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GENERAL CONSIDERATIONS FOR STRUCTURAL INSPECTION OF OLDER AIRCRAFT

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16. Abstract

Generalized considerations for structural inspections needed to maintain airworthiness of older aircraft are reviewed. Recommendations are made to account for accumulated service usage by counting flights rather than flight hours, to inspect structures made of flaw-sensitive materials more frequently than those made of flaw-tolerant materials, and to inspect structures having little redundancy more frequently than those having more redundancy. Occasional destructive inspections of high-time aircraft are suggested as being useful, but expensive, sources of either continued confidence or impending problems.

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GENERAL CONSIDERATIONS FOR STRUCTURAL INSPECTION OF OLDER AIRCRAFT*

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INTRODUCTION

A large number of rather old (20 years, or over 40,000 hours of service) aircraft are in the passenger and freight-carrying registry in the United States. Because of high utilization, many of the newer jet aircraft are also approaching the same total number of flight hours. Background information provided by the FAA to the members of its FAA-Industry Advisory Group on Airworthiness of Older Aircraft indicates that a number of nearly disastrous incidents have occurred in these aircraft. Because many of the older aircraft were designed and constructed before fatigue life and fail-safe characteristics were prime considerations, it is prudent to establish policies that will assure continued airworthiness of these aircraft.

The state of the art of fatigue design is inadequate to allow a meaningful analytical assessment of continued airworthiness of a given aircraft. Therefore, elaborate inspection programs have been instituted to detect incipient fatigue damage. A commendable cooperation among the manufacturers, operators, and regulatory agency (FAA) has helped to develop these programs for inspections and repairs that have been the key factors in maintaining high reliability in operating aircraft. More recently, fail-safe considerations have been introduced in design with additional mitigation of hazards due to moderate damage. This general philosophy seems generally appropriate for the current state of affairs. The overall successful experience of civil aircraft is ample proof that the policies adopted have been effective.

The present paper is intended to point out some of the general considerations that should be used to develop future airworthiness policies for older aircraft. The particular topics to be treated include the most rational basis for measuring service usage, the influence of material and structural configuration on the rate of crack growth and residual strength, and the need for occasional intensive inspections to supplement analyses and extrapolations of past experience.

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*This material was originally contained in an informal document presented at a meeting of the FAA-Industry Advisory Group on Airworthiness of Older Aircraft in December 1968.

THE CASE FOR MEASURING FATIGUE LIFE AND DAMAGE BY FLIGHTS RATHER THAN BY HOURS

Traditionally, aircraft usage is recorded and discussed in terms of flight hours. Flight loadings, on the other hand, are frequently reported on a per-mile basis. However, since flight speeds are reasonably uniform for a specific airplane, the conversion from one frame of reference to the other is direct.

Coleman (ref. 1) has examined a very broad range of data on frequency of occurrence of flight loads for a variety of commercial aircraft. One of his conclusions reads: "For the wide range of airplanes and operations covered by the review, the in-flight acceleration histories have remained unexpectedly consistent when viewed on a per-flight rather than on a per-mile basis. This consistency exists because most of the repeated loads occur in the climb and descent phases of flight rather than during cruise. The greater consistency of the acceleration histories on the flight basis suggests that per-flight may be a better basis for fatigue assessment than the conventional per-mile basis." Note: For this purpose, a flight includes all operations for one cycle of take-off, cruise, and landing.

The data supporting this conclusion are documented in the reference. The basic demonstration of the conclusion is in figure 1, which shows the same set of data on frequency of occurrence of acceleration increments plotted on a per-mile and on a per-flight basis. The narrower band in the "per-flight" diagram indicates the improved consistency of the data when viewed this way.

Unpublished studies performed by the Airworthiness Branch of the NASA Langley Research Center have indicated a consistent trend toward shorter average flights as aircraft grow older. The prime reason for this trend is that newer, faster, larger aircraft are used for long haul service and older aircraft tend to find their way into short haul or feeder-line service. The impact of this trend combined with the better correlation when loads are counted per flight is clear: Older aircraft must be accumulating more fatigue damage per hour now than they have over most of their service to date. Thus, inspection intervals should be reviewed and adjusted accordingly. The simplest method for insuring against surprises is to base inspection intervals on the number of take-offs and landings rather than on hours of service. Portions of some aircraft are already serviced on this basis, so no new concepts are involved.

QUALITATIVE CONSIDERATIONS FOR ADJUSTING INSPECTION INTERVALS

In principle, structures should be inspected just often enough so that a crack too small to be found on one inspection does not grow to critical size before the next inspection. The most rational basis for selecting inspection intervals is the fatigue crack propagation curve. Figure 2 is typical of fatigue crack propagation curves observed in a wide variety of tests and in service. Generally, a fatigue crack grows slowly for a reasonably long time, the crack then accelerates, and finally fracture occurs.

The actual crack propagation curve for a specific station in an aircraft structure is dependent upon a large number of parameters: the material, detailed configuration, stress level, service loading, chemical environment, temperature, etc. Thus the behavior of each station of an airframe is described by a different crack propagation curve. Generally, these curves are not known with any useful precision for older aircraft. Analytical tools for computing such curves are being developed which could furnish useful guideline information. However, the analysis of a complete airframe requires a much more detailed stress analysis than has been done on current aircraft. The formidable cost of performing this analysis probably precludes its implementation. Thus, more qualitative considerations and past experience must be employed to set inspection intervals.

The general character of fatigue crack growth dictates that older aircraft must be inspected frequently to avert rapid crack growth and fracture in service unless one can guarantee that all potentially critical cracks are found at a very early stage. The occasional discovery of a rather long crack that was not anticipated weakens the needed guarantee.

The following sections treat several specific factors that must be considered in establishing inspection intervals and procedures.

Crack Propagation in Various Materials

A very major factor in determining how rapidly a fatigue crack will grow and how long it can grow before causing failure is the material from which the structure is constructed. In figure 3 are plotted the typical crack growth curves for tests of three aluminum alloys. The example is for simple sheet specimens of equal size subjected to the same nominal stress conditions $\left(R = 0,\ S_{max} = 20 \text{ ksi}\right)$, but a similar comparison would result for any other configuration as long as it was identical for each material and the same nominal stress was applied to each.

Obvious from the curves is the fact that the higher strength materials experience higher rates of crack propagation. Recent results obtained at Langley Research Center indicate that the rate was between 2 and 6 times faster in 7075-T6 than in 2024-T3 for the same stress. Further, it is well known that a given size crack reduces residual strength more drastically in the higher strength material than in lower strength material. In the figure, failure was calculated to occur when a single load producing 50 ksi gross tensile stress was applied at just that instant when the crack was long enough to cause failure at that stress. The trends indicated would be emphasized still more if the tests were conducted at a stress level that was a given percentage of the original tensile strength.

These observations are not intended to condemn the use of high strength materials generally, but rather to call attention to the fact that smaller cracks must be found in such materials to preclude failure. Generally, more frequent inspections are also required to be sure to catch cracks because of their faster rates of propagation. Obviously, if the higher strength alloy is being utilized at a low enough stress level, the importance of these considerations is reduced.

Integral Versus Redundant Construction

Figure 4 shows crack propagation curves for tests of two 7075-T6 aluminum alloy box-beam structures having integrally stiffened and skin-stringer covers. The gross area of each was the same, the stiffener spacing was the same, and both tests were conducted at the same stress level (ref. 2). The much more rapid growth in the integrally stiffened cover after the crack passed the first stiffener is obvious. The integral stiffeners provided little or no crack-stopping resistance like that provided by riveted stringers. This observation suggests that integral construction should be inspected more frequently than other types. Experience has also shown that integrally machined components are vulnerable to corrosive attack because unfavorable grain structure is present at highly stressed points and is exposed to the environment.

Compensating considerations are the following. Integral construction contains fewer fasteners; thus fewer crack initiators are present. Integrally stiffened structures are frequently made up of narrow panels so that a given crack is contained within one panel which provides a smaller fraction of the total load-carrying capability of the structure. Integral construction frequently contains sculptured doublers that reduce the stress level at critical fasteners and joints.

However, a crack, once started by fatigue, corrosion, or accidental damage, usually has much more serious consequences in integral construction than in other types. Thus, special care should be exercised in inspecting such structures.

Fail-Safety in Older Aircraft

Improvements in design procedures and the increased use of machining to provide just enough structural material to carry the expected loads has led to more nearly uniformly stressed structure. Furthermore, as an aircraft sees more service, the more critical areas are identified and repaired or reinforced. As a result, one might expect cracks in more places in older aircraft so that the condition of the "one-hoss shay" is approached. The rate of total fatigue crack growth under these circumstances is higher because more cracks are working. Later, they may coalesce to suddenly form a rather long crack where two or more short ones were a little earlier.

To the writer's knowledge, at least two full-scale fatigue tests have produced catastrophic failures because of this sequence of events and before any cracks were detected. In at least one other case the progress of several cracks at a particular station at a wing root was monitored and crack coalescence was observed. Some service failures have been attributed to similar behavior.

On the other hand, fail-safe characteristics are usually demonstrated or calculated on the basis of sound material everywhere except for that which was cracked or cut. A critical look at the level of fail-safety present in "experienced" aircraft appears justified. To the writer's knowledge the problem has not been studied to any significant extent, and thus no rules are available at this time.

THE CASE FOR DESTRUCTIVE INSPECTIONS AND SUPPLEMENTARY TESTS

The foregoing discussions and recommendations are necessarily qualitative because the current state of the art does not permit quantitative rules to be developed with useful reliability. Continued inspections for cracks are the basis for maintaining integrity and must remain so for the forseeable future.

However, the operator must make judgments on when and where to inspect specific structures. To date he has guided his inspection procedures by previous experience – his own and that of others inspecting the same type of structure. If one concedes that all previously identified cracks are being handled adequately, he must still be concerned about potential cracks that have not been identified to date. As aircraft grow older more new cracks are bound to appear.

A destructive inspection of a high-time aircraft is considered to be the best and most reliable source of information on potential crack sites. Previous experience with such inspections raises questions about whether they uncovered enough new cracks to be worthwhile. However, identification of any crack that could become critical would be extremely valuable. Further, the absence of new cracks should be of tremendous value in inspiring continued confidence in a given vehicle type. The cost of an airframe for such an inspection should be small, because aircraft are occasionally retired after damage too severe to warrant repair. The cost of the inspection is significant. For maximum benefit the inspection should be accomplished by the original builder or with his intensive participation.

Selected parts of dismantled aircraft should be studied in the laboratory to develop realistic estimates of how quickly a representative crack is likely to grow in that structure. These tests could also provide valuable information on possible changes (or lack thereof) in material properties and on fail-safe characteristics of the structure. Depending upon the results, fleet-wide reinforcements could be made or effective inspection intervals could be prescribed. Some of the insight gained could be of benefit to future designs.

CONCLUSIONS

A brief review of general considerations for inspection policies for older aircraft leads to the following conclusions:

1. Aircraft usage and damage should be recorded and interpreted in terms of numbers of flights rather than in terms of time or distance flown.

2. Because of their higher rates of fatigue crack propagation and lower crack strengths, structural components made of high strength materials require more frequent and more diligent inspection than do parts similarly shaped and stressed, but made of lower strength materials.

3. Similarly, integral and other nonredundant construction deserves more frequent and diligent inspection than does multiple-load-path construction.

4. The fail-safety of structures potentially containing a number of cracks should be assessed.

5. An occasional destructive inspection of a high-time airframe is recommended to help identify potential cracks or to reinforce confidence in a given aircraft type.

6. Selected laboratory tests are recommended to obtain detailed information regarding rates of fatigue crack propagation not available from any other source.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., July 5, 1973.

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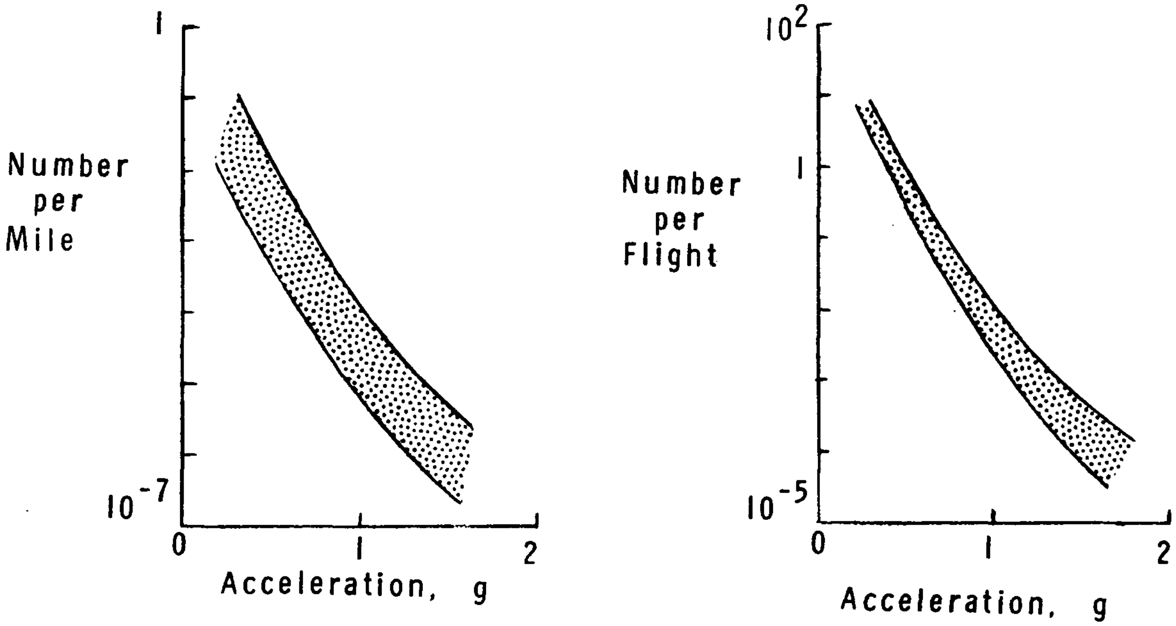

Figure 1.- In-flight accelerations.

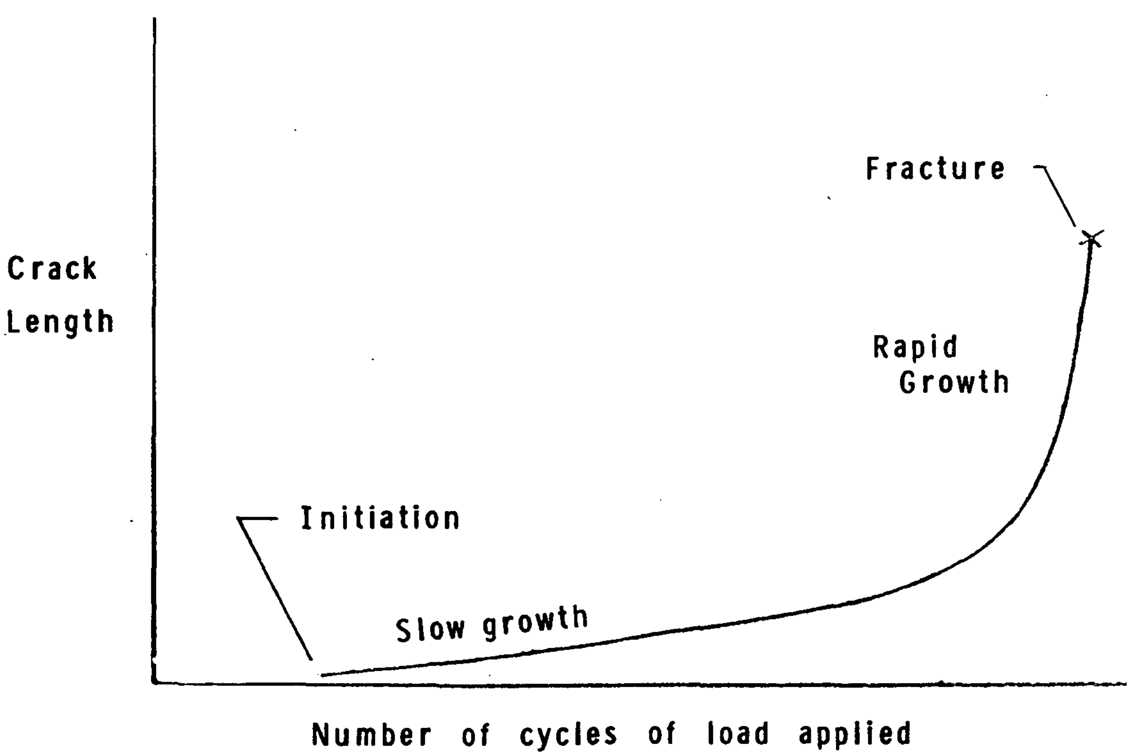

Figure 2.- Typical fatigue crack propagation.

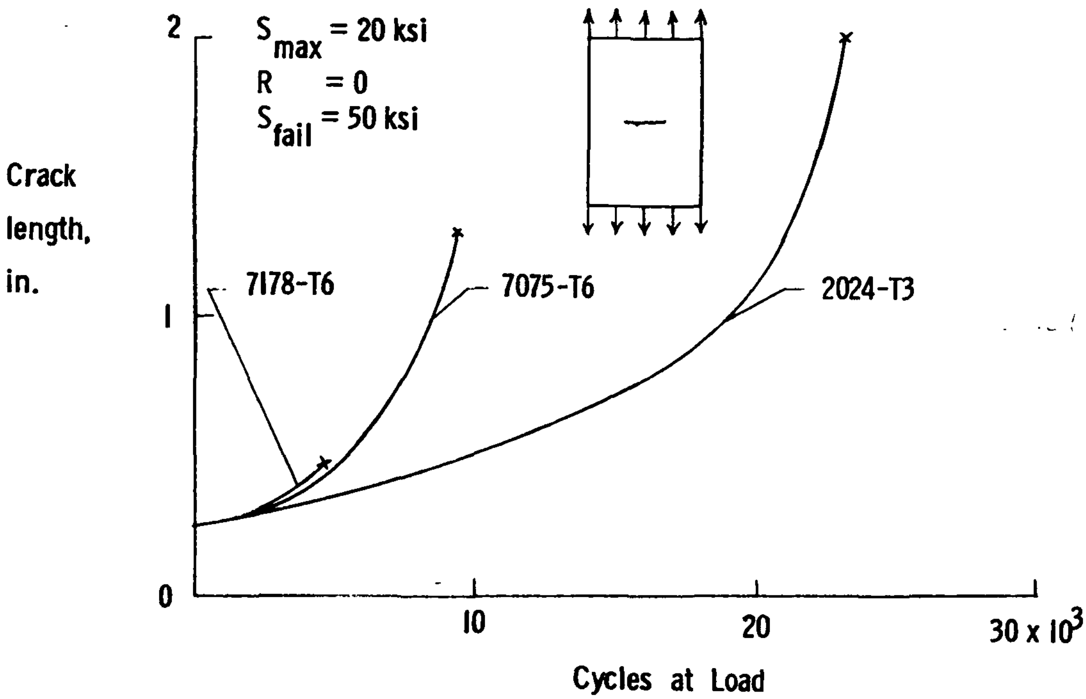

Figure 3.- Crack growth in typical aluminum alloy sheets.

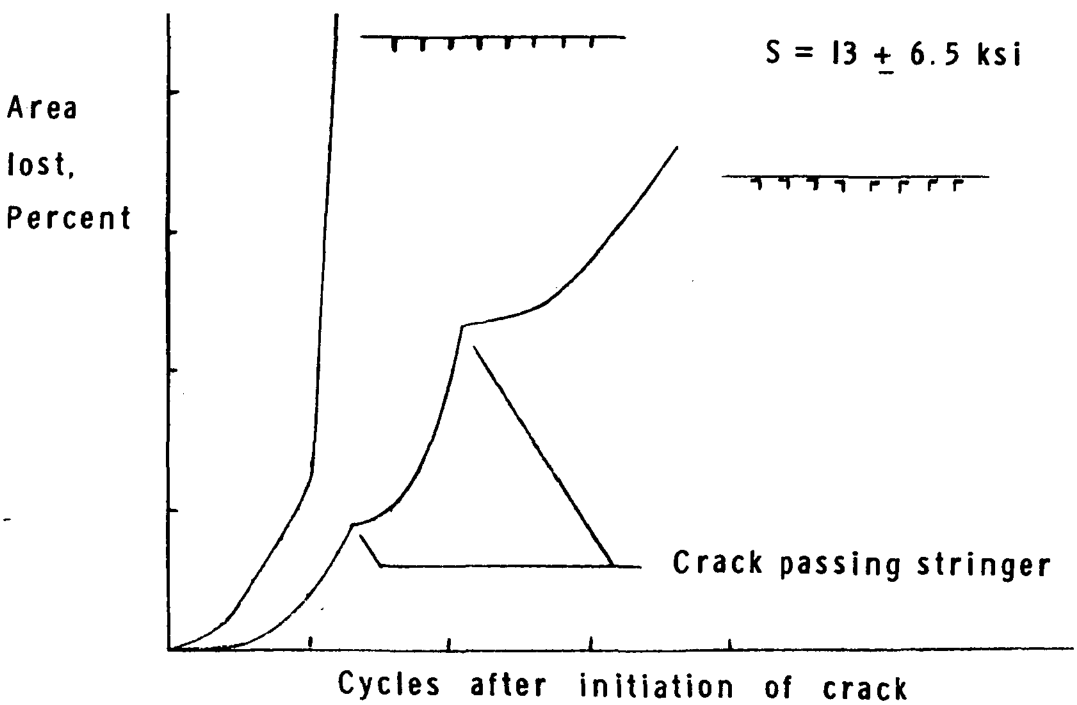

Figure 4.- Fatigue crack propagation in 7075-T6 aluminum alloy box beams.

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