERPRETATION AND ANALYSIS OF SMALL CRACK MEASUREMENTS

3.1 Introduction-Interpretations

One feature often missing in the field of structural integrity is quantitative flaw growth data significant to the structure. Structural analysts need data of sufficient volume and accuracy to make definitive statements of the safety and reliability of their structures. Currently, safety and durability criteria are designed into USAF structures by utilizing conservative initial flaw assumptions (MIL-A-83444, ref. 18). As an example, damage tolerance initial flaw sizes of 1.25 mm are required at fasteners for design. Initial flaws of 0.125 mm in size must be assumed at every fastener hole for the purpose of durability or economic life. The military specification is written such that these durability initial flaw size assumptions can be reduced or made less conservative if data become available indicating that smaller sizes are appropria for a given structure, manufacturing process, or configuration.

Small crack data, if it can be obtained copiously and inexpensively, can ..ve to define the actual initial flaw size population of a given structure. With th efinition of structural small cracks as shown in Chapter 1, further analyses can accomplished that will answer many questions associated with materials, structural ura-tion, manufacturing technology, and their effect on the durability.

The purpose of this chapter is to expand on the interpretations possible with the small crack data obtained in chapter 1. To be discussed are small crack populations, initial flaw size representations, populations of flaw sizes as a function of usage or life, and time to a given initial size crack.

3.2 Small Cracks and the Flaw Size Population

Figure 4 shows a large amount of data on continuously growing cracks. These cracks were fractographically traced back as far as optically possible. The fractographic data procedure used provided 1204 crack length measurements from the 37 specimens of the XWPF test series. Given this amount of data, it is possible to construct cumulative probability distributions which represent the flaw size population at any given time in the projected usage of a structure.

Figure 7 shows the flaw size data of Fig. 4 plotted as a function of cumulative probability at the 4000, 8000, 12000, and 16000 flight hour intervals. These data reflect the actually measured flaw population of these test samples at different times during the life of a structure. Other population representations are possible because of the quantification possible in the small crack data. The mean as well as plus and minus one standard deviation in flaw growth behavior are plotted as a function of flight hours in fig. 8. These data show a flaw population that increases monotonically with a slope of approximately 1.5 decades of flaw size per each 8000 flight hours (one design lifetime) of usage. This power law relation indicates that these XWPF flaws increase by a factor of 30 for each design lifetime of usage. This data can have many uses including design and extrapolation to long term reliability. Rudd, et. al., present the statistical aspects of small crack data in a separate paper (Ref. 2) given in this document.

3.3 Small Cracks and the Initiation Life

In the last section, the small crack data from fig. 4 were examined to determine the flaw size population at a given usage period. This was done by making a vertical slice through the crack size data at a given number of flight hours. If, instead, a horizontal slice were taken at a given crack size, it would produce the population of the flight hours to reach that crack size; a sort of a time-to-crack-size or crack-initiation population. Figure 9 shows the mean time to crack size populations for the XWPF data for the crack sizes of 0.25, 0.5, 1.0 and 2.0mm length.

These data have tremendous potential for making quantitative comparisons of different structures, materials, and manufacturing methods on the basis of the amount of usage necessary to grow a crack to a given size. For instance, it may be of interest to quantitatively know the latest time when a structure may be subjected to an inspection allowing a clean-up size drill to remove a defined flaw. In the USA, cleanup drills are conveniently available at 1/64 th inch intervals. Therefore, it may be of interest to know when a one, two, or three 64 th oversize drill will be expected to clean up any crack. A one 64 th inch oversize would remove 0.008 inch or 0.2 mm of hole wall during a clean-up. Figure 9 could be used to determine the limit of the time to expect success with a given drill size. The companion paper by Rudd, et. al., will also discuss the subject of time-to-crack-initiation in greater detail.

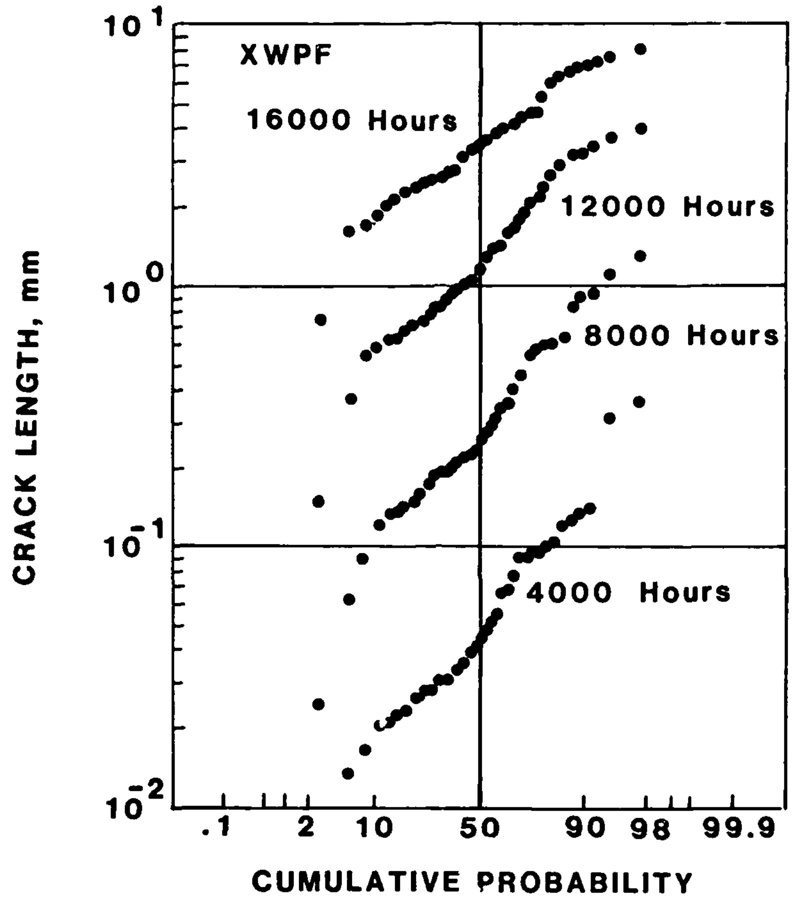

Fig. 7 FLAW SIZE DISTRIBUTIONS

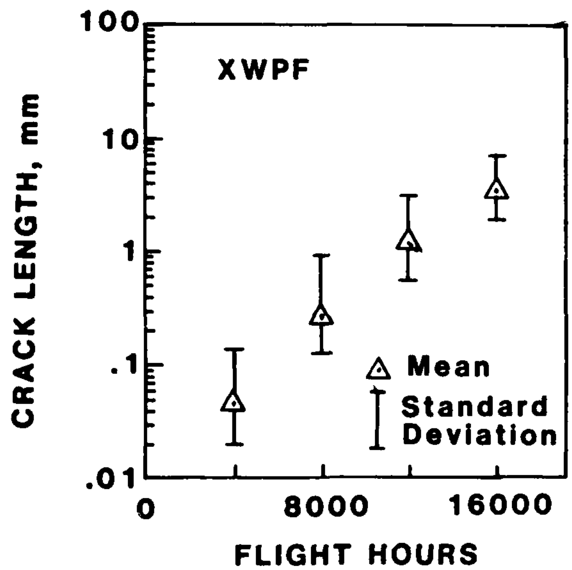

Fig. 8 MEAN AND ONE STANDARD DEVIATION OF CRACK LENGTH AT A GIVEN USAGE

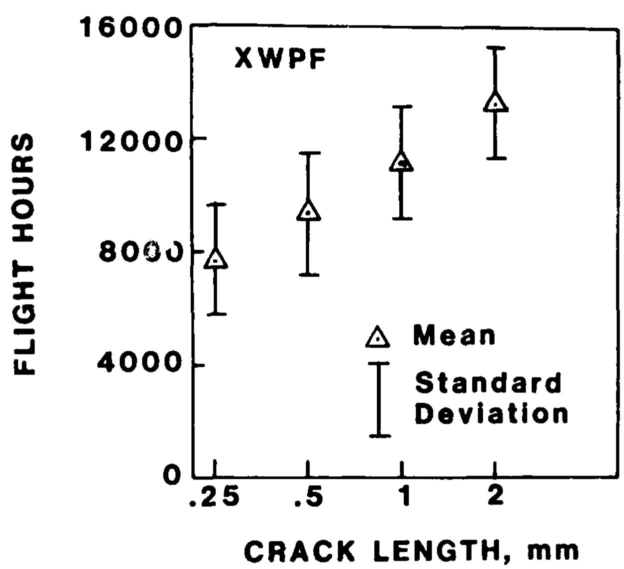

Fig. 9 MEAN AND ONE STANDARD DEVIATION OF FLIGHT HOURS TO REACH A CERTAIN SIZE CRACK

3.4 Small Cracks and the Equivalent Initial Flaw Size

The data from fig. 4 do not allow for a direct determination of the actual initial flaw size since the fractographic data do not extend to the actual origin. The concept of an equivalent initial flaw size can be utilized to extrapolate from the existing data to the apparent flaw which would be of the appropriate size to cause the observed cracking. The Equivalent Initial Flaw Size (EIFS) is a function of both the flaw growth analysis method and the data obtained. For purposes of this paper, the EIFS is used as *a simple representation of the quality of these fastened joints.*

The data from fig. 4 indicate a simple exponential relationship between fastener flaw depth and the usage (flight hours) for flaw sizes larger than 0.1 mm. Also, the data from fig. 5 indicate a simple power law (exponential) relationship exists between crack growth rate and the crack length for these specimens. In order to extrapolate to the apparent initial flaw, it is reasonable to extend the fig. 4 data to the zero-flight-hours axis using a continuous, power law function. This extrapolation must be consistant with the requirements of the design analysis in order for the EIFS flaw to accurately project to the observed flaw growth. In order to assure this consistency, the average growth rate data from fig. 5 were combined with a flaw growth integration methodology to determine an analytical "master curve" of crack growth from an extremely small crack size. This master curve was then "placed over" the data of fig. 4 and "best fit" using a computer program to provide an unique EIFS for each individual specimen. The "best fit" criterion was based on the desire to determine an EIFS which would most accurately depict the flaw sizes below "clean-up" sizes (less than 1 mm); that is, the EIFS approach was chosen to assure a representation which would most accurately describe the amount of usage to equate to the clean-up crack size.

The resultant EIFS population is shown in fig. 10. These data indicate that the 90 percentile EIFS for the XWPF specimens is approximately 0.02 mm (0.0008 inches). Obviously, higher reliability percentiles will result in larger EIFS values. The significance of this figure is that it is possible to quantitatively represent the apparent "quality" of a set of specimens. Other, *more complicated representations can* be possible by varying the assumptions for the best-fit criteria. As examples, Rudd, et al.(ref. 2), Manning, et al. (ref. 15), Shinozouka (ref. 16), and Yang (ref. 17) have labored to provide generic EIFS interpretations of this same data for the purpose of durability design.

The EIFS values determined from the XWPF specimens are very much smaller than those specified in Mil-A-83444 for durability design considerations. It may be possible for a fracture analyst to utilize these smaller demonstrated initial flaw sizes to justify a less conservative design while retaining safety and durability instead of accepting a specified initial flaw size.

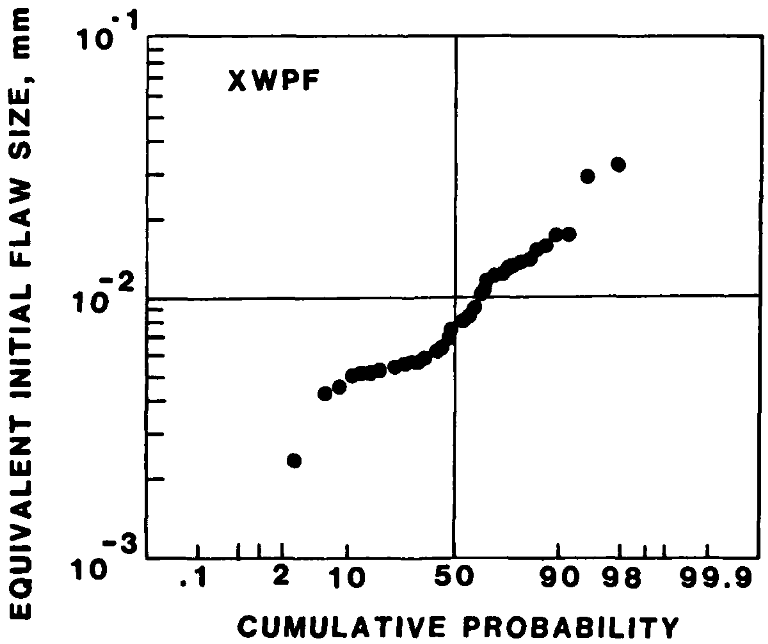

Fig. 10 EQUIVALENT INITIAL FLAW SIZE POPULATION

3.5 Small Cracks and the "Short Crack Effect"

A "short crack effect" has been identified by Pearson(ref. 5), and el Haddad, Smith, and Topper(ref. 6) and discussed by Hudak(ref. 7) and Ritchie and Suresh(ref. 19) and others(see Compilation of short crack reports, ref. 9). The short crack effect has been observed in some specimens as either a faster than "normal" flaw growth rate at small crack sizes or by an initially fast growth rate at small crack sizes followed by a transitional slowdown and a return to some steady-state condition at larger flaw sizes. Many mechanisms have been hypothesized to explain this data since, if it is consistently present, this would constitute a considerable problem for the fracture mechanics analyst.

The data obtained for test series XWPF, as shown in fig. 4 and 5, indicate no effect of short cracks in spite of meeting all of the criteria discussed by Ritchie and Suresh(ref. 19). These data exhibit a smooth, continuous, monotonically increasing flaw growth rate for all specimens. The reason that the Noronha, et al.(ref. 1 and 3) data did not show a short crack effect is not known. One possible difference between the specimens with short crack effects and those of fig. 4 and 5 are the means of initiating the cracks; those of Noronha, et al., were naturally occurring cracks whereas the specimens with the short crack effect had been preflawed. It may be possible that the preflaw procedure was responsible of the "short crack" effect.

3.6 Summary-Interpretations

The fractographic techniques utilized produced an average of thirty-two (32) crack length measurements for each specimen. These data on the large number of specimens of test series XWPF lead to the generation of statistically significant data for defining the flaw size population at any given usage, time-to-a-given-crack size, and equivalent initial flaw sizes.

This data indicates that the flaw size is seen to increase in accordance with a power law relationship fully in accordance with engineering fracture mechanics analyses practices. No "short crack effect" was apparent in any of the specimens.

For these stress-and-load spectrum conditions, the flaws were seen to increase by a factor of 30 for each design service lifetime. The equivalent initial flaw size for the XWPF test series was shown to be .008mm (0.00032 inches) which is much shorter than that specified in the military standards for durability.

4. CHAPTER 3 -- APPLICATIONS OF SMALL CRACK DATA TO IMPROVING STRUCTURAL INTEGRITY

4.1 Introduction-Improvements to Structural Integrity

Fracture Mechanics has evolved over the past 30 years to a stage where it is primarily used to evaluate a structure's capability to withstand projected usage. Since a given damage tolerance flaw size must be assumed, the fracture analyst has become a checking station during design. In durability design, the opportunity exists for the fracture analyst to provide an active input to the design process. The durability design process allows for a variation in the initial flaw size by demonstration. This provides the cognizant analyst an opportunity to apply his skills in observation to define and verify mechanisms leading to poor structural performance, hypothesize changes to eliminate these mechanisms, and later specifically determine if improvements have The analyst must be able to specifically and quantitatively define the original condition and any resultant change in structural integrity in order to be able to play this active role in design and manufacturing.

The purpose of this chapter is to discuss the application of data obtained in small crack investigations to the enhancement of structural integrity. Discussed are determination and verification of means to improve the structural integrity for the structure of interest, and extrapolation to long term life cycle costs and maintenence costs.

4.2 Determination of a Source of Early Life Failures

The data presented in Chapters 1 and 2 serve to definitively and quantitatively describe the flaw growth behavior of the XWPF test series specimens. In order to improve on the durability of a similar structure, we must determine where there are problems and try to eliminate these deficiencies. A review of the data of ref. 3 from XWPF specimens revealed that 28 of 37 specimens had failure origins at the hole surfaces with frequent references to scratches as the source. A detailed microscopic evaluation of these specimens revealed that the initiation sites were, in actuality, small axial scratches in the bore of the hole. The significant scratches found in the fastener holes were of a size on the order of 25 microns in depth making them difficult or impossible to detect by manufacturing inspection or by the unaided eye. Because of the existance of these scratches, the metal removal processes were examined in detail.

High speed motion pictures were taken of the drill operation. These indicated that the drill bit had the tendency to stop rotation in the hole during retraction. The drill equipment is a complicated air-powered device. The air-powered rotating drill bit is driven into the workpiece by an integral air-operated piston. During the retraction cycle, the air supply is completely diverted from the motor, and directed to the retraction piston. In this case, it is hypothesized that friction between the drill and the hole was sufficient to stop the drill bit from rotating during retraction. Further, it was hypothesized that the retraction of the stopped drill bit was responsible for the scratches which coincided with shorter fatigue lives.

4.3 Hypothesis and Verification of a Solution

Since it appeared that the damaging scratches were caused by the problem in the retraction phase, positive steps were taken to modify the drill motor such that the bit rotated continuously during retraction. The air logic port system of the drill motor was changed to insure that the drill bit rotated continuously during retraction. Secondly, the extraction rate was reduced making the bit turn many times during the retraction phase. An additional 30 specimens were manufactured using the drill equipment with this trial modification to the retraction mechanism. These specimens were designated as series YWPF and are referred to as "Improved Drilling" specimens. The 30 YWPF specimens were subjected to fatigue testing and analysis just as in the XWPF series. The result of these tests was an improvement in the number of initiation origins at the hole surface as postulated; for the XWPF series, 28 of 37 had started at the hole but only 5 of 30 started there for the YWPF series. The mean flaw size at 16,000 flight hours was reduced marginally from 3.4 to 3.1 mm as a result of these modifications.

The flaw growth data for this test series is shown in Figure 11. The data of fig. 11 appears to be consistent with that of fig. 4 except that there are more specimens with longer initiation lives. A comparison of crack growth rates for the XWPF and YWPF specimen sets is shown in fig. 12. These data indicate that the growth rates did not change significantly, though there was the change in initiation site. The YWPF data also, does not support a "short crack effect" observation. The data indicate that, even though the improved drilling has resulted in fewer flaw origins at the hole, the final flaw size populations are similar with little likely improvement in structural integrity. Thus, with little effort and in a short span of time, it has been possible to specifically determine that the failure initiation mechanism can be altered by a change in the drilling process.

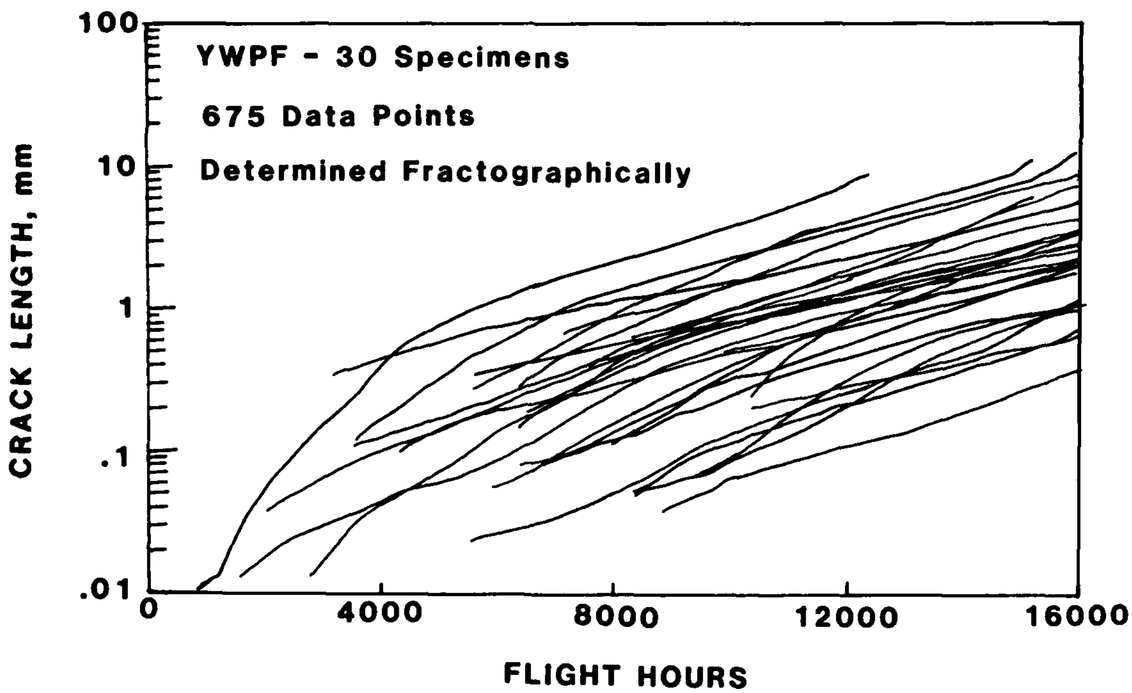

Fig. 11 FRACTOGRAPHIC CRACK GROWTH DATA FOR IMPROVED DRILLING SPECIMENS

4.4 Refinement of the Observations

The bolt hole initiation failure mechanism had been reduced in significance by the changes to the drilling equipment. Because the new dominant failure mechanism had shifted to the faying surface, a decision was made to change the specimen manufacture to reduce faying surface contact in the area of the fastener. This modification was referred to as "Improved Drilling and Assembly." A test series designated as VWPF was developed which consisted of 36 specimens. Fastener holes for each specimen were made using the improved Winslow drill and, in addition, the faying surface was spot-faced to approximately 0.005 inches in depth by 0.5 inches in diameter. The theory behind the spot-facing procedure was that it would alleviate bearing forces and thereby reduce the tendency to fretting.

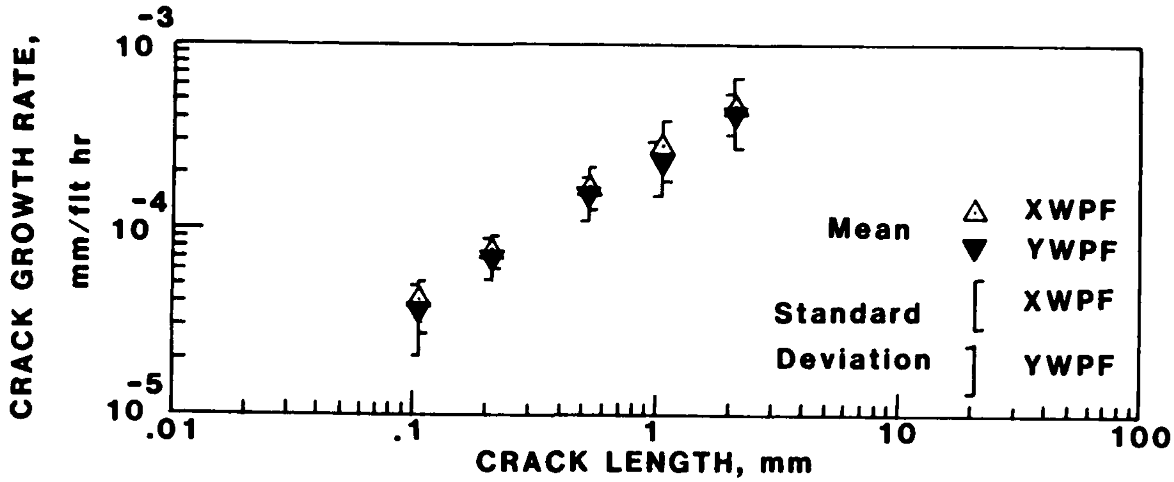

Fig. 12 COMPARISON OF CRACK GROWTH RATES FOR CONVENTIONAL AND IMPROVED DRILLING SPECIMENS

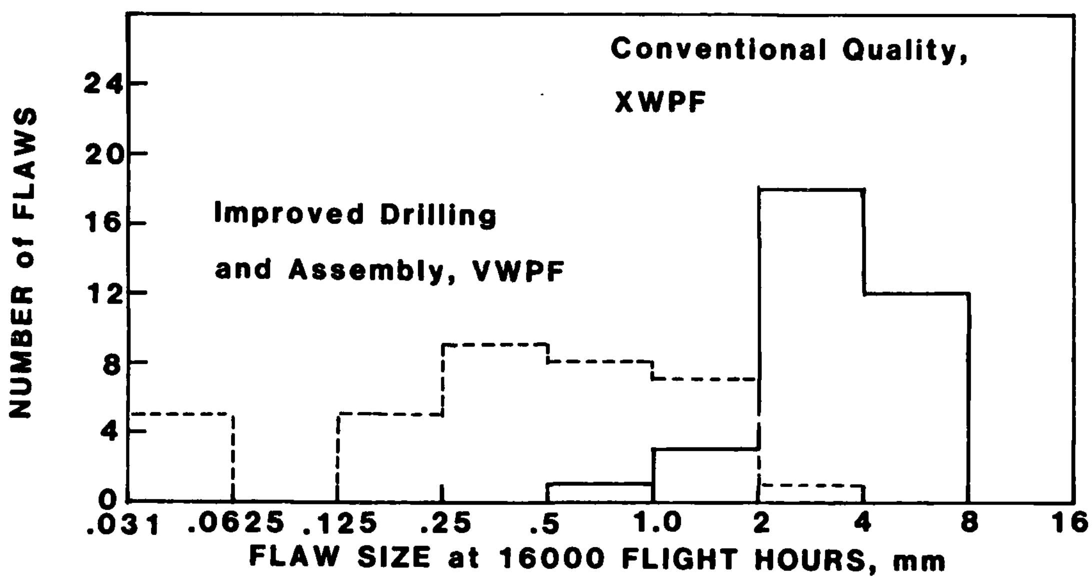

Fig. 13 COMPARISON OF FINAL FLAW SIZES FOR CONVENTIONAL AND IMPROVED DRILLING AND ASSEMBLY SPECIMENS

4.5 Extrapolation to Long Term Benefits

The improvements made to the "Improved Drilling and Assembly" test series (VWPF) compared to the conventional drilling (XWPF) shows almost an order of magnitude decrease in flaw size after 16,000 flight hours. In fig. 8, it was determined that approximately 8000 flight hours (or one design lifetime) was required in these specimens to give a factor of thirty (30) increase in flaw size. Extrapolating from fig. 8, it is possible to infer that the Improved Drilling and Assembly specimens would reach similar flaw populations as the XWPF series but at a usage of approximately 5000 flight hours. In the case of this typical fighter usage, it could mean that after 13,000 flight hours the Improved Drilling and Assembly airframe would have a flaw population equivalent to an 8000 flight hours vehicle manufactured with Conventional Quality. Alternatively, these trends could be viewed as saying that, for the same usage, the flaw population would be significantly reduced. The implications to the reduction in cost of repair due to structural cracking could be enormous. If the trends in these small cracks could be extended to actual aircraft structures, significant money could be saved through a reduction in the amount of repair necessary in a given system.

TABLE 1 -- Effect of Manufacturing Method Variations on Location of Flaw Origin and Flaw Sizes

	TEST SERIES		
	XWPF	YWPF	VWPF
Number of specimens	37	30	36
No. of initiation origins at the hole surface	28	5	n/a
No. of initiation origins at faying surface or corner	9	25	n/a
No. of specimens failing before 16,000 flight hours	5	2	0
50 Percentile flaw size at 16,000 flight hours	3.4 mm	3.1 mm	0.46 mm
No. of flaws exceeding 2 mm in length at 16,000 flight hours	33	21	1

4.6 Summary-Improvements to Structural Integrity

Small crack technology has been utilized to determine the specific flaw growth behavior of conventionally manufactured and assembled fastened structures. The information has been used to define procedures which could result in improvements to structural integrity of these coupons. Subsequent fatigue tests and small crack evaluation techniques indicated that the Improved Drilling and Assembly approach resulted in almost an order of magnitude reduction in the flaw population at equivalent usage.

The relative ease of defining the improvements is indicative of the power of the fractographic technology in providing quantitative information even in the most challenging small crack regime.

5.0 CONCLUSIONS

1. Small crack technology provides a uniquely definitive mechanism for determining the durability of actual structures. Only small crack technology can provide the crack propagation data necessary to define durability and structural integrity at structurally significant geometric details in the flaw size range of less than 1mm.

2. The crack growth rates for naturally occurring small flaws from fastener holes are exponentially related to the crack length.

3. No evidence was found to support a "short crack effect" for these naturally occurring cracks at fastener holes.

4. Small crack growth behavior as measured by fractography has a variation in crack growth rate that is consistent with that of conventional measurement techniques for much larger size flaws.

5. Details of the drill bit retraction process and interface surface preparation following hole manufacture appear to be responsible for variations in fatigue life; increased fatigue life was obtained when taking positive measures to assure continuous rotation during retraction and to reduce interfacial contact stresses at holes.

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FOREWORD

This report describes a co-authored effort accomplished in both the AFWAL Flight Dynamics Laboratory and General Dynamics' Material Research Laboratory in preparation for a presentation to the AGARD Structures and Materials Panel Specialists Meeting on "Behavior of Short Cracks in Airframe Components." This paper appears as a part of AGARD-CP-328 dated April 1983. The US Air Force contribution was accomplished under project 2401, "Structures and Dynamics," Task 240101, "Structural Integrity for Military Aerospace Vehicles," Work Unit 24010179, "Life Analyses and Design Methods for Aerospace Structure."

The work was performed for the Structural Integrity Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/FIBE), Wright-Patterson Air Force Base, Ohio.

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fastener holes in terms of the equivalent initial flaw size. Fractographic crack length data and design flaw growth analysis were combined to determine an equivalent initial flaw size level and compare data from different hole preparation methods. This study produced excellent fracture-design-level data on hole quality, but did not address the