Problem No. UDRI-2

Title: **Structural Risk Assessment for a Discrete Source Damage Threat to the Fail Safety Capability of a Stringer**

Objective:

To illustrate the use of PROF for the calculation of the probability of failure due to discrete source damage at a stringer.

General Description:

This sample problem illustrates the use of the PROF risk analysis computer program for evaluating the fail-safe capability of a wing stringer given a discrete source damage event. The probability of failure as a function of flight hours given a two bay crack is calculated using data representative of a Boeing 707 JSTARS airframe. An equivalent initial flaw size distribution was used to model hole quality for the structure as it enters service. The initial flaw size distribution was grown using the crack growth life curve for an intact structure under normal operating conditions. Probability of failure was calculated using the stress distribution and residual strength of the stringer with the two bay discrete source damage event having occurred. The risk analysis was used to estimate the number of flight hours for the airframe to reach a probability of failure of 10^{-4}. In some applications, the 10^{-4} failure probability is the maximum acceptable risk for fail safety and the flight hours to reach this risk level is the time of the onset of widespread fatigue damage.

Topics Covered: Failure probability, discrete source damage, onset of WFD, residual strength, crack size distributions, crack growth life curves

Type of Structure: wing stringer

Relevant Sections of Handbook: Section 8

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Overview of Problem Description

The goal in analyzing the effect of widespread fatigue damage (WFD) in the discrete source damage (DSD) problem is to evaluate the ability of the structure to complete the current mission when a partial structural failure occurs. This analysis is aimed at one of two or more structural details that interact by providing a fail-safe capability in the event that one or more of the structural details has failed. The evaluation will use the conditional single-flight probability of failure, given that DSD is present as the measure of this ability. The prototype for this analysis is the ability of the structure to survive the sudden appearance of a two-bay crack in the fuselage or wing skin.

The two-bay crack is a crack that spans two bays in the skin, including the stringer or frame between the two bays. The size of two bays is considered an upper bound on the damage that would directly result from penetration of an engine blade thrown from the engine in an uncontained failure or from battle damage. The concern in this damage scenario is whether the crack-stopping structures on either side of the damage will hold through the remainder of the mission. The conditional probability that the crack-stopping structure will fail, given that the DSD has occurred, provides a measure of the ability of the structure to complete the mission.

Since the flaw size distribution changes in time, the PROF DSD analysis is calculated as a function of time. The presence of DSD only affects the structure during the flight in which it occurs. Therefore, the same model of the growing crack size population that is used in a standard PROF analysis can be used to assess the influence of aging on the conditional probability of failure given DSD. The details of the crack growth model are given in Berens, et al.[1991]. Because of its severity, DSD, will be detected and repaired before the next flight so that a model of crack growth in the presence of DSD is unnecessary.

Example Input Data

The data from the B-707 teardown inspection performed as part of the JSTARS assessment will be used to illustrate the procedures for an analysis of the impact of WFD on the fail safety in the presence of DSD using PROF. A detailed description of the data and the problems associated with using the B-707 for the JSTARS was given by Lincoln [1997]. The example presented here centers on the fail-safety capability of stringer 7 in the lower wing skin after stringer 8 and the adjacent wing panels have failed.

Figure UD-2.1 contains a schematic of the B-707 wing. The left half of Figure UD-2.1 shows the entire structure and the location of stringer 8 (S8). A cross-section of the skin and stringers is shown in the right half of Figure UD-2.1. The example will analyze the effect of a break in stringer 8 and the adjacent skins on the large adjacent stringer S7.

The data were collected and the structural analyses were performed by Boeing under an Air Force contract. The data and analysis results were delivered in a series of letter reports and in Excel spreadsheets. The data used for this example were extracted from the spreadsheets.

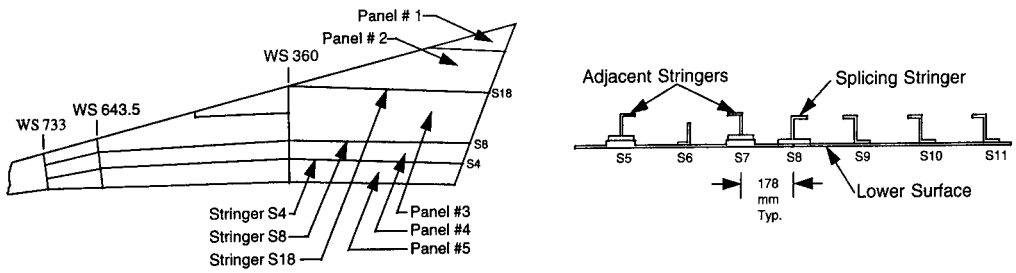

Figure UD-2.1. *Schematic of the B-707 Wing and Side View of the Skin and Stringer Structure [Lincoln, 1997].*

The structural analyses relevant to the DSD analysis include the crack growth curve, the stress exceedance data in the presence of DSD and the residual strength of stringer 7 in the presence of DSD. Figure UD-2.2 contains a plot of the crack growth curve; which was determined for intact structure under normal conditions. The DSD analysis is not concerned with crack growth in the presence of DSD because it is assumed that the DSD will be detected and repaired before the next flight.

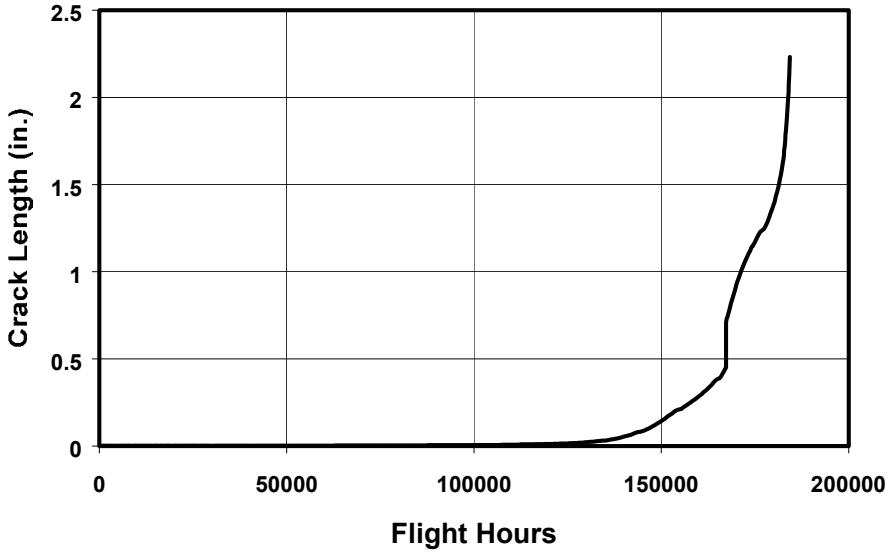

Figure UD-2.2. *Crack Growth Curve for Stringer 7 with All Structure Intact.*

Figure UD-2.3 illustrates the analysis of the peak load distribution from the exceedance data. The basis for the exceedance data is the spectrum used to generate the crack growth curve. The stresses were transformed to account for the damage to stringer 8 and the adjacent panels to get the empirical stress versus exceedance probability illustrated by the points in Figure UD-2.3. The straight line represents the Gumbel distribution that was fit to the data.

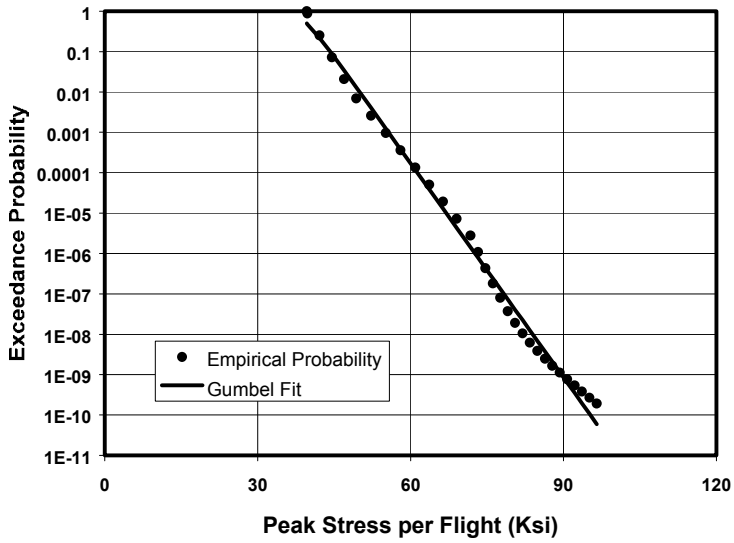

Figure UD-2.3. *Peak Stress Distribution with DSD Present.*

The residual strength function is plotted in FigureUD-2.4. The shape of the stringer is responsible for the flat region in the residual strength function. The residual strength function was derived primarily from the stress intensity curve for the stringer. Modifications from the Irwin criterion were required at low crack lengths and at the flat region in the middle of the curve. At low crack lengths, the Irwin criterion would push the residual strength to infinity, so it was necessary to truncate the residual strength function to the maximum material strength. The stress intensity factor actually dips between 0.5 and 1.5 inches because of the shape of the stringer. The residual strength does not, however, decrease, resulting in the flat region in the residual strength function.

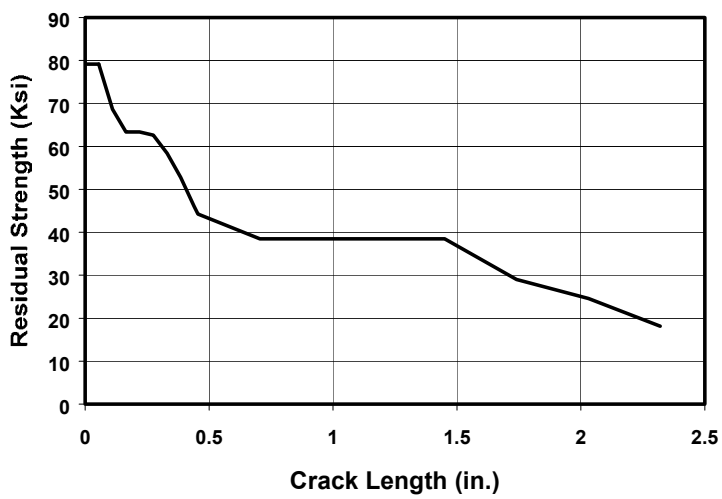

Figure UD-2.4. *Residual Strength as a Function of Crack Length in Stringer 7.*

The analysis was performed for two different initial crack length distributions. The crack length data were collected from an aircraft with 57,382 flight hours. The single-flight probability of failure is unacceptably high for the distribution seen in the teardown data. Since many of the JSTARS aircraft will have fewer hours, the distribution was adjusted to an age of 40,000 flight hours. The two-crack length distribution functions are

illustrated in Figure UD-2.5. A lognormal distribution was fit to the upper tail of the teardown data and the time adjustment was made by back extrapolating the percentiles from the 57,382 distribution using the crack growth curve.

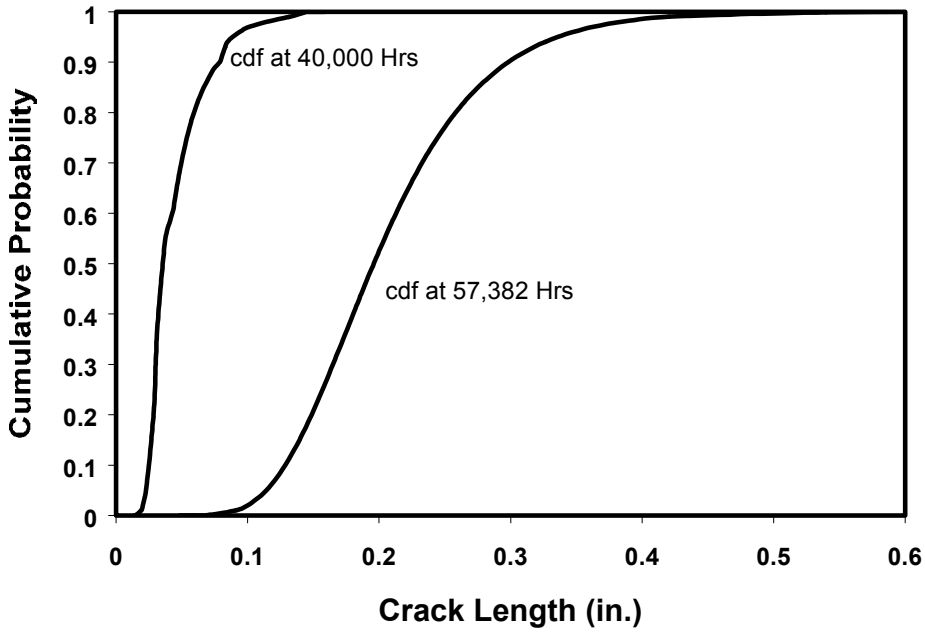

Figure UD-2.5. *Comparison of the Flaw Size Density Function at 40,000 Hours with the Density Function at 57,382 Hours.*

The results of two different PROF DSD analyses are plotted in Figure UD-2.6. The solid line represents the analysis using the flaw size distribution from the 57,382-hour aircraft as the starting point. The dashed line plots the results from using the flaw size distribution adjusted to a 40,000-hour aircraft. The two curves show close agreement in the overlap; however, some difference is expected since the time points at which calculations are made do not coincide from the two analyses.

Lincoln [1997] cited 10^{-7} as the desirable overall single-flight probability of failure and an estimated probability of DSD as 10^{-3}. The resultant requirement for the fail-safe capability of stringer 7 is 10^{-4}. Clearly, the aircraft at 57,382 hours does not meet this requirement. Starting at 40,000 hours, an aircraft will have approximately 16,000 hours before the conditional single-flight probability of failure exceeds the 10^{-4} requirement.

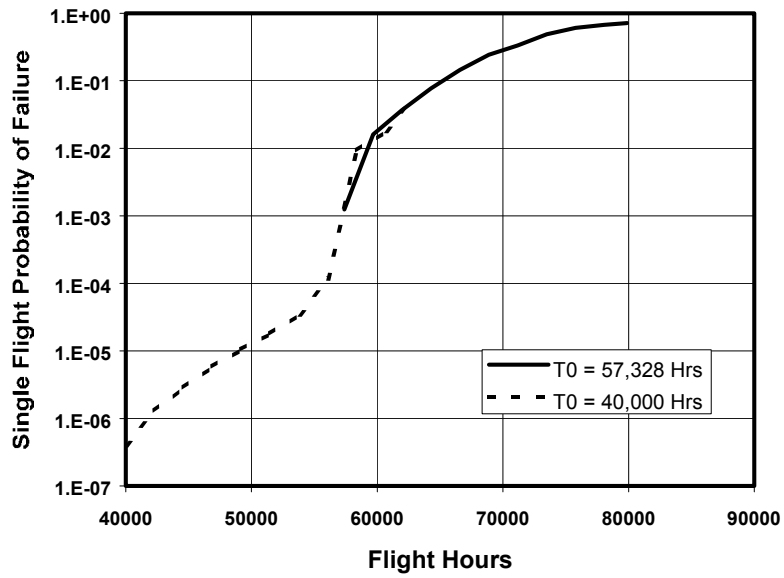

Figure UD-2.6. *Comparison of Single-Flight Probability of Failure Starting from 57,382 Hours versus 40,000 Hours.*

The use of the PROF DSD analysis module has been illustrated using data from the B-707 JSTARS aircraft. The problem of evaluating the fail safety capability of lower wing stringers in the B-707 is an example of the prototype DSD analysis. The essential elements that made the problem suitable for the PROF DSD module are:

a) interest in the conditional probability of failure, given that adjacent structural elements have failed,

b) likelihood of failure is increased by the presence of MSD,

c) prediction of the growth of MSD cracks with time being available, and

d) analysis of residual strength as a function of MSD crack size being available.

References

Berens, A.P., Hovey, P.W., and Skinn, D.A. (1991) *Risk Analysis for Aging Aircraft, Volume 1 – Analysis*, WL-TR-91-3066, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio.

Lincoln, John W. (1997), "Aging Aircraft – USAF Experiences and Actions," *ICAF 97 – Fatigue in New and Aging Aircraft*, R. Cook, P Poole Eds., Proceedings of the 19th Symposium of the International Committee on aeronautical fatigue, Edinburgh Scotland.