Structures Bulletin

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Subject: Correlating Durability Analysis to Unanticipated Fatigue Cracks in Metallic Structure

References:

1) DAU Program Managers Tool Kit, Fourteenth Edition, April 2008.
2) AFRL-ML-WP-TR-2007-4113, Investigation and Root Cause Analysis Guideline for Undetected Cracking Incidents In Safety-of-Flight Aircraft Structure, January 2007.
3) MIL-STD-1530C, *Aircraft Structural Integrity Program,* 18 April 2002.
4) Structures Bulletin EN-SB-11-001, Guidance on Correlating Finite Element Models to Measurements from Structural Ground Tests, 24 June 2011.
5) Structures Bulletin EN-SB-09-001, Methodology for Determination of Equivalent Flight Hours and Approaches to Communicate Usage Severity, 15 June 2009.

Background and Purpose:

Many operational aircraft have experienced unanticipated structural fatigue cracking. In some cases, the engineering analysis was inaccurate and lacked sufficient fidelity to predict the location and length of the fatigue crack. This Structures Bulletin identifies sources of possible errors in the structural engineering disciplines, each of which provides input analyses to the predictions. Guidelines for each discipline are provided to use in the correlation process for unpredicted fatigue cracking in metallic aircraft structure.

Introduction:

Root cause analysis is a methodical approach to identifying the factors that result in the nature, magnitude, location, and timing of a failure or an event. Root cause analysis is used to identify what behaviors, actions, inactions, or conditions need to be changed to prevent recurrence of the problem. Many of the problem solving tools available to support root cause analyses are described in Reference 1, and several commonly used tools such as KNOT (**K**now, **N**eed to Know, **O**pinion, **T**hink We Know) charts, Ishikawa or "fishbone" diagrams, fault tree diagrams, etc., are shown in the Appendix of this Bulletin. However, the intent of this Structures Bulletin is neither to cover the use of these tools, nor to elaborate on the root cause analysis process.

The first step after the finding of an unanticipated fatigue crack is to perform a failure analysis on the affected component(s). Failure analysis is the process of collecting and analyzing observations to determine the cause of the failure. The first goal of a failure analysis should be to determine if the component was manufactured as specified, including material composition, heat treatment, and dimensions. A failure analysis would also likely include other testing such as metallographic examination of microstructure, hardness and conductivity verification. Findings during the course of an analysis may indicate the need to perform a review of the entire manufacturing process. Examination of fracture surfaces can usually determine if the component failed in overload, fatigue, or by some other mechanism such as stress corrosion cracking. In some cases, the orientation and magnitude of the loading can be determined. Often, observations made during the analysis of the failed article(s) can give support or refute hypotheses regarding the failure scenario. In some cases, demonstrating specific mechanical properties is warranted. Reference 2 is an excellent resource that describes the investigation and failure analysis process for aircraft structural issues.

Once the failure analysis is complete, and the failure mode is determined, the next step is the analysis correlation. If the analysis correlation is *good*[1] and accounts for all conditions identified in the failure analysis, and predicts the cracking, then the root cause analysis is complete. However in many cases, cracking is not anticipated or predicted by the analysis, then the poor correlation may be the result of errors in any of the sources as discussed below.

[1] *Good* correlation is somewhat subjective and this SB does not attempt to quantify the level of goodness required for all situations. However, the analysis correlation should compare: life ratios, crack growth curve shapes, critical crack sizes, reasonableness of initial flaw size assumptions, etc. when evaluating "goodness".

Discussion:

For the purpose of examining the multiple causes of poor correlation, a fishbone diagram will be used as shown in Figure 1, to address the primary sources of error involved with fatigue crack predictions:

1) Loads Analysis (Ref. 3, Section 5.2.2)
2) Stress Analysis (Ref. 3, Section 5.2.5)
3) Durability Analysis (Ref. 3, Section 5.2.7)
4) Aircraft Usage Analysis (Ref. 3, Section 5.4.4)
5) Failure Analysis (Ref. 3, Section 5.3.7)

Each of the five sources will be examined in detail to identify possible causes for inaccurate predictions. In terms of priority, loads analysis, stress analysis, and durability analysis sections should be reviewed first for possible errors contributing to the poor correlation. If no errors can be identified, a review of the aircraft usage analysis and the failure analysis sections should follow.

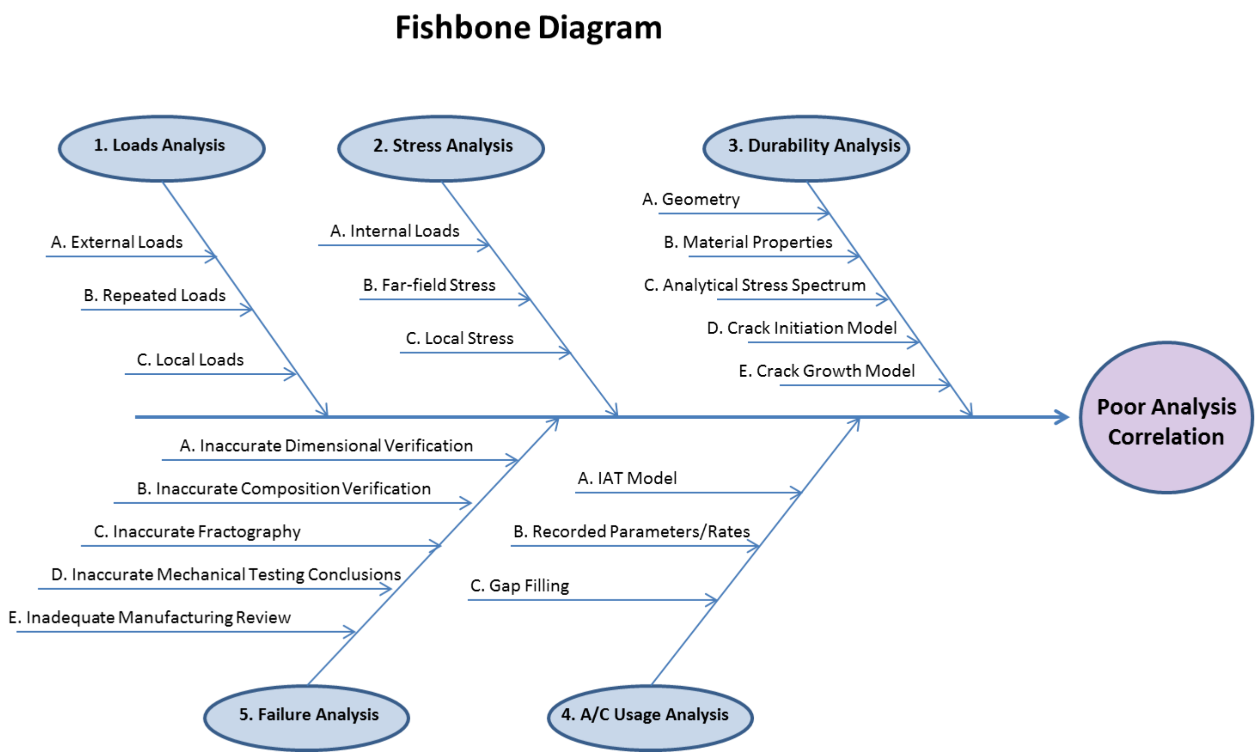

Figure 1 - Error Identification Fishbone Diagram

1) Loads Analysis:

External loads on the airframe are determined by the magnitudes and distributions of both aerodynamic and inertial loads including the dynamic response of the structure resulting from transient or sudden application of these loads. Loads on the airframe are a result of flight, landing, ground handling and miscellaneous loads encountered during service.

External airframe loads are based on the established structural design criteria for the air vehicle which describe the specific loading limits to be considered for the aircraft. Airframe requirements apply equally to any equipment or system installed within the air vehicle. All members of the airframe must withstand the limit loads and thermal effects without detrimental deformation. The airframe structure uses the “design limit load” (DLL) as the maximum load authorized for operations.

External loads are validated via quantitative and qualitative flight test data obtained during a flight test program to detect deficiencies and evaluate corrections. Similar to other disciplines, qualification is an incremental buildup process where component level (or sub-system) validation is accomplished via analyses like Computational Fluid Dynamics (CFD) code and via wind tunnel tests prior to actual systems level flight loads testing on the air vehicle. The subsystem-level tests and analyses are designed to achieve certain minimum goals prior to initiation of system-level tests to build confidence in the design.

Flight testing is an incremental and progressive activity during which progress assessments are made prior to proceeding to the next phase of the flight test program. The principal objective of loads flight testing is to validate the analytical models used in the design of the aircraft by checking the loads and strains at significant points on the airframe. The loads are expressed in terms of shear, bending moment, and torque at a number of stations on the wing, tail surfaces, fuselage, and pylons, plus control surface hinge moments. Flight loads test data is also compared with analytical results to validate repeated or fatigue load trends and service life predictions.

Loads engineers use flight parameters that are correlated with flight loads through multivariable regression techniques to create transfer functions that are used to track loads on a representative portion of the fleet. These transfer functions are then utilized by the Loads Environment Spectra Survey (L/ESS) to monitor loads for fleet management which is required by the Aircraft Structural Integrity Program (ASIP). Strain gages are sometimes utilized in sustainment to support ASIP tracking requirements to identify if loads change over time.

Over time, aircraft configurations and usage may change from the time when flight loads were originally documented (along with the original transfer functions) due to modifications or other changes which could affect the loads without the transfer functions being updated to reflect the change. An L/ESS program may not capture this change if it relies on flight parameters only (i.e. no strain gages).

Dynamic loads (such as those for gust, buffet, landing impact, or taxi) are considered "quasi-static" for airframe design. However, repeated loads from vibratory or acoustical sources may be an important component of the operational loading and also need to be addressed.

Possible load analysis sources of error that could lead to missed predictions of unanticipated fatigue cracking are as follows and are displayed in Figure 2:

A. External loads
    1. Aerodynamics not properly characterized
    2. Weight growth or change in mass distribution
    3. Correlation forced to match flight test data that was incorrect
B. Repeated loads (maneuver, gust, buffet, etc.)
    1. Incorrect frequency
    2. Incorrect magnitude
    3. Incorrect order of assumed loading
    4. Flight parameters to loads "transfer functions" are not updated as modifications are implemented
    5. Flight limits exceeded
C. Local loads
    1. Thermal loads not included
    2. Pressure loads not included
    3. Inertia loads (local mass distribution) not included or updated

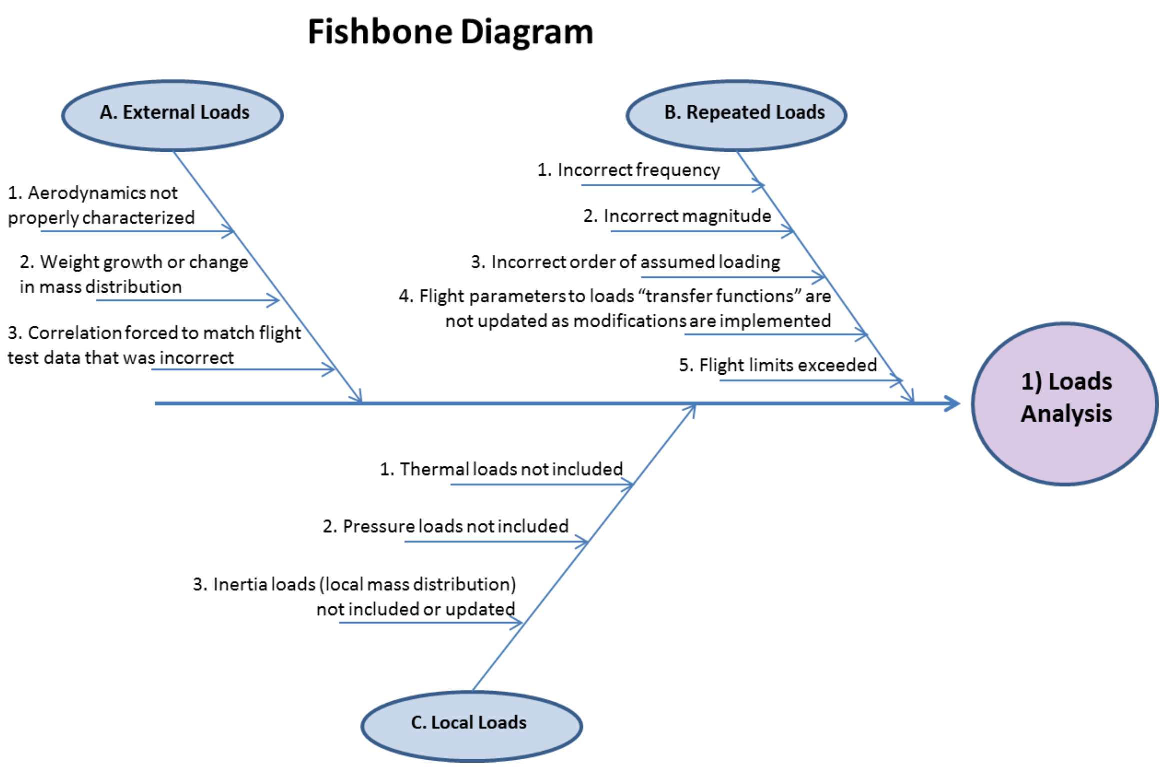

Figure 2 – Loads Analysis Fishbone Diagram

2) Stress Analysis:

In the development of an aircraft system, external loads are applied to analytical models of the aircraft to determine the internal loads on each of the structural members. Typically, a finite element model (FEM) is constructed as a mathematical representation of the structure, and is used to determine the magnitude and distribution of loads throughout the airframe. Using geometry and material properties, the stresses can be calculated either with detailed fine-grid FEMs or with textbook formulas and methods. The deflections of the airframe and each component are usually calculated from the FEM directly.

As part of the ASIP "building block" approach, analytical models are required to be validated using test results. The validation process is referred to as "certification analysis" in Ref. 3, and is described in detail in Ref. 4. A list of possible stress analysis sources of error that could lead to missed predictions of unanticipated fatigue cracking are as follows and are displayed in Figure 3:

A. Internal loads
    1. Finite Element Model (FEM) correlation issue
    2. FEM modified to match incorrect ground test data
B. Far-field stress
    1. FEM correlation issue
    2. FEM modified to match incorrect ground test data
C. Local stress
    1. Incorrect stress concentration
    2. Incorrect stress gradient
    3. Local bending due to eccentricity not included
    4. Residual stresses (manufacturing, assembly, etc.)
    5. Higher stresses due to corrosion (thinning)

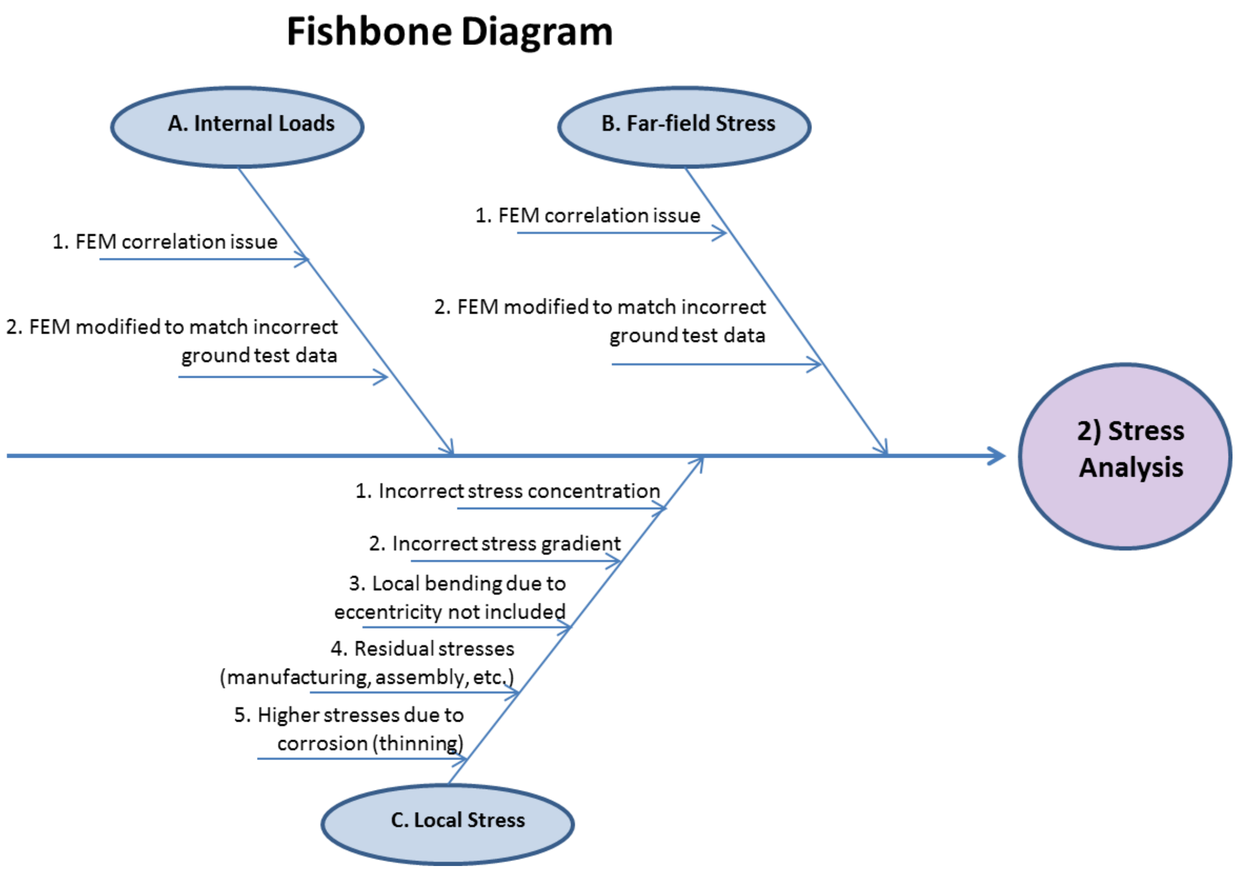

Figure 3 - Stress Analysis Fishbone Diagram

3) Durability Analysis:

Durability analysis is conducted to substantiate the ability of the structural components to comply with the detail requirements for durability. The design flight-by-flight stress/environment spectra should be used in the initial durability analysis at the start of the program and should be updated as necessary throughout the life of the aircraft. The updated analysis should consider any change in the service loads spectra, change of materials/properties, and should also include any adjustments found during correlation analysis of test results or in-service findings.

Composite materials may be subjected to changes in properties over time that could impact strength and durability. This phenomenon could also occur in metals that are subjected to corrosion or temperature extremes. A list of possible durability analysis sources of error that could lead to missed predictions of unanticipated fatigue cracking are as follows and are displayed in Figure 4:

A. Geometry
    1. Not built to print
    2. Incorrect Stress Intensity Factor (SIF) solutions
B. Material properties
    1. Using wrong properties because of material substitution (e.g. – fracture toughness)
    2. Current stress-life or strain-life curves different from initial characterization
    3. Current crack growth rate different from initial characterization
    4. Improper processing of materials (target properties not achieved)
C. Analytical stress spectrum (repeated loads + stress analysis)
    1. Incorrect truncation
    2. Incorrect clipping
D. Crack initiation model
    1. Equation not a good match of material data
    2. Environmental interaction
E. Crack growth model
    1. Equation not a good match of material data
    2. Incorrect SIF for actual cracking scenario, geometry, stress gradient, etc.
    3. Incorrect crack retardation model
    4. Incorrect crack acceleration model
    5. Environmental interaction (e.g. corrosion, stress corrosion cracking, etc.)

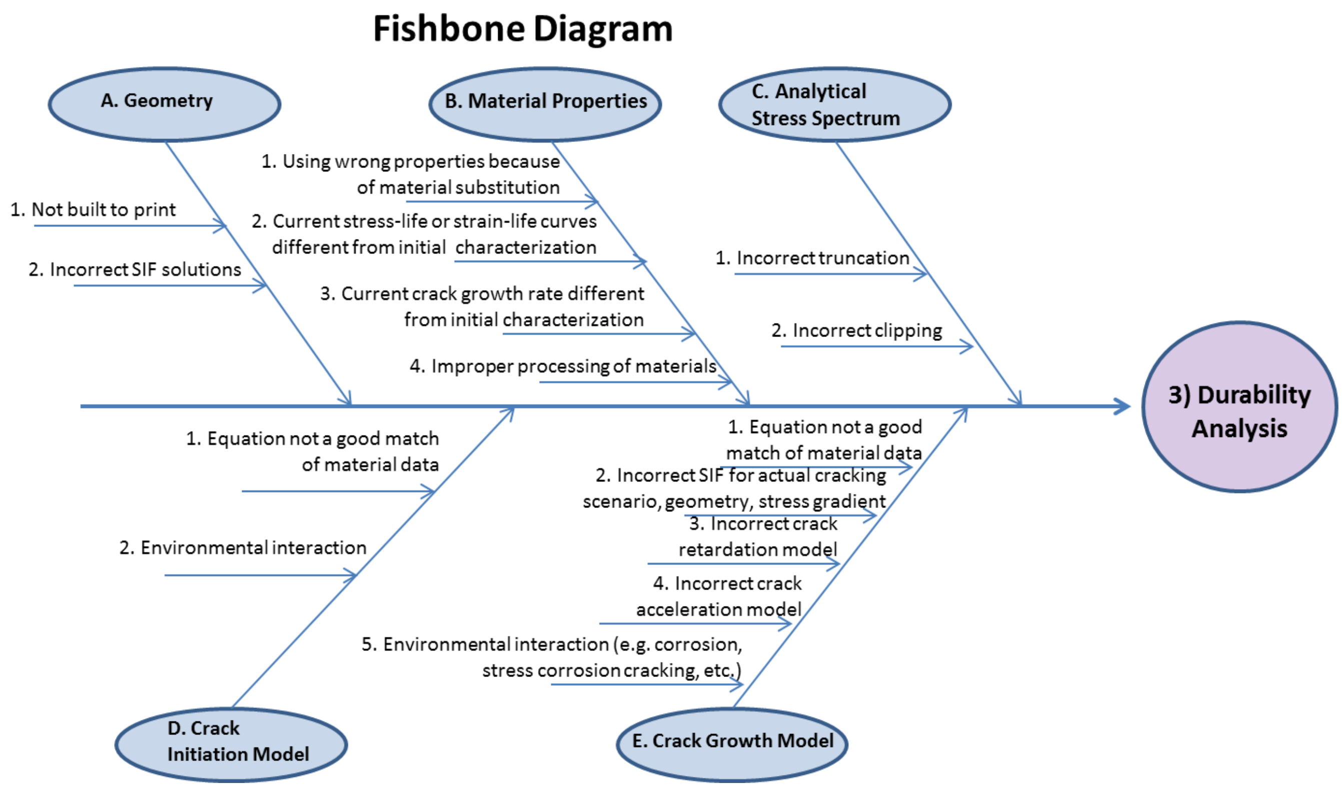

Figure 4 - Durability Analysis Fishbone Diagram

4) Aircraft Usage Analysis:

Reference 3 requires each program to perform individual aircraft tracking (IAT) by utilizing actual usage data to adjust maintenance intervals on an individual aircraft “by tail number” basis. All aircraft shall have systems that record sufficient usage parameters that can be used to determine the damage growth rates throughout the aircraft structure. The systems shall have sufficient capacity and reliability to achieve a 90-percent minimum valid data capture rate of all flight data throughout the service life of the aircraft. The systems shall include serialization of interchangeable/replaceable aircraft structural components, as required. The IAT Program shall be ready to acquire data at the beginning of initial flight operations.

To accomplish the IAT Program, analysis methods shall be developed which adjust the inspection and modification times based on the actual measured usage of the individual aircraft. These methods shall have the ability to predict damage growth in all critical locations and in the appropriate environment as a function of the total measured usage, and to recognize changes in operational mission usage. The methods shall also provide the ability to determine equivalent flight hours (EFH) as described in Reference 5.

A list of possible aircraft usage analysis sources of error that could lead to missed predictions of unanticipated fatigue cracking are as follows and are displayed in Figure 5:

A. IAT Model
    1. Crack acceleration incorrect or not considered
    2. Crack retardation incorrect or not considered
    3. Obsolete stress transfer functions
B. Recorded parameters & sample rate
    1. Insufficient to capture actual usage severity
C. Gap-filling for missing data
    1. Insufficient data capture rate
    2. Inadequate or un-conservative gap-filling method

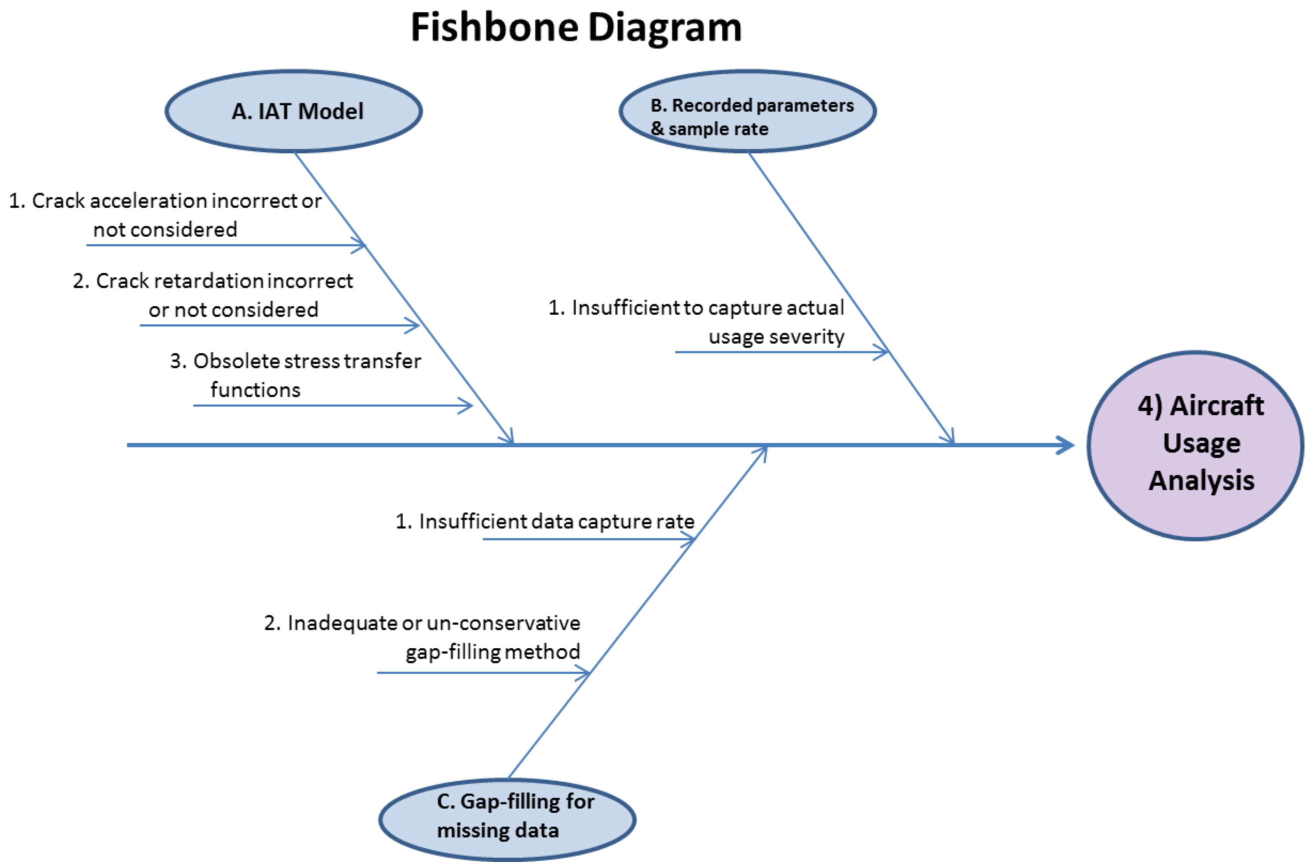

Figure 5 – Aircraft Usage Analysis Fishbone Diagram

5) Failure Analysis

Failure analysis was discussed in the introduction as the first step to be performed after discovering unexpected fatigue cracking. Understanding the mode of failure may help to reveal the root cause of unexpected fatigue cracking and ultimately to specify the most appropriate corrective actions to prevent recurrence. Therefore, the consequences of an inaccurate failure analysis include diverting resources from the most expedient method of prevention. A list of possible failure analysis sources of error that could lead to missed predictions of unanticipated fatigue cracking are as follows and are displayed in Figure 6:

A. Inaccurate Dimensional Verification
    1. Measurements performed incorrectly
    2. Dimensional requirements not available
    3. Articles distorted during service or failure
B. Inaccurate Composition Verification
    1. Composition verified using less accurate techniques, i.e. energy dispersive spectroscopy (EDS) vs. atomic absorption (AA) or inductively coupled plasma (ICP)
    2. Specified material unknown (drawings not made available to the analyst)
C. Inaccurate Fractography
    1. Incorrect morphology interpretation (i.e. fatigue vs. overload vs. stress corrosion)
    2. Failure to identify stress concentrations
    3. Incorrect measurement of the dimensions of a pre-cracked region
    4. Incorrect measurement of striation spacing[2] (i.e. measured out of plane, micro structural effects complicating interpretation of striations, microscope resolution limitations, etc.)
D. Inaccurate Mechanical Testing Conclusions
    1. Misalignment in testing
    2. Un-calibrated load cells
    3. Improper requirements (assuming the wrong material and/or product form or grain orientation)
E. Inadequate Manufacturing Review
    1. Improper Processing not identified
    2. Relevant Process changes not identified
    3. Relevant Material Review Board (MRB) actions not identified

[2] Inaccurate striation spacing estimates can result in non-conservative analyses. If striation spacing is used for correlation efforts, the measurements should be carefully evaluated as a potential cause for poor correlation.

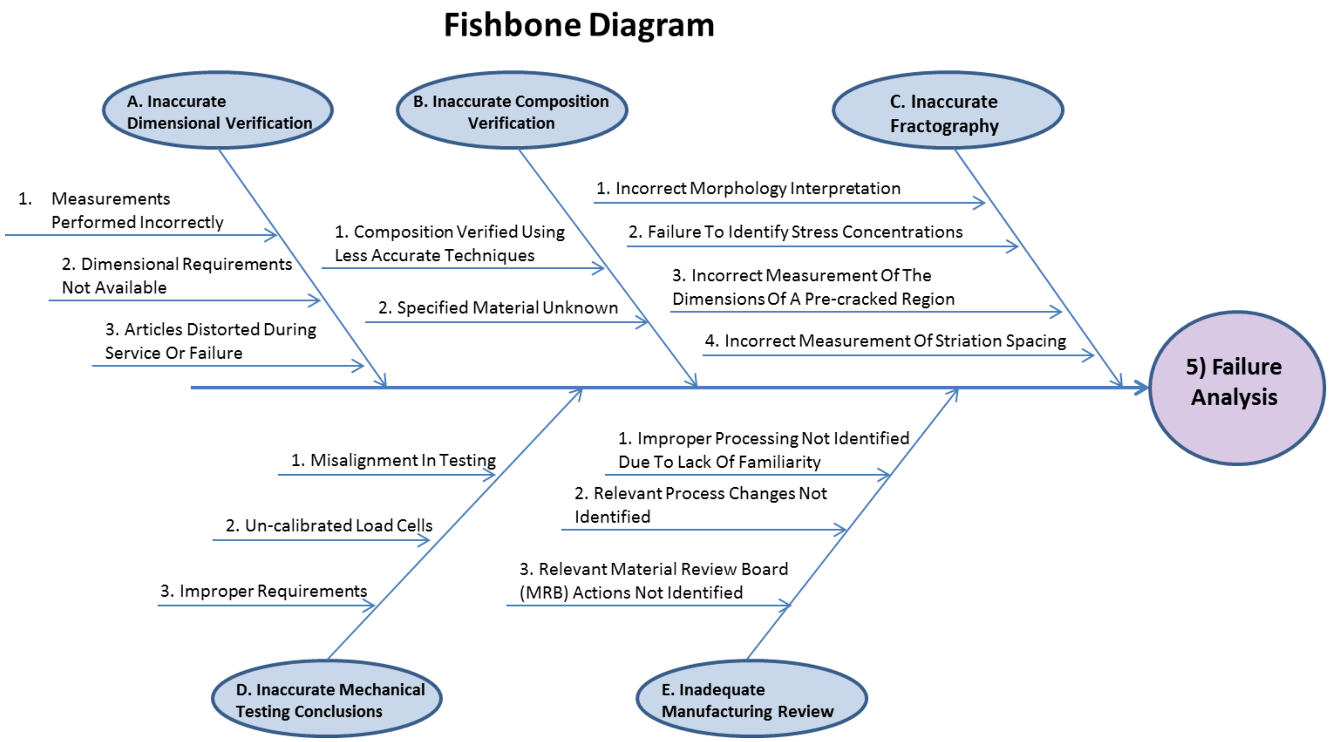

Figure 6 - Failure Analysis Fishbone Diagram

Summary

This Structures Bulletin has provided guidelines to identify possible sources of error when trying to match results of the durability analysis with the actual occurrence of unanticipated cracks found in the field or during testing. The identification of these sources of errors should allow for sufficient correlation between analyses and crack findings.

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Appendix

A KNOT chart (see Table A1) describes what is known (K), what needs (N) to be known, what is an opinion (O), and what is thought (T) to be known. It is useful for initially sorting the wheat from the chaff and organizing/coordinating the next steps of the problem-solving process. As you work your way through the problem, everything should move into the left column – Know. Fishbone (Ishikawa) diagrams (sometimes referred to as a herringbone diagram or a cause-and-effect diagram as seen in Figure A1) show the causes of a specific event. A fault tree is shown in Figure A2.

Table A1 – KNOT Chart

Know	**N**eed to Know	**O**pinion	**T**hink We Know

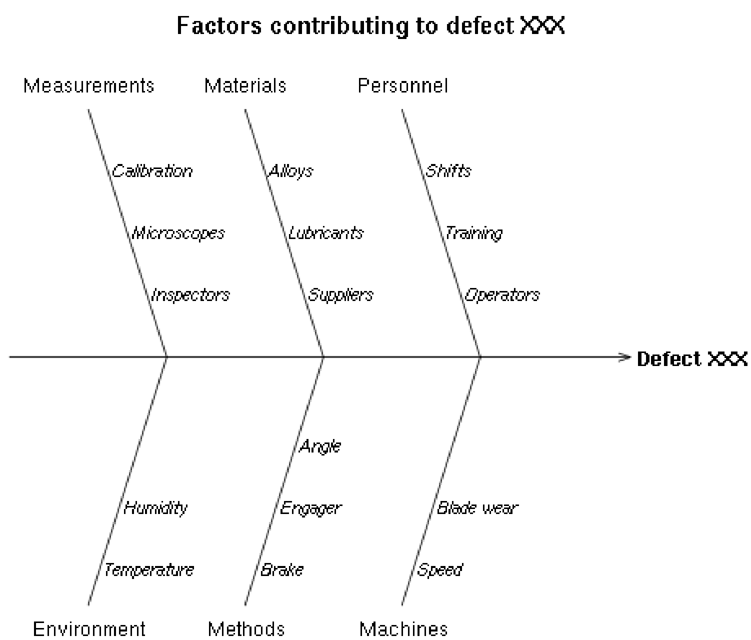

Figure A1 – Fishbone (Ishikawa) Diagram Example
(Ref Image: http://en.wikipedia.org/wiki/Ishikawa_diagram)

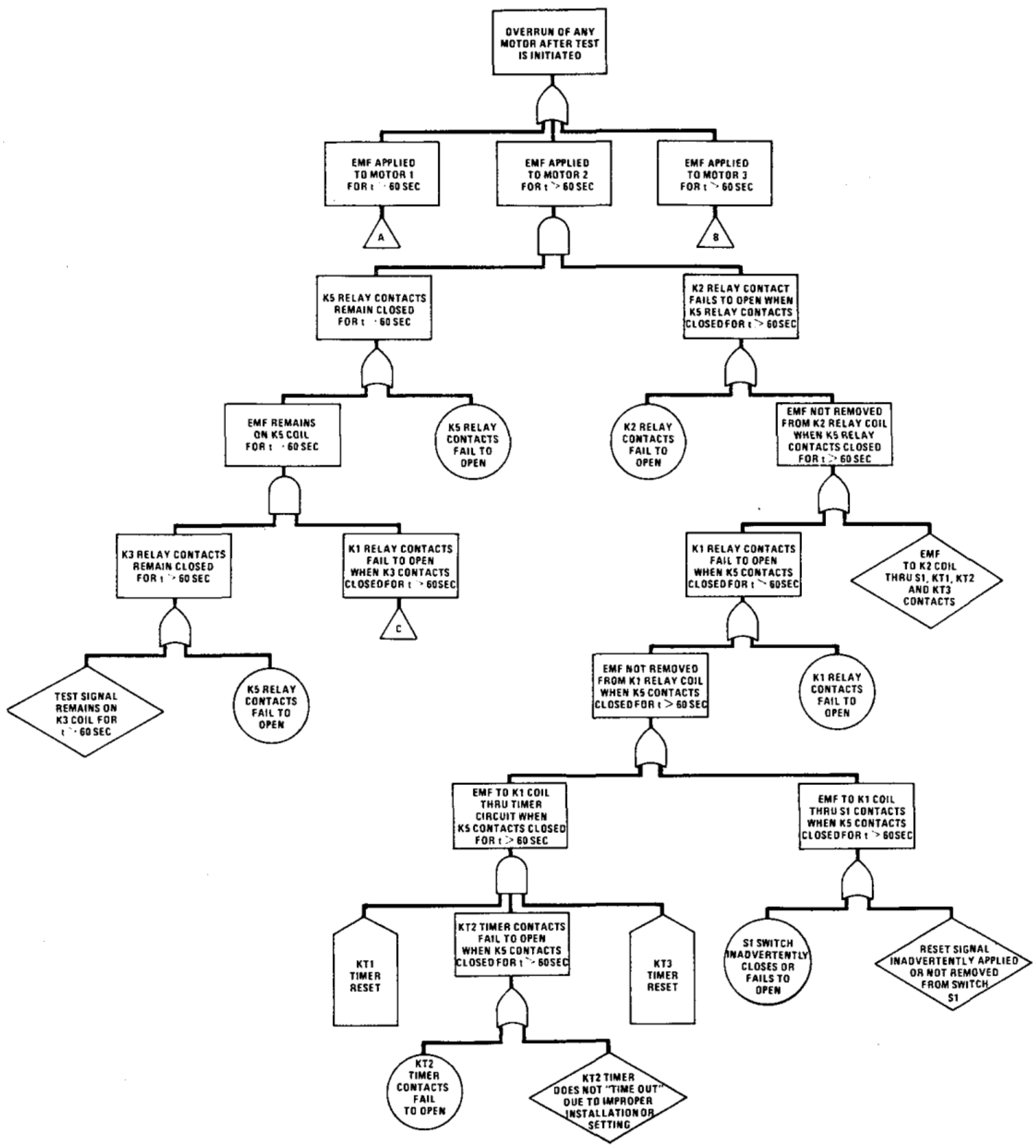

Figure A2 – Fault Tree Example
(Ref Image: NUREG-0492, Fault Tree Handbook, Jan 1981, Pg IV-2)