Tracking Potential Crack Growth Damage in U.S. Air Force Aircraft

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This paper provides basic information on the two major U.S. Air Force aircraft force management activities: the Force Structural Maintenance (FSM) plan and the Individual Aircraft Tracking (IAT) program. Details are only presented, however, on requirements and concepts applicable to the IAT program activity. The control point tracking concept and the supporting methodology are presented to identify procedures that can be used to simplify the IAT program for tracking potential crack growth damage. The damage and life transfer functions that provide the basis for tracking crack growth damage at control points are generally applicable to most IAT programs. The paper focuses attention on crack growth gage as one device for monitoring damage in a more direct sense than the currently employed indirect measuring devices. The crack growth gage is shown to provide a single number that can be related to damage and, thus, life expended. A description is provided on how to relate an individual aircraft's control point crack growth behavior to the standard time frame associated with the defined mission usage.

I. Introduction

WHEN Coffin and Tiffany[1] discussed the current U.S. Air Force Aircraft Structural Integrity Program (ASIP) requirements,[2] they identified two major force management activities; the Force Structural Maintenance (FSM) plan and the Individual Aircraft Tracking (IAT) program. Section II of this paper briefly reviews the interrelationship of these activities and their basis under the current U.S. Air Force policy. In Sec. III, the reader will find background information on Individual Aircraft Tracking (IAT) programs and concepts, the U.S. Air Force requirements for an IAT program, and some interpretations of Air Force policy based on currently operating IAT programs. Sec. IV provides basic transfer functions that can be utilized when estimating 1) the potential crack growth behavior and 2) the remaining service life capacity of a structure, given monitored information at a structural control point. This section also introduces the concept of using a crack growth gage for directly monitoring fatigue crack growth information at a control point. The crack growth gage concept is highlighted for two reasons: 1) to present this simplified concept for monitoring structural crack-life related information and 2) to give examples for the suggested IAT program transfer functions. The last section summarizes the paper and adds concluding remarks.

II. Force Management Based on Crack Growth Damage

The current U.S. Air Force ASIP Force Management policy[1,2] is based on a desire to anticipate and control cracking problems throughout the service life of the airframe structure. There are two major force management activities designed to focus attention on each potential cracking problem. Fig. 1 provides a schematic which can be used to illustrate the interrelationship and crack growth damage basis for these two activities, the Force Structural Maintenance (FSM) plan and the Individual Aircraft Tracking (IAT) program. As noted in Fig. 1, a common source of information, identified in the left-hand block, supports both major force management activities. The supporting analysis activities are those developed to meet the damage tolerance and durability requirements identified in Refs. 2-5. In conjunction with the evaluation of design verification test data, these analysis activities define the crack size damage limits (a_o and a_f) for each potential cracking problem, and a critical (structural) parts list. The critical parts are categorized according to the definitions given in Table 1.[2,3]

Fig. 1 also shows that the damage limits (a_o and a_f), established for each critical area of the structure, are used in both the FSM plan and the IAT program. The upper damage limit (a_f) can be associated with either safety or functionally related problems, or with a limit established for repairing or modifying a structure at an economically opportune time. Reference 6 reviews a method that has been suggested for establishing the lower damage limit (a_o). This paper will use the damage limits as boundaries but will not define methods for establishing these damage limits. Referring again to the center of Fig. 1, note the behavior exhibited by the two damage-time curves. The set of upper and lower damage limits for both curves are the same; however, the time scales (the abscissae) for the two curves are normally different.

A. Force Structural Maintenance (FSM) Plan

The upper damage-time curve provides the time (life) estimate (t^*_{MU}) that is associated with achieving the specified damage limit and therefore provides a direct input to the FSM plan for each maintenance action, i.e., for each inspection, repair, modification, replacement, or retirement action. The abscissa, i.e. the time t_{MU}, for this upper curve is established in terms of U.S. Air Force defined mission usage and is herein referred to as the standard time. For example, the time t_{MU} may reflect accumulation of flight hours based on 1) the design (specified) mission usage, 2) the average (current) mission usage for the complete force of a given series aircraft or 3) the required service life/mission usage spectrum (specified by the U.S. Air Force).[7]

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Index categories: Structural Durability (including Fatigue and Fracture); Structural Design; Reliability, Maintainability, and Logistics Support.

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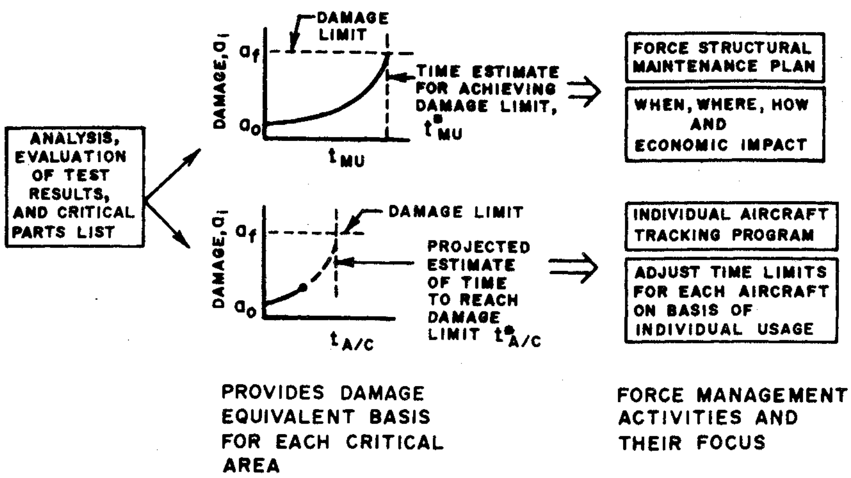

Fig. 1 The basis for the two major force management activities.

Table 1 Critical part definitions[2,3]

Identification title for critical part	Type of structure	Category I	Category II	Category III[b]
Fracture	Safety-of-flight[a]	Designed and sized by MIL-A-83444 requirements	Could be sized by MIL-A-83444 if fracture control procedures are not employed	Other structural criteria (e.g. buckling) control design
Durability	Expensive, uneconomical to replace	Designed and sized by MIL-A-8866B requirements	Could be sized by MIL-A-8866B if special control procedures are not employed	Other criteria control design

[a] Safety-of-flight: that structure whose failure could cause direct loss of the aircraft or whose failure, if it remained undetected, could result in loss of the aircraft.
[b] This category contains all parts not covered by Categories I and II.

The standard time t_{MU} may be changed several times during the life cycle of a given series of aircraft to reflect changes in usage patterns for the given force or to include a new mission usage requirement. An element of force management that supports the updating of the standard time, subsequent to the design phase, is the loads/environment spectra survey. Approximately 10 to 20% of the production airplane force is extensively instrumented for the purpose of measuring parameters that can be used to sense both mission usage and potential damage accumulation. Data reduced from these instrumented aircraft provide (in conjunction with the analysis activities) the means to update the standard time. Additional detail on this major force management activity can be found in the ASIP document[2] (Tasks IV and V) and the Coffin-Tiffany publication[1] on this policy.

B. Individual Aircraft Tracking (IAT)

The time scale ($t_{A/C}$) for the lower damage-time curve shown in Fig. 1 expresses the time that reflects how an individual aircraft accumulates flight time as a function of its missions. Note that this damage-time curve stops at a point associated with current usage and is projected to an estimated time ($t^*_{A/C}$) for achieving the upper damage limit (a_f). The damage that accumulates up to the present time can be equated to the damage on the upper diagram and then can be related to the standard time (t_{MU}).

The collection and analysis of individual aircraft damage accumulation data provides the ASIP force manager with the capability for budgetary planning and individual aircraft scheduling to meet inspection, modification, and retirement requirements identified by the Force Structural Maintenance (FSM) plan and for controlling force utilization in a theater of operations that is significantly damaging. The potential flaw growth will be keyed to damage limits established by damage tolerance and durability analysis methods to insure that the structural integrity requirements defined by Refs. 2–5 are met for each aircraft.

III. Individual Aircraft Tracking (IAT)

A. Historical Background

Individual aircraft tracking made its first appearance as an ASIP defined requirement in 1966 in conjunction with the parametric fatigue analysis (PFA) requirement.[8] The purpose of both requirements was to collectively monitor damage accumulation on each aircraft as a function of its actual operational usage and mission mix. It was suggested that the results of the IAT/PFA program would have a direct impact on "establishing and projecting modification schedules, performing life vs utilization trade studies, and assessing fatigue design and certification methods."[6] The first application of the IAT/PFA philosophy to a U.S. Air Force aircraft force, however, was conceived by the Boeing Airplane Co. in 1960 in order to solve B-52 structural wing problems resulting from Air Force redefined required service life/mission usage.[9,10]

The concept of tracking individual aircraft to monitor damage accrued due to different operational usage is not new; but normally IAT programs were only designed after the life-limiting crack damage facts became known. However, even then such programs can produce substantial cost benefits for the force manager—as demonstrated by the reported work on the B-58 bomber IAT/PFA program by Whitford and Dominic.[11] In fact, Whitford and Dominic provide a master plan that can be used even today for summarizing required force management actions.

B. Current Policy

The ASIP document[2] and the Coffin-Tiffany publication[1] provide the current U.S. Air Force IAT program policy and the basis for that policy, respectively. For the value of continuity, we will briefly review this policy. The objective of the present IAT program requirements is to predict 1) the potential flaw growth in critical areas of the airframe, 2) inspection times, and 3) repair times. The potential flaw growth in fracture critical areas (see Table 1) of the airframe shall be keyed to the damage growth limits of Ref. 3. The damage tolerance and durability analyses and associated test data will be used by the contractor to establish the IAT program analysis method. The IAT analysis method will be used to establish and adjust maintenance actions for each critical area of the airframe based on individual airplane usage data. The analysis will be required to predict crack growth rates, time to reach the crack size limits, and the crack length as a function of total flight time and usage data.

If a critical part (Table 1) can be removed from an aircraft (say, during a programmed depot level maintenance action) and be subsequently placed on another aircraft, then this particular component must have its own individual component tracking program according to the current ASIP document.[2] Serialization of major components (wings, landing gears, etc.) during production is now specified so that component tracking can be implemented by the Air Force.

Requirements have recently been identified in the ASIP document[2] and the ground test specification[5] for incorporating devices and instrumentation necessary for tracking crack growth damage in the flight loads test vehicle and in the static and durability test articles. These requirements have been added to the design verification test activities in order to thoroughly evaluate IAT concepts and devices before utilizing them in service.

In meeting the instrumentation and data recording system requirements for IAT programs, the contractor is asked to provide the simplest system possible and still supply those parameters necessary to support the analysis methods. Counting accelerometers, electrical or mechanical strain recorders, electrical resistance gages, simplified manual data forms, etc, shall be considered.

C. Some Interpretations

The methodology employed in design for evaluating the life limiting characteristics of the structure in terms of the U.S. Air Force defined mission usage (the standard) time-frame provides the basis for determining the potential flaw growth resulting from individual aircraft usage. The difference between the application of this methodology to establish the design service life and the individual aircraft life limits is normally one of degree. In IAT programs, simplification of the damage calculation schemes is accomplished whenever justified using, for example, linear transfer functions between recorded flight parameter data and the estimated damage growth increment. Also, force-wide averages are used whenever possible to characterize those parameters shown to have a minor effect on the damage accumulation rate.

Feasibility studies of concepts, instrumentation, and plans applicable to IAT programs should be initiated with other design and test verification studies as implied by the ASIP document.[2] These studies should enhance the probability that future IAT programs will have the required combination of accuracy, efficiency, and cost effectiveness for sensing crack growth damage accumulation. Future U.S. Air Force tracking programs will focus on developing inexpensive, accurate, and efficient methods and devices for measuring crack growth damage that depends on actual structural usage and can be expressed in terms of the standard time frame (see upper damage-time curve in Fig. 1).

1. Identifying IAT Locations

The IAT analysis methods must be applied to establish and adjust the maintenance action time intervals for each critical area of the airframe. But, to develop the efficiency and cost-effectiveness of an IAT program, special attention must be given to the criticality of the maintenance action identified in the FSM plan and to the accuracy required in estimating the time at which action must be taken. Some of the (FSM plan) maintenance actions are designed to prevent potential failures in safety of flight structure (as in Category I, see Table 1).

To quantify the accuracy required for life estimates at each critical location, there should be several IAT "accuracy required" categories. One type of IAT "accuracy required" category could be based on specified levels in the risk of failure, either due to loss of safety or to incurred costs, which result from missing the maintenance action by a given increment of time. Alternately, IAT accuracy critical categories could be developed by rank ordering critical areas as a function of having the highest potential for yielding the shortest aircraft service life if the appropriate maintenance action is not taken. The highest degree of accuracy in the IAT program would be achieved for the "most" critical areas, and instrumentation would record data that best sense how crack growth damage accumulates in these critical areas.

2. Control Point Concept

A control point is a structural location selected as the site for monitoring the expended service life of a specified critical area. The potential crack growth damage that reduces the structural life of this critical area is established by design and verification test results, and provides the damage limits (a_o and a_f, as shown in Fig. 1) for this control point. Estimates of the crack growth damage accumulation as a function of usage can be made in many different ways. Monitoring strain directly at a control point with onboard instrumentation (e.g. strain gages and strain range counters or magnetic tape recorders) and subsequent offboard data reduction to determine the damage increment has been one popular approach. Another approach popular to fighter airplanes has been monitoring of n_z, the center-of-gravity vertical-acceleration component, with onboard instrumentation (e.g. g meters or peak counters), followed by subsequent offboard conversion to stress at the control point and then calculation of the damage increment. Based on past experience, the important point is that whatever parameter is being monitored, it must be related to the types of crack damage that reduce the structural life.

In the F-4 force management program, the calculated crack growth damage behavior at a single control point located on the lower wing surface has been used to describe the usage at all critical areas in the structure.[12,13] In the A-7 force management program, the calculated crack growth damage behavior at three control points (one wing, two tail) is used to define life expended.[14] Both F-4 and A-7 IAT programs use counting accelerometers (n_z counts) to sense the operational usage of individual aircraft. Extensive analysis is necessary to translate IAT counting accelerometer information into the calculated increment of crack growth damage incurred at the control point as a result of operational usage. The number of critical areas that can be monitored using data generated at a single control point depends on: 1) the similarity of the types of crack growth damage limits associated with the various maintenance actions for different critical areas; 2) the capability for developing appropriate transfer functions that sense the effect of stress history and geometrical differences on the damage accumulation process in different critical areas that have been subjected to a mission usage similar to the design mission usage; and 3) the capability of defining the effect that dissimilar individual aircraft mission usage has on the relative rates of crack growth damage accumulation in different critical areas.

Application of a control point tracking procedure requires that crack growth behavior be monitored at certain structural locations in order to predict damage accumulation in all the critical areas of the structure. The "transfer functions" presented in the next section provide the opportunity for reducing the number of these aircraft control points to a minimum. The authors use the term "transfer functions" to define the collection of relationships that transfer crack growth damage/life information 1) between two locations in a structure or 2) from the individual aircraft control point to the ASIP force manager in terms of the standard time frame (see Fig. 1).

IV. Individual Aircraft Tracking Transfer Functions

A. Overview

The objective of this section is to indicate how crack growth knowledge determined for a given control point may be used 1) to estimate the behavior of flaws located elsewhere in the structure and 2) to characterize the remaining service life capability of the aircraft in terms of the standard time frame. This section identifies the methodology that is generally applicable for control point tracking concepts and presumes that control point tracking has already been selected to satisfy IAT program requirements. While the transfer functions presented are generally applicable to control point tracking concepts and are independent of the instrumentation employed, the focus here is on showing the simplicity by which crack growth gages directly monitor the control point's crack growth behavior.

Introducing an intentional flaw in a "gage" that can be mounted on an aircraft at a control point location provides a direct method for accessing crack growth damage and for determining rates of crack growth as a function of usage. This concept is schematically illustrated in Fig. 2. As discussed in Ref. 15, it is possible to relate the observed crack length (a_g) in the attached gage with extension of another defect (a_s) located elsewhere in the structure. Work conducted to date indicates that this relationship, shown schematically in Fig. 3, is relatively insensitive to stress history when both the gage and structural member experience the same loading. Thus, measured extension of the gage crack provides a direct estimate of the growth of another crack *assumed* to be located in the structural member. Calculation schemes can be developed to relate gage crack length (or control point crack length) to the crack growth behavior for any structural crack geometry of interest. One scheme has been discussed previously[15] and the overall scheme is outlined in a later subsection. The main use of Fig. 3 type curves would be to establish the level of damage accumulated at a given structural location; a curve of this same type could be constructed between the control point and each structurally critical area being monitored by the control point behavior.

Tracking crack growth damage in aircraft structures requires, however, more than knowledge of the damage transfer functions between structurally critical locations and specified control points. It is essential that one can relate the calculated crack growth damage at the structurally critical locations to the life expended (or remaining) at these locations. The life expended must be related to actions identified in the force structural maintenance plan. The next subsection describes a transfer function which meets these requirements.

B. Normalized Crack Growth Curves

The normalized crack growth (NCG) curve relates crack growth damage to life, independent of individual aircraft usage and possibly location.[16,17,12,13] There are two basic uses for NCG curves, such as shown in Fig. 4. The first (and foremost) use is to relate the crack growth damage (a real or hypothetical crack length) sensed at a structurally critical location as the direct result of individual aircraft usage to the standard time frame associated with the defined mission usage (see Fig. 1). In this context, a NCG curve will be defined for every critical point in an aircraft. The critical point NCG curve will be constructed so that it monitors the (life) rate at which structural damage accrues in the critical area of interest.

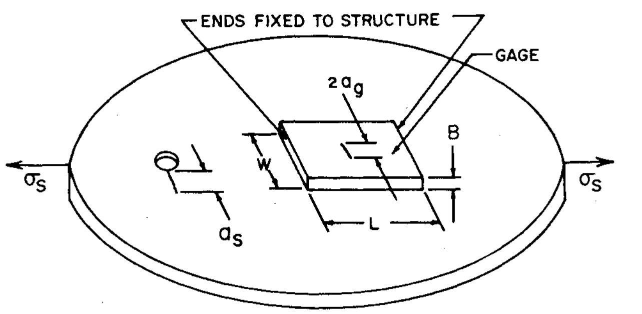

Fig. 2 Schematic view of crack growth gage attached to flawed structural component.

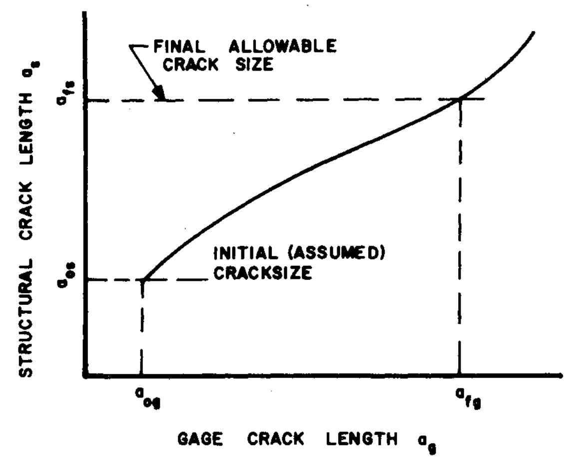

Fig. 3 Schematic representation of the relationship between the gage and structural flaw sizes; the damage transfer function between two locations.

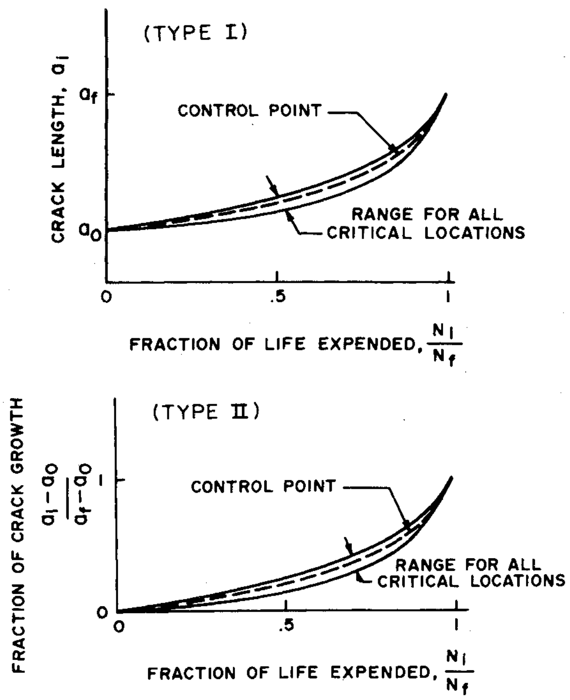

Fig. 4 The two types of normalized crack growth curves.

The second use of the NCG curves is associated with relating life expended at the control point to that at other critical locations in the structure.[13] In this context, if the maintenance action at every location in the structure has the same NCG curve controlling the scheduling for such actions, then a single control point NCG curve can be used to measure life expended for all critical areas. A single control point NCG curve can also be used when all the damage transfer curves are linear, i.e. when the control point crack is linearly related to every other critical location crack (see Fig. 3). Gallagher and Bader[16] showed that NCG curves will not normally be independent of crack geometry or location unless special precautions are taken. Therefore, it is not always possible to use the same NCG curve throughout the structure, making the combined use of Fig. 3 and Fig. 4 type curves necessary.

NCG curves, such as those described by Fig. 4 provide the capability for estimating crack growth life independent of usage, because the crack growth damage at the particular location is expressed in terms of cyclic life expended (N_i/N_f) and not in terms of any absolute time. If N_f is expressed in terms of the standard time (t_{MU}), (i.e. $N_f = t^*_{MU}$, see Fig. 1), then knowledge of the current crack length in the structure (i.e. $a_i = a_s$, current) defines the life expended (N_i) in terms of

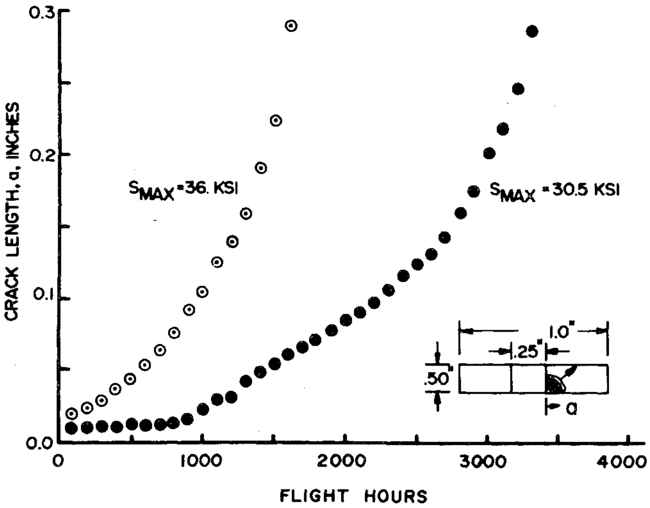

Fig. 5a Typical effects of stress on crack growth behavior. Experimental propagation behavior of corner crack with a low loads truncated F-4E/s spectrum.

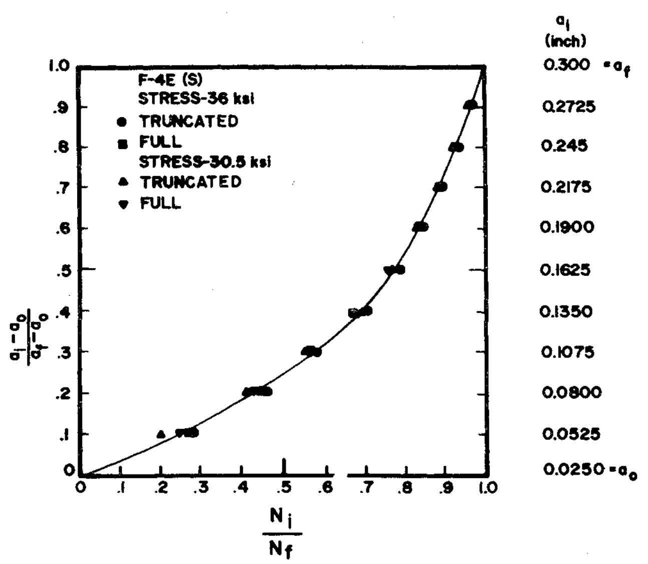

Fig. 5b Normalized crack growth curve; left ordinate is percent damage increment, right ordinate damage a_i. (The NCG curve derived from Fig. 5a and a similar figure based on different stress history.)

the standard time frame. Since Fig. 3 determines the structural crack size a_s from the measured gage crack length a_g, the ordinate parameter ($a_i = a_s$) in Fig. 4 is known, and the corresponding cyclic life expended (N_i/N_f) in the critical structural area is readily established.

As can be noted from Fig. 4, the abscissa for each normalized curve is the cyclic life expended in producing the damage, i.e., the ordinate. The type I NCG curve shown in Fig. 4 has an ordinate where the damage is measured by the current crack length a_i. The type II NCG curve has an ordinate where the damage is measured in terms of a crack increment ratio, i.e., amount of crack extension (current) to total expected. It is fairly simple to generate NCG curves directly from the normal crack growth life curve such as was accomplished in Ref. 16. Some data from Ref. 16 are repeated in Fig. 5 to demonstrate the procedure for formulating the NCG curve.

When experimental data are scarce, one can utilize crack growth-life estimating tools and establish NCG curves in the same way demonstrated by Fig. 5. The Appendix provides a methodology for generating the transfer functions being presented here. Utilizing the normal assumption that the stress histories associated with the control point location exhibit steady-state cracking behavior, the following simple procedure based on Eq. (A3) can be used. Form the ratio N_i/N_f by identifying it with

$$\frac{F_i}{F_f} = \int_{a_o}^{a_i} \frac{\mathrm{d}a}{f(K_{\max})} \Bigg/ \int_{a_o}^{a_f} \frac{\mathrm{d}a}{f(K_{\max})} \tag{1}$$

where the total crack interval (a_o, initial, to a_f, final) requires F_f flights to traverse and the intermediate crack interval (where $a_o \le a_i \le a_f$) requires F_i flights to traverse. The ratio $N_i/N_f (= F_i/F_f)$ is the abscissa and can be expressed as a function of the damage, i.e., either as a_i or as $(a_i - a_o) \div (a_f - a_o)$, depending on requirements.

C. Relating Crack Growth at Separate Locations

This subsection will show how Eq. (A3) given in the Appendix can be used to relate crack growth damage at two points in a given structure which experience the same flight history. Equation (A3) can be applied to both the control point and any other crack location under consideration. Since in a given aircraft, both locations will experience the same number of flights F, one obtains

$$F = F_{\text{control point}} = F_{\text{structure}} \tag{2}$$

which gives

$$\int_{a_{ocp}}^{a_{cp}} \frac{\mathrm{d}a}{f_{cp}(K_{\max|cp})} = \int_{a_{os}}^{a_s} \frac{\mathrm{d}a}{f_s(K_{\max|s})} \tag{3}$$

where the subscripts cp and s refer to the control point and structure location, respectively. As described in Ref. 15, it is possible to solve Eq. (3) numerically for a_s as a function of a_{cp}, yielding the results shown schematically in Fig. 3. In this figure, the gage crack a_g represents the control point crack a_{cp}. Calculations based on the integral equation form of Eq. (A1) are discussed in Ref. 15. A significant feature of those calculations was the result that, if the control point and the structural location have the same material properties, then the calculation for a_g as a function of a_{cp} is effectively independent of the stress history characterizing parameter $\bar{\sigma}$. This parameter implicit in Eqs. (1) and (3), is the maximum stress in fatigue history ($\sigma_{\max}$). If one chooses to use the crack growth law of Eq. (A2) for the computational scheme, a value must be assigned for $\bar{\sigma}$. Results examined to date indicate, however, that the a_s vs a_{cp} curves are relatively insensitive to $\bar{\sigma}$.

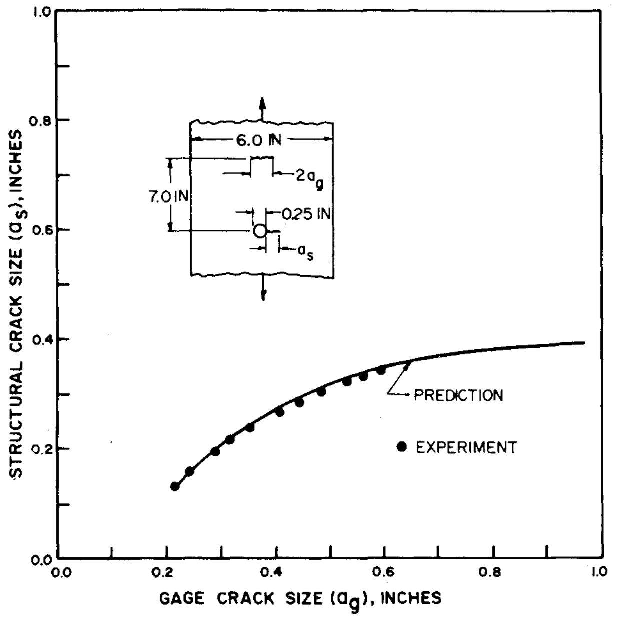

Fig. 6 **Comparison of experimental data with analytical prediction for the relationship between two different flaw geometries in the same specimen.**

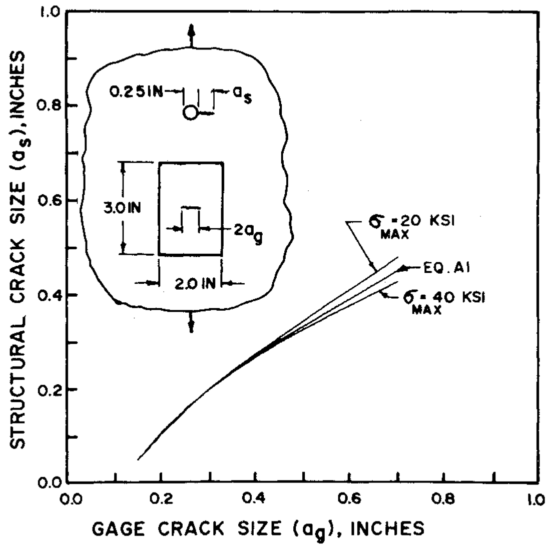

Fig. 7 **Analytical results showing the effect of Eqs. (A1) and (A2) in developing gage/structural crack relationships.**

An experimental justification for the calculation scheme just described may be obtained by considering the following example. A long tensile specimen which contained both a central through-the-thickness flaw and a radially cracked hole (as shown in Fig. 6) was tested to the variable amplitude loading described in Ref. 17. The objective here is to relate the growth of these two flaws by the analytically predicted crack growth relation given by Eq. (A2), which was established for the test material by the procedures discussed previously in Ref. 17. The value of $\bar{\sigma}$ which characterized the stress level during a given flight for the test described here was 36.1 ksi. The excellent agreement between prediction and experiment indicated in Fig. 6 provides encouraging verification for the proposed computational method for relating the growth between two different flaws subjected to similar loading. Additional work is underway to provide an indication of the limits of Eqs. (2) and (3) for nonsimilar loading.

D. Crack Growth Gage

We have described the crack growth gage approach in an earlier paper[15] and note that other researchers are working along related lines. A patent[18] was recently granted to H.W. Smith of the Boeing Company for the use of a bonded edge-cracked coupon as a device to monitor fatigue crack initiation type damage. Although the Fatigue Damage Indicator (FDI, the Boeing device) was designed for monitoring fatigue crack initiation, it appears to have stress intensity factor characteristics (based on the FDI crack growth results presented to support the patent application) that would make the rate of crack movement independent of the FDI crack length. Through the use of procedures outlined in this paper and in Ref. 15, the FDI could presumably be used for relating its crack growth behavior with crack growth damage accumulation in the substrate structure. Thus, the FDI gage might be directly applicable for measuring crack initiation life, crack propagation life, or their sum. Additional work will be required to substantiate this identified potential.

Johnson and Paquette[19] are also suggesting the use of crack growth gages for service life monitoring. An interesting feature of Johnson and Paquette's gage is that it is instrumented with crack wires that will break as the crack length in their gage extends and, thus, provides an electrical resistance change that would be detectable at a remote location. Additional developments along these lines could simplify the recording of data from the crack growth gage.

The growth behavior of two cracks (different crack geometry, but identical stress history loading) were interrelated in the previous subsection as an example of the crack growth damage transfer function. The procedure for relating crack growth behavior in a crack growth gage which monitors the control point behavior (see Fig. 2) to that expected in the structure is similar. Care is required, however, in establishing the stress intensity factor in the gage as a function 1) of stress in the structure and 2) of crack length in the gage. To demonstrate application of the crack growth gage concept more thoroughly, a hypothetical example is discussed here. The example considered consists of a center-cracked gage mounted on a tensile member that contains a precracked hole as shown in Fig. 7. It is necessary to determine the load transferred into the gage from the structural member. In general, this load transfer will be a function of material properties, geometry, and gage crack length.

In Ref. 15, the load shedding was computed by determining the compliance of the cracked gage and the structural member. An alternate approach used in this paper was to employ a stress intensity factor solution which directly reflects the fixed displacement boundary conditions assumed to exist along the ends of the gage. Isida[20] has reported such solutions for center-cracked strips of various lengths that are subjected to stress or displacement loading. Comparisons (not reported here) made between computations with the fixed displacement K solutions and with the compliance technique employed in Ref. 15 indicate that both procedures give nearly the same results for long gage lengths (i.e., length L in Fig. 2), but that the methods may differ somewhat for short gage lengths.

After using the Isida stress intensity solution to reflect the displacement loading of the gage, two different methods for relating a_s and a_g were used to obtain the analytical results given in Fig. 7. First, computations employing the empirical crack growth equation of the form given by Eq. (A1) were used. The only information required to relate the crack lengths are the constants given in Table 2 for Eq. (A1) and the stress intensity factor formulations for the flaw geometries under consideration. As discussed in Ref. 15, knowledge of the actual applied loads is not required, since the loading effectively cancels in the calculations. In order to use a transfer function based on Eq. (A2), however, one must select a value for the stress history characterizing parameter (σ_{max}). Figure 7 demonstrates that varying σ_{max} from 20 to 40 ksi had little effect on the resulting crack growth relationship. Moreover, the difference exhibited by the σ_{max} variation had the effect of bounding the results obtained previously by Eq. (A1). All constants used for the calculations shown in Fig. 7

were obtained from Ref. 17, where the two equations were fitted to the same experimental data.

The last paragraph implies invariance of transfer functions relating gage and structure crack growth, as regards to the stress history. Any compression load effects, dwell time, and load sequence effects would thus have to be assumed to be the same for gage and parent structure. Work has been initiated to verify this assumption.[21]

E. Concept Summary

Transfer functions have been presented which make it feasible to monitor control point crack growth behavior with a crack growth gage and to relate damage accumulated in the individual aircraft structure to the standard time (t_{MU}, shown in Fig. 1 and related to defined mission usage). The collective use of the crack growth damage transfer function and the NCG curve concept is illustrated by Fig. 8. Periodic measurements of the crack length in the gage, possibly using an instrumented procedure such as suggested by Johnson and Paquette, can provide a direct measure of the rate at which damage accumulates.

The crack growth gage may also be thought of as an onboard damage calculator. All the normal off-aircraft data reduction required when other instrumentation is used to determine the potential structural crack damage is eliminated when the crack growth gage is used. Furthermore, by decreasing the number of required analysis steps, the crack growth gage helps to eliminate the associated opportunities for error. Measurements of the gage crack length provide a single number related to damage and, thus, life. This might be the crack growth gage's best feature.

A potential drawback of crack growth gage instrumentation is that it only provides a limited amount of information if major usage changes are not adequately sensed by the aircraft's crack growth gages. Those aircraft in which loads/environment spectra survey instrumentation are installed will permit a periodic cross correlation between vehicle-dynamics-parameter data and accumulated damage in the aircraft's crack growth gages. The next several years should determine the accuracy and reliability of the crack growth gage control point tracking concept.

V. Summary and Concluding Remarks

The paper presents basic information on the two major U.S. Air Force force management activities: the Force Structural Maintenance (FSM) plan and the Individual Aircraft Tracking (IAT) program. Figure 1 provides the basis for discussing these two interrelated activities. Detailed discussion of ASIP requirements and concepts is limited, however, to the IAT program activity. The control point tracking concept and the transfer functions that support this concept are presented to identify procedures that simplify IAT programs designed to track potential crack growth damage in critical areas of the structure. We have suggested using the crack growth gage as an instrument for control point tracking (see Fig. 2) because only two transfer functions (one is illustrated in Fig. 3, the other in Fig. 4) are required to describe the potential crack growth behavior for each critical area of any aircraft. The procedure for using the transfer functions in practice for each critical area is described by Fig. 8. Multiplying the abscissa of the NCG curve in Fig. 8 by t^*_{MU} (see Fig. 1) gives the life expended by the individual aircraft in terms of the standard time t_{MU} (related to U.S. Air Force defined mission usage).

The subsections IV.B through IV.D provide the detailed development of the transfer functions for a flight-by-flight stress history which exhibits crack growth behavior that is similar to that exhibited during constant amplitude loading. This paper does not imply that the suggested transfer functions (Figs. 3 and 4) can only be derived by the methodology presented herein. It must be demonstrated during IAT program feasibility studies that the curves shown in Figs. 3 and 4 are independent of stress histories, so that usage changes do not affect the damage or life transfer functions. While work conducted to date justifies the assumption that the curves are reasonably independent of stress history, additional work will be necessary to verify this.

Finally, the concept of using a simple, onboard device as a damage calculator that provides an output directly related to life expended is not new. The S-N gage[22] was proposed in 1966 for a similar purpose. However, the nature of the damage accumulation process in a structure is sufficiently complex that any device must be carefully constructed such that it closely duplicates the response generated by the damage process occurring in the structure. The crack growth gage seems to fulfill this basic requirement. The crack growth gage control point monitoring technique appears feasible and deserves additional attention.

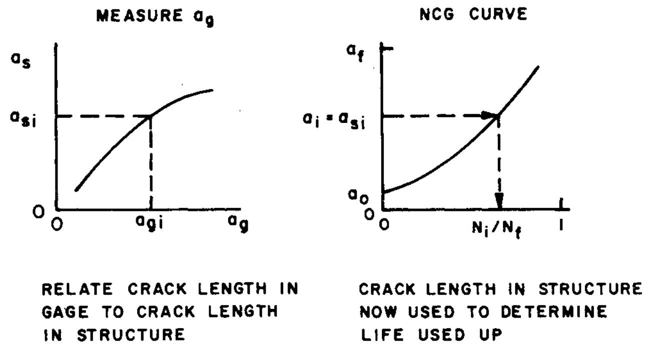

Fig. 8 Schematic representation of damage tracking using the crack gage transfer function and the normalized crack growth (NCG) curve.

Appendix

Simple crack growth rate equations such as

$$\frac{\mathrm{d}a}{\mathrm{d}F} = DK^{m}_{\max} \tag{A1}$$

or

$$\frac{\mathrm{d}a}{\mathrm{d}F} = \frac{CK^{p}_{\max}}{K_c - K_{\max}} \tag{A2}$$

can be used to describe steady-state variable amplitude crack growth rate data collected using different stress scaling factors applied to a load history in which sequence remains unchanged.[17] Equations (A1) and (A2) are not being suggested as unique formulas for describing variable amplitude crack growth data, but they are simple enough to demonstrate the applicability of the transfer function concepts presented in the text. Table 2 summarizes the constants derived in Ref. 17 by fitting Eqs. (A1) and (A2) in a least-squares sense to experimental fatigue crack growth data.

The operations performed in a tracking program to establish the required life related curves depend on the use of the integral equation forms of Eqs. (A1) and (A2). In general, these integral equations can be defined by

$$F = \int_{a_o}^{a_F} \frac{\mathrm{d}a}{f(K_{\max})} \tag{A3}$$

Table 2 Constants[a] for crack growth rate equations[17]

Eq.	D or C	m or p	K_c
(A1)	0.1122×10^{-7}	3.28	...
(A2)	1.64×10^{-5}	2.21	70

[a] Crack growth rate units are in inches per flight and the stress intensity factors units are ksi $\sqrt{\text{in.}}$.

Here the life measured in flights (F) is related to the crack geometry (including crack interval, a_o = initial crack length, a_F = final crack length), stress history, and material properties through the function f, which relates the characterizing stress intensity factor (in this case K_{max}) to the flight-by-flight crack growth rate behavior.

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