REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
26-10-2006	Technical Report	January 2006 - September 2006

4. TITLE AND SUBTITLE
Failure Analysis and Prevention for the Air Logistics Center Engineer: CAStLE Course Development Summary

5a. CONTRACT NUMBER
F05611-03-D-003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gregory A. Shoales, Jason Avram, James M. Greer, and Sandeep Shah

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Aircraft Structural Life Extension (CAStLE)
Department of Engineering Mechanics, HQ USAFA/DFEM
2354 Fairchild Drive, Suite 2J2, USAF Academy CO 80840-6240

8. PERFORMING ORGANIZATION REPORT NUMBER
USAFA-TR-2006-08

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
WRALC/EN
450 Third St., Bldg 323
Robins AFB, GA 31098

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
United States Air Force (USAF) Air Logistics Center (ALC) engineers are assigned to support the maintenance of operational aircraft fleets. As a result, they need to be well trained in specialized engineering topics related to that mission. Not the least of these topics are those of structural failure analysis and designing structure to prevent failure. While many commercially available short courses may appear to address these topics by their title, none have been found that target the specific needs of the ALC engineer. Furthermore, few such courses have instructors with first-hand knowledge of the duty requirements of and challenges faced by ALC engineers. These shortcomings not withstanding, sending ALC engineers to a vendor site for a week-long short course presents further challenges. Supporting the USAF aircraft fleet, while minimizing the impact to operations, requires

15. SUBJECT TERMS
course development, failure analysis failure prevention, Air Logistics Center training, case studies

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Gregory A. Shoales, P.E.
Unclassified	Unclassified	Unclassified		366	19b. TELEPHONE NUMBER *(Include area code)* 719.333.6213

Best Available Copy

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g.' F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Failure Analysis and Prevention for the Air Logistics Center Engineer: CAStLE Course Development Summary

Gregory A. Shoales, Jason Avram, James M. Greer, and Sandeep Shah

Center for Aircraft Structural Life Extension (CAStLE)
Department of Engineering Mechanics

HQ USAFA/DFEM
2354 Fairchild Drive, Suite 2J2
USAF Academy CO 80840-6240
(719) 333-6213, DSN 333-6213

September 2006

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DEAN OF THE FACULTY
UNITED STATES AIR FORCE ACADEMY
COLORADO 80840

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)
USAFA-TR-2006-08

Coordination and Approval

This article, *Failure Analysis and Prevention for the Air Logistics Center Engineer: CAStLE Course Development Summary*, is presented as a competent treatment of the subject, worthy of publication. The United States Air Force Academy vouches for the quality of the research, without necessarily endorsing the opinions and conclusions of the authors. Therefore, the views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the US Government.

This report has been cleared for open publication and public release by the appropriate Office of Information in accordance with AFI 61-202 and USAFA FOI 190-1. This report may have unlimited distribution.

Prepared by:

Gregory A. Shoales, Ph.D., P.E. _ **30 Sep 06** ___
Senior Research Engineer Date
Center for Aircraft Structural Life Extension

The report has been reviewed and is approved for publication.

SCOTT A. FAWAZ, Lt Col, USAF _ **27 Oct 06** ___
Director Date
Center for Aircraft Structural Life Extension

Abstract

United States Air Force (USAF) Air Logistics Center (ALC) engineers are assigned to support the maintenance of operational aircraft fleets. As a result, they need to be well trained in specialized engineering topics related to that mission. Not the least of these topics are those of structural failure analysis and designing structure to prevent failure. While many commercially available short courses may appear to address these topics by their title, none have been found that target the specific needs of the ALC engineer. Furthermore, few such courses have instructors with first-hand knowledge of the duty requirements of and challenges faced by ALC engineers. These shortcomings not withstanding, sending ALC engineers to a vendor site for a week-long short course presents further challenges. Supporting the USAF aircraft fleet, while minimizing the impact to operations, requires quick response to all engineering issues. Having ALC engineers off-site and away from their duties, for even a week, adds an unnecessary schedule burden to that support process. While some commercial vendors will provide on-site training, this option is not without a further cost burden over and above the already high short course cost.

The ALC Engineering Directorate at Warner-Robins Air Logistics Center sought to address the aforementioned training shortfall by tasking the USAF Academy's Center for Aircraft Structural Life Extension (CAStLE) to design a course to meet this need. This report details the result of that tasking. It presents the unique qualifications of CAStLE engineers as providers of current aging aircraft data and analysis tools, engineering faculty members and experienced ALC engineers. The development of the course, *Failure Analysis and Prevention for the ALC Engineer*, is chronicled in detail. These details include the course goal, course objectives, lesson objectives and all material used to present 30 topic lessons, guest lectures and case studies. This report further details the first course delivery at Robins Air Force Base (AFB) along with a complete analysis assessing the result of that delivery. Extensive attachments include student handouts for course administration, graphical material used for each lesson, case study scenario handouts, guest lecture material and raw assessment critique data. The course was very well received at the ALC and, as a result, additional offerings are planned in the future both at Robins AFB and at other USAF locations. As verified by student assessment, the resulting CAStLE course was directly on target with the current needs of the ALC engineer. This specialized course was delivered on-site with up-to-date professionally produced course books and electronic media for less than 40% of the cost of the typical commercially available general failure analysis course.

Contents

List of Figures

List of Tables

1. Background

The Engineering Directorate at Warner-Robins Air Logistics Center (ALC) is, among other things, responsible for maintaining the technical excellence of the ALC's engineering workforce. While it is expected that all engineers are products of accredited engineering programs, the Engineering Directorate seeks to ensure their engineers are up to date in topics which are relevant to the ALC engineer. To this end, they execute and track individual training programs for each of their assigned engineers. Topics which are particularly appropriate to the ALC engineer is that of structural failure analysis and, to even greater extent, design aimed at the prevention of such failures. This need is in fact common to all United States Air Force (USAF) ALCs.

A number of organizations offer short courses in failure analysis but few have the flexibility or expertise to tailor a course to specific ALC needs. Additionally, courses that require travel to an off-site facility are difficult to schedule around the high demands of supporting the operational USAF fleet.

The USAF Academy Center for Aircraft Structural Life Extension (CAStLE) is uniquely qualified to answer this ALC need. The primary mission of CAStLE is to provide data and tools aimed at solving current aircraft structures issues, and many of CAStLE's past and present projects respond to specific ALC requirements. CAStLE is integrated into the USAF Academy's Department of Engineering Mechanics (DFEM) and as such has complete access to all curriculum, instructional tools and faculty. Lastly, many of the CAStLE engineers are former DFEM faculty themselves with a combined 26 plus years of curriculum development, course directorship and classroom instruction at both the USAF Academy (USAFA) and the USAF Test Pilot School (TPS). Their faculty experience is in addition to over 70 combined years of aerospace engineering experience with more than 25 of that in the air logistics engineering specialty.

Given the need and the stated CAStLE qualifications, a program was undertaken in Fiscal Year 2006 (FY06) to design and deliver a course of instruction in *Failure Analysis and Prevention for the ALC Engineer*. This report documents the result of that program.

2. Course Development

2.1 Target Student

The starting place for this course development was the DFEM course titled Engineering Mechanics (EM) 445, Failure Analysis and Prevention. EM 445 is an undergraduate, optional course offered to USAFA Engineering majors after they have completed the required prerequisite courses which cover the following topics:

- elastic deformation
- failure criteria
- yielding and strengthening mechanisms
- linear elastic fracture mechanics
- fracture toughness
- fatigue failure

- fatigue crack growth
- fatigue life estimation
- creep

Given the diverse sources of engineering education across the ALC, it was unreasonable to assume that all potential students would have familiarity with all of these topics. Therefore, the decision was made to only limit attendance to engineers that had, at minimum, a modest level of experience in the ALC environment.

The following excerpt from the Course Introduction (Appendix A) captures the pre-requisite knowledge which served as the basis for the subject course development.

***Target Student*:** A company grade officer or GS-9/11/12 with a B.S. (minimum) in mechanical engineering, aeronautical engineering or engineering mechanics and one to five years of aircraft structures experience and at least one year of retainability at Robins AFB.

2.2 Course Goal and Objectives

The emphasis in the USAF Academy's EM 445 course is in failure analysis to include the laboratory techniques associated with evaluating failed structure. Additionally, the structure analyzed in EM 445 is not limited to aircraft. Laboratory techniques studied include specimen sectioning, specimen preparation and use of the multitude of tools that could be involved in a metallographic and/or fractographic evaluation. While such detail is appropriate to the undergraduate course, and may be useful background for an ALC engineer, it is not generally part of their day-to-day duties. Early on in the course development program, the Engineering Directorate identified *prevention* as being the focus of the ALC course. While the course would still address failure analysis, the instructional methodology was directed at addressing the prevention issue as it applies to typical aircraft structure. Laboratory techniques were sufficiently addressed only to the extent that students would understand the methods and effort involved in conducting a metallographic and/or fractographic evaluation, without necessarily being qualified to conduct one themselves.

The next step in development, as with any course, was the establishment of a course goal and supporting course objectives. These were developed by the CAStLE curriculum team and approved by the customer at the beginning of the development program. Table 1 is excerpted from the Course Introduction portion of the Administrative Student Handouts found in Appendix A and shows the resulting course goal and objectives.

Table 1: Failure Analysis and Prevention for the ALC Engineer course goal and objectives.

Course Goal
Students will understand how structural components fail. They will use this understanding to analyze failed components and determine the causes of failure as well as make recommendations to prevent future occurrences of failure.
Course Objectives:
Upon completion of this course, students will be able to:
1. ***Analyze*** structures for the mechanisms of failure by elastic and plastic deformation, linear elastic fracture mechanics, fatigue, corrosion and wear.
2. ***Identify*** and ***differentiate*** between observable fractographic features that indicate failures caused by yielding, fracture, fatigue, corrosion and wear in metals.
3. ***Identify*** the elements of failure in composite materials.
4. ***Recommend*** qualitative and quantitative changes to prevent future occurrences of failure.
5. ***Understand*** the history and impact of structural failure upon Air Force operational readiness and its Aircraft Structural Integrity Program.

2.3 Instructional Format

Ordinarily the next step in a course development is the establishment of lesson objectives that support the course objectives. In the case of a professional education course to be delivered to engineers at their duty stations, however, an additional step was necessary. This was to arrive at an agreement as to the amount of time to be allocated for the course. Equally important was how that time would be distributed in each day of instruction. Given this information the total time could be divided into reasonable blocks of instruction, thereby setting the number of lesson blocks available. These blocks were then allocated to individual lesson objectives in order to best serve the course goal.

Direction from the ALC Engineering Directorate set the course time block to be from 0800 to 1530 on Monday through Friday in a single week. This daily schedule was chosen so that engineers could still access their office during part of the normal duty day in order to address their most urgent duty requirements. Further discussions between the Engineering Directorate, CAStLE and other USAFA faculty members led to the decision that a fifty (50) minute block of instruction followed by ten (10) minute breaks would form the building block for each lesson. This length would permit enough time to address a topic, present examples or work on case studies without being unduly fatiguing to the students. Given the necessary time for lunch break, the chosen format resulted six lesson blocks per day with three in the morning and three in the afternoon, 30 lesson blocks in all.

The CAStLE plan for distribution of lesson topics amongst the 30 lesson blocks took into consideration a variety of factors. The first was the perceived importance of each topic to the daily mission of the USAF ALC engineer. This input was based on discussions with engineers in the Engineering Directorate as well as those assigned to the various ALC Program Offices to include the Aircraft Structural Integrity Program (ASIP) managers themselves. Additionally, such inputs were received directly from CAStLE engineers and DFEM faculty as many of them served in these positions during previous assignments. Another consideration was directed at serving the course development goal of having a course adapted to the "Target Student" as identified in Section 2.1. Given the expectedly diverse educational and experiential backgrounds in the potential student, this consideration required a gradual building of topic complexity. Introductory lessons would start with basic engineering knowledge (statics, strength of materials, etc.) as it applies to the analysis and prevention of structural failure. More advanced topics would then build on these introductory lessons. They would address objectives which are directly aimed at performing failure investigations and designing preventative courses of action. A related consideration was to make use of the daily schedule so as to present multi-lesson topics together in the same day. Since the multi-part topics build upon one another in sequence, scheduling them together maximizes student retention and therefore enhances instructional efficiency. Lastly, hands-on in-class student group analysis projects, called Case Studies, were used to reinforce blocks of topics. These Case Studies made use of real-life scenarios to emphasize the presented topics. Here again, in order to maximize efficiency, a case study was incorporated at the end of the relevant block of topics. Case Studies also served to "break up the day" by diverting from the sequence of class recitations. These lesson-block long exercise required student to apply what they just learned.

The resulting course syllabus and schedule is presented in Table 2.

Table 2: Failure Analysis and Prevention for the Air Logistics Center Engineer course syllabus and schedule.

	Monday	Tuesday	Wednesday	Thursday	Friday
0800-0850	Lesson 1: Introduction to Failure Analysis	Lesson 6: Distortion Failures	Lesson 11: Corrosion I	Lesson 16: Fatigue I	Lesson 21: Nondestructive Inspection Guest Lecture
0900-0950	Lesson 2: The Failure Analysis Method	Lesson 7: Fracture Modes and Stress Systems	Lesson 12: Corrosion II	Lesson 17: Fatigue II	Lesson 22: Composites Failures
1000-1050	Lesson 3: Conditions for Failure	Lesson 8: Ductile vs. Brittle Fracture	Lesson 13: Corrosion Guest Lecture	Lesson 18: Fatigue III	Lesson 23: Manufacturing Failures
			Lunch		
1230-1320	Lesson 4: Residual Stresses I	Lesson 9: Metallography and Fractography	Case Study 3: Corrosion	Lesson 19: Nondestructive Inspection I	Case Study 5: Summary Case Studies
1330-1420	Lesson 5: Residual Stresses II	Lesson 10: Metallography and Fractography Applications	Lesson 14: Wear	Lesson 20: Nondestructive Inspection II	Lesson 24: Material Substitution for Failure Prevention
1430-1520	Case Study 1: Residual Stress	Case Study 2: Failure Modes	Lesson 15: LEFM	Case Study 4: NDI and Fatigue	Lesson 25: ASIP

A final aspect of the instructional format was class size. The desired class size was set at approximately twenty students. The goal here was to accommodate as many students as possible while not making the class so big that it would hinder individualized attention.

Individual attention is critical during any type of instruction in order to make dynamic adjustments to the pace of each lesson. One example of such an adjustment would be to slow down and re-emphasize a point with a relevant example if the pace was "losing" some students. At the same time if the topic is too familiar to the majority of the students, the pace can be accelerated, giving time to add more detail to a given lesson, thus keeping the class engaged. Having too many students hinders the ability of any instructors to assess the appropriateness of the lessons pace. A reasonable instructor-to-student ratio was also important during the Case Studies in order to allow that sufficient attention be given to each group. An ideal class size of twenty (20) students was chosen was based on the combined experience of the hundreds of engineering sections taught at USAFA and USAF TPS by the course developers.

2.4 Lesson Development

The final phase of course development was to establish individual lesson objectives that would best support the course objectives and goal. Lesson objectives by definition are measurable statements of achievement for each lesson. Lesson objectives most frequently take the format of specifying what the student will know at the conclusion of each lesson. In the simplest terms, if a student satisfies the requirements of a set of lesson objectives which support the course objectives, then the instructor can be reasonably sure that the course goal has been met. In the typical class environment these objectives are assessed through graded events such as homework, projects and exams. One of the stated requirements from the Engineering Directorate of our development effort was that there would be no out of class assignments. The goal of this requirement was similar to the need for having our course offered on base in the first place; to deliver the course while minimizing the burden on the already heavily tasked ALC engineer. Achieving lesson objectives was therefore, for the most part, left up to the professionalism of the student. One exception was our integration of the Case Studies into the daily schedule. These exercises were done in small groups. As such, there was a certain amount of peer pressure to know the material presented and contribute to the group's effort. Additionally, the student interaction with instructors during lessons and their responses to various surveys was used to qualitatively assess the objectives.

The lesson objectives for each of the 30 lesson blocks shown in Table 2 are included in the Administrative Student Handouts found in Appendix A. The lessons can be divided into three primary categories as described in the following sections.

2.4.1 Topical Recitations

These lessons include introductory lessons of the more elementary material and advanced topics. The introductory lessons were designed to help "level the field" of education background in the course participants. These lessons built from the assumed prerequisite knowledge of any student which met the *target student* population. Advanced topics built off the introductory lessons to address specific knowledge required to achieve the course objectives and therefore meet the course goal. The delineation between what constituted an introductory lesson as opposed to an advanced lesson was of course dependent upon the specific educational background and professional experience of the individual student. Part of the curricular design included the incorporation of "topic teasers." The topic teasers were essentially small case studies which could be presented in just a few minutes. All topic teasers applied directly to the lesson topic and were case studies of real-world failures. The instructor would use these at various times during the lesson to motivate the topic and to provide insight as to its application. The recitation lessons are the light blue boxes in Table 2. The graphical materials used to present each of these topics are included in Appendix B.

2.4.2 Case Studies

As previously stated, the Case Studies served to reinforce a given block of lesson objectives by practical application of those objectives. They also provided a daily change of pace from the recitations. Case Studies afforded students exposure to real-world failure analysis scenarios that they might not have otherwise experienced in their current duties. The case study topics are shown by the tan boxes in Figure 1. Using a building block approach, the case study scenarios evolved during the course from a guided exercise to the more open ended analysis which required synthesis of a variety of course topics. All Case Study handouts are included in Appendix C.

2.4.3 Guest Lectures

As the name implies, these lesson brought in a guest from some particular USAF center of expertise. The intent of these lessons was to not only provide additional detail but also to obtain an official USAF point of view. Guests from the Air Force Research Laboratory (AFRL) non-destructive inspection office and the Air Force Corrosion Prevention and Control Office (AFCPCO) served in this capacity. It is worth noting that the guests were provided with lessons objective, as given in Appendix A, to ensure their presentation supported the course objectives. Their lessons are noted by the yellow boxes in Figure 1. The graphical materials used by the guests to present their topics are included in Appendix D.

An additional guest lecture was added to the schedule shown in Figure 1. This was a lesson in the usage of the AFGROW crack growth software. The opportunity to have Mr. Jim Harter of AFRL present AFGROW to the class arose after the schedule had been set. Rather than eliminating a topic to make room, arrangements were made to have a working lunch on Thursday. This period was then used by Mr. Harter to give his AFGROW overview. All presentation material along with supplemental AFGROW guidance is also included in Appendix D.

3. Course Development Results

This section describes the result of the course development effort based on its first offering.

3.1 Delivery

The first offering of *Failure Analysis and Prevention for the ALC Engineer* was delivered the week of 17-21 April 2006 at Robins AFB, GA. The CAStLE instructors for this first offering are shown in Table 3.

There were 22 students in this offering. In addition to Robins AFB students, this total included two students from Tinker AFB and one from Hill AFB. Students ranged from very junior engineers to senior ASIP managers. The class included both military and civilian engineers.

Table 3: CAStLE instructors for 17-21 April 2006 delivery of Failure analysis and Prevention for the ALC Engineer at Robins AFB, GA.

Name	Title
Dr. Gregory A. Shoales, P.E.	CAStLE Senior Research Engineer and former DFEM Professor of Engineering Mechanics
Dr. Sandeep Shah	CAStLE Senior Metallurgist
Capt. Jason Avram	DFEM EM 445 Course Director and former ALC Engineer

All students were provided with printed copies of all items presented in Appendices A through D in a course notebook. This course notebook was not only intended to be used during the course delivery but also to be available as a reference after the course was complete. Each document was also provided electronically to all students on a CD. Additionally, this CD contained a wide variety of supplemental material also intended as a useful reference for students. These included publications which addressed corrosion, structural integrity programs, material substitution, NDI techniques and a vast assortment of failure analysis case studies.

The facility used was the Eagle Conference Room in the Robins AFB Museum. The room was configured with large tables which afforded each student ten to twelve square feet of work space. All graphical materials were projected onto an eight foot wide screen. The projection system had sufficient lumens to provide clear, high contrast images under full room lighting.

3.2 Assessment

All students were made aware of the developmental nature of the course and that their input would greatly enhance the development process. To this end they were asked to complete a brief survey after each lesson and an end-of-course survey after the very last lesson block on Friday.

3.2.1 Lesson Surveys

The lessons surveys all included the same four questions shown in Figure 1 from Lesson 1.

Lesson 1: Introduction to Failure Analysis
This material was new to me:

0	1	2	3	4
Not at All		About Half		All of It

This material will be useful to me in my job:

0	1	2	3	4
Not at All		Moderately		Most Useful

I would improve this lesson by (changing, emphasizing, adding, deleting…):
(Your comments here)

I have an idea for a Case Study for this lesson:

Figure 1: Typical lesson survey which students filled out after each lesson.

The first two questions called for a quantitative assessment of the presented topic. The first of these called for a judgment of the whether or not the lesson taught them something new. The second simply asked for whether or not the lesson topic was applicable to their assigned duties in the ALC. An average response of greater than 2.0 on the first would indicate that the majority of the lesson was new material to the class. Similarly, an average response of 2.0 or greater on the second would indicate that the topic was useful to the class. It was expected that the introductory lessons, the earlier topics, would be useful to most but not necessarily new. It was hoped that all topics would be considered useful to the class as this was the goal of the topic selection process.

The averaged results from both quantitative course survey questions are presented graphically in Figure 2.

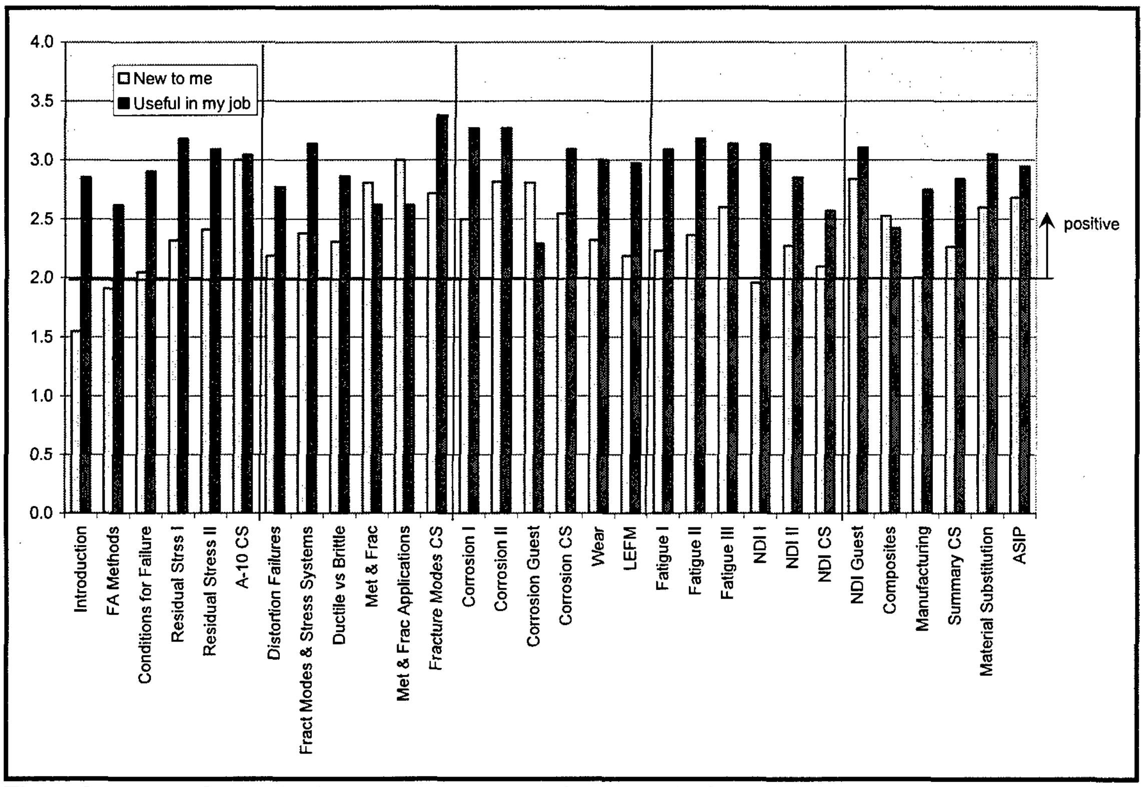


Figure 2: Averaged quantitative course survey questions listed by lesson title.

As expected, some of the introductory topics did not present new material to the majority of the students. All lessons addressed topics which the class considered useful to their assigned ALC duties.

The last two lesson survey questions sought comments to help enhance the lessons for future offerings. The last of these was specifically targeted at obtaining new case studies from the recent experiences of the class members. Unfortunately the responses to both questions were extremely limited. The only significant comments addressed the guest lecturers. Several comments agreed that the presentation made by the guest from the AFCPCO did not support the lesson objectives or the course goal. While this comment was shared by nearly half the class it was curious given the somewhat high average ratings of 2.8 and 2.3 for "*new to me*" and "*useful in my job*" for this lesson. In contrast most students agreed that the NDI guest was not given enough time. While the presentation was very well received, the students just wanted to hear more of it. In fact, as an example of the dynamic adjustment discussed in Section 2.3, the NDI guest's time slot was extended by 30 minutes. The next two lessons were accelerated somewhat to keep the daily schedule within the given allotment.

3.2.2 End-of-Course Surveys

The end-of-course survey contained eight questions which were intended to evoke more input from the class of specific course enhancements. These questions are given in Figure 3.

1. **What did you like about this course?**
2. **What did you dislike about this course?**
3. **Were having printed materials (your binder) an aid to your experience this week?**
4. **Do you think you will reference your book after this week? YES NO**
5. **Do you think you will reference your CD after this week? YES NO**
6. **Did the hour-long daily case studies support the course objectives?**
7. **What changes or additions would you suggest to make this course better for future offerings?**
8. **Would you recommend this course to another ALC engineer? YES NO Why or why not?**

Figure 3: End-of-course survey questions.

The raw data from the end-of-course survey is included in Appendix E. These data are transcribed precisely as it was received. The remaining paragraphs in this subsection summarize the class response. All students liked the fact that the lessons were targeted at what they needed as ALC engineers. A repeated favorable comment was the application focus designed into the presentation of each topic. Another favorable comment was the feeling that the instructors were very knowledgeable in the subject and qualified, experienced instructors. Many topics were particularly cited by students as favorable inclusions in the course because of their applicability and/or the fact that they had little or no preparation for this material in school. Some of these topics included; LEFM, fatigue, NDI and corrosion.

As with all questions we urged student to think of some input for each. When it came to negative comments there was balance of responses that said more time should be spent on certain topics while other students said less time should be spent on those very same topics. This result is not surprising and confirms the expectation that the class would come from diverse education backgrounds. Other comments addressed delivery aspects such as the classroom image projection size and the comfort of the chairs. Overall, the negative comments were not very telling when it comes to improvement. The one repeated negative comment addressed our decision to have AFGROW presented over a working lunch. As one student put it, this "made for a very long day". Others simply stated it was too much material in too short a period.

All students strongly agreed that having all material printed in advance and provided at the beginning of the course enhanced their learning experience. All students universally commented that they expected to reference both their course book and their course CD after the course week was complete. Another unanimous comment was in favor of the daily case studies. Students felt that the case studies, topic teasers and other in class examples were a critical component to being able to fully achieve the lesson objectives. One student even suggested it would be worth extending the class day in order to add to the number of case studies.

In answering question 7, while one student suggested the course could be shortened, most thought adding time material would improve future course offerings. Most agreed that the extra time should be devoted to increasing the number of case studies and real life examples.

Finally, all students said they would recommend this course to other ALC engineers. The reasons cited are similar to the favorable comments made in answering the previous questions. They emphasized the course's application to the ALC engineer's mission and the use of real-world examples. Students commented that this course should be required for all ALC engineers as well as all acquisition engineers. One student said "I grew a basic understanding of structural failure and analysis despite not having a structures background."

4. Conclusions and Recommendations

After reviewing all the data there did not seem to be any compelling reason to eliminate any particular topics nor significantly change the course sequence. In the initial course delivery three lessons lacked a topic teaser. Given the overwhelming importance students attached to this and other examples, future offering must include at <u>least</u> one topic teaser for each lesson.

The input of extending the class day must be balanced with the duty requirements of the participants. Clearly the three students that traveled away from their home station to take the course had more time available in their days. However, this surplus availability did not seem to be shared by the local participants. CAStLE concurred with the input from the Warner Robins ALC that student must be left with time in the day, however minimal, to address urgent tasks. Future offerings should be reevaluated by the participating ALC to determine the best balance of time to be dedicated to class time.

The guest lectures are somewhat dependent on the availability of the right individual from the outside agency. Some ALCs may even have in house individuals that would be more applicable to their mission than those used for the subject offering. Keeping the offering time equal, CAStLE would concur with the student comments that the guest time could be redistributed. The AFCPCO in particular did not adequately address the course objectives. Unless a better understanding of course requirements could be achieved, CAStLE would recommend deleting that guest from future offerings. CAStLE suggests using that time for a more complete AFGROW presentation rather than use the working lunch concept. One caveat would be that the presenter must be highly experienced in the *teaching* the use of the AFGROW software package. Overall, guests must be well prepared by the course faculty and fully understand the course goal and their role in achieving the course objectives.

Follow-up conversations have taken place since this first offering. One of the students from the Oklahoma City ALC took his comments back to his engineering leadership. As a consequence of this input, CAStLE is slated to present the course to at least one class at Tinker AFB in FY07. Additionally, those responsible for engineering training at Warner-Robins ALC have expressed interest in one or two more additional offerings delivered during FY07 at Robins AFB. It is worth noting here that part of the subject course development tasking was to deliver all course material to the Robins AFB Engineering Directorate. Despite having accomplished this delivery, those in charge of the training programs have expressed a strong desire to have CAStLE present all future course offerings.

This Page
Intentionally
Left Blank

APPENDIX A: Course Administrative Student Handouts

USAFA RESEARCH

Failure Analysis and Prevention for the Air Logistics Center Engineer

Course Description: Failure mechanisms in typical aircraft structure are presented along with methods to identify each mechanism and its potential impact on structural integrity and life. Various laboratory and field techniques are presented to evaluate structural components to include nondestructive inspection and fractographic/metallographic analysis. Failure prevention methodologies are discussed including component redesign (changes in geometry, material selection and material processing), changes in operation (e.g., flight restrictions) and application of coatings.

Instructors: USAF Academy's Center for Aircraft Structural Life Extension

Primary Citations: Donald J. Wulpi, *Understanding How Components Fail*, 2nd ed. ASM International, 1999.
Norman E. Dowling, *Mechanical Behavior of Materials*, 2nd ed., Prentice Hall, Inc., 1999.

Course Goals: Students will understand how structural components fail. They will use this understanding to analyze failed components and determine the causes of failure as well as make recommendations to prevent future occurrences of failure.

Course Objectives: Upon completion of this course, students will be able to:

1. ***Analyze*** structures for the mechanisms of failure by elastic and plastic deformation, linear elastic fracture mechanics, fatigue, corrosion and wear.
2. ***Identify*** and ***differentiate*** between observable fractographic features that indicate failures caused by yielding, fracture, fatigue, corrosion and wear in metals.
3. ***Identify*** the elements of failure in composite materials.
4. ***Recommend*** qualitative and quantitative changes to prevent future occurrences of failure.
5. ***Understand*** the history and impact of structural failure upon Air Force operational readiness and its Aircraft Structural Integrity Program.

Target Student: A company grade officer or GS-9/11/12 with a B.S. (minimum) in mechanical engineering or aeronautical engineering or engineering mechanics and one to five years of aircraft structures experience and at least one year of retainability at Robins AFB.

ADDITIONAL COURSE CITATIONS

Boyer, H.E., and Gall, T.L., eds., ASM Metals Handbook - Desk Edition, ASM International, Materials Park, OH, 1985.

Davis, J.R., ed., Corrosion: Understanding the Basics, ASM International, Materials Park, OH, 2000.

Davis, J.R., ed., Aluminum and Aluminum Alloys, ASM International, Materials Park, OH, 1993.

Dickson, J.I., ed., Failure Analysis: Techniques and Applications - Conference Proceedings, ASM International, Materials Park, OH, 1992.

Cartz, Louis, Nondestructive Testing, ASM International, Materials Park, OH, 1995.

Feld, Jacob and Carper, Kenneth L., Construction Failure, John Wiley & Sons, Inc., New York, 1997.

Gibala,, R. and Hehemann, R.F., eds., Hydrogen Embrittlement and Stress Corrosion Cracking, American Society for Metals, Metals Park, OH, 1984.

Gordon, J.E., Structures: Or Why Things Don't Fall Down, Da Capo Press, New York, 1978.

Gordon, J.E., The New Science of Strong Materials, Princeton University Press, Princeton, NJ, 1968.

Hutchings, F.R. and Unterweiser, P.M., Failure Analysis: The British Engine Technical Reports, American Society for Metals, Metals Park, Ohio, 1981.

Levy, Matthys and Salvadori, Mario, Why Buildings Fall Down, W.W. Norton & Co., New York, 1994.

Naumann, F.K., Failure Analysis: Case Histories and Methodology, American Society for Metals, Metals Park, OH, 1983.

Pilkey, W. D., Peterson's Stress Concentration Factors, 2nd Edition, Wiley Interscience, 1997.

Petroski, Henry, To Engineer is Human, Vintage Books, New York, 1982.

Petroski, Henry, Design Paradigms: Case Histories of Error & Judgement in Engineering, Cambridge University Press, Cambridge, UK, 1994.

Powell, G.W., et al, A Fractographic Atlas of Casting Alloys, Battelle Press, Columbus, OF, 1992.

Powell, G.W., ed., ASM Handbook, Volume 11: Failure Analysis and Prevention, ASM International, Materials Park, OH, 1986.

Raj, B., Jayakumar, T., and Thavasimuthu, M., Practical Non-Destructive Testing, ASM International, Materials Park, OH, 2002.

Schlager, Neil, Breakdown, Visible Ink Press, Detroit, MI, 1995.

Uhl, R.C., ed., Handbook of Case Histories in Failure Analysis, ASM International, Materials Park, OH, 1992.

Witherell, Charles E., Mechanical Failure Avoidance – Strategies & Techniques, McGraw-Hill, New York, 1994.

Lesson Objectives

Lesson 1: Introduction to Failure Analysis

1. **Define** "failure analysis"
2. **Identify** the main goal of failure analysis
3. **Identify** the most common aircraft structural failure modes

Lesson 2: Failure Analysis Method

1. **Discuss** steps of a failure analysis and **describe** their relationship to one another
2. **Describe** the guiding principles of failure analysis
3. **Identify** the basic questions that a failure analyst should be able to ask and answer
4. **Describe** how the concept of failure applies to more than just the fracture of a component

Lesson 3: Conditions for Failure

1. **Distinguish** between fracture and other failure modes
2. **Identify** the differences/similarities between various failure modes
3. **Describe** the relationship between conditions, capabilities and corresponding failure modes.

Lesson 4: Residual Stresses I

1. **Describe** how residual stresses are caused and describe their results
2. **Distinguish** between various types of residual stresses and their sources.

Lesson 5: Residual Stresses II

1. **Describe** how to produce beneficial residual stresses and know where they are useful
2. **Identify** potential applications of residual stress to failure prevention

Lesson 6: Distortion Failures

1. **Define** distortion failure
2. **Describe** various distortion modes and the stress states that cause them
3. **Describe** the relationship between distortion and failure

Lesson 7: Fracture Modes and Stress Systems

1. **Distinguish** between the shear, cleavage, intergranular and fatigue modes of fracture
2. **Describe** the five basic stress systems that cause failure
3. **Identify** distinguishing visible features of tensile, torsional, bending, compression, & fatigue stress systems causing failure in brittle & ductile materials

Lesson 8: Ductile vs. Brittle Fracture

1. **Determine** differences between brittle and ductile fracture
2. **Describe** fractographic appearances/differences of/between brittle and ductile fracture surfaces
3. **Discuss** the various factors which determine whether a component will fail in a brittle or ductile manner

Lesson 9: Metallography and Fractography

1. **Define** the difference between *metallography* and *fractography*
2. **Discuss** the principles of fractography and metallography
3. **Describe** the techniques used in performing a metallographic or fractographic evaluation

Lesson 10: Metallography and Fractography Applications

1. **Know** how a typical failure analysis investigation might be conducted
2. **Describe** fracture surface characteristics and terminology associated with various failure modes
3. **Describe** the limitations of metallography and fractography techniques/equipment

Lesson 11: Corrosion I

1. **Describe** the principles of corrosion
2. **Discuss** the material and environmental factors that contribute to corrosion

Lesson 12: Corrosion II

1. **Identify** the differences/similarities between different types of corrosion
2. **Describe** potential corrosion preventive measures

Lesson 13: Corrosion Guest Lecture

1. **Discuss** the USAF/DoD Corrosion Prevention Program

2. **Describe** how corrosion impacts structural life
3. **Describe** how corrosion impacts fleet management

Lesson 14: Wear

1. **Discuss** differences between types of wear and where each may be found
2. **Describe** contact stress fatigue
3. **Describe** the benefits/application of lubrication and other wear preventatives

Lesson 15: LEFM

1. **Discuss** the concept of stress concentrations
2. **Discuss** the foundations of fracture mechanics
3. **Describe** geometry factors used to solve fracture problems.
4. **Describe** how K_C varies as thickness varies.
5. **Describe** how LEFM is used during the design (or re-design) process.
6. **Discuss** why fracture receives so much attention in failure analyses

Lesson 16: Fatigue I

1. **Define** fatigue
2. **Identify** the 3 stages of fatigue crack growth
3. **Describe** the primary fractographic features of fatigue in metals

Lesson 17: Fatigue II

1. **Describe** how specific fractographic features relate to fatigue stress conditions
2. **Describe** the effects of overloads on crack length, crack growth rate, and striation spacing

Lesson 18: Fatigue III

1. **Describe** the stress-based approach to fatigue analysis
2. **Describe** the fracture mechanics-based approach to fatigue analysis

Lesson 19: Nondestructive Inspection I

1. **Discuss** the relationship between failure analysis, prevention, and nondestructive inspection (NDI)
2. **Describe** various common NDI techniques
3. **Identify** the appropriate NDI technique to use for a given application

Lesson 20: Nondestructive Inspection II

1. **Define** basic NDI terms such as POD, POI and a_{DETECT}
2. **Differentiate** between an indication and a finding
3. **Discuss** the reasonable expectations of various NDI techniques

Lesson 21: Nondestructive Inspection Guest Lecture

1. **Discuss** the field-ability of various NDI techniques/equipment
2. **Describe** how field-ability impacts the probability of inspection

Lesson 22: Composites Failures

1. **Define** a composite material
2. **Identify** the various types of failure in composite materials
3. **Describe** how processing quality impacts failure and/or life
4. **Describe** composite structure failure inspection and prevention methods

Lesson 23: Manufacturing Failures

1. **Discuss** how mechanically fastened joint quality impacts failure and/or life
2. **Describe** how material processing quality impacts failure and/or life
3. **Describe** how bonded joint quality impacts failure and/or life

Lesson 24: Material Substitution for Failure Prevention

1. **Describe** the life cycle of alloy development
2. **Discuss** how seemingly "poor" alloy choices may be made by manufacturers
3. **Discuss** how material substitution, without geometric redesign, can prevent failure

Lesson 25: ASIP

1. **Distinguish** between the safe-life, fail safe, and damage tolerant approaches to design
2. **Define** the USAF's Aircraft Structural Integrity Program (ASIP)

3. **Discuss** the magnitude of the USAF's "Aging Aircraft" problem
4. **Discuss** the relationship between ASIP and failure prevention

Case Study 1: Residual Stress

1. **Apply** failure analysis tools to the assessment of a real-world failure
2. **Recommend** possible corrective action(s) for a real-world failure

Case Study 2: Failure Modes

1. **Apply** failure analysis tools to the assessment of a real-world failure
2. **Recommend** possible corrective action(s) for a real-world failure

Case Study 3: Corrosion

1. **Apply** failure analysis tools to the assessment of a real-world failure
2. **Recommend** possible corrective action(s) for a real-world failure

Case Study 4: NDI and Fatigue

1. **Apply** failure analysis tools to the assessment of a real-world failure
2. **Recommend** possible corrective action(s) for a real-world failure

Case Study 5: Summary Case Studies

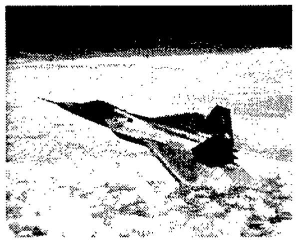
1. **Apply** failure analysis tools to the assessment of a real-world failure
2. **Recommend** possible corrective action(s) for a real-world failure

APPENDIX B: Graphical Material used to Present Recitation Lessons

This Page Intentionally Left Blank

Lesson 01

Failure Analysis and Prevention



1

Introductions

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The Course
  - Policies
  - Theme: *Preparation for Practice*
  - Approach
- You
- Your Instructors
  - Dr. Greg Shoales
  - Dr. Sandeep Shah
  - Capt. Jason Avram

2

Dr. Gregory Shoales, P.E.

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Professional:
  - Currently Senior Research Engineer with CAStLE
  - Professor of Engineering Mechanics
  - USAF Flight Test Engineer
  - USAF Acquisition Engineer
  - OEM Aircraft Structural Design Engineer
  - USA Large Caliber Weapons Development Engineer
- Education:
  - PhD, Engineering Science and Mechanics, Penn State
  - Masters and BS, Aeronautical Engineering, RPI
  - SOS, ACSC
  - APDP Level III: SPRDE, PM, T&E

3

Dr. Sandeep R. Shah

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Professional:
  - Currently Research Engineer with CAStLE
  - Research Associate, University of Colorado 2000-2004
  - Guest Scientist, Max Planck Institute, 2002
- Education:
  - PhD, Mechanical Engineering, University of Colorado
  - MS, Metallurgy, Indian Institute of Science, Bangalore
  - BE, Production Engineering, University of Mumbai.
  - LME Mechanical Engineering, VJTI, Mumbai, India

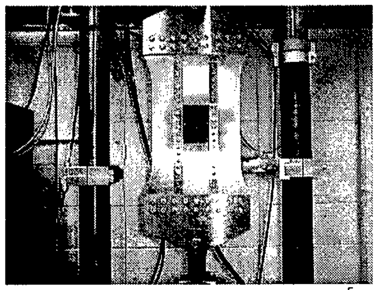
4

Capt. Jason Avram

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Mechanical Engineer, 62E3H

- May 1996: USAFA Commission
- 1998 - 2001: Wright-Patt AFB (Dayton, OH)
  - Aeronautical Systems Center (AFMC)
    - Collocated to Air Force Research Laboratory
    - Materials Process Engineer in Bonded Repair Technology
  - Air Force Institute of Technology
    - M.S. Material Science
    - Composite Bonded Repair



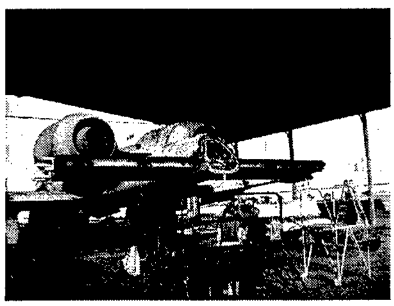
5

Capt. Jason Avram

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Mechanical Engineer, 62E3H

- 2001-2004: Hill AFB (Ogden, UT)
  - Process Development Engineer (MAPA Directorate)
  - Deputy Lead, A-10 Structural Engineering
  - A-10 ABDR Chief Engineer



- 2004 - present: USAFA, CO
  - Instructor of Engineering Mechanics
  - Center for Aircraft Structural Life Extension (CAStLE)

6

Course Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this course, engineers will be able to:
  - **Understand** how (structural) components fail
  - **Analyze** failed components and make recommendations for improvement
- In order to reach this goal, the following objectives must be satisfied:
  - **Analyze** structures for the mechanisms of failure by elastic and plastic deformation, linear elastic fracture mechanics, fatigue, corrosion, and wear
  - **Identify** and **differentiate** observable fractographic features that indicate yielding, fracture, fatigue, corrosion, and wear in metals
  - **Identify** the elements of failure in composite materials
  - **Recommend** changes to prevent future occurrences of failure
  - **Understand** the history, impacts, and ethical implications of failure on the U.S. Air Force operational readiness

7

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

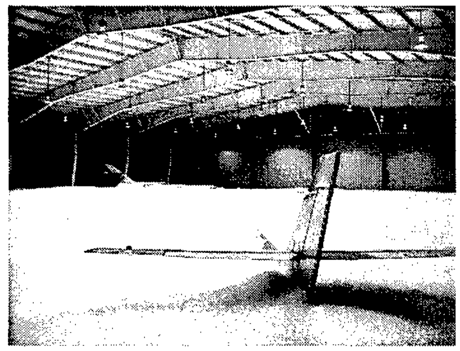
- After this lesson, engineers will have an understanding of failure, failure analysis, and the goals of failure analysis.
- Objectives
  - **Define** failure
  - **Define** "failure analysis"
  - **Identify** the main goal of failure analysis
  - **Identify** the most common aircraft structural failure modes

8

What is Failure?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fracture
- Excessive Yielding
- Environmental
  - Corrosion
  - UV Attack
  - Atomic Oxygen attack
- Discoloration
- "Failure to fail"
- IN GENERAL: The inability of a component to function as intended (usually unexpectedly)

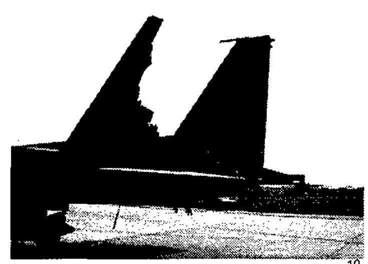


9

What is Failure Analysis?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

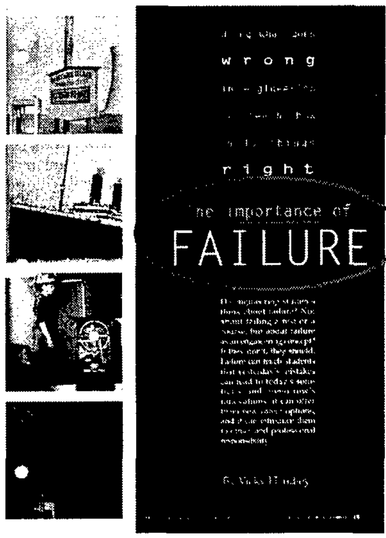
- Asking Questions
  - What caused the failure?
    - Poor initial design - Hartford Civic Center
    - Inadequate design information – A-10 quadrupled # of high-G turns versus designed-for case
    - Change in use - B-52s from high- to low-level mission
    - Failure to manufacture according to design - KC Hilton
    - Failure to maintain properly – TN ANG C-141
  - How many affected?
  - Can it be tolerated until repair?
  - How can we fix it?
  - WHO IS RESPONSIBLE?
- Doing Analysis
- Observing
- Simulation/Re-creation



10

Why is Failure Important?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



?

11

What is Failure Prevention?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Learning From Mistakes
  - There <u>is</u> a benefit to failure
    - *Failure is success if we learn from it.* (Malcom Forbes)
  - Progress, far from consisting simply of change, depends on a knowledge of the past....
    - *Those who cannot remember the past are condemned to repeat it* (George Santayana, <u>The Life of Reason</u>)
  - SO...We study failures in order to know how to prevent them in future designs!
- A key part of learning how to design

12

Why Aircraft Fail

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

	Percentage of Failures	
	Engineering Components	Aircraft Components
Corrosion	29	16
Fatigue	25	55
Brittle Fracture	16	-
Overload	11	14
High Temperature Corrosion	7	2
SCC/Corrosion Fatigue	6	7
Creep	3	-
Wear/Abrasion/Erosion	3	6

13

Case Histories

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Pertinent information in failure case histories
  - Short (10-15 minutes)—Topic Teasers
  - Long (50 minutes)—Case Studies
- Key information
  - Summary of Event(s) [WHO? WHAT? WHERE? WHEN?]
  - Documentation & Analysis [HOW?]
  - Discussion of ramifications [SO WHAT?]
  - Recommendations [NOW WHAT?]
- Interesting and, if done properly, easy to learn from
- A primary tool for teaching this course

14

Topic Teaser: Aloha Airlines Flt 243

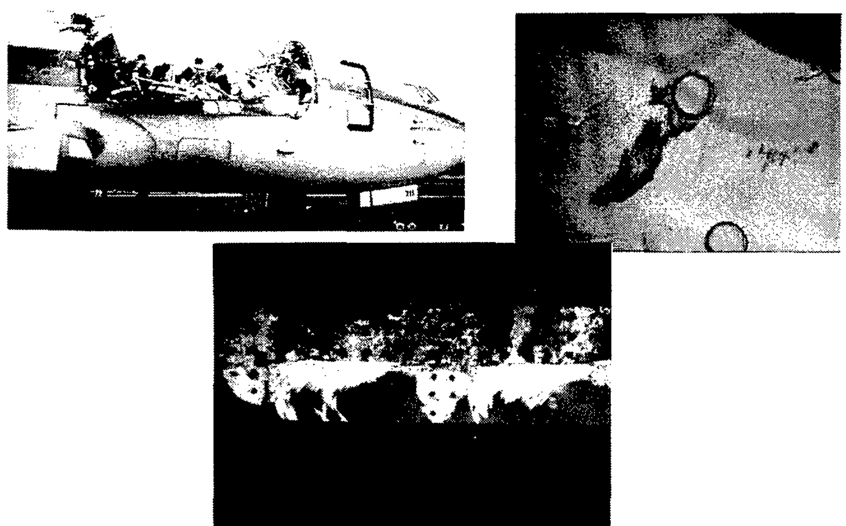
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Aloha Airlines' Boeing 737-200
  - **Built in 1969, Boeings 152nd 737**
  - **35,496 flight hours; 89,680 landings (2nd highest worldwide)**
- Fuselage lap splice joints were cold bonded & riveted
  - **Structurally efficient**
  - **But poor processing could lead to delams, moisture intrusion**
  - **Boeing discontinued process & issued service bulletin (SB)**
  - **FAA never made SB compliance mandatory**
- Aloha's maintenance performance was questionable
  - **Difficult marine environment**
  - **Much "finger pointing"**
- Upper fuselage lap joint failed
  - **Explosive decompression at 24,000 feet; Loss of 18 feet of crown skin**
- Toll: **1 stewardess**
- Results:
  - **Launched aging aircraft programs in civil & military fleets**

15

Topic Teaser: Aloha Airlines Flt 243

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



16

Lesson 02

A Failure Analysis Method

Lesson Goals & Objectives

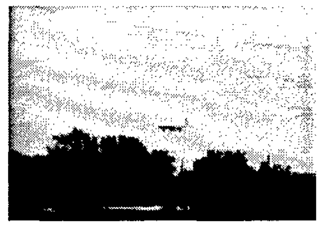
- After this lesson, engineers will have been introduced to a failure analysis method and know the guiding principles behind analyzing failures.

- Objectives
  - **Describe** how the concept of failure applies to more than just the fracture of a component
  - **Discuss** steps of a failure analysis and **describe** their relationship to one another
  - **Describe** the guiding principles of failure analysis
  - **Identify** the basic questions that a failure analyst should be able to ask and answer

A Failure Analysis Method - Steps

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

0. DO NOTHING! Just Observe
    a. The most important step in any failure investigation
    b. Take lots of pictures

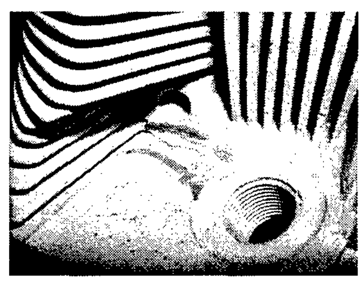


1. Collect Background Data
    a. service history
    b. any abnormal conditions
    c. begin to compile photo record
    d. any missing parts?
2. Preliminary Visual Examination and Record Keeping
    a. low magnification or no mag photos
    b. ***STRESS ANALYSIS***
    c. CRUCIAL!!!

3

A Failure Analysis Method - Steps

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



3. Nondestructive Testing/Inspection
    a. <u>Stress Analysis</u>
    b. x-ray (radiography)
    c. ultrasound
    d. magnetic particle
    e. liquid penetrant
4. Mechanical Testing (BE JUDICIOUS!)
    a. tensile
    b. hardness

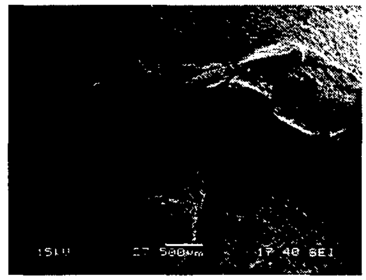
5. Selection/Preservation of Fracture Surfaces
    a. avoid cleaning and touching
    b. do not place mating surfaces together
    c. beware of heat generated by cutting

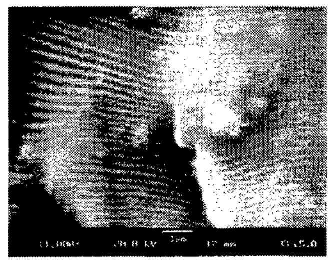
4

A Failure Analysis Method - Steps

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

6. Macroscopic Examination
    a. usually 100X and below
    b. look for deformation
    c. crack direction
    d. texture
7. Microscopic Examination
    a. more detailed
    b. smaller features
    c. SEM/TEM
        i. fatigue striations
        ii. inclusions





5

A Failure Analysis Method - Steps

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

8. Metallography (DESTRUCTIVE—Choose Wisely!)
    a. "cut and polish"
    b. shows grains and, therefore, heat treatment
    c. correct etchants are critical
    d. take samples from various areas
9. Determine Failure Mechanism
    a. ductile
    b. brittle
    c. wear
    d. fatigue
    e. etc. *we'll discuss these further*

6

A Failure Analysis Method - Steps

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

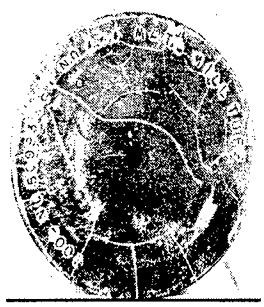
10. Chemical Analysis
    a. done last
    b. use SEM for X-ray scattering all over specimen
    c. "spot" testing of material dissolved in solvent
11. Fracture Mechanics
    a. consider pre-existing notches or cracks
    b. Look for striations, spacing, location, etc.
12. Test Under Simulated Service Conditions
    a. useful, but time and money act against you
    b. be careful to accurately simulate situation
    c. ex: accelerated salt tests for corrosion
13. Final Analysis and Report

7

Failure Analysis - Principles

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Wulpi's Methodology is one of many and is not a simple "laundry list" – it's a *guide*
- Order of steps taken is not important (to an extent)– as long as it makes sense
- Important Principles to Remember
  - First, DO NOTHING! Observe!
  - Locate the origin(s) of the fracture (failure)
  - Do not put mating fracture surfaces back together!!!
  - Think considerably before destructive testing



8

Issues to Ask Questions About

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Surface of Fracture (Failure)
- Surface of Part
- Geometry & Design
- Manufacturing & Processing
- Properties of Material
- Residual & Applied Stresses
- Adjacent parts
- Assembly
- Service Conditions
- Maintenance Conditions
- Environmental Reactions

9

Organization!

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

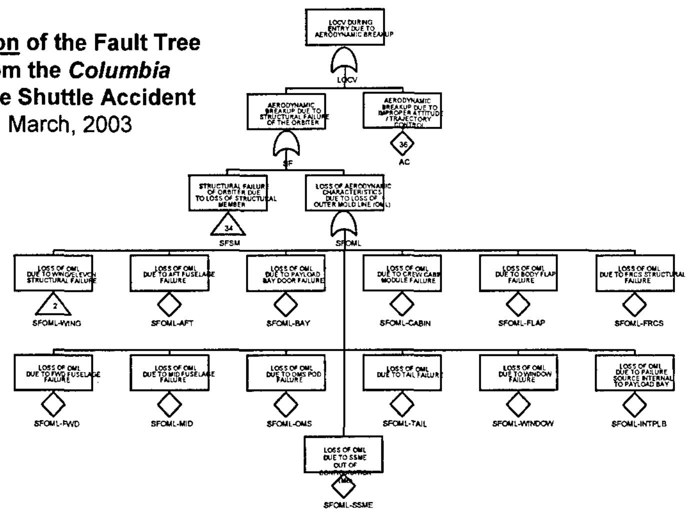
- Failure Analyses depend upon extensive and thorough documentation
- Organize
  - Notes
  - Photos
  - References
  - Your organization system (eg. encyclopedias)
- The more complex the failure, the more organization is required
- Example: C-17 Landing Gear Pin vs. Colombia Fault Tree

10

Colombia Fault Tree

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

<u>Portion</u> of the Fault Tree from the *Columbia* Space Shuttle Accident
March, 2003



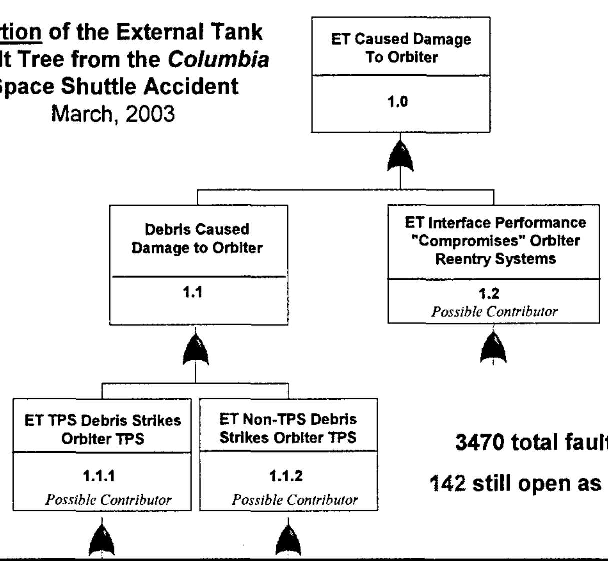
LOCV - LOCV DURING ENTRY DUE TO AERODYNAMIC BREAKUP 2003/03/27 Page 1

11

Colombia Fault Tree

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

<u>Portion</u> of the External Tank Fault Tree from the *Columbia* Space Shuttle Accident
March, 2003



3470 total fault tree blocks

142 still open as of 5 June 2003

12

Topic Teaser: C-17 Landing Gear Locking Pin

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

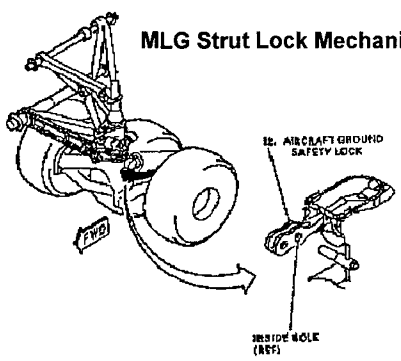
- Locking pin on strut lock mechanism of C-17 MLG
  - Shear pin that connects strut lock to MLG post failed
  - Occurred during jacking of aircraft for wheel replacement/repair

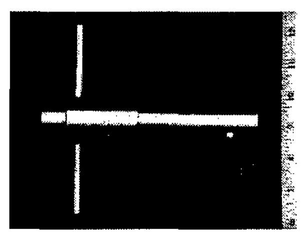
13

Mechanism & Operation

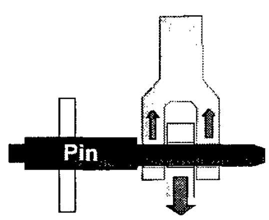
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

MLG Strut Lock Mechanism





Intact Pin

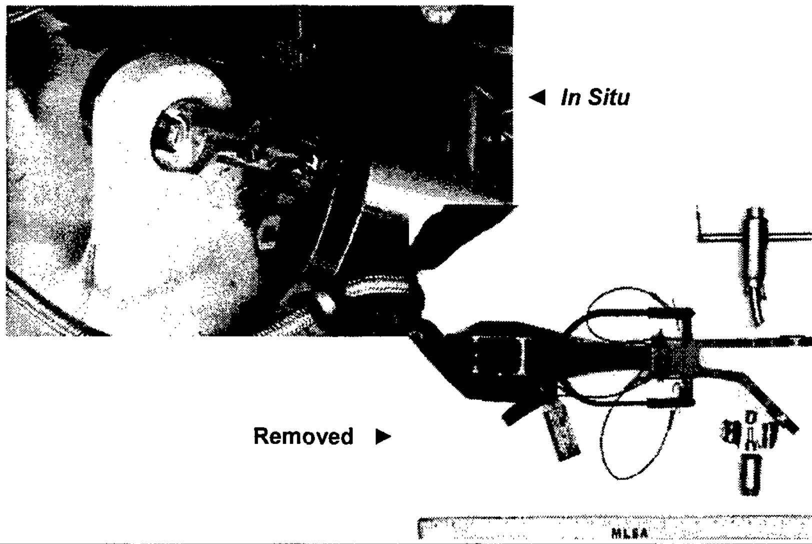


Strut Lock Basic Mode of Operation

14

Failed Assembly

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

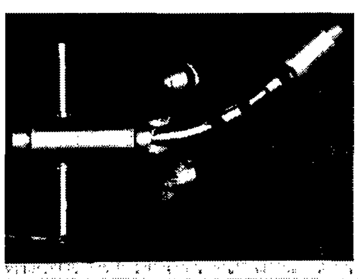


◄ *In Situ*

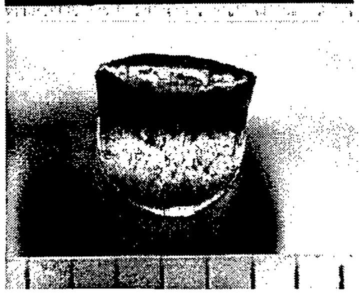
Removed ►

Failed Component (Pin)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

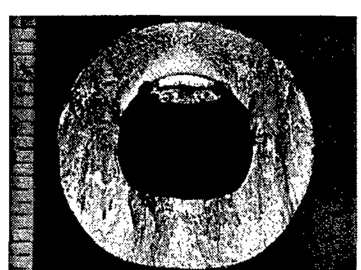


◄ Failed Pin



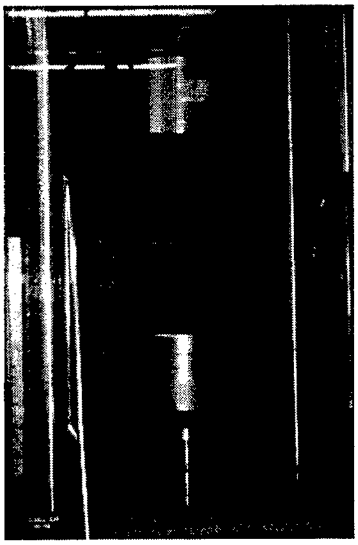
◄ Inner Pin Spindle

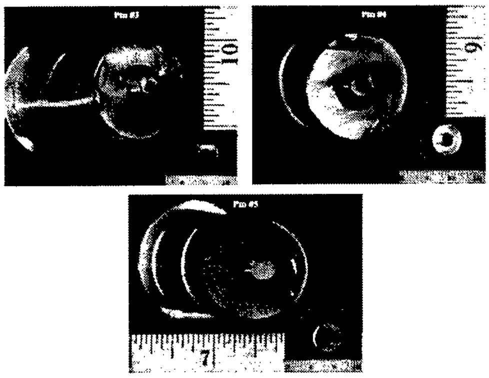
Outer Pin Body ►



Testing

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)





Failure Surfaces of 3 New Pins Tested During Investigation

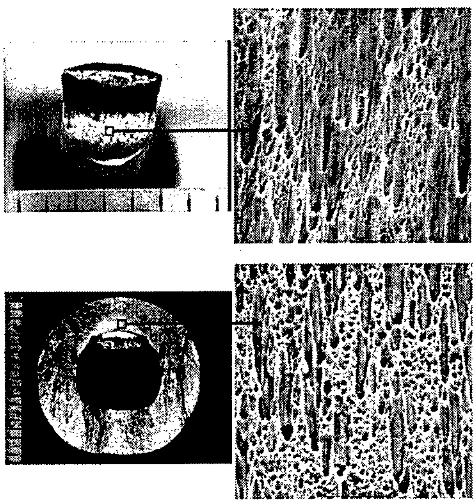
17

Fractography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Type of Fracture?

Direction of Force?



◄ **Inner Pin Spindle**

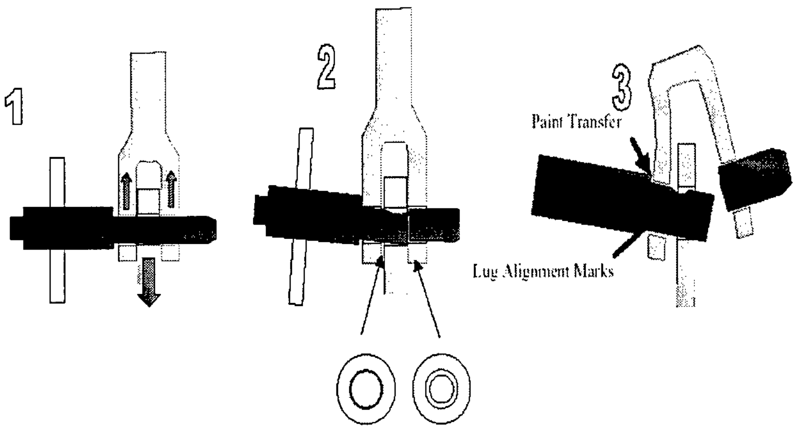
Scale: **14 μm**

◄ **Outer Pin Body**

18

Proposed Failure Sequence

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

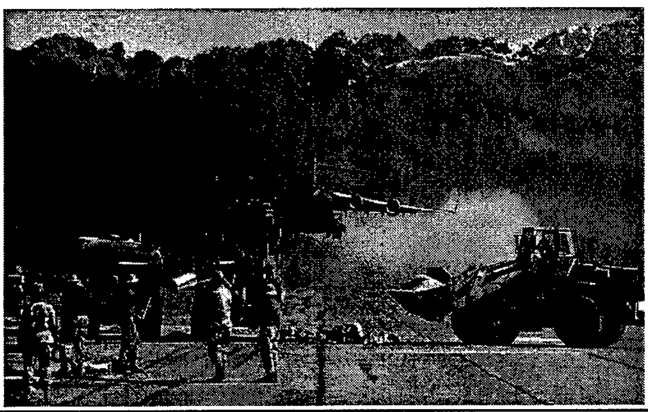


19

C-17 Landing Gear Locking Pin

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- What additional info do you need?
- Why did the pin fail?
- What recommendations would you make?



20

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 03

Conditions for Failure

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will understand how fracture relates to failure, and also the conditions required for failure.

- Objectives
  - **Distinguish** between fracture and other failure modes
  - **Identify** the differences/similarities between various failure modes
  - **Describe** the relationship between conditions, capabilities and corresponding failure modes.

2

Modes of Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fracture
- Ductile Yielding
- Fatigue

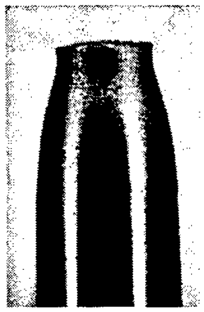
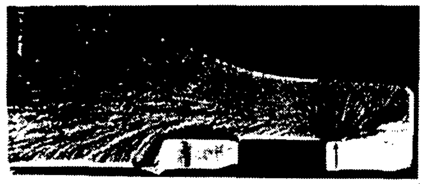
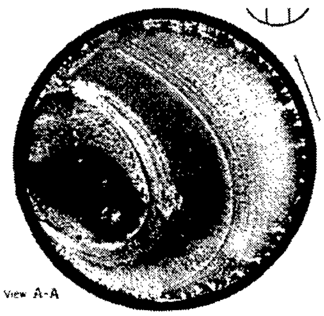


Fig. 9 Fracture surface exhibiting chevron pattern (left) pointing toward fracture origin, at a sharp corner



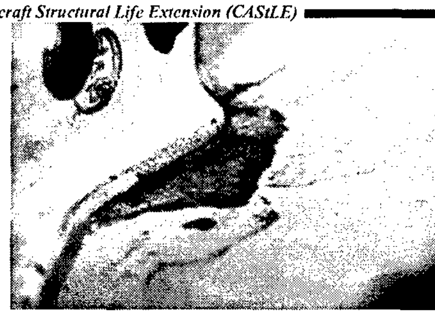


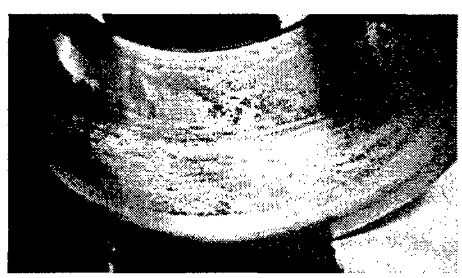
3

Modes of Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Corrosion
- Wear
- Creep



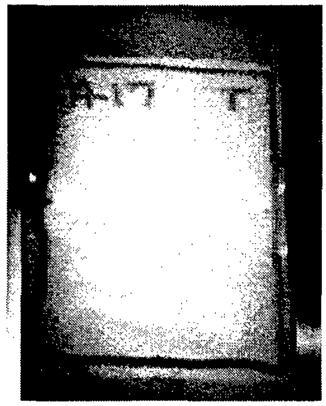


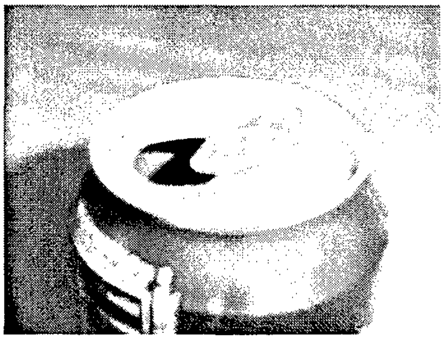
4

Modes of Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Disbonding/Delamination
- "Failure to Fail"



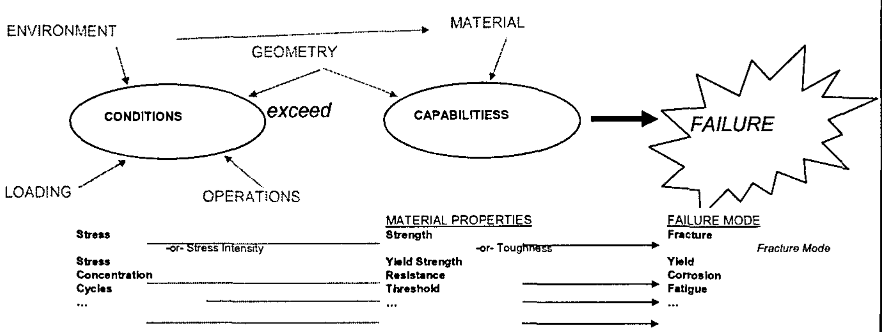


5

Conditions for Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

IF:



6

Topic Teaser: Boston Molasses Tank Spill

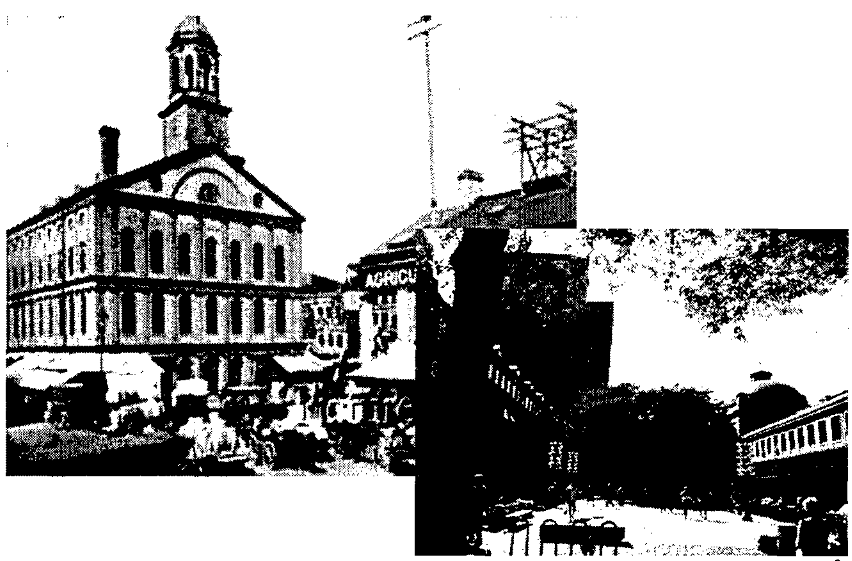
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **The Boston Molasses Spill, 15 Jan 1919**
  - Location: Boston's North End
  - Date: 15 Jan 1919
  - Time: 12:40 p.m.
  - Conditions: Warm winter day (~43°F)
    - Overnight low: ~2°F
  - Purity Distilling Company's Molasses Storage Tank
    - 58 feet high
    - 90 feet wide
    - Contents: 2.3 million gallons of molasses--Density: ~12 lbs/gallon

7

Quincy Market - Boston

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



8

The Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fabricated in 1916 by Hammond Iron Works
  - Their largest tank ever made
- Cast Iron or Steel ? (accounts differ)
  - Plates/sheet thickness: 0.687 in at bottom, 0.312 in at top
- Multi-plate, Riveted Construction
  - 7 stacked rows of partial ring sections
    - Ring sections joined with butt joints & splice plates (bottom) or lap joints (top)
    - 3 rivet rows on each side of each joint
    - Rows joined with lap joints
    - 1 rivet row
  - Access through manhole in near bottom
    - Directly beneath ring section joint in 2nd row
- Roof: conical supported by rafters

9

The Event

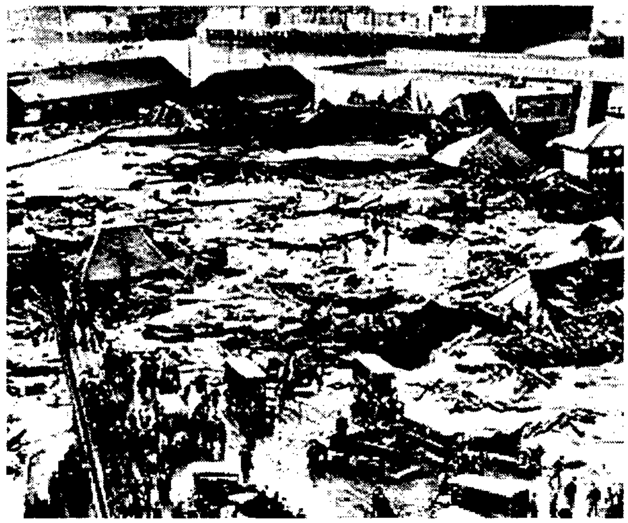
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Sound: "like machine-gun fire"
- Lower section of tank ruptures ("explodes")
  - Wreckage propelled with force high enough to slice steel girders
  - 2.5 ton section found 182 feet away
- Wall of molasses 15 feet high travels through streets
  - Speed: up to 35 mph
- Subsequent vacuum contributes to devastation
  - Powerful enough to suck a nearby truck into the goo
  - Forced elevated train off its rails
- Toll
  - 21 deaths, 150 injuries
  - Massive damage in 2 square block area
  - Numerous losses of livestock

10

Devastation

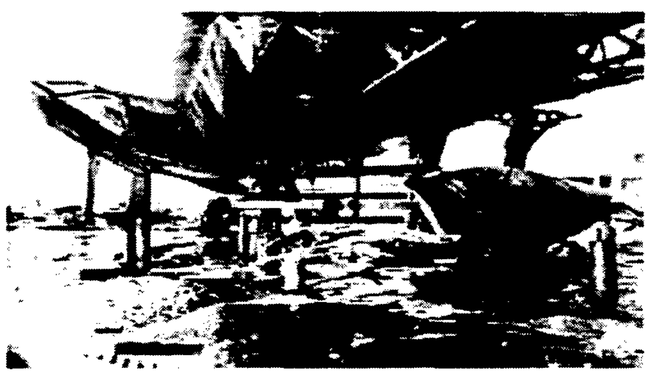
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



11

... More Devastation

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Destroyed Elevated Train Tracks

12

Impact & Results

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Boston Building Dept. issues new requirements
  - Calculations must be submitted with drawings
  - Drawings must be signed & stamped ("certified")
  - Certification laws soon appeared in other states
  - Registration for engineers
  - Building permits
- Massive court case
  - 3,000 witnesses
  - 40,000 pages of records
  - $1M (1925 dollars) paid in damages
- Heightened public and industry awareness of poor designs

13

This Page Intentionally Left Blank

Lesson 04

Residual Stress I

Lesson Goals & Objectives

- After this lesson, engineers will understand how residual stresses are formed and interact with each other, and have knowledge of the main types of residual stresses.
- Objectives
  - **Understand** how residual stresses are formed and describe their results
  - **Distinguish** between various types of residual stresses and their source

Residual Stress Definition

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Internal stresses locked into a part or assembly, even though no external loads are being applied

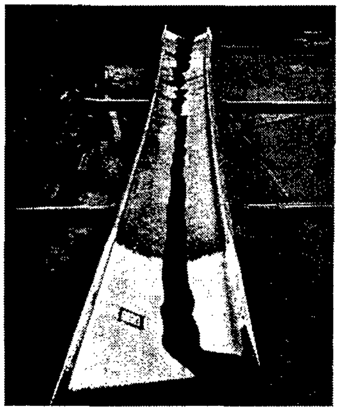
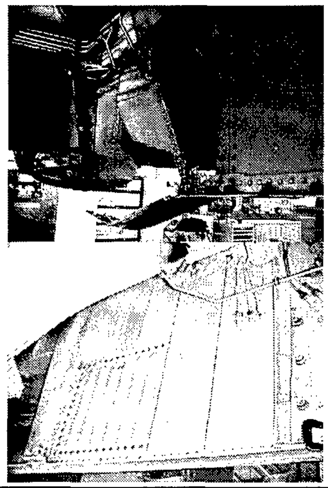


Fig. 1 Spontaneous residual stress fracture in a 40 ft long I-beam under no external load. Source: Ref 1



3

Residual Stress Definition

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Beneficial or detrimental
- Tensile, compressive, or shear
- Always 3-D
- Difficult to visualize of verify nondestructively
- Spring example ➔

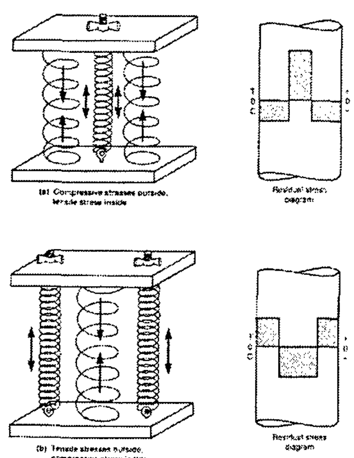


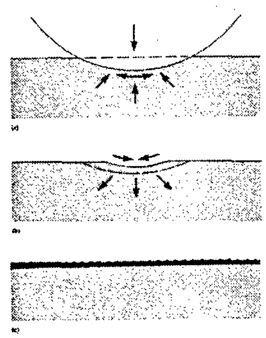
Fig. 8 Residual stress systems illustrated by spring analogy (left illustrations), and diagrams of corresponding stress systems (right illustrations)

4

Types of Residual Stresses--Mechanical

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Key Concept
  - Compressive yielding results in tensile residual stresses—BAD!
  - Tensile yielding results in compressive residual stresses—normally Beneficial!
  - Ex: Shot peening
- AF uses this to it's advantage
  - Fatigue and SCC
  - More on this in Residual Stress II



5

Types of Residual Stresses--Thermal

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Key Concepts
  - Requires ΔT <u>and</u> restraint!
  - Material that cools last is in residual tension—bad!
- Two Cases
  - + ΔT
  - - ΔT
- AF Examples
  - Ground, or polished surfaces
  - Welds (not often)
  - Composite bonded repairs to metallic structures

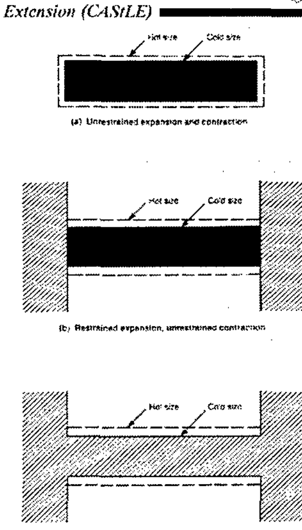


Fig. 2

6

Types of Residual Stresses--Thermal

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Welding example
- Welds are not the most common in aircraft
  - they do exist
  - used (often incorrectly) in a few repairs.

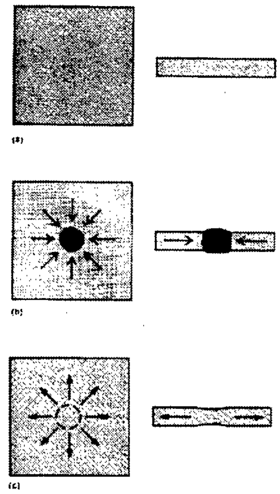


Fig. 4 Thermal residual stresses caused by spot heating. [illegible]

7

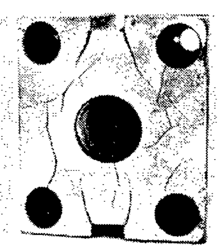
Other Types of Residual Stresses

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Chemical
  - Associated with removal of material
  - AF examples: chem milling, etching, corrosion
- Metallurgical
  - Requires volume-changing phase change (steel)
  - <u>Material that hardens last is in residual compression</u>
  - Ex: Martensite formation in steel

Fig. 3 AISI O1 tool steel die that cracked during oil quenching

Note the cracks emanating from the sharp corners. The four holes, which are close to the edge, also contributed to cracking. Temper color was observed on the crack walls.



8

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Two Stainless Steel Helium Storage Tanks exhibited cracking near weld areas during pressurization
  - Type 304 Stainless Steel
  - Dished ends cold-formed, then welded to cylindrical portion of tanks
  - Stored for 4 years in coastal environment
    - No applied load during storage
    - Visual examination revealed red corrosion product on surface
  - Exhibited cracks during pressurization check
    - Cracking occurred in the weld heat-affected zone (HAZ)
    - Cracks occurred in areas of corrosion product

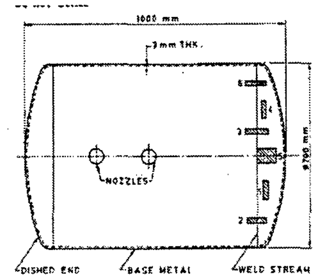


Fig. 1 Schematic of the helium storage tank. The areas where samples were taken are indicated: 1, intergranular corrosion testing; 2, hardness testing; 3, microscopy; 4, fractography; 5, residual stress measurement; 6, chemical analysis

9

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Thoughts
  - Residual stresses due to cold-working
  - Residual stresses due to fit-up
  - Corrosive environment attacking HAZ
- Additional Information
  - Evidence of "severe hammering" to get dished ends fastened to tank cylinder
  - Residual stress measured (x-ray diffraction) at 20 Ksi
  - Fractographic Inspection
  - Metallographic Inspection
  - Chemical Analysis

10

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fractographic Inspection

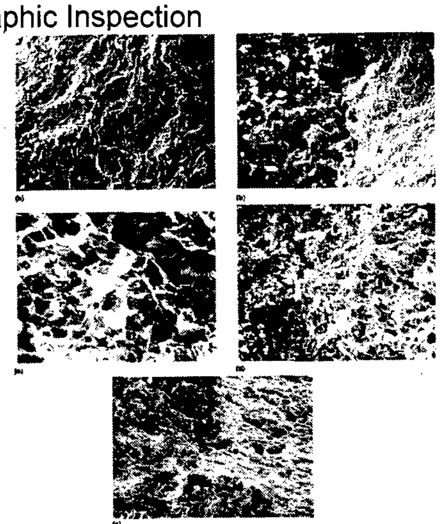


Fig. 2 SEM fractographs showing mode of fracture at different stages of crack propagation. (a) Close to weld seam. (b) First intermediate location in HAZ. (c) Second intermediate location in HAZ. (d) Third intermediate location in HAZ. (e) Dished end unaffected by heat of welding

11

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Metallographic Inspection

Fig. 3. Micrographs showing transition in mode of fracture. Electrolytically etched in 10% oxalic acid. (a) Transgranular cracks near the weld. (b) Transition from transgranular to intergranular mode while propagating toward the dished end. (c) Intergranular mode in HAZ

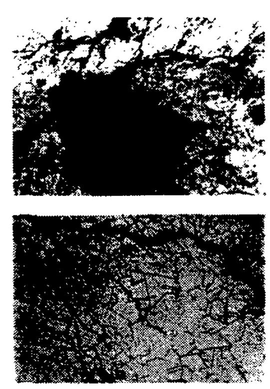


Fig. 4. Micrographs showing a pit and a crack near the nozzle. (a) Crack starting from a pit. (b) End of the crack in (a)

12

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Chemical Analysis

Table 1 Results of chemical analysis

Element	Composition, % Shell	Composition, % Dished end
Carbon	0.063	0.09
Sulfur	0.014	0.013
Phosphorus	0.038	0.038
Manganese	0.45	0.47
Silicon	0.53	0.60
Nickel	8.3	8.3
Chromium	16.9	17.4

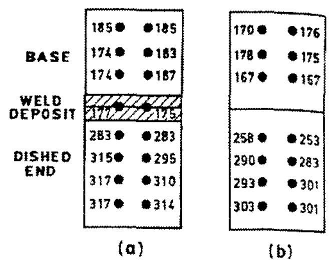


Fig. 5 Hardness profile across the weldment on the inner surface of the tank (a) and on the outer surface (b)

13

Topic Teaser: Helium Tank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Final Conclusions
  - Failure Attributed to intergranular stress corrosion cracking (SCC) in sensitized weld HAZ
  - Sensitization due to chloride from the environment

- Recommendations for Prevention
  - Use AISI 304L stainless steel—lower carbon content
  - Anneal after cold-working to reduce residual stresses
  - Cool immediately after welding to prevent sensitization
  - Minimize fit-up stresses
  - Cover during storing for environmental protection

14

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 05

Residual Stress II

1

Lesson Goal & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will know how to produce beneficial residual stresses and some typical USAF applications.

- Objectives
  - **Know** how to produce beneficial residual stresses and know where they are useful
  - **Identify** potential applications of residual stresses and their source

2

Beneficial vs. Detrimental

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- In what direction does a fatigue crack grow?
  - Perpendicular to maximum internal <u>tensile</u> stress
- What three ingredients are necessary for stress corrosion cracking (SCC)?
  - A hostile environment, susceptible material system, and internal <u>tensile</u> stresses
- Limit internal tensile stresses to delay or eliminate the onset of SCC and fatigue crack nucleation!
  - Tensile residual stresses make the problem worse
  - Compressive residual stresses can be induced to combat internal tensile stresses!

3

Beneficial vs. Detrimental

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

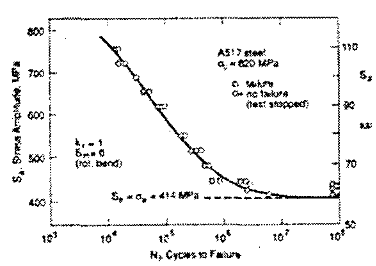
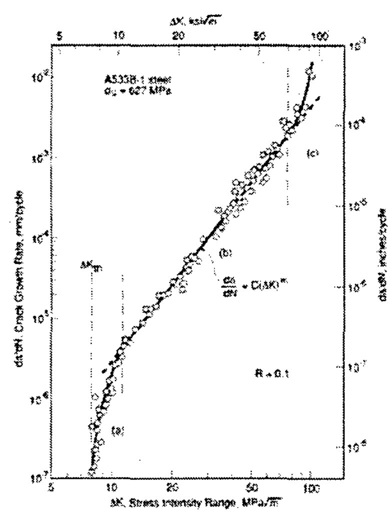


Figure 9.5 Rotating bending S-N curve for unnotched specimens of a steel with a distinct fatigue limit. (Adapted from [Brockenbrough 81]; used with permission.)



4

Main AF Applications

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

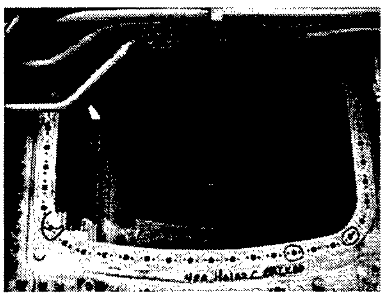
- Two Main AF Aging Aircraft Problems
  1. Corrosion (SCC a large contributor)
  2. Fatigue Crack Propagation

5

Main AF Applications

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- How do you decide where to apply residual stresses?
  - Stress risers
    - Fillets
    - Holes
    - Thickness changes
  - High tensile stresses
    - Wing attach points
    - Bottom wing skins
  - Susceptible materials **(7075-T6 example)**
  - Areas prone to SCC and Fatigue (Fatigue Critical Locations—FCL's—will be discussed later)



6

Common AF Application Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Shot Peening
  - Sheet or plate material
  - Notches or surface stress risers
  -
- Cold Working
  -

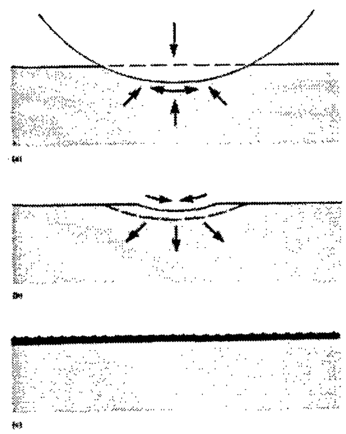


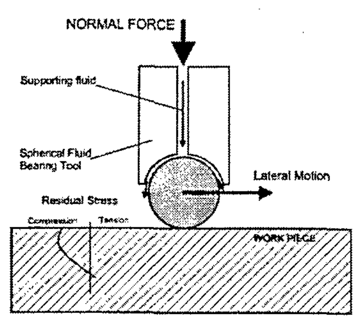
Fig. 7

7

Additional Application Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Hard Squeezing Rivets
- Cold Rolling
  - Sheet or plate
- Low Plasticity Burnishment (LPB)
  - Rollers press steel ball into surface
  - Similar to shot peening
  - Can be applied to critical areas
  - Currently used on engine components



8

Additional Application Method

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Laser Shock Peening (LSP)
  - Black paint or tape is applied to part
  - Small spot size, high energy pulsed laser beam is directed through a "water curtain" onto the part
  - Laser energy rapidly combusts black paint or tape (causes it to explode)
  - Explosion is contained on one side by the water curtain and on other side by the part
  - Explosions imparts residual compression into part in same way as shot peening
  - Laser location is indexed across part to cover an area
- Currently the same application as LPB

9

Natural Residual Stress Effect

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fatigue Crack Tip Undergoes Residual Compression
  - In metals, as the crack grows, it creates plastic zone in front of the crack tip
  - Plastic zone—residual compression—blunts the crack tip
  - Without this effect, any crack would cause instantaneous brittle fracture

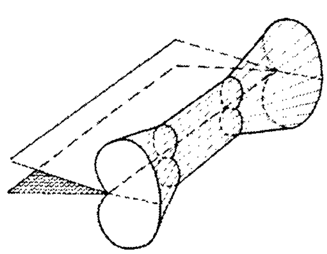
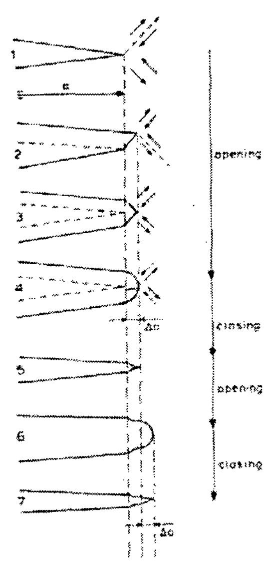


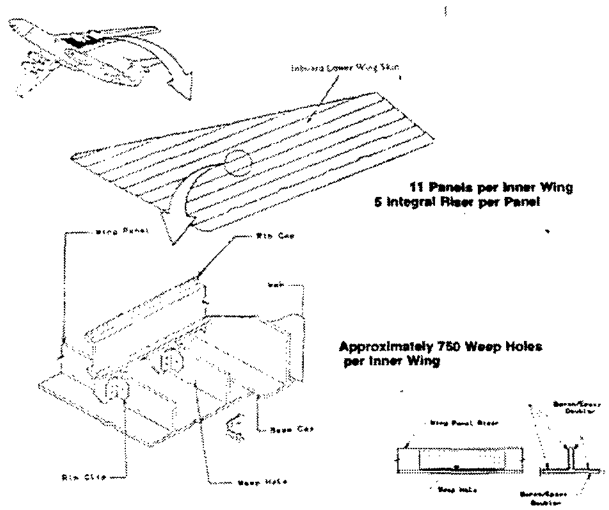
Figure 4.10 Three-dimensional plastic zone



10

C-141 Topic Teaser

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

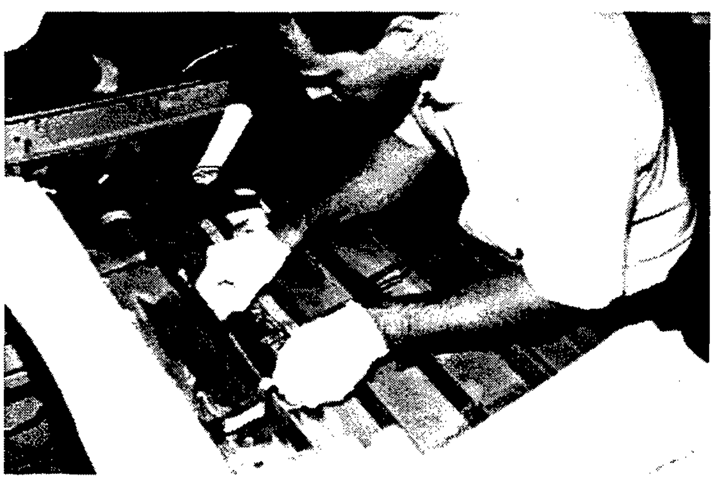


11

C-141 Topic Teaser

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Boron patches adhesively bonded to the structure for repair

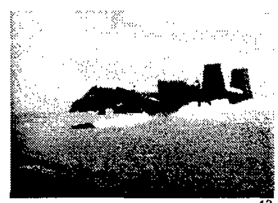


12

Topic Teaser: A-10 Wing Early Fatigue

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- A-10 wing early fatigue cracking (circa 1998)
  - Early fatigue cracking found in several critically loaded areas of A-10 spar
  - Aircraft were experiencing higher G loads than anticipated; more "jinks"
  - Service life was anticipated to be greatly reduced
- Solution: Imparting Favorable Residual Stresses
  - Shot peening of critical locations induced favorable residual compressive stresses
  - Restored "lost life" to A-10 fleet



13

This Page Intentionally Left Blank

Lesson 06

Distortion Failures

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

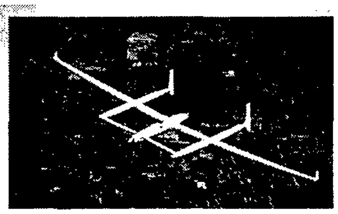
- After this lesson, engineers will have a thorough understanding of the difference between distortion and failure, the main distortion modes, and the ways to prevent the main types of distortion failures
- Objectives
  - **Define** distortion failure
  - **Describe** various distortion modes and the stress states that cause them
  - **Describe** distortion failure prevention methods
  - **Describe** the relationship between distortion and failure

2

Distortion Failure Defined

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

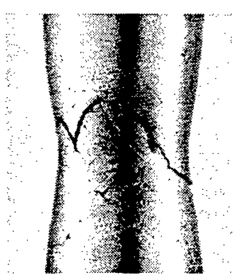
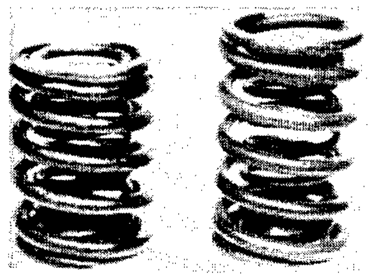
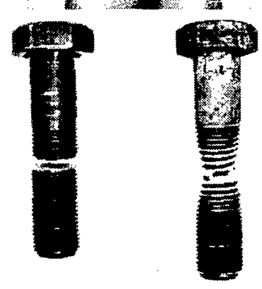
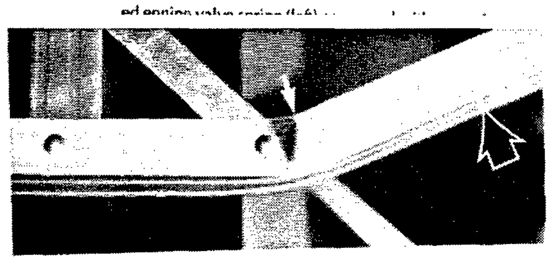
- Distortion Failure: *distortion* is the root cause of a failure
  - Electrical components distort and can't complete circuit
  - Beams buckle under compressive loading
  - Wings deform too far and impact the ground
  - Turbine blades elongate due to *creep* and impact other blades or the engine cowling
- *Ductile* failures exhibit distortion; *Brittle* failures do not

3

Macroscopic Appearance

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

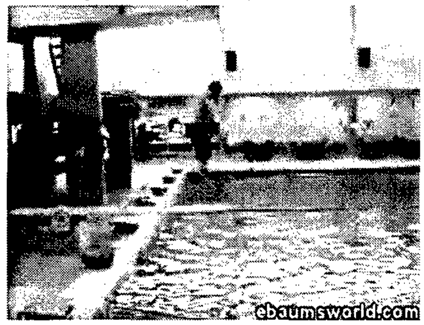





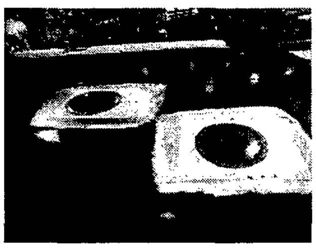
4

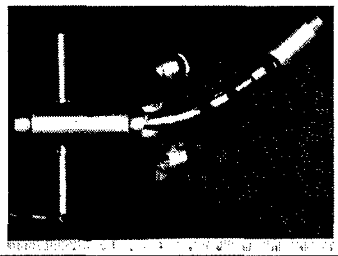
Types of Distortion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Temporary**—material stays in the elastic region
- **Permanent**—material exhibits plastic yielding
- **Size**—shrinkage or expansion; adhesively bonded composite patches, for example
- **Shape**—bending, stretching, twisting, buckling







5

Causes & Prevention Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Tensile/Compressive Distortion
  - Axial or bending loading
  - Prevention
    - Reduce Stresses
    - Different Material
- Compressive Buckling: $P_{cr} = \frac{\pi^2 EI}{(KL)^2}$
  - Compression:
    - First and foremost a geometry problem
    - Secondly a material problem
  - Prevention
    - Design change
    - Material change

6

Causes & Prevention Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Creep
  - Applied load + elevated temperature ($T>.4T_m$)
    - $\dot{\varepsilon} = \frac{A_2\sigma^m}{d^q T}\exp(-\frac{Q}{RT})$
  - Prevention
    - Reduce stress (geometry change)
    - New material
    - New material process (↑ grain diameter, d)
    - Reduce temperature

7

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The Structure
  - Built in 1972-73
  - $70M structure
  - Capacity: 12,500 seats plus affiliated shops
  - Home of the New England Whalers
- The Roof
  - Weight: 1400 tons
  - Size: 2.5 acres (360' x 300' x 21')
  - Design: Steel Space Truss, flat profile, 4-point support
- Conditions
  - January 1978
  - 4.8 inches of heavy wet snow
  - Collapse happened hours after a college basketball game

8

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

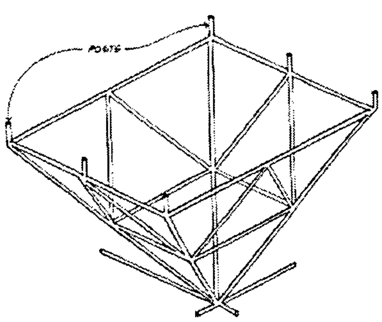
Hartford Civic Center

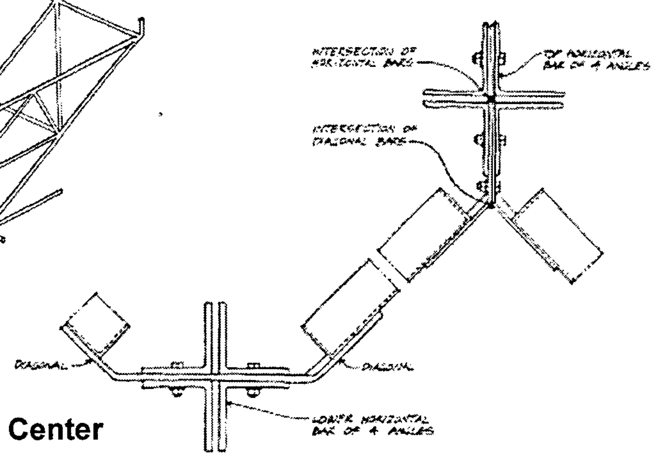
Plan View

9

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)





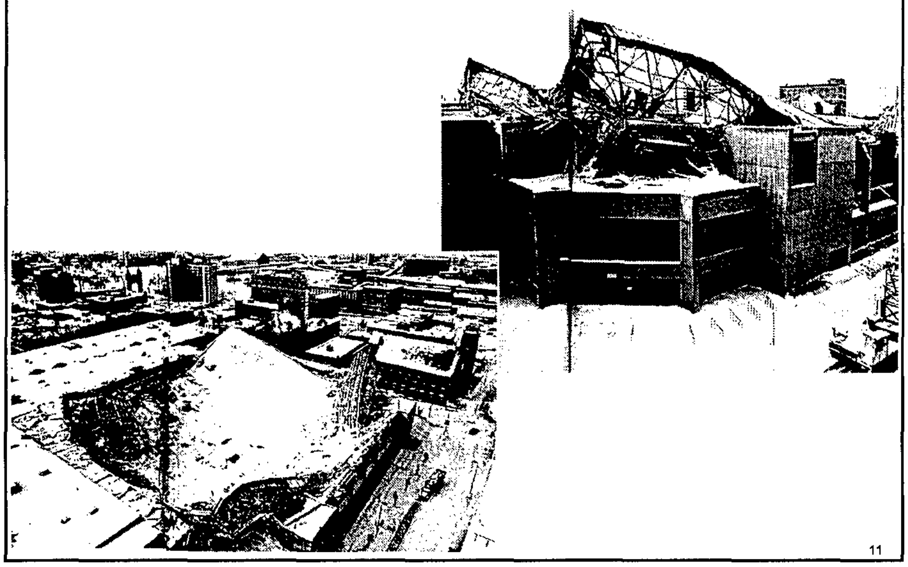
Hartford Civic Center

Space Frame Detail

10

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



11

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- What Happened?
  - Computerized design
  - Problems during construction
    - Sags (2X design)
    - Hole misalignment → welds used rather than bolts on fascia pieces
  - Weight of roof was 25% over spec
  - Buckling of longest span under weight of snow ... BUT ...
    - Weight of roof + snow < design maximum load
  - "House of cards" effect
- Impact
  - Loss of location for over 300 events annually
  - Loss of focal point of urban renewal
  - Loss of $20M in revenue
  - 1.5 to 2 years to rebuild

12

Case Study: Hartford Civic Center

USAF Academy Center for Aircraft Structural Life Extension (CASTLE)

- Recommendations
  - Reconsider:
    - Cross section of structural members
    - Length of structural members
    - Joint Complexity
    - Use of computerized design
  - Review manufacturing & assembly records
  - Building Code revisions?
    - Factor of Safety
  - Responsibility?

13

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 07

Fracture Modes & Stress Systems

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will understand the stress systems that lead to failure and distinguishing characteristics of those failures. Also, engineers will be able to describe the four main modes of fracture

- Objectives
  - **Describe** the five basic stress systems that cause failure
  - **Distinguish** between the shear, cleavage, intergranular and fatigue modes of fracture
  - **Identify** distinguishing visible features of tensile, torsional, bending, compression, & fatigue stress systems causing failure in brittle & ductile materials

2

Stress Systems and Fracture Modes

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

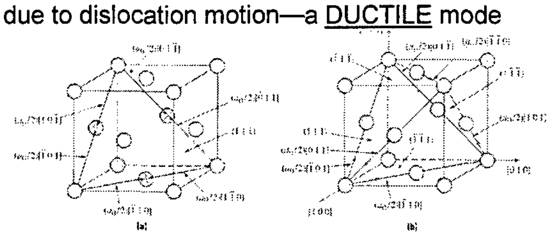
- Five Basic Stress Systems
  - Tension—lower wing skins, fuselage σ_h
  - Compression—upper wing skins, landing gear
  - Bending—wings, fuselage, empennage
  - Torsion—engine drive shaft, flight control gears/shafts
  - Fatigue—wing attach fittings, engine attach points, holes, notches, fillets, everywhere!
- "Fracture" is One of Many Failure Modes
- Four Main Fracture Modes
  - Shear
  - Cleavage
  - Intergranular
  - Fatigue

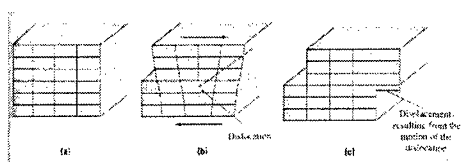
3

Shear Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Deformation of a unit cell along slip systems
- Occurs due to dislocation motion—a DUCTILE mode





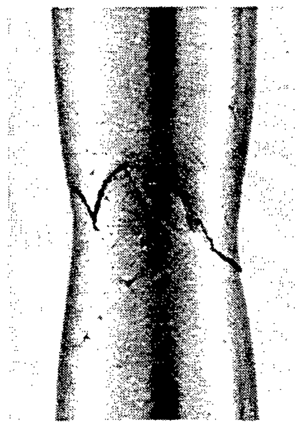
- Macroscopic deformation possible without fracture
- Most common in soft, ductile materials
- Physical Manifestation: dull, fibrous fracture surface; visible deformation; microscopic dimpling; transgranular fracture surface

4

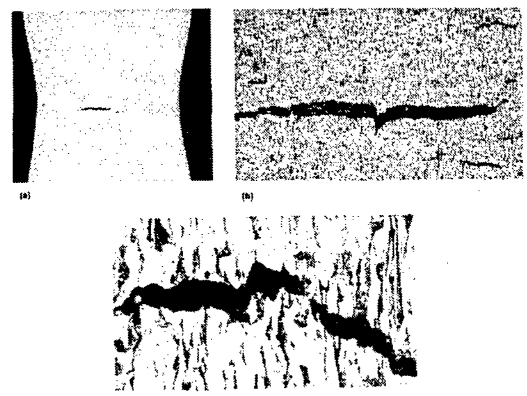
Shear Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Luder Lines; necking; visible plastic deformation



Microvoid Coalescence

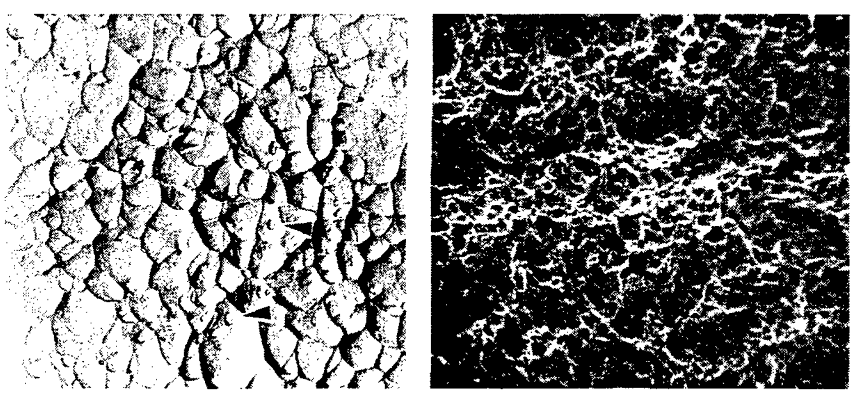


5

Shear Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Microvoid coalescence leads to dimpled fracture surface



Equiaxed dimples on flat fracture surfaces of Q&T 4140 steel *(left, 10,000X)* and 1020 steel *(right, 100X)*

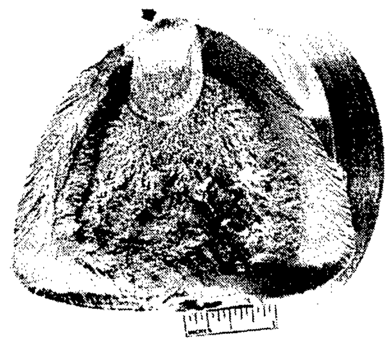
ASM Metals Handbook, 9th ed., Vol. 11, pg 76

6

Cleavage Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Separation of a unit cell along cleavage planes
  - Analogy—suction cup “popping” off of a surface
  - Little, to no, deformation—a BRITTLE fracture mode
- Most common in hard, brittle (high strength) materials
- *FCC (aluminum, austenitic SS) structures do not cleave!*
- Physical Manifestation
  - Bright, shiny appearance
  - “Crystallized” fracture surface
  - Chevrons
  - Microscopic River Patterns
  - Transgranular Cracking (through grains)



7

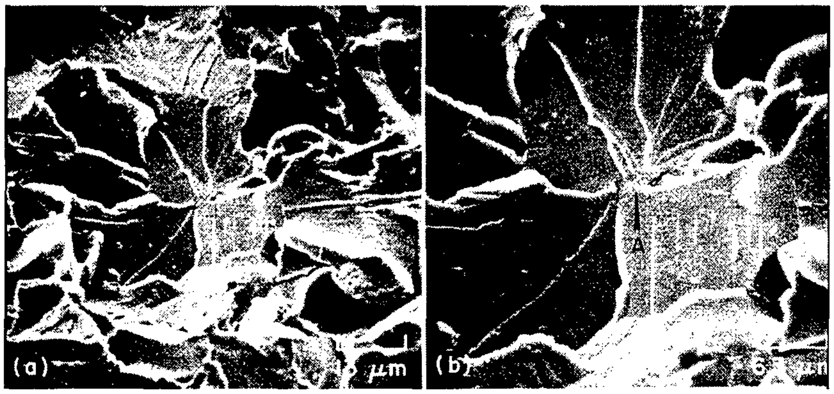
Cleavage Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

8

Cleavage Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Cleavage crack nucleation site in 1040 steel
(left, 790X) (right, 1590X)

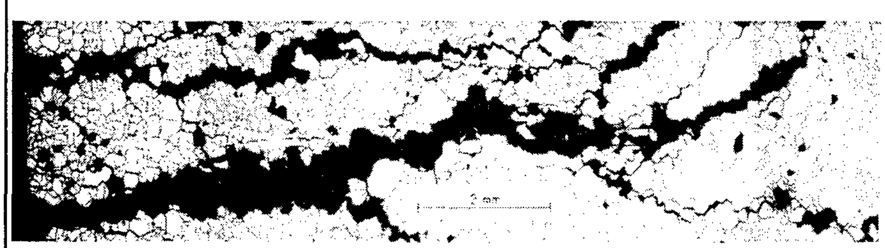
ASM Metals Handbook, 9th ed., Vol. 11, pg 23

9

Intergranular Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Fracture propagates between grains—through the boundary
  - Little, to no, plastic deformation—Brittle fracture mode
  - "Rock Candy" appearance, due to grains separating
- Common to materials subject to hostile environments
  - Sensitization of stainless steels
  - Hydrogen embrittlement
  - Weld Heat-Affected Zones (HAZ)

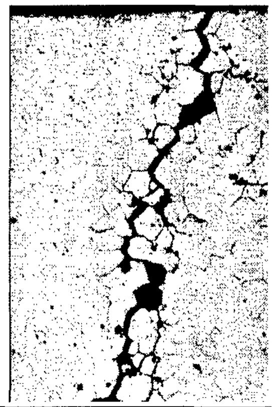


10

Intergranular Mode of Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Intergranular Fracture of Duranickel due to Hydrogen Embrittlement
(95X)
ASM Metals Handbook,9th ed., Vol. 12, pg. 397



- Branching intergranular crack is indicative of SCC!

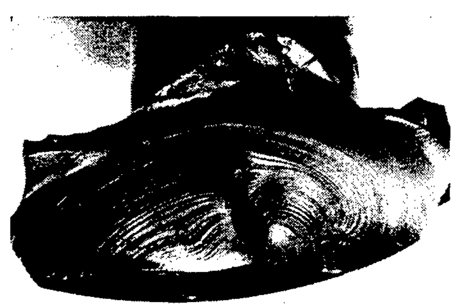
ASM Metals Handbook, 9th ed., Vol. 7, pgs 181 & 204

11

Fatigue Fracture Mode

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

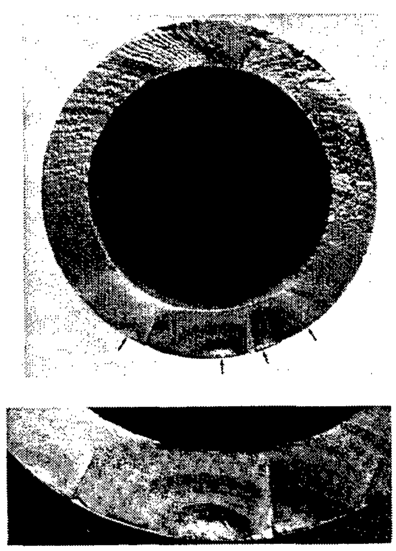
- Crack initiates and propagates at $\sigma_{app} < F_{t,y}$!
- Consists of crack propagation and final failure regions
  - Propagates according to applied cyclic loading
  - Final fracture either brittle or ductile
  - Size of final fracture area vs. fatigue area is telling
- Crack normally initiates at stress riser
- Physical manifestation:
  - Beachmarks
  - Striations
  - Either ductile or brittle final fracture area

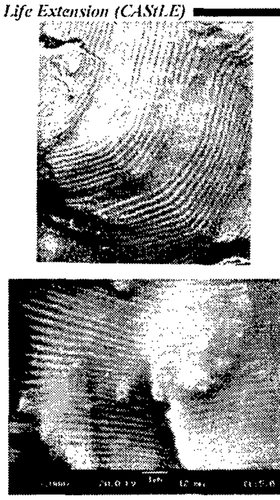


12

Fatigue Fracture Mode

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



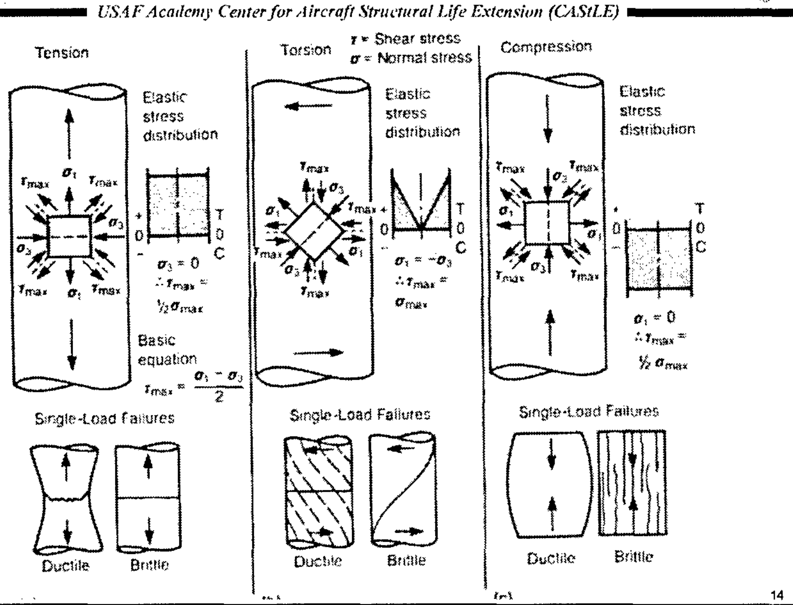


Fatigue Striations
(11,000X)

13

Fracture Planes vs. Material & Loading

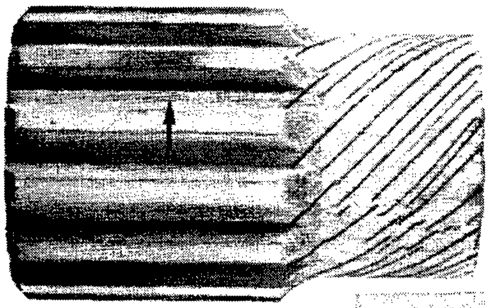
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

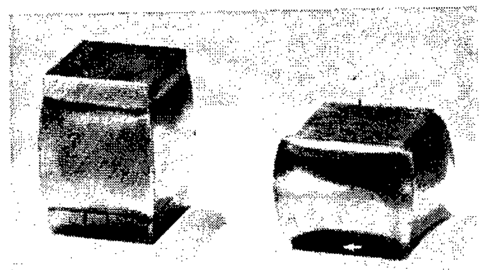


14

Fracture Planes vs. Material & Loading

USAF Academy Center for Aircraft Structural Life Extension (CASTLE)





15

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 08

Ductile vs. Brittle Fracture

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

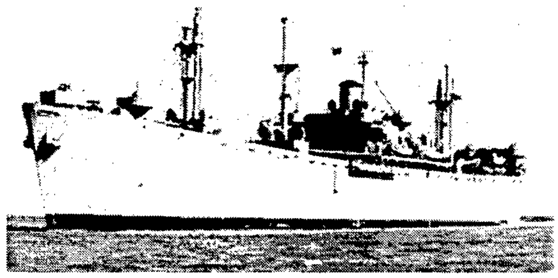
- After this lesson, engineers will understand the differences between brittle and ductile fracture modes and the factors that determine which will occur in a component

- Objectives
  - **Determine** differences between brittle and ductile fracture
  - **Comprehend** fractographic appearances/differences of/between brittle and ductile fracture surfaces
  - **Discuss** how various factors determine whether a component will fail in a brittle or ductile manner

2

Topic Teaser: Liberty Ships

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



- Leading up to, and during, World War II, U.S. was franticly producing cargo ships
  - Supplying ships to Britain as part of Lend-Lease Act
  - Providing ships for U.S. war effort following Pearl Harbor attack
- 2,580 Liberty ships were produced
  - To accomplish this feat, new and faster production practices were employed

3

Topic Teaser: Liberty Ships

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

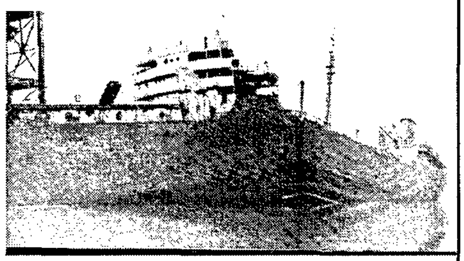
- To save time:
  - Ships were welded together, not riveted
  - Square hatches were cut in the hull
  - Shortcuts were taken on steel quality
  - Testing in the usage environment was not conducted
- Problems:
  - Welding didn't provide an arresting point for cracks
  - Square hatches induced k_t's of 2 – 3.4, which allowed for crack initiation
  - Poor steel quality, along with cold temperature usage environment, reduced the toughness of the material
    - North Atlantic temperatures approaching freezing
    - Reduced toughness allows for smaller critical crack lengths

4

Topic Teaser: Liberty Ships

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Results
  - Approximately 13% of all ships experienced major hull fracture
  - Loss of $50 million
  - Cost hundreds of sailors lives



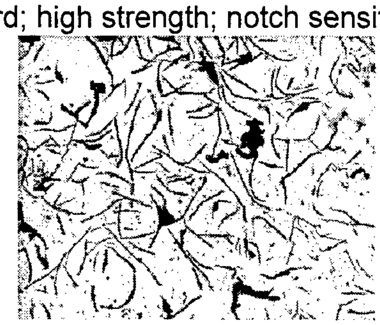
- Biggest Issue: *Quality* was sacrificed for *Quantity*
- Indication that normally ductile materials can behave in a brittle manner

5

Brittle Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Speed: Fast; sudden; unexpected or *without warning*
- Deformation: Little or not observable
- Energy: Low
- Fracture Surface Orientation: Perpendicular to max internal tensile stress
- Susceptible Materials: Hard; high strength; notch sensitive
  - High carbon steels
  - Gray cast Iron



6

Ductile Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Speed: Slower than brittle
- Deformation: High; visible plastic deformation
- Energy: High (compared to brittle materials)
- Fracture Surface Orientation: Related to direction of max shear stress
- Susceptible Materials: Softer; lower strength materials

Macroscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Brittle
  - Shiny; crystalline; relatively flat fracture surface
  - Little or no deformation—pieces can fit together
  - Chevron pattern; a.k.a. herringbone pattern; radial ridge marks;
    - Features fan out away from crack origin
    - Indicate a rapid fracture mechanism

Fig. 9 Fracture surface exhibiting chevron pattern (left) pointing toward fracture origin, at a sharp corner

Fracture initiated at the location indicated by the arrow, where the corner of a snap-ring slot was specified to have a zero minimum radius. Fracture surface is that of a forging of AMS 6434 (vanadium-modified 4335) steel that was heat treated to a yield strength of 196 MPa (190 ksi).

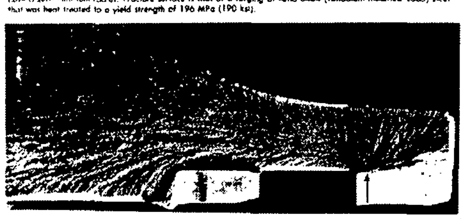


Fig. 5 Chevron patterns in low-alloy steel ship-plate samples broken over a range of temperatures

Each fracture began at the notch (top). Mating fracture halves are shown for each temperature. (Courtesy of G.F. Vander Voort)

Macroscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

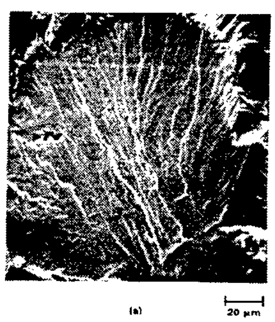
- Ductile
  - Dull, fibrous appearance on fracture surface
  - Primary indicating feature: *deformation*
    - Fracture surfaces won't fit back together
    - Necking in tension
    - Change in shape
    - Lüders bands
    - Shear lips

9

Microscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Brittle: Cleavage
  - River Patterns—crack propagates "down river"
  - Feather Markings—Fan-shaped array of cleavage steps
  - Wallner Lines—Intersecting, semicircular lines



10

Microscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Brittle: Intergranular
  - Due to hostile environment
  - "Rock Candy" appearance
- Brittle: Fatigue
  - Considered brittle mode due to hydrostatic stress state at crack tip
  - Striations, river patterns, cleavage indications
  - Will be discussed at length in later lesson

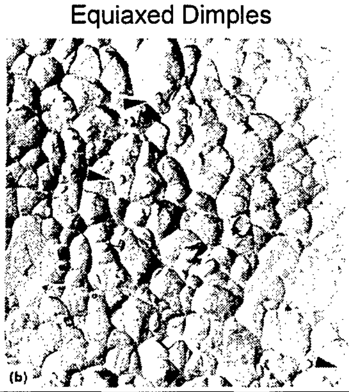
11

Microscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Ductile: Dimples
  - Microvoid coalescence leads to fracture, and subsequent dimpled fracture surface
  - Orientation of dimples give clues to loading conditions

Equiaxed Dimples



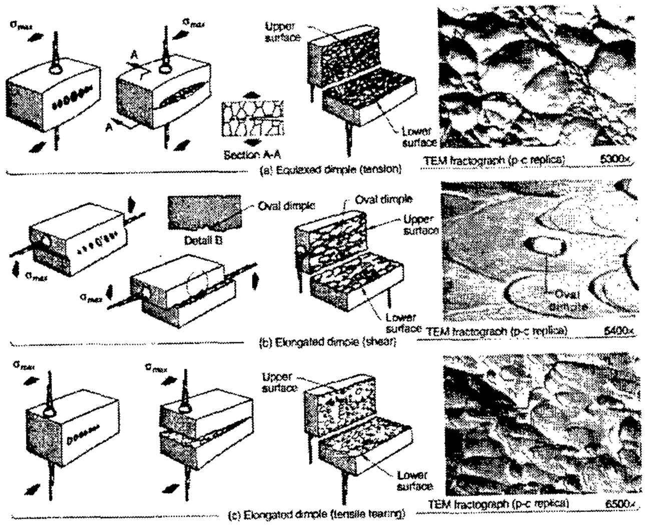
Elongated Dimples

12

Microscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Dimple orientation



13

Factors Affecting Material Ductile vs. Brittle Behavior

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Loading (strain) rate
- Existence of stress risers
- Environment and Processing Effects
  - Temperature
  - Processing Temperature
  - Hostile/Corrosive Environment (ex. Hydrogen embrittle)
- Triaxiality
- Strength of Material

14

This Page Intentionally Left Blank

Lesson 09

Metallography and Fractography

Lesson Goals and Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- At the end of this lesson, engineers should understand the failure analysis and prevention tools and services available through fractographic and metallographic labs.

- **Objectives**
  - **Define** the difference between metallography and fractography
  - **Understand** the principles of fractography and metallography
  - **Comprehend** the techniques of performing a metallographic or fractographic evaluation

Definitions

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Fractography – the examination of a fracture surface; to view fracture surface topography

Metallography – examination of a polished/etched surface; to view grains and microstructure

3

Fractography as a Failure Analysis Tool

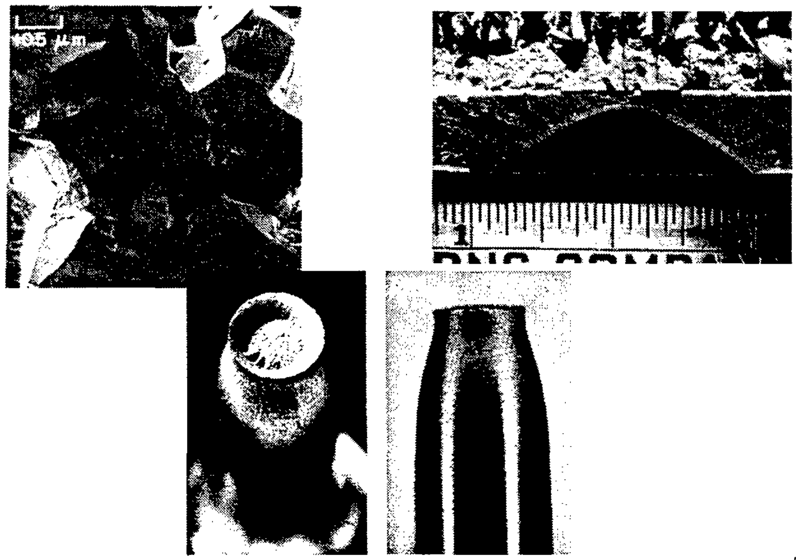
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- What can be determined?
  - Fracture Mode
    - Type
    - Origin
    - Direction
    - Speed
  - Loading Type
  - Magnitude of Loading

4

Fracture Mode

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

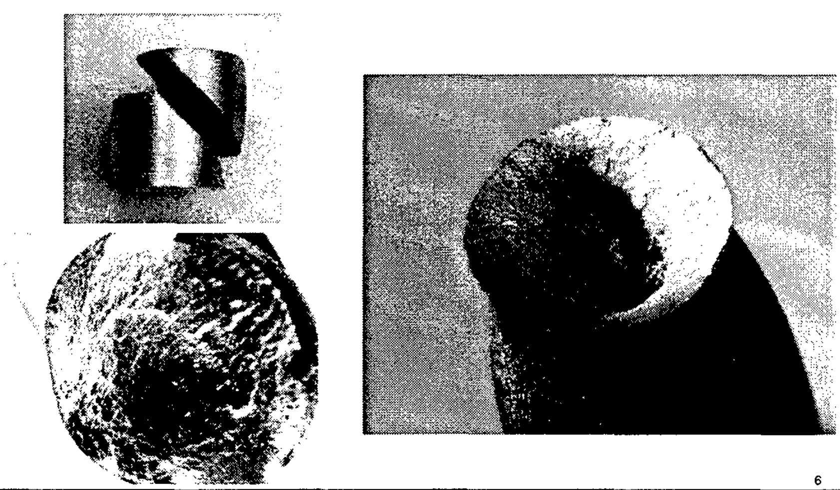


5

Loading Type

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

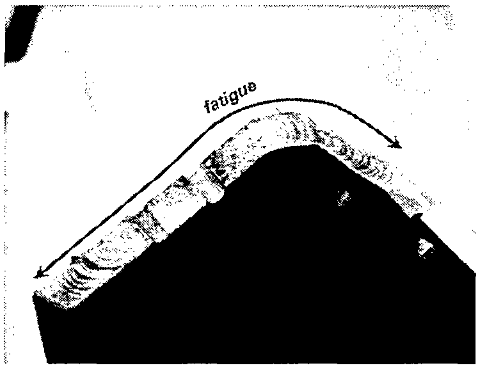
- Both are ductile materials loaded axially
  - Why are they different?

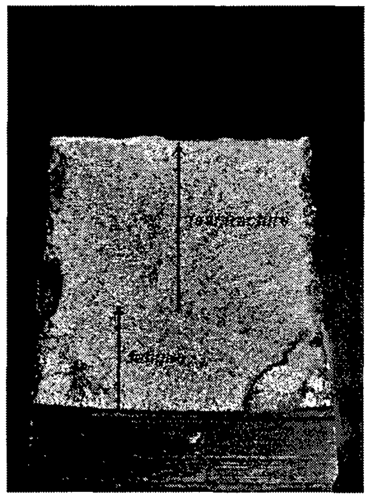


6

Loading Magnitude

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)





7

Metallography as a Failure Analysis Tool

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- What can be determined?
  - Microstructure
  - Processing History
  - Corrosion
  - Heat Damage
  - Fracture origin

8

Metallography Process

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Steps
  - Cutting specimen
  - Mounting
  - Polishing
  - Etching
- Can be Expensive
  - Labor Intensive
  - Time consuming
  - Destructive

9

Common Equipment

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Visual (unassisted) Inspection
  - Always the first step
  - eyeball or very low magnification
- Macroscopic Magnification (<100X)
  - Equipment
    - Hand lens
    - Stereo imaging
  - What can you learn?
    - Brittle vs. ductile based on fracture orientation
    - Fracture origin (sometimes)
    - Beachmarks for fatigue—if visible
    - Heat/chemical effects (if discolored)

10

Common Equipment

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Microscopic Magnification (>100X)
  - Equipment
    - Light microscope
    - SEM (100X and up)
  - What can you learn?
    - Brittle vs. ductile
    - Origin
    - Striations
    - Heat/chemical effects (if discolored)
    - Composition (if EDAX equipped)

11

Topic Teaser

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

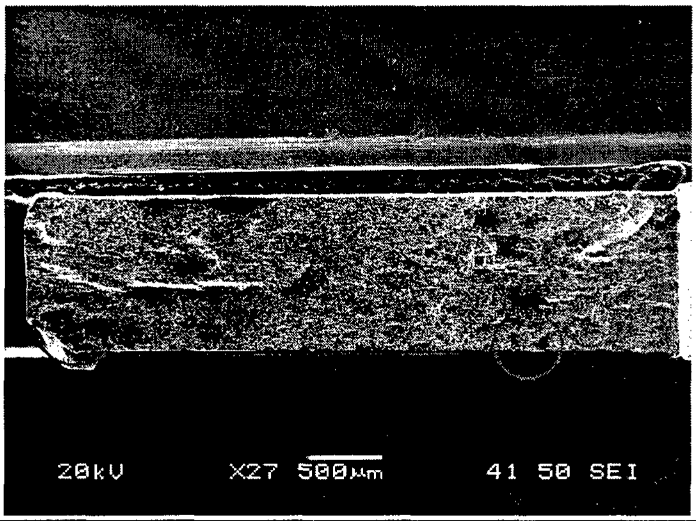
- Is this a striation?

12

Topic Teaser: Striation?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- No, they are actually smear marks in circled regions

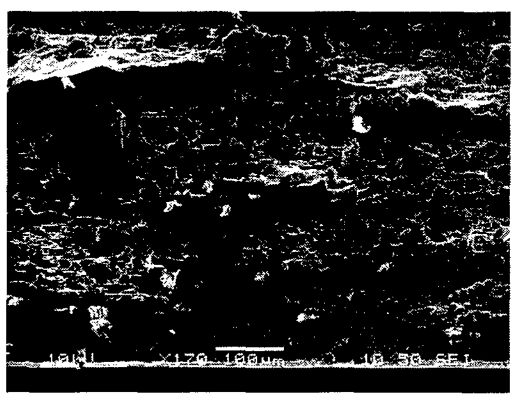


13

Topic Teaser: Striation?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Note the flow outside the region with the "striations"
- Fracture mode was actually by SCC
- Lesson? Don't base conclusions on a single observation



Higher mag macroscopic image from left most circle in previous

14

Guidance

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Protect your specimen!
- Try not to clean
  - Only if absolutely necessary
  - Only after un-cleaned surface is fully evaluated
- Dealing with large specimens
  - Excise samples
  - Make replicas
- How do you know what to look for?
  - Experience
  - ASM Handbooks

15

Lesson 10

Metallography and Fractography Applications

1

Lesson Goals and Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers should appreciate the process of conducting a typical fractographic and metallographic evaluation.
- Objectives
  - **Know** how a typical failure analysis investigation might be conducted
  - **Describe** the steps involved and their importance for detailed metallurgical failure analysis
  - **Describe** the limitations of metallography and fractography techniques/equipment

2

Macroscopic Analysis (C-130 CWB Corner Fitting)

Visual inspection of the part with unaided or aided eye (up to 20X).

Advantages:

- Ease and convenience
- Larger area can be inspected with "Bird's Eye View".

Limitations:

- Only macro defects can be analyzed
- Subject to individual interpretation

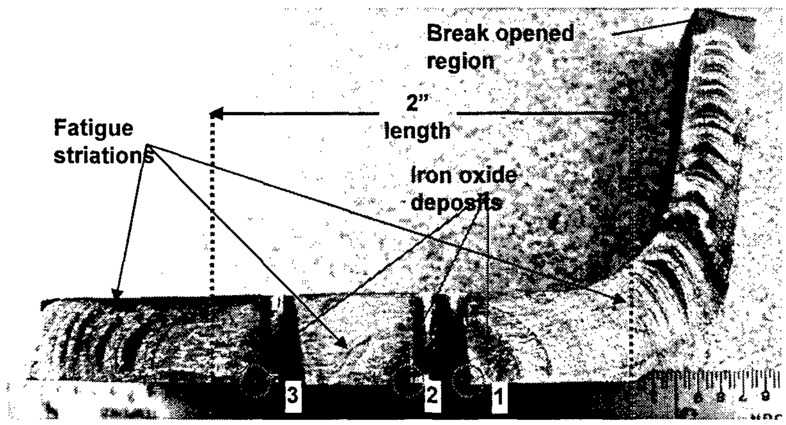
Macroscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Macro photograph of the corner fitting from C130E SN 62-1789 and the location of the visible crack. The location of the cut notch along with the load direction used for crack opening is also indicated.

Macroscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Macrograph of the as –opened fracture surface. Three Initiation sites that are clearly visible are marked by red circles labeled 1, 2 & 3. Reddish brown deposits of iron oxide "rust" from the fasteners are shown by brown arrows.

5

Macroscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Analysis of Macro-Photos

- The beach marks indicates crack propagation by fatigue.
- Orientation of beach marks indicates three separate initiation sites.
- Initiation sites located on the faying surface of the fitting at the fastener holes.
- Initiation sites are located by converging radially inside from the propagating beach marks.

6

Microscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Optical or Electron Microscopy at Magnifications > 20X.

Advantages:

- Minute Details can be revealed.
- Interaction of microscopic features of material to the environment can be understood.
- Micro-analytical tools can be used to study variety of microscopic features such as elemental analysis, dislocation activity/density, grain morphology, texture and others.

Limitations:

- Only small area can be analyzed at a time.
- Careful interpretation required.

7

Microscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Site 2 Site 1

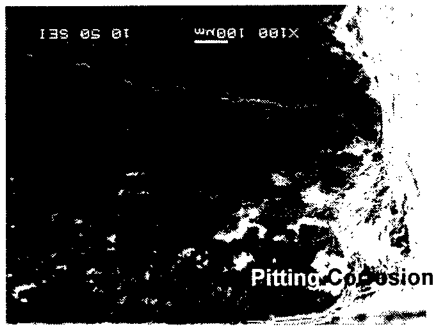
SEM Images near the initiation sites 1 and 2 shown in the previous slide

8

Microscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Site 3

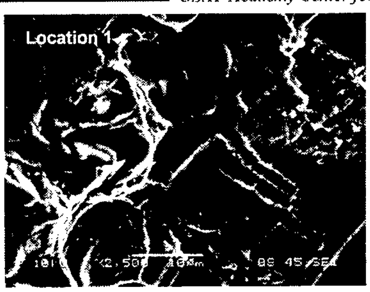


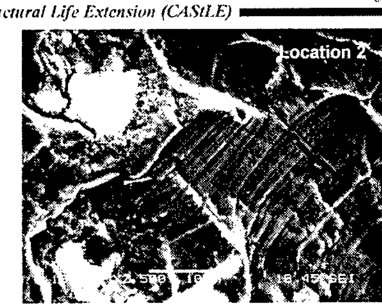
SEM Images near the initiation site 3 shown in the previous slide. Higher magnification also reveals extensive pitting corrosion at the initiation site.

9

Microscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



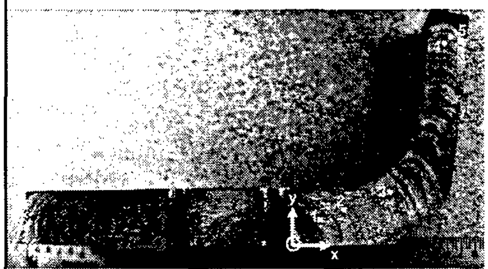


SEM images showing striations at various locations from Initiation Site 1

10

Microscopic Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Site	ID	x, y, mm	Crack length, mm (in)	da/dn, nm
1	1	(6.16, 2.98)	6.84 (0.27)	212
	2	(10.63, 4.78)	11.65 (0.46)	283
	3	(19.65, 7.5)	21.03 (0.83)	427
	4	(29.67, 34.51)	45.51 (1.79)	242
	5	(31.33, 35.61)	47.43 (1.87)	133
2	1	(1.68, 4.12)	4.45 (0.18)	100
	2	(3.82, 4.46)	5.87 (0.23)	400
	3	(7.2, 7.66)	10.51 (0.41)	390
3	1	(5.36, 4.07)	6.73 (0.26)	150
	2	(21.2, 5.23)	21.84 (0.85)	205
	3	(25.53, 4.96)	25.78 (1.01)	130

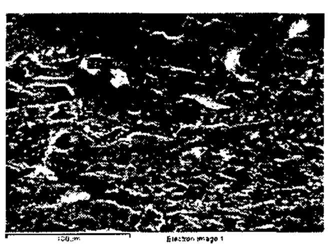
Striation spacing as a function of distance from the initiation site

Microscopic analysis can be used to study the crack propagation rate to compare with predictive models as well as can be used to find out when the crack started propagating by fatigue using the crack growth models such as AFGROW.

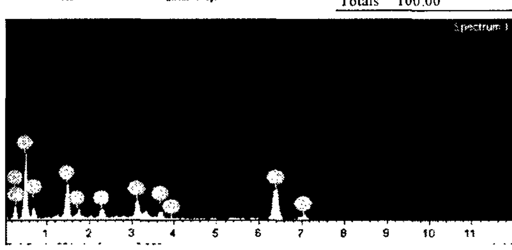
11

EDX Analysis (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Element	Weight%	Atomic%
C K	14.65	25.94
O K	41.88	55.67
Al K	6.19	4.88
Si K	1.04	0.79
S K	1.81	1.20
Ca K	1.84	0.97
Fe K	22.87	8.71
Cd L	9.71	1.84
Totals	100.00	



EDX Detector fitted on an SEM can be used for this purpose. The graphic here represents SEM image. EDX spectrum and elemental analysis of the reddish brown deposit seen near the initiation sites. Elemental analysis shows significant presence of iron and oxygen with cadmium. Steel fasteners are often coated with cadmium.

12

Conclusion (C-130 CWB Corner Fitting)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The crack initiated and then grew by steady state high cycle fatigue.
- Initiations sites were at fastener holes on faying surface.
- Pitting corrosion initiated the cracks which then grew by fatigue.
- There was no evidence of abnormal crack growth or overload region until the cracks became highly extended.
- There is a substantial amount of chemical deposits due to the flowing liquids in and out of crack during the service period that followed the fatigue crack growth.
- While pitting corrosion may have significantly contributed to fatigue initiation there is no indication that shows corrosion contributed to crack extension.
- The presence of chemical deposits, fretting and smearing observed on the fracture surface indicates that the cracks existed for a long period of time, prior to the crack opening during this failure analysis.

13

C-130E CWB – Skin Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Tail # : 68-10942

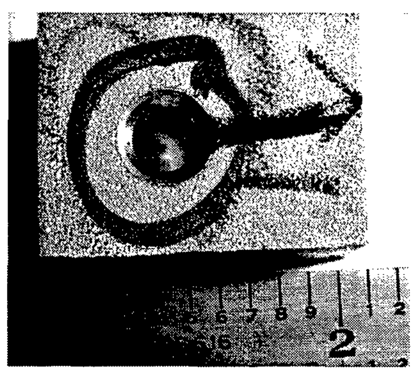
Part: Left Lower Wing Skin

Location: Stringer 16 Hole D4

Wing Station Location: 110

Indication: 100%HC-BHEC – AFT Orientation

Analytical tools: Stereo Microscopy, Optical Microscopy, SEM

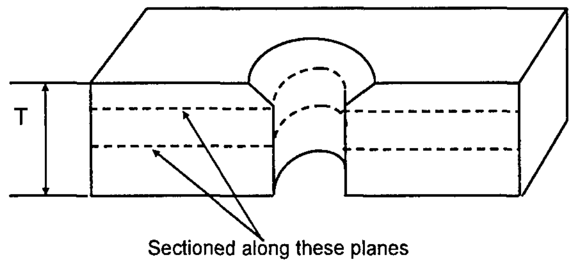


Extensive Visual, Optical and Electron Microscopy, did not reveal any crack in the indicated orientation.

14

C-130E CWB – Skin Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

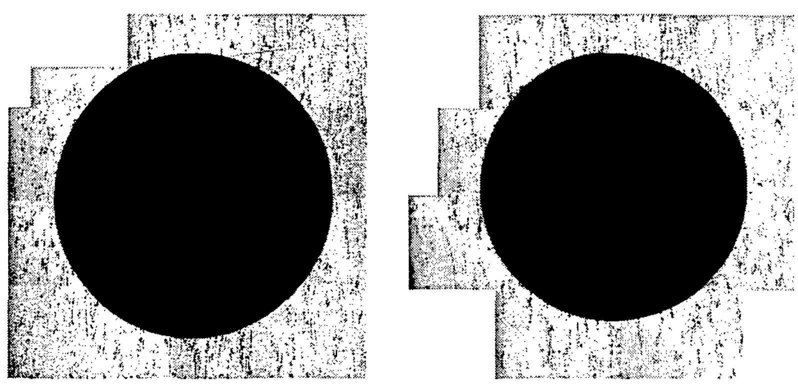


To verify the presence of crack, the specimen was cut along the indicated planes, followed by polishing and optical microscopy.

15

C-130E CWB – Skin Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Composites of optical micrographs of the sectioned surfaces suggest absence of any crack in the sectioned area. However, the grain boundaries are oriented in FWD-AFT direction. The noise from these boundaries may have been picked up as an indication.

16

C-130E CWB – Stringer Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Tail #: 68-10942

Part: Left Lower Wing Stringer

Location: Stringer 13 Hole A23

Wing Station Location: 091

NDI Findings: 90% HC-BHEC AFT Orientation

Analytical tools: Stereo Microscopy, Optical Microscopy, SEM

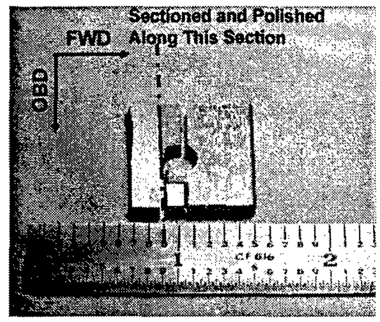
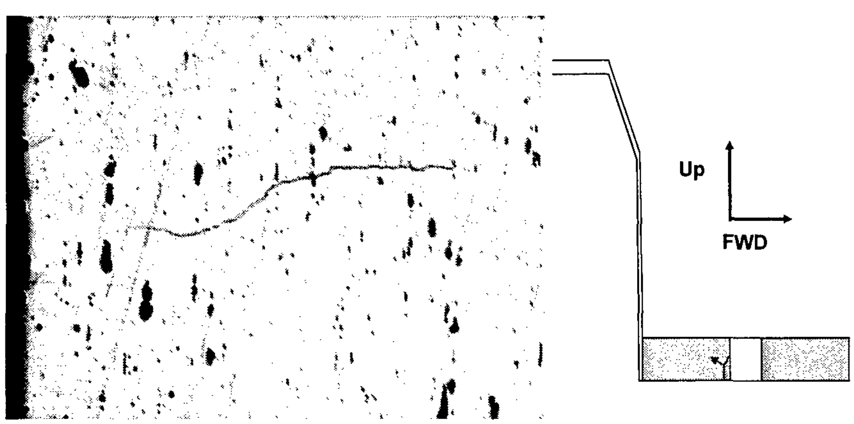


Photo showing sections along which the sample was cut

17

C-130E CWB – Stringer Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

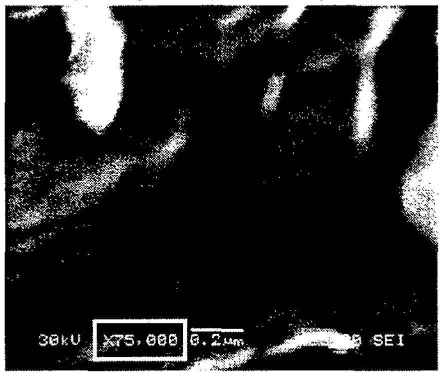


Polishing revealed a Fine crack emanating from faying surface. This crack tends to close as it reached free surface, which made it difficult to observe without sectioning and polishing.

18

C-130E CWB – Stringer Panel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

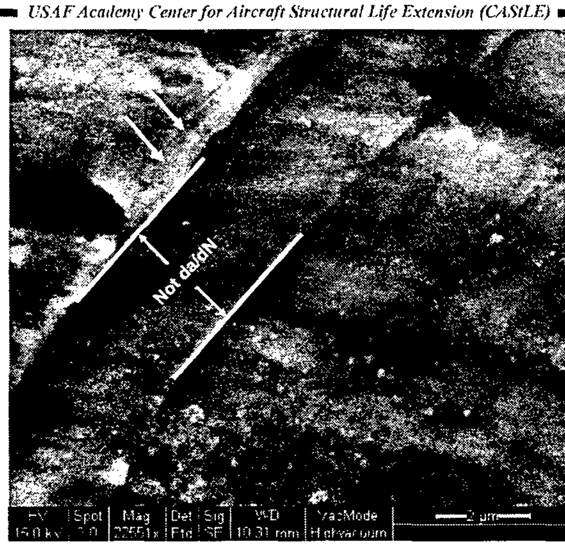


High Magnification SEM reveals fine striations indicating the fatigue crack.

Measurements:
Initiation site: 24.0 µm in thickness (UP), 27.4 µm in length (FWD)
Crack Length: 520 µm in thickness (UP), between 340 µm and 540 µm in length (FWD)
Striation spacing: 55.6 nm at 279 µm from initiation site

Common Pitfalls in Metallography

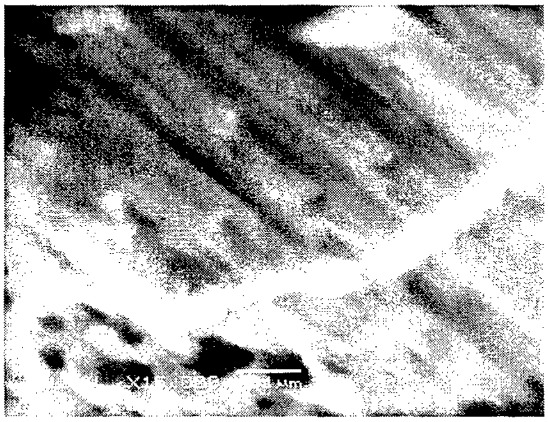
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Magnification is not high Enough

Common Pitfalls in Metallography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

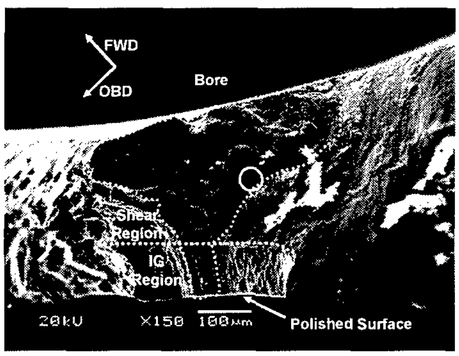


Are these fatigue striations?

21

Common Pitfalls in Metallography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Those are actually smear marks at the location pointed by the circle.

Fracture Mode is by shear due to tool gouging at fastener hole.

Always look at the complete picture.

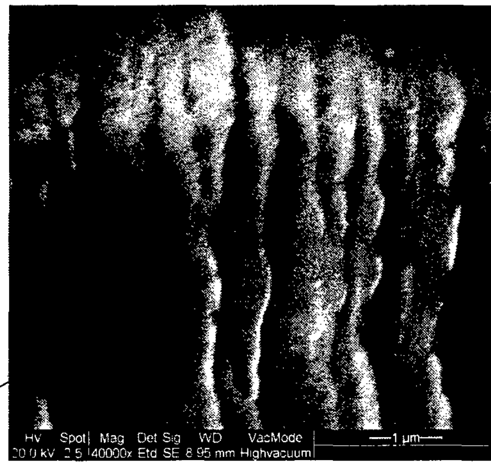
Handle samples properly to prevent such artifacts.

22

Common Pitfalls in Metallography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Possible Striations Direction

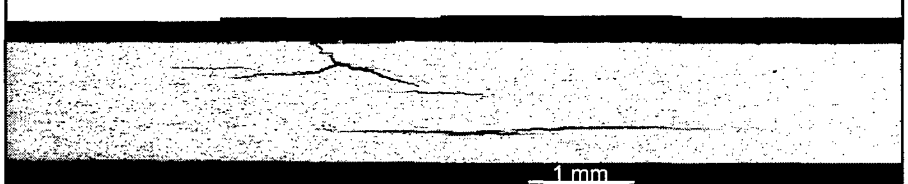


Tear Marks vs. Striations. Tear marks are perpendicular to striations. Do not depend on auto functions of the instruments alone.

23

Common Pitfalls in Metallography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Section 2B

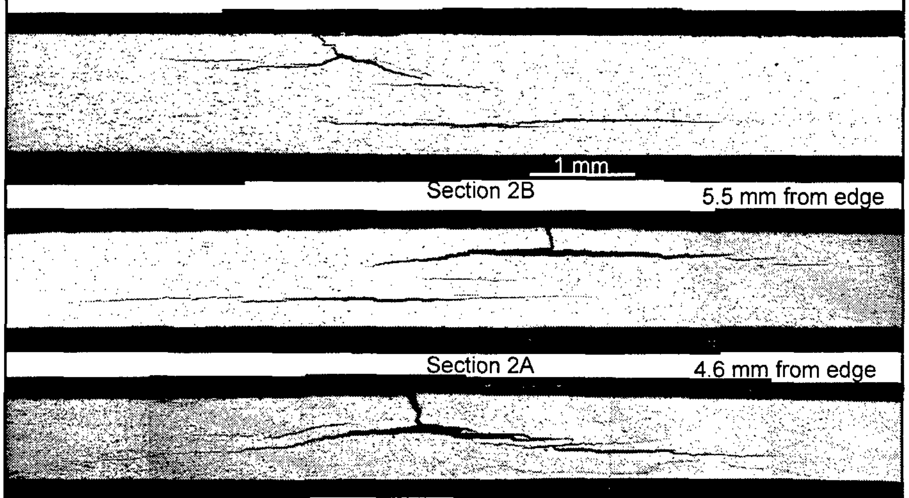
5.5 mm from edge

Crack originating from nowhere?

24

Common Pitfalls in Metallography

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Section 2B 5.5 mm from edge

Section 2A 4.6 mm from edge

Section 1B 2.2 mm from edge

There is always a third dimension to any feature.

25

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 11

Corrosion I

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers should understand the fundamental principles of corrosion and the factors which contribute to it.
- Objectives
  - **Describe** the principles of corrosion
  - **Discuss** the material and environmental factors that contribute to corrosion

2

C-130E Center Wing Corrosion Damage

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Sep 2002: SN 68-10942 was found with severe corrosion during the accomplishment of TCTO 1799 at Hill AFB

3

C-130E S/N 68-10942

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

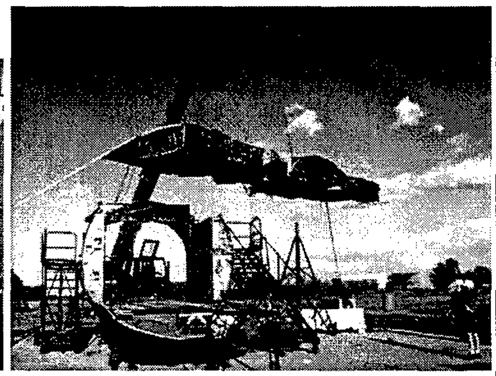
- Details
  - Wing had ~20K hours TT and ~46K hours equivalent time
  - Fuel bladders in center wing
  - Traps environment on structure
- Aircraft permanently grounded
  - Corrosions damage mostly isolated to rear spar region
  - Deemed to costly to repair
  - Reached economic service life

4

C-130E S/N 68-10942

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Follow on details
  - Wing used for destructive teardown analysis
  - Wings currently not flown past 45K equivalent hours for fatigue concerns



5

Overview

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Size of Problem:
  - 1995: $296 BILLION
  - An estimated 4.2% of GDP
  - $104 Billion is considered avoidable
- Prevention
  - Most common approach to prevention is "find and fix"
  - very expensive as it is not really prevention at all

6

What is Corrosion?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Reverse refining
  - Metal ore (oxide, sulfide, etc.)
  - Refining creates what we know as metal
  - Corrosion returns to an ore-like state
- Electrochemical Reaction
  - Oxidation
  - Reduction
- A Process
  - Thermodynamics
  - Kinetics

7

Oxidation

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Anodic
  - Loss of electrons
  - Loss of electrons ➔ CORROSION
- M ➔ M+n + ne- where n = valence of material
  - For example: $Fe \rightarrow Fe^{2+} + 2e^{-}$

8

Reduction

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Cathodic
  - Electroplating process
- Reduces the charge towards the negative
  - Material gains electrons
  - Reactions depend on the environment
- Example: $O_2 + 2H_2O + 4e^- \rightarrow 4OH$

9

Thermodynamics

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Answers the question: "Will it happen?"
  - The answer is usually "YES"
- Based upon G, Gibb's Free Energy
  - Δ G is found in tables/charts for various reactions
  - If ΔG is negative for a system of reactions, corrosion will happen
- Relative placement in the galvanic series

10

Kinetics

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

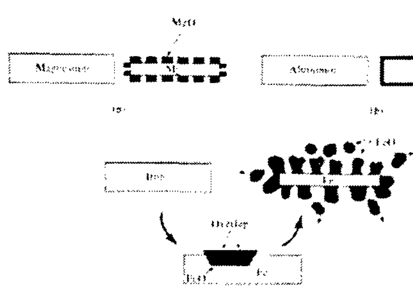
- Answers the question: "How fast will it happen?"
- Expressed as an Arrhenius relation
  - CORROSION RATE = $Aexp^{(-Q/RT)}$
- In an one process Reduction Rate = Oxidation Rate
- Kinetics linked to thermodynamics
  - Slow one and the other slows
  - Slow the corrosion rate

11

Active vs. Passive

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Based on Pilling-Bedworth Ratio
- Active: easily re-actable or corrodible
- Passive: lower corrosion potential



Pilling-Bedworth (PB) Ratio	
PB < 1	Porous
1 < PB < 2	Tight
PB > 2	Spalling

FIGURE 22-17 Three types of oxides may form, depending on the volume ratio between the metal and the oxide: (a) magnesium produces a porous oxide film, (b) aluminum forms a protective, adherent, nonporous oxide film, and (c) iron forms an oxide film that spalls off the surface and provides poor protection.

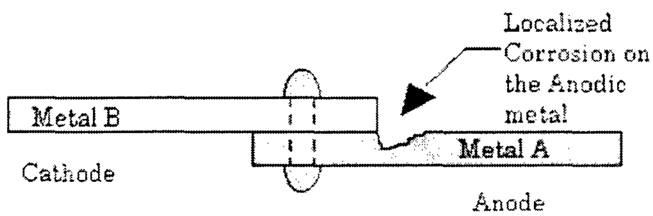
Courtesy of: Askeland

12

Galvanic Cell

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The central theme to all corrosion processes
- Driven by the potential between materials



GALVANIC CORROSION IN DISSIMILAR METALS

13

Galvanic Cell

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

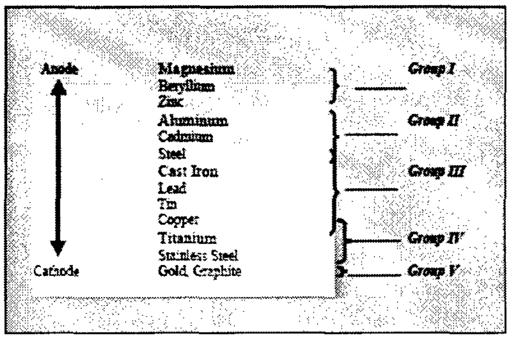
- Anywhere there are dissimilar materials
  - Metals or non-metals
  - Anode corrodes, cathode is protected
  - Electrolyte connects the materials
- Rate
  - Highest near the connection
  - High dissimilarity, high rate
  - Higher for small anode

14

Galvanic Series

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Reactivity higher with more dissimilarity
  - Carbon to Aluminum → highly reactive
  - Why is cadmium used to coat steel pins in aluminum structure?
  - Why is steel galvanized with zinc and not tin?



15

Corrosion Factors

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Environment
- Metal Surface Geometry
- Metallurgical Structure
- Material Properties
- Stress
- Temperature
- Temperature Gradients
- Relative motion of fluid

16

What next?

- Next lesson period
  - Specific types of corrosion
  - Corrosion factors in USAF structure

17

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 12

Corrosion II

1

Lesson Goals & Objectives

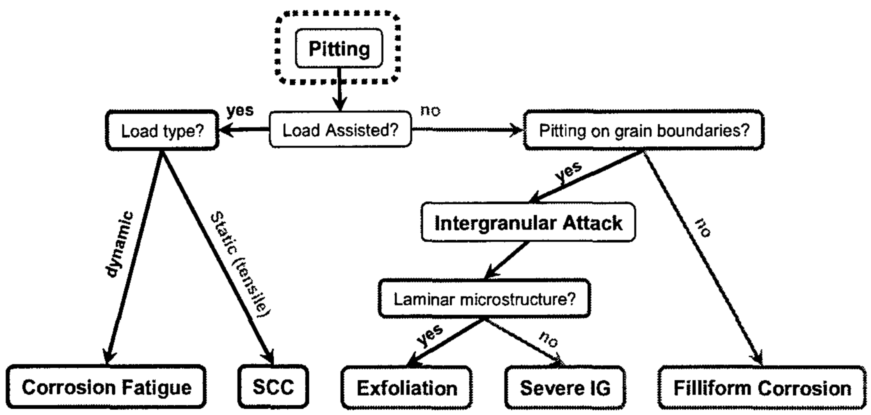
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers should be familiar with types of corrosion which are common to USAF aircraft structure.
- Objectives
  - **Identify** the differences/similarities between different types of corrosion
  - **Describe** potential corrosion preventive measures

2

A Path to Corrosion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



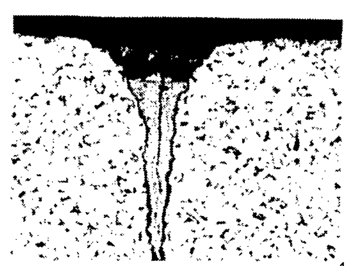
REMEMBER: the Galvanic Cell at the heart of it all

3

Pitting Corrosion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

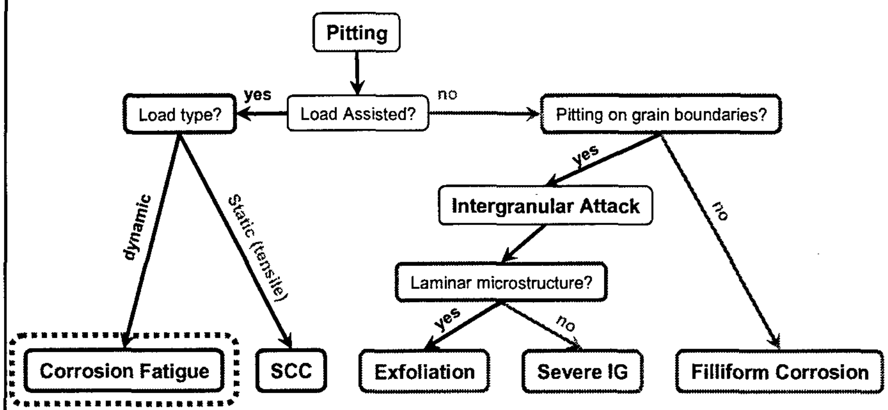
- Extremely localized
  - local inhomogeneity, loss of passivity, loss of coating
  - one area becomes anodic with respect to another area due to environment or processing
- Rate
  - Related to the aggressiveness of environment
  - Can be10-100 times faster than uniform corrosion
- Prevention
  - Uniform coatings
  - Control environment



4

Dynamic Load Assisted

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



5

Corrosion Fatigue

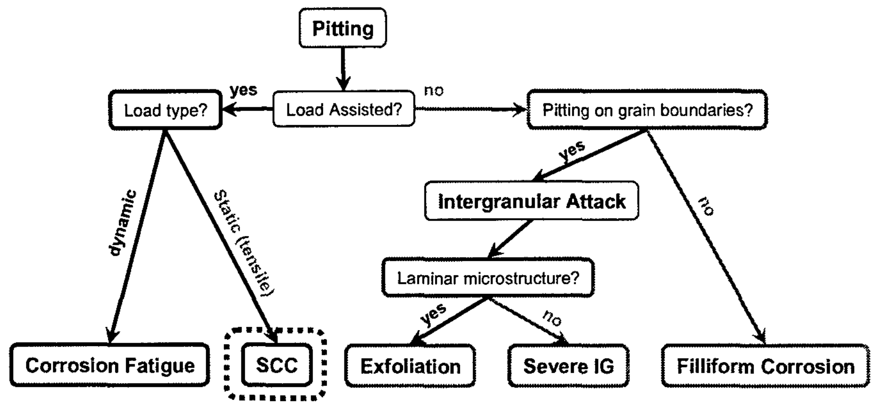
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Combines fatigue and corrosion crack growth mechanisms
- Dynamic load assists in the opening of the crack
- The longer and more frequent the fatigue crack is open to the environment, the worse the effect
- Fracture surface
  - Striations
  - Obscured by corrosion product

6

Static (Tensile) Load Assisted

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

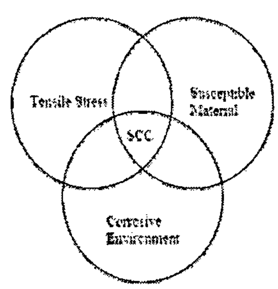


7

Stress Corrosion Cracking (SCC)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

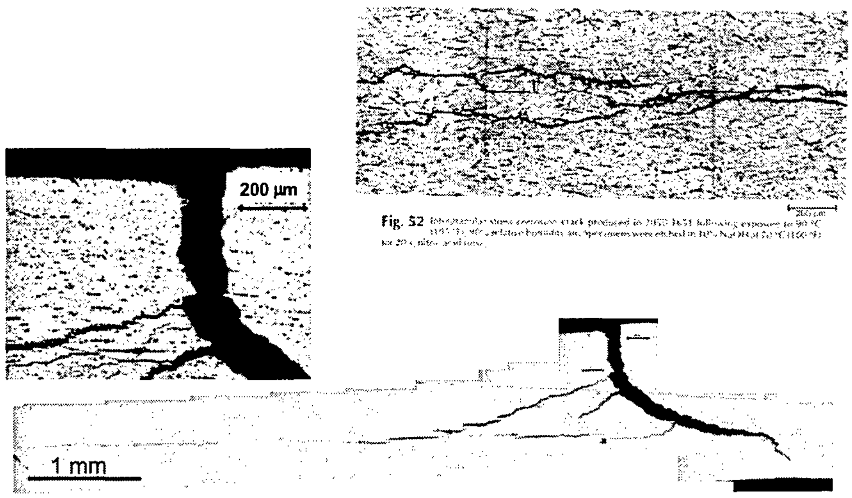
- Needs all three
  - Sustained tensile stress
  - Environment
  - Susceptible material
- Stress?
  - Ramp loads
  - Fit-up, interference
  - Residual
- Features
  - Predominant crack path with branching
  - Transgranular OR intergranular



8

SCC Features

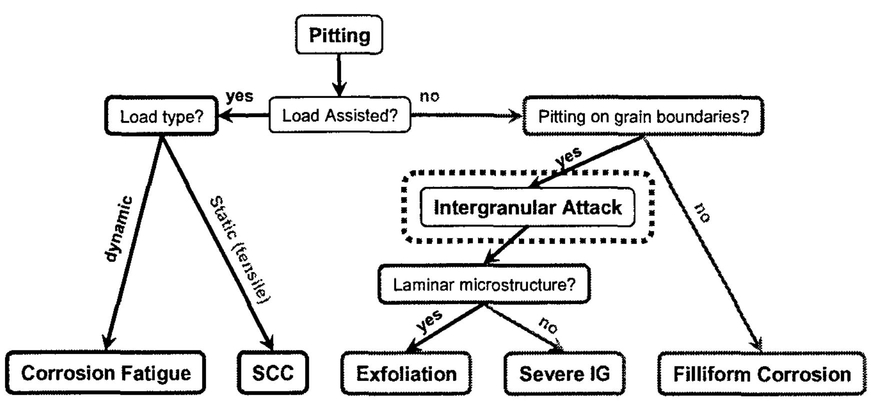
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



9

No load, pitting on GBs

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

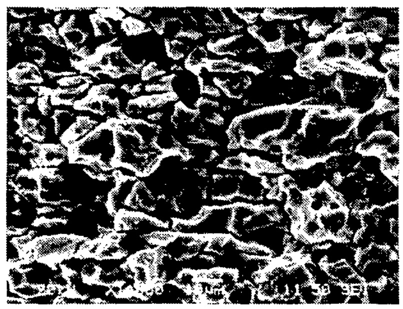


10

Intergranular Corrosion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

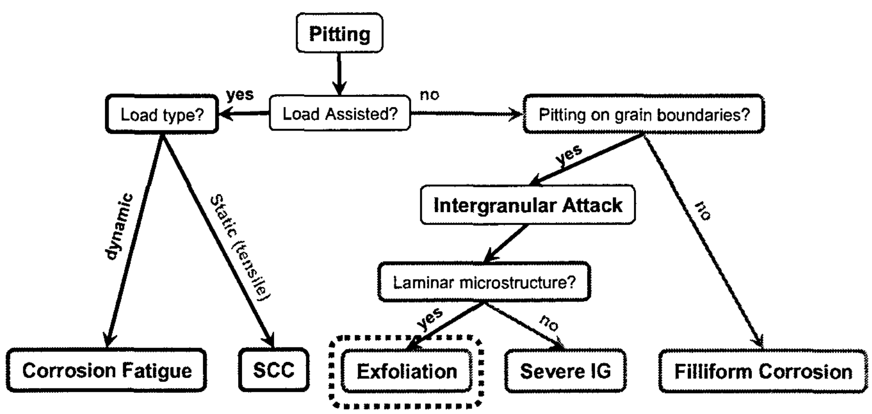
- No load interaction, pitting on the grain boundaries
  - precipitation of a second phase or other segregation at grain boundaries produces a galvanic cell
- Corrosion of or near grain boundaries with less attack on bulk material
- Rate: depends on concentration of corrodible materials on the grain boundaries



11

No load, pitting on GBs, laminar MS

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

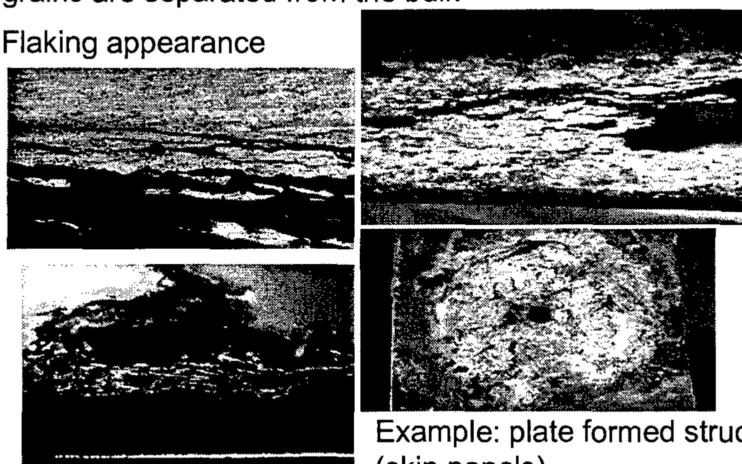


12

Exfoliation

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Severe progress of IG causing material loss as laminar grains are separated from the bulk
- Flaking appearance

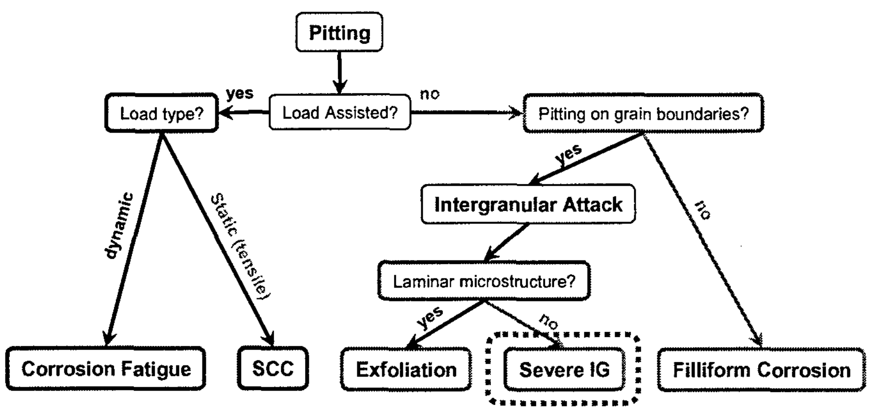


Example: plate formed structure (skin panels)

13

No load, pitting on GBs, non-laminar MS

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



14

Severe IG

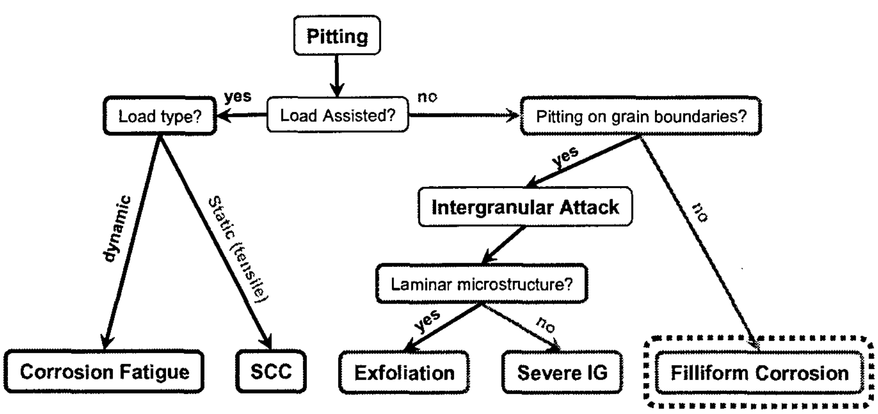
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- IG continues along GBs but more equi axed grain structure present
- "flaking" material loss does not occur
- Example: forged structure C-5 Tie box

15

No load, no pitting on GBs

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

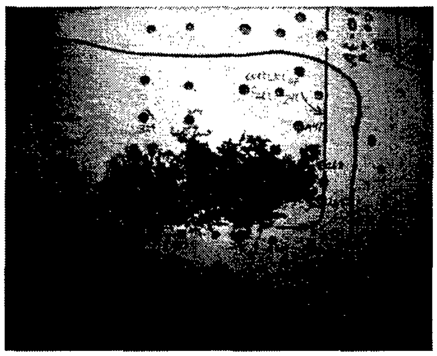


16

Filliform Corrosion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Continued severe pitting across a surface
- More common in steels but has been seen in aluminum



17

Anything Else?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Crevice Corrosion**
  - **Capillary action of a joint pulls fluid (electrolyte) inside the crevice**
  - **Protected from the outside**
  - **Example:**
    - **joints**
    - **under deposits**
- **Erosion Corrosion**
  - **As the name suggests combines corrosive event with a moving corrosive fluid**
  - **Enhances the kinetics of any corrosion process**

18

Prevention

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Change Environment
- Change Design
- Change Kinetics
- Coat or Inhibit
- Remember you a have a friend in the corrosion business:

U.S. Air Force Corrosion Prevention and Control Office
Design
Prevention
Detection
Control

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 14

Wear

1

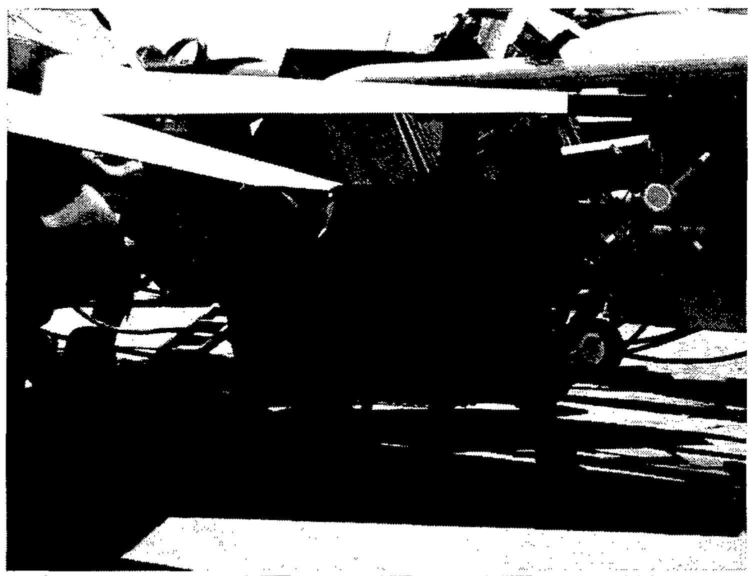
F-16s at Al Udeid

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Initial unconfirmed reports indicate that a taxiing F-16 lost all hydraulic power and ran into a parked F-16 at about 10 knots.
  - One maintenance troop on top of the parked F-16 was thrown or jumped off theF-16 and was slightly injured, abrasions to his back.
  - Both F-16's were fully loaded with LIVE Ordinance, there were also 3 pieces of AGE equipment involved.
  - After the impact, some sort of electrical short is suspected from one of the AIM 9 missiles, that possible ignited some of the fuel and started a fire in the motor of the AIM -9 and on a below mounted avionic POD.
    - This fire was reportedly quit large, it was extinguished by another maintenance troop, possible saving (7) fully loaded F-16's!
- Both F-16's are from a Guard unit at Hill AFB. The same unit lost an F-16 in Iraq the previous week.

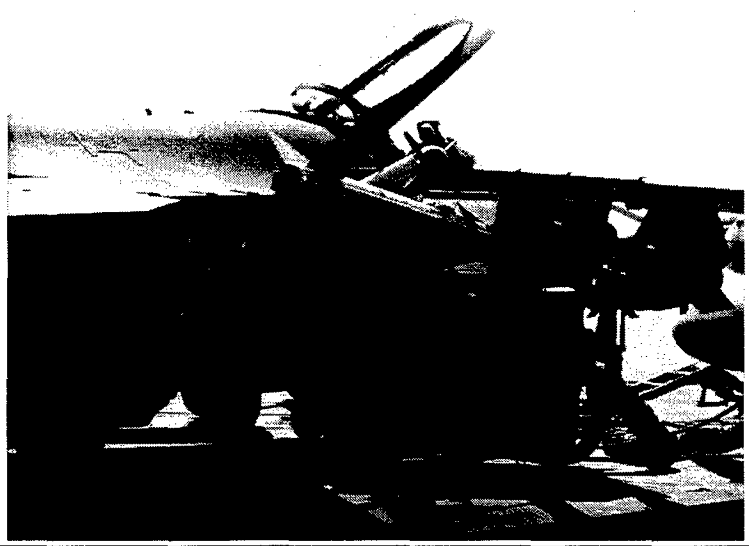
2

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



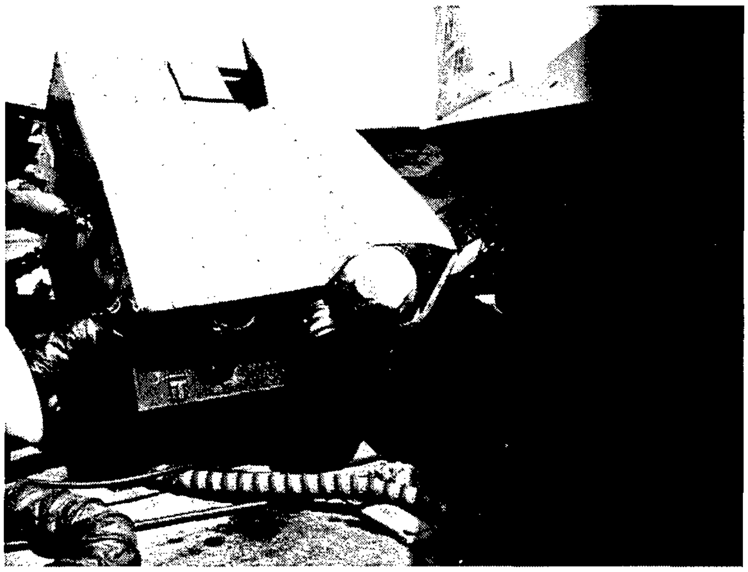
3

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



4

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

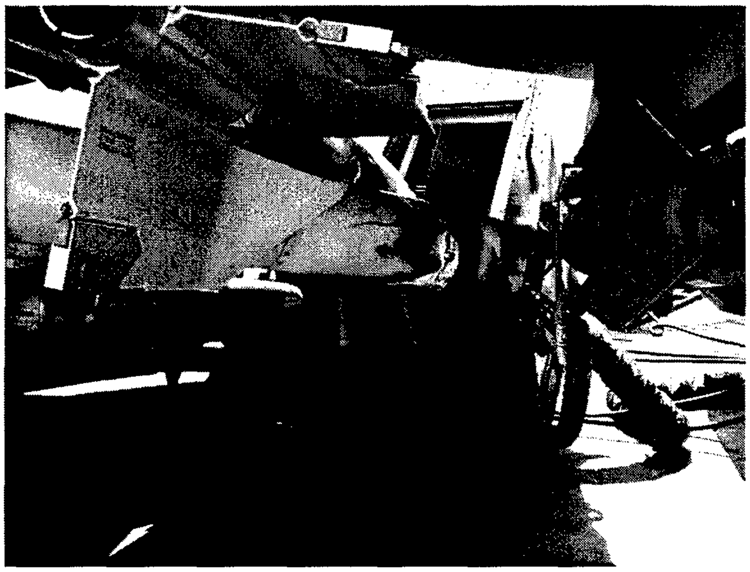


5

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

6

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



7

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

8

So what happened?

Something wore out

Lesson Goal and Objectives

- After this lesson, engineers will understand how wear can be a factor in maintaining aircraft structure.
- Objectives
  - **Discuss** differences between types of wear and where each may be found
  - **Describe** contact stress fatigue
  - **Describe** the benefits/application of lubrication and other wear preventatives

Wear

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

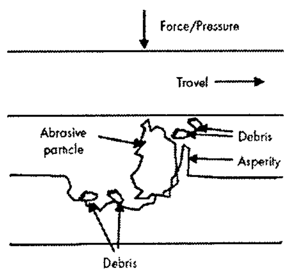
- Definition: The **Undesired** removal of material from contacting surfaces by mechanical action
- Five main categories
  - Abrasive
  - Adhesive
  - Fretting
  - Surface Fatigue
  - Corrosive

11

Abrasive Wear

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The cutting of one surface by another rolling or scraping past it
- Types
  - Erosive
  - Grinding
  - Gouging
  - 2 Body or 3 Body

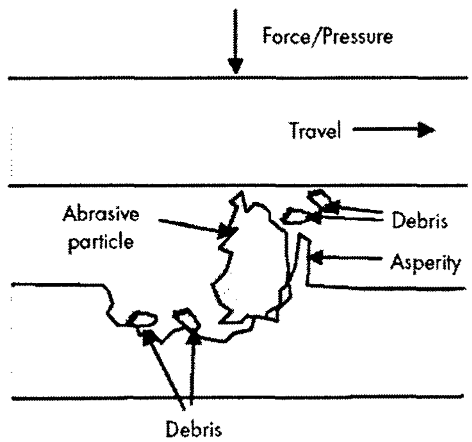


- Prevention
  - Increase hardness (but you lose ductility)
  - Hard coatings
  - Lubrication
  - Filter
  - Cheap and easy parts replacement

12

Abrasive Wear Illustration

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Courtesy of Material Failure Modes – Desk Reference, AMPTIAC, Rome, NY

13

Adhesive Wear

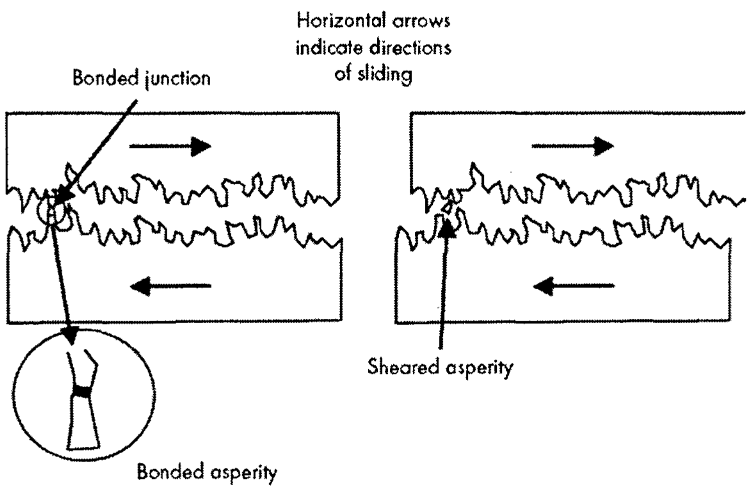
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Two materials in relative motion
- High contact stress from inherent roughness
- Asperities (ridges) on two surfaces micro-weld together
- Relative motion continues → weld breaks
  - Material transfer between parts
  - Debris created → abrasive wear
- Also called scouring, galling and seizing

14

Adhesive Wear illustration

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Courtesy of Material Failure Modes – Desk Reference, AMPTIAC, Rome, NY

15

Adhesive Wear Prevention

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Do not use the same type of metals when designing parts that rub against one another
  - Similar materials micro weld easier
- Use insoluble metals (gold, silver-plating)
- Lubricate parts
- Use extremely smooth parts

16

Fretting Wear

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Similar to Adhesive Wear (micro-welding)
  - Occurs between parts not designed to move
  - Interface is essentially stationary
  - Small amplitude oscillatory motion (vibrations)
- Adhesion occurs relative small scale but relative large quantity
- Debris remains between the parts
- Can initiate fatigue cracks
- Prevention
  - Reduce vibration (dampen)
  - Tighten Joint (can lead to extra problems if it doesn't work)
  - Lubricate
  - Separation layer between materials (ex. sealant)

17

Surface Fatigue Wear

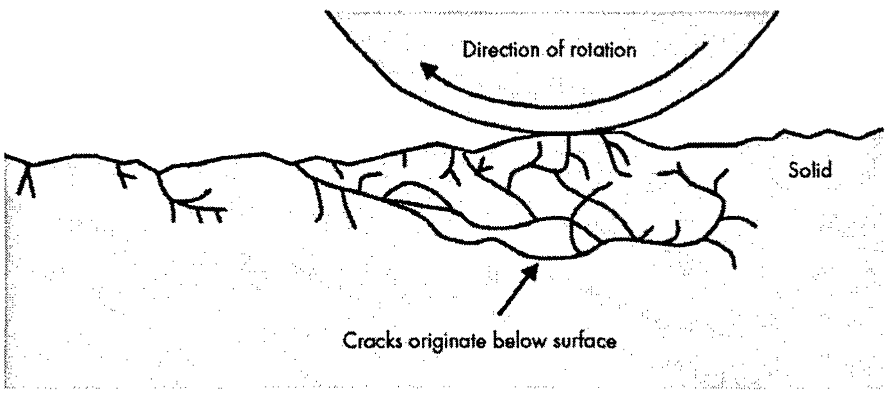
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Two materials in contact that are rolling and/or sliding
- Creates alternating stress normal to contact surface
- Subsurface cracks form
  - Initiate at hard inclusion or case/core interface
  - Cracks grow back to the surface
- Pits form as material is ejected
- Cracks can also originate on surface due to high friction

18

Surface Fatigue Wear Illustration

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Courtesy of Material Failure Modes – Desk Reference, AMPTIAC, Rome, NY

19

Surface Fatigue Wear Prevention

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Eliminate hard inclusions
- Reduce contact stresses
- Change relative motion
- Lubricate

20

Corrosion Wear

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Surface protected from corrosive processes
- Abrasive or Adhesive wear degrades coating
- Surfaces corrode
- Corrosive products (oxides) form
  - Dislodged from the surface
  - Act as abrasive particles

21

Wear Analysis

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Examine surfaces
- Examine debris
- Examine lubricants and sealants
- Define relative motions
- Identify wear mechanism
- Propose solution

22

Generalized Wear Solutions

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Lubrication
- Filtering
- Materials Engineering
- Proper Design

Lesson 15

Linear Elastic Fracture Mechanics

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will understand the foundations of fracture mechanics and how LEFM is used to during the life cycle of AF aircraft

- Objectives
  - **Understand** the concept of stress concentrations
  - **Understand** the foundations of fracture mechanics
  - **Understand** geometry factors used to solve fracture problems.
  - **Know** how K_C varies as thickness varies.
  - **Understand** how LEFM is used during the design (or re-design) process.
  - **Discuss** why fracture receives so much attention in failure analyses

2

Stress Riser Effect

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Stress Risers
  - k_t (static)
  - k_f (fatigue)

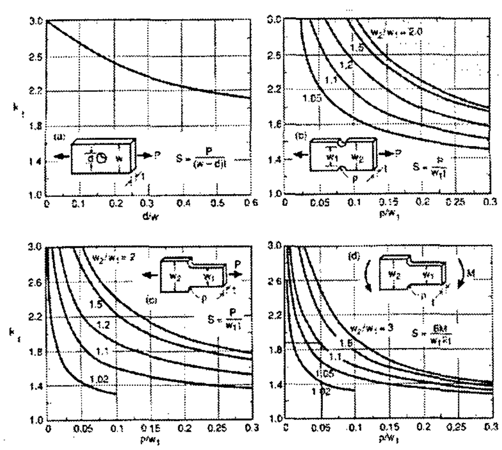


Figure A.8 Elastic stress concentration factors for various cases of notched plates. (Values from [Peterson 74] pp. 35, 89, 98, and 150.)

3

Stress Riser Effect

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- For an elliptical hole . . .
  - Significant k_t increase near the hole tip
  - K_t ↑ as c/d ratio ↑
- For a crack:
  - c/d approaches ∞ (or ρ approaches 0)
  - k_t and σ_{max} approach ∞

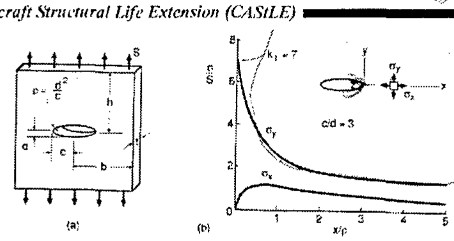


Figure 8.3 Elliptical hole in a wide plate under remote uniform tension, and the stress distribution along the x-axis near the hole for one particular case.

c/d ratio	k_t
1/1	3.0
1/4	1.5
4/1	9.0
10/1	21
100/1	201

Linear Elastic Fracture Mechanics (LEFM)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Infinitely large stress doesn't really occur
  - If it did, any size crack would result in sudden fracture
  - Localized plastic yielding prevents this

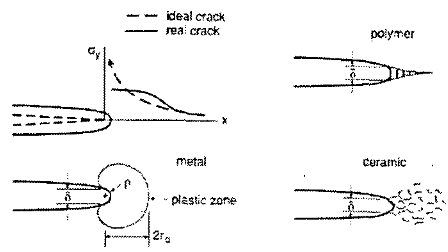


Figure 8.4 Finite stresses and nonzero radii at tips of cracks in real materials. A region of intense deformation forms due to plasticity, crazing, or microcracking.

  - K (stress intensity factor) replaces k_t for a crack

LEFM

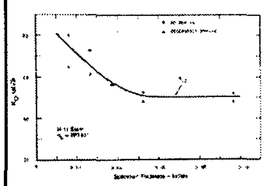
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

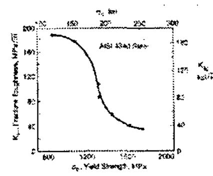
- One main equation: $K = \sigma F \sqrt{\pi a}$
  - K is applied stress intensity factor
  - σ is the applied gross stress
  - F is a geometric correction factor, base on:
    - Finite width
    - Crack, or flaw, shape
    - Crack length
    - Loading type
  - "a" is the crack length for one crack tip

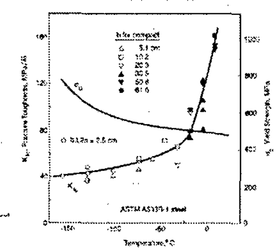
Material Fracture Toughness

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- K as a material property
  - Materials will undergo sudden fracture if $K_{app} \geq K_c$, or critical for material—K_c called fracture toughness
  - Plane Strain Fracture toughness, K_{IC}, is most conservative







- Fracture Toughness Trends
  - K_{IC} dependent on strength: as $F_{tu,ty} \uparrow$, $K_{IC} \downarrow$
  - K_{IC} dependent on temperature: as $T \downarrow$, $K_{IC} \downarrow$

7

LEFM in Design

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

$$K = \sigma F \sqrt{\pi a}$$

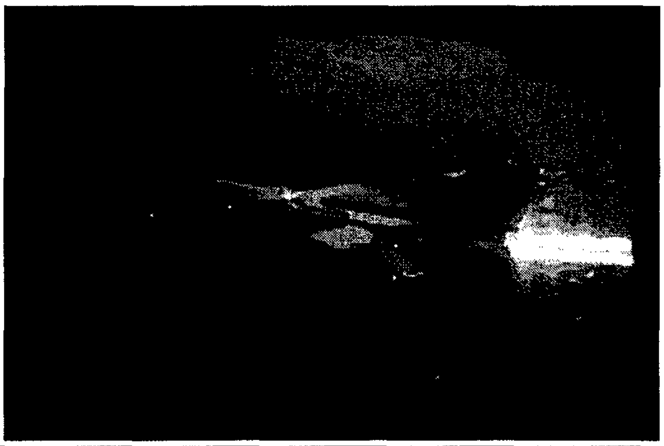
- If K_{IC} and S_g are plugged into the equation→solve for a_c
  - Pressure vessels: if $a_c > t$, then Leak-before-Break
- If K_{IC} and current crack length→solve for S_c

8

Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

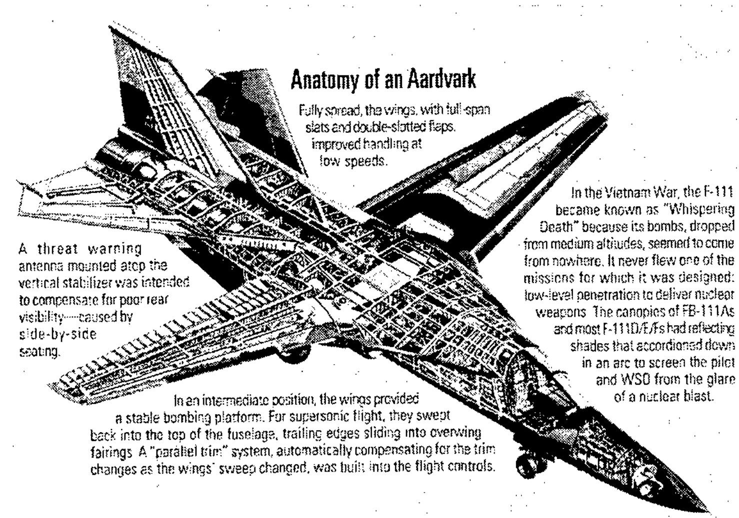
- Loss of F-111 in 1969 ushered in the era of fracture mechanics usage in the USAF and much of the aerospace industry



9

Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

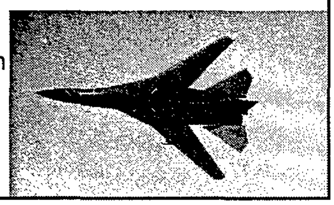


10

Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

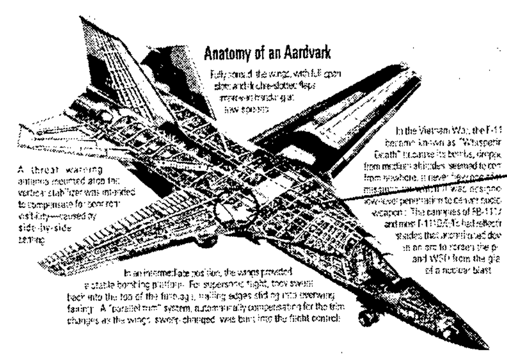
- Key features of the F-111
  - First variable geometry (swing-wing) aircraft in USA inventory
  - Designed as long-range fighter/bomber, large internal bay
  - Short takeoff, supersonic dash capability
  - Low altitude, terrain-following capable
  - Originally a joint AF-Navy aircraft ... Navy later pulled out
  - Specifications:
    - Length: 74 feet
    - Wingspan: full sweep – 32 feet, min sweep – 65 feet
    - Engines: 2 P&W TF-30 afterburning turbofans
    - Max weight: 119,000 (FB model)
    - Speed: Mach 2.2 (35,000 ft), Mach 1.2 (on the deck)
    - Crew: 2
  - Trivia: What is the only country with an active F-111 fleet?
    Australia



Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Details of the crash
  - 1969 at the Nellis Range
  - Aircraft had 109 flight hours
  - Test flight originating at Edwards AFB
  - Catastrophic failure of wing pivot fitting (D6AC Steel)
  - Pilot & co-pilot both killed



Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- The Flaw
  - Semi-elliptical surface flaw
  - Pre-existing before flight service began
  - Grew by fatigue before final fracture
  - a_c was smaller than a_{DETECT}

FIGURE 14.1 Fracture surface of F-111 wingbox area. Dark, semielliptical surface flaw preexisted the flight service. Smooth bright band at boundary of dark flaw represents fatigue crack propagation zone prior to unstable fracture. (After Wood[2]; reprinted with permission from *Eng. Fract. Mech. 7*, 557 (1975), Pergamon Press, Ltd.)

From Hertzberg, 4th ed

13

Case Study – F-111

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Aftermath
  - USAF, FAA, and JAA transitioned toward "Damage Tolerance" vs. "Safe Life" for aircraft design
  - Development of MIL-A-83444 "Damage Tolerance Design Requirements for Aircraft Structures"
    - MIL-A-83444 replaced by JSG-2006 in late '90's
  - Cold Proof Testing for the F-111
    - Inspect (as thoroughly as possible)
    - Prep (ready as for flight)
    - Cool down (-65F ambient, -45F internal, 6000 gal LN2)
    - Load (-2.4 to +7.3 Gs)
    - Monitor (acoustic emission)
    - Inspect

From Hertzberg, 4th ed

14

This Page Intentionally Left Blank

Lesson 16

Fatigue I

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson Goals & Objectives

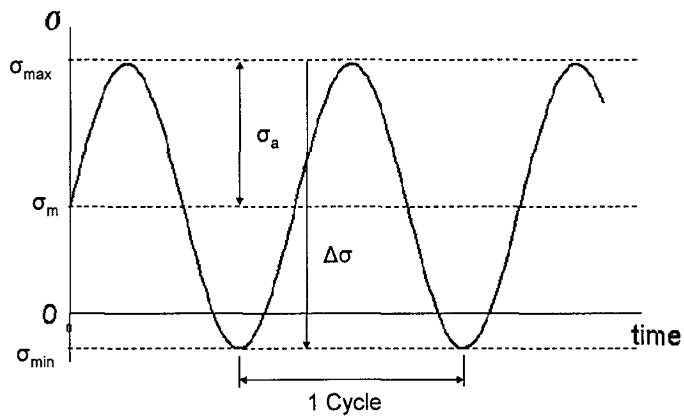
- After this lesson, engineers will understand the stages of fatigue crack growth and be able to discern the primary features of a fatigue fracture

- Objectives
  - **Define** fatigue
  - **Identify** the 3 stages of fatigue crack growth
  - **Describe** the primary fractographic features of fatigue in metals

Fatigue Failure Definition

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Failure due to repeated internal tensile loading at stresses *<u>less than material yield strength, F_{ty}.</u>*

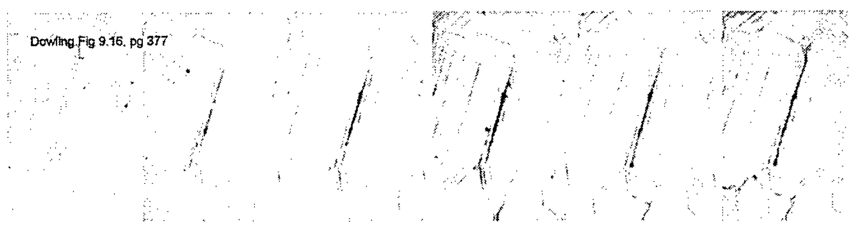


3

Stages of Fatigue

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Crack Nucleation
  - Slip occurs on crystallographic shear planes
  - Tiny voids form, then coalesce to form a crack



N = 0 10^4 2×10^4 6×10^4 10^5 2×10^5

σ_a = 137 MPa, $N_f \cong 1.1 \times 10^6$ Axial direction ←→   50 μm

  - Normally will initiate at a stress riser
  - This stage represents largest percentage of fatigue life

4

Stages of Fatigue

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Crack Propagation
  - Crack grows incrementally with each cycle
  - Crack propagates <u>perpendicular</u> to max principal tension
    - Tension does not have to be *applied*
    - Ex. Plate with a hole under compression
  - Propagation develops unique fractographic features
  - Considered a brittle fracture mode due to crack tip 3-D stress state
- Final Rupture
  - Occurs when crack length reaches critical value; $a \geq a_{cr}$
  - Can be Brittle or Ductile
    - Brittle: occurs when $K \geq K_c$
    - Ductile: occurs when $\sigma_{net} \geq F_{ty}$

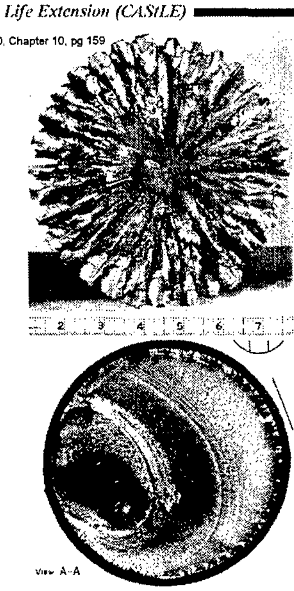
5

Macroscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Macroscopic Features
  - Nucleation Region
    - Many nucleation sites = high applied stress
    - Ratchet marks usually indicative of torsion failure
  - Propagation Region
    - Can be large or small area compared to final fracture
    - Beachmarks—changes in environment or stress level; visible at no magnification
    - Could be cleavage indication—<u>Why</u>?

Wulpi Fig 30, Chapter 10, pg 159

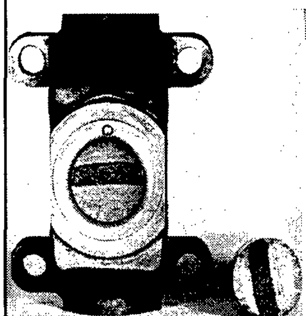


6

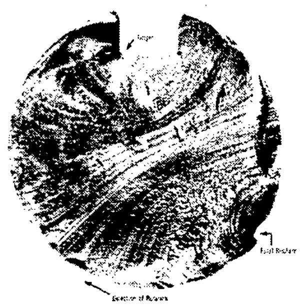
Macroscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

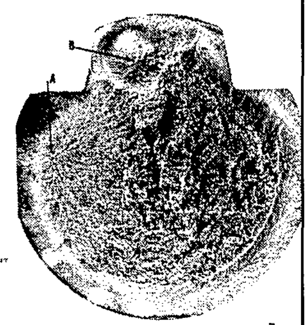
- Final Fracture Region
  - Either brittle or ductile, with corresponding fractographic features
  - Size/shape of final fracture area is telling of applied stress



Wulpi Fig 22, Chapter 10, pg 152.



ASM Volume 12, Fig. 199, pg 261



Macroscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

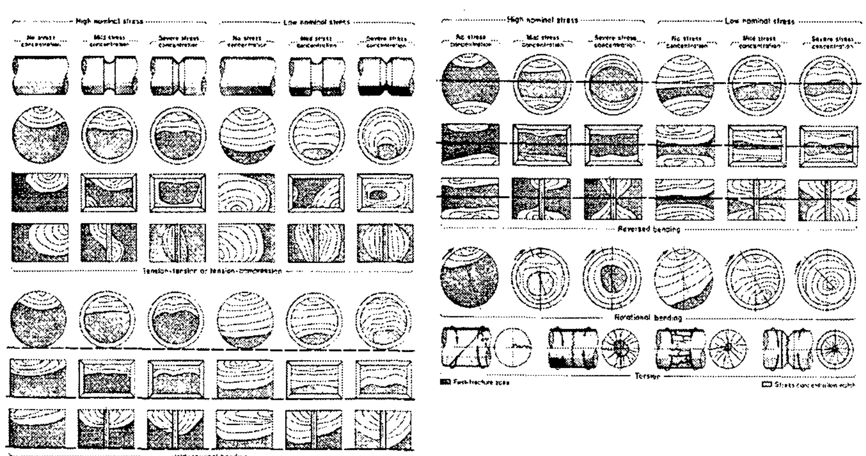
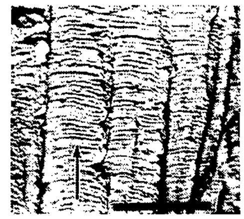


Figure 13. Schematic representation of marks on surfaces of fatigue fractures produced in smooth and notched components with round, square and rectangular cross sections and in thick plates, under various loading conditions at high and low nominal stress. Dashed lines indicate bending axes.

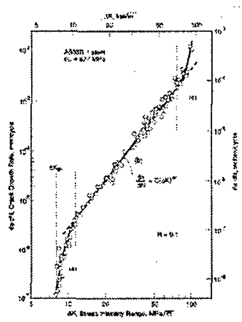
From: Wulpi, D.J, Understanding How Components Fail, 2000, & ASM Principles of Failure Analysis , 1990

Microscopic Fractographic Features

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



- Propagation Region
  - <u>Striations</u>--ridges denoting loading cycles
    - Each striation denotes a cycle
      - Not every cycle forms a striation
      - Striation spacing provides rough estimate of da/dN
    - Striation Characteristics
      - Striations <u>never</u> intersect (Important?)
      - They propagate away from origin (like pebble thrown in water)
      - Striation spacing (da/dN) gets *bigger* as the crack grows longer
  - River Marks could also be visible
    - Why?
    - What distinguishes river marks from striations?
- Final Fracture Region
  - Brittle: river marks; feather marks; Wallner lines
  - Ductile: equiaxed or elongated dimples



9

Topic Teaser: DeHavilland Comet

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- DeHavilland Comet (design started 1945, first flight 1949, first revenue flight '52)
  - Beat first US commercial jets (707 and DC-8) by years
    - 36-44 passengers
    - Cruise speed 490 mph
    - Range 1750 miles
  - Pressurized Al alloy fuselage
    - Cabin altitude 8,000 ft (p = 8.5 psi)
    - Cruise altitude up to 40,000 ft
    - Faster, smoother than prop-driven DC-6 competition
    - Large *rectangular* windows

10

Topic Teaser: DeHavilland Comet

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

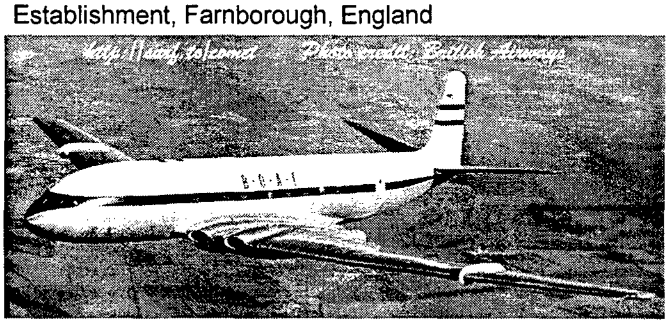
- 26 Oct '52, late abort, no deaths
- Jan '53, landed short, 1 runway death
- 3 Mar '53, failed takeoff on hot day, 11 killed
- 2 May '53, 1649th flight, broke up in T-Storm, 43 deaths
  - British Air Registration Board requires static & fatigue testing
  - By autumn '53, *fatigue cracks at window corners* found "after repeated applications of excessive loads."
- 10 Jan '54, "Yoke Peter" broke up in clear air on its 3681st flight while climbing through 27,000 ft; wreckage scattered in Mediterranean Sea off Elba, 35 killed
  - Massive search for wreckage by Italian authorities
  - Comets voluntarily grounded by BOAC
  - Autopsies show explosive decompression of cabin
  - Engine failure suspected, turbines now armored
  - No definite conclusion reached on cause of breakup
  - Comets re-entered service on 23 Mar '54 (only 10 weeks!)

11

Topic Teaser: DeHavilland Comet

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- 7 Apr '54, "Yoke Yoke" disintegrated on clear night on 2704th flight while climbing through 30,000 ft, wreckage scattered in Mediterranean Sea SE of Naples, 21 perished
  - Comets again grounded by BOAC, now worst safety record
  - Autopsies show explosive decompression, but no bomb
  - Evidence points to fatigue failure, but where?
  - Exhaustive investigation undertaken by the Royal Aircraft Establishment, Farnborough, England



12

Topic Teaser: DeHavilland Comet

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Full-scale fuselage test performed in water tank, with periodic overloads to 11 psi
- Cracks found in wings and near wheel wells
- Cabin pressure failure in tank occurs at window corner
  - Repairs made, tests resumed
- Catastrophic failure on 1800th flight (8 ft long crack!) originated from a cabin window corner
- ADF antenna cutouts show cracks too
- (Aug '54) Center fuselage of Yoke Peter recovered from sea. Cracks in manufacturing! had occurred at rivets placed too close to ADF cutouts and had been stop-drilled. Fatigue failure confirmed.

13

Topic Teaser: DeHavilland Comet Lessons Learned

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Orders for Comet 1 canceled, at cost of £40M
- Comet 1 production halted
  - Comets 2 and 3 used to test long-range Comet 4
  - 67 Comet 4's produced; 25 years of safe success
  - Boeing, Douglas given time to catch up
  - DeHavilland never again a major player
- Underscored importance of full-scale testing before certification
- Wings must have realistic (variable amplitude) testing
- Large overloads may lead to unconservative test results
- Need to balance "High-strength" with adequate fracture toughness
- Perform a good analysis on stress risers

14

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 17

Fatigue II

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will know the best course of action for dealing with fatigue loading in different parts of an aircraft. They will also understand the AF approach to managing fatigue in the fleet
- Objectives
  - **Identify** available and preferred options for dealing with fatigue damage
  - **Describe** the stress-based approach to fatigue analysis
  - **Describe** the fracture mechanics-based approach to fatigue analysis
  - **Describe** the AF approach to managing fatigue damage

2

Options for Fatigue Management

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Part Replacement**
  - Safest Option
  - Probably the most expensive option
  - Sometimes not an option; sometimes the only option!
- **Repair Part**

3

Options for Fatigue Management

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Part Repair**
  - Dependence on engineer and maintainer competence
  - Repair Options
    - Stop drill—temporary fix, or to buy time
    - Impart Residual Stresses
    - Mechanically fastened repair
    - Bonded repair
  - Not always an option!
- Monitor the Fatigue Crack
  - Dependent on da/dN rate
  - da/dN rate is not constant!

4

Fatigue Analysis Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Stress-Based Approach**
  - Assumes No Cracks--*Failure is Crack Nucleation*!
  - Used for high strength, low toughness, critical parts
    - Landing gear
    - Turbine blades
  - Stress risers are bad!
  - Utilizes Stress vs. Log N (S-N) curves
    - Highly Dependent on specific, empirically-based data
    - Other less accurate methods available when no specific data
    - Terms
      - **Fatigue Strength**
      - **Endurance Limit** (not aluminum alloys; only carbon steels)

5

Fatigue Analysis Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

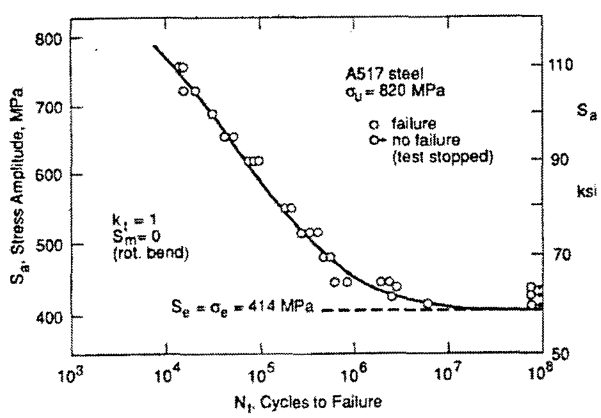


Figure 9.5 Rotating bending *S-N* curve for unnotched specimens of a steel with a distinct fatigue limit. (Adapted from [Brockenbrough 81]; used with permission.)

6

Fatigue Analysis Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Fracture Mechanics-Based Approach**
  - Once a crack has nucleated, uses LEFM to determine:
    - Critical crack length, a_c
      - Brittle: $K \geq K_{IC}$ $$K_{IC} = F\sigma\sqrt{\pi a}$$
      - Ductile: $\sigma \geq F_{ty}$
      - Solve for a in each case, then a_c is the smallest
    - N_{IF}—Cycles to failure from an initial crack size, a_i, to a_c
      - ***Eqn 11.32 in Dowling: as long as m≠2, and where***

$$N_{if} = \frac{a_f^{1-m/2} - a_i^{1-m/2}}{C\left(F\Delta S\sqrt{\pi}\right)^m (1-m/2)}$$

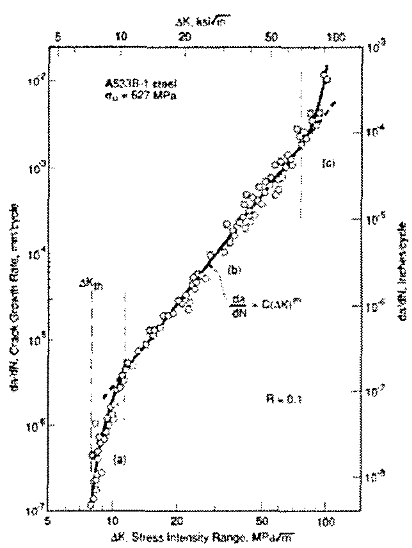
$$C = \frac{C_1}{(1-R)^{m(1-\gamma)}}$$

  - Course of action determined by N_{if} calculation

7

Fatigue Analysis Methods

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



<u>Paris Law</u>

$$\frac{da}{dN} = C\Delta K^m$$

$\frac{da}{dN}$ is the crack growth rate

C, m are material constants

ΔK is the cyclic stress intensity factor

8

AF Approach to Fatigue

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Damage Tolerant Design**
  - Assumes an initial crack per JSSG-2006; 0.050" is typical
  - Uses LEFM approach to determine a_c
  - Determines N_{if}, assuming Paris Region crack propagation
  - Sets crack inspection interval as ½*N_{if}

  - Uses S-N approach when LEFM not feasible
    - Extremely hard, strong, brittle materials
    - Hard to inspect parts
    - Ex. Landing gear; turbine blades

9

This Page Intentionally Left Blank

Lesson 18

Fatigue III

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers know how fatigue critical locations are defined and determined for aircraft. They will also understand fatigue trends related to materials, geometry, loading, and environment.

- Objectives
  - **Define** fatigue critical location (FCL)
  - **Describe** trends in fatigue relating to material, geometry, loading, and environment
  - **Determine** location of FCL's on aircraft structure

Fatigue Critical Location

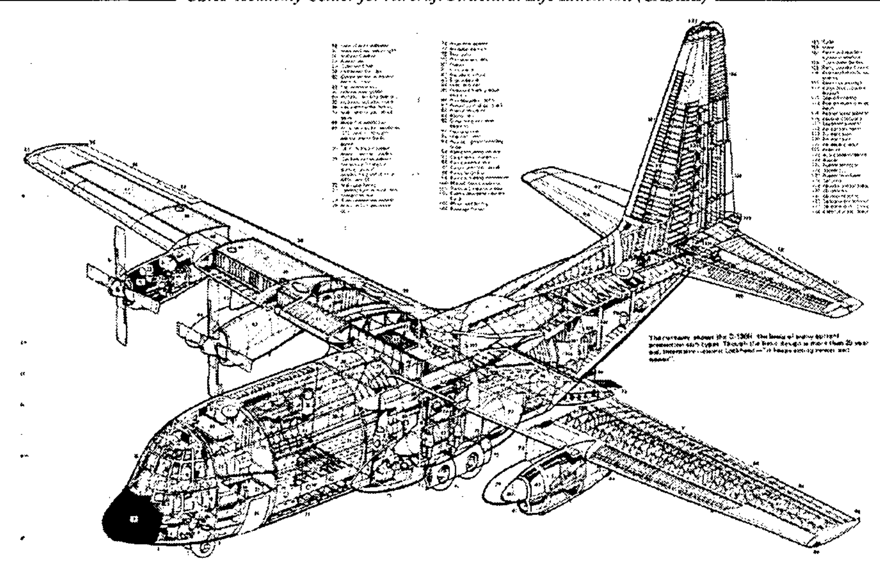
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Structural location that is more prone to developing fatigue cracking
  - Material
  - Geometry
  - Processing
  - Loading
  - Environment
- Affects safety of flight or maintenance/cost

3

Fatigue Critical Locations

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

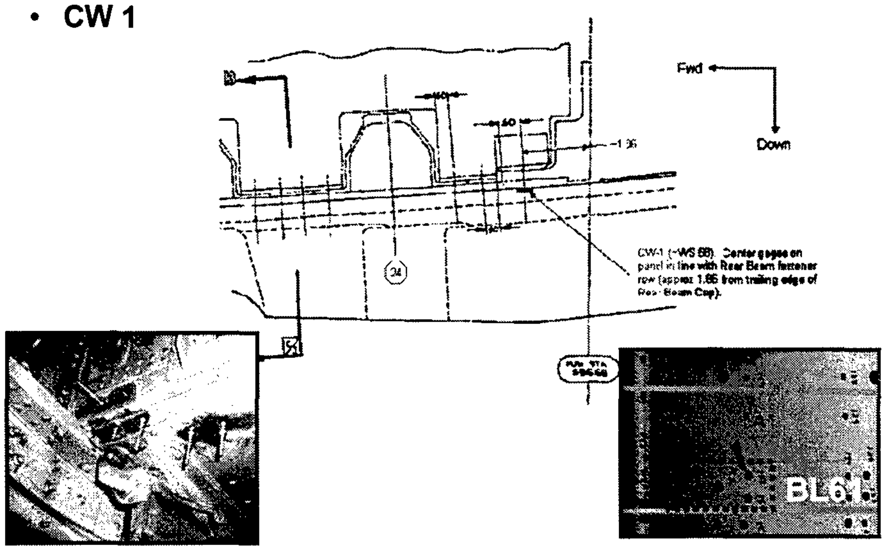


4

FCL C-130 Example

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **CW 1**



5

Trends Affecting FCL's

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Material
  - Strength
  - Grain Size
  - Processing
- Geometry
  - Stress Risers
  - Thickness
  - Orientation

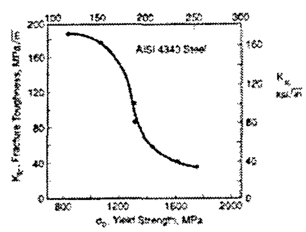


Figure 8.31 Fracture toughness vs yield strength for AISI 4340 steel quenched and tempered to various strength levels. (Adapted from an illustration courtesy of W. G. Clark, Jr., Westinghouse Science and Technology Ctr., Pittsburgh, PA.)

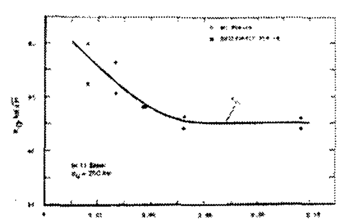
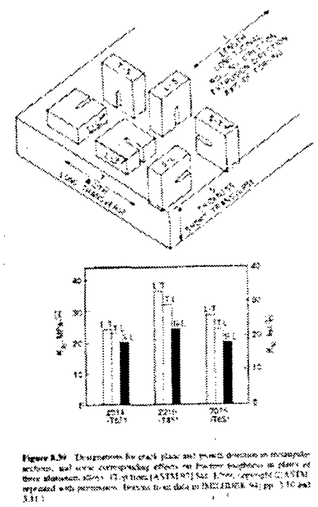


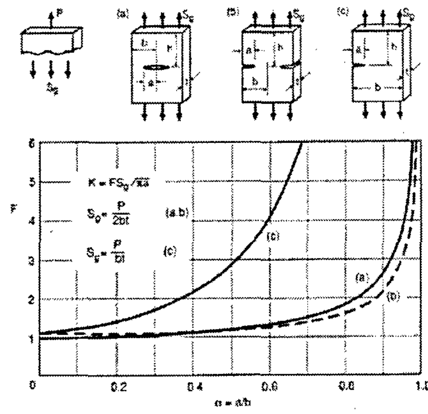
Figure 8.30 Effect of thickness on fracture toughness of an alloy steel heat treated to the high strength of σ_o = 1520 MPa. (Adapted from [Steigerwald 70]; copyright © ASTM; reprinted with permission.)

6

Trends Affecting FCL's

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)





Values for small a/b and limits for 10% accuracy:

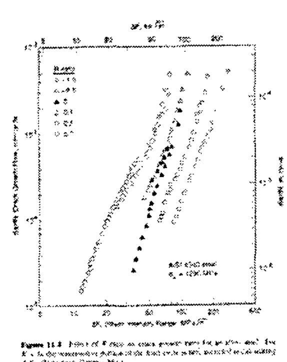
(a) $K = S_g\sqrt{\pi a}$ $(a/b \leq 0.4)$ (b) $K = 1.12S_g\sqrt{\pi a}$ $(a/b \leq 0.6)$ (c) $K = 1.12S_g\sqrt{\pi a}$ $(a/b \leq 0.13)$

7

Trends Affecting FCL's

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Loading
  - Type
    - Shear nucleates cracks
    - Tension propagates cracks
  - Magnitude
    - Mean Stress effects
    - R-ratio

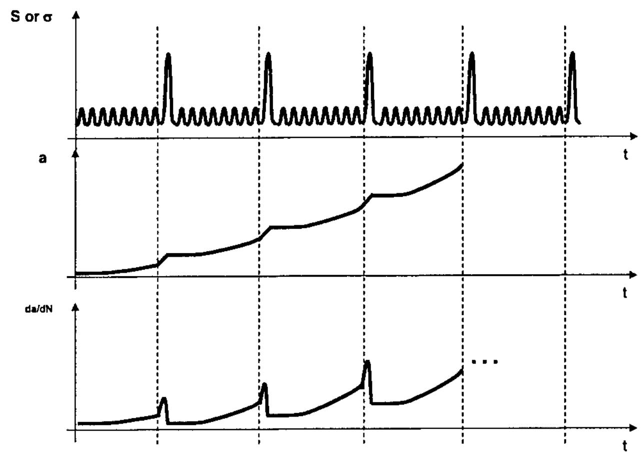


8

Trends Affecting FCL's

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Load sequence

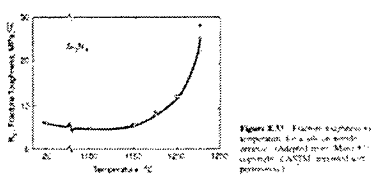


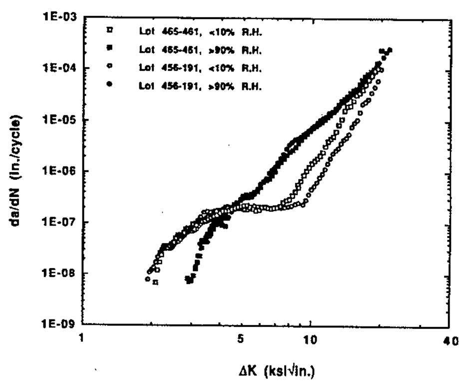
9

Trends Affecting FCL's

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Environmental Effects





10

FCL Determination

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Determined by the Original Equipment Manufacturer (OEM) or user
- Determined either during design, production, or in-service
  - **Design**: analytically and through experience
  - **Production**: through full-scale fatigue testing
  - **In-service:**
    - Fatigue crack problems identified that were not predicted
    - Change in mission can significantly change loading and FCL's (B-52's changing from a high-altitude mission to low-altitude)
- All known FCL's are monitored closely at analytically or computer model determined inspection intervals
  - ½*N_{if}
  - **NDI crucial!**

11

Topic Teaser: Rocket Motor Casing

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Fig. 8(a) [illegible]

Fig. 8(b) [illegible]

12

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 19

Nondestructive Inspection I

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will better understand what nondestructive inspection (NDI) is, and know how NDI affects failure analysis and prevention. They will also be able to identify common AF NDI techniques and applications.

- Objectives
  - **Discuss** the relationship between failure analysis, prevention, and nondestructive inspection (NDI)
  - **Describe** common AF NDI techniques
  - **Identify** the appropriate NDI technique to use for a given application

2

NDI Overview

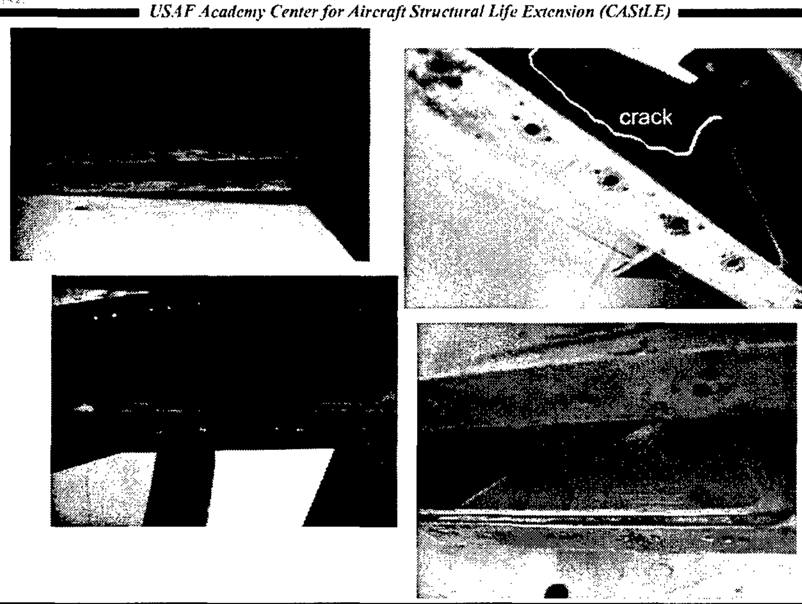
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Nondestructive Inspection (NDI)
- Used for numerous applications:
  - Production facilities; maintenance facilities; field units; failure analysis labs
- **#1 Benefit—inspecting for defects/damages without inducing damage**
- A-10 Wing Flap Track example

3

NDI of Aircraft Structure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



4

NDI's Role in FA & Prevention

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

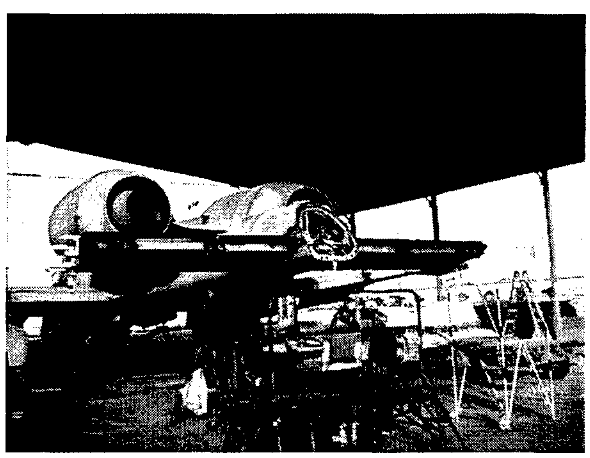
- NDI is used to inspect failed parts
- NDI is used to inspect in-service components for failure prevention
- Safe-Life Parts! (Landing gear, engine, etc)
  - NDI is critical! Cracks would be catastrophic
  - NDI used to catch initiation, then the part is replaced
- Damage Tolerant Components
  - Assumed to have a crack
  - First inspection is Nif/2
  - NDI utilized to monitor crack growth and prevent sudden, brittle fracture

5

Common AF NDI Techniques

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

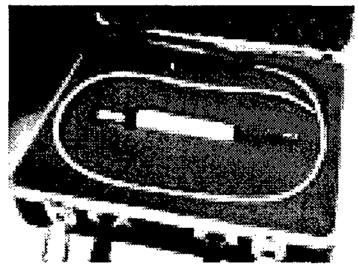
- Field/Deployed Units
- Depot



6

Field/Deployed Units

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

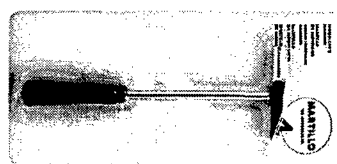


- Visual Inspection
- Tools Required
  - Inspector (anyone!)
  - Microscope
  - Boroscope
  - Endoscope
- Types of Flaws detected—Mainly surface
  - Cracks, corrosion
  - Porosity, impurities, disbonds, delaminations
- Advantages/Disadvantages
  - Simple, fast, low-cost, relatively effective
  - Low magnification, accessibility, surface flaws (or slight subsurface), operator fatigue

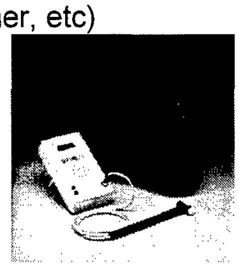
7

Field/Deployed Units

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



- "Tap" Test
- Tools Required
  - Inspector
  - Something to tap with (coin, tap hammer, etc)



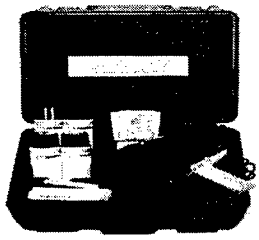
- Operation—Very easy; just tap and listen
- Types of flaws detected
  - Mainly for disbonds and delaminations
  - Also useful for detecting corrosion
- Advantages/Disadvantages
  - Quick, easy application, inexpensive, reliable method
  - The more experience, the better the results; limited applications

8

Field/Deployed Units

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Dye Penetrant; Fluorescent Dye Penetrant**
- **Tools Required**
  - Inspector and Instructions
  - Cleaner/Remover
  - Penetrant (AF Only Uses Fluorescent)
  - Developer
  - Black light, if performing Fluorescent DPI



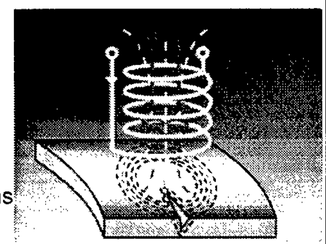
- **Operation**
  - Clean surface, then apply liquid dye
  - Dye drawn in to cracks by capillary action
  - Wipe off excess
  - Apply developer and inspect (UV for fluorescent)
- **Types of flaws**
  - Mainly cracks
  - Down to 2.5 mm or 0.10 in
- **Advantages/Disadvantages**
  - Simple, fast, low-cost, low technical difficulty
  - Messy, some penetrants corrosive

9

Field/Deployed Units

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Eddy Current**
- **Tools Required**
  - Inspector
  - Eddy Current Inspection Equipment (per AF T.O. 1-1-36)
  - Testing Standard for particular assembly
- **Operation**
  - Apply current to a coil
  - Place part in/near coil
  - Monitor change in coil's current



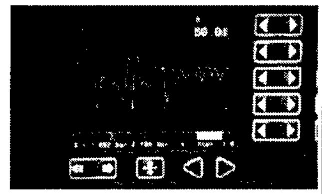
- **Types of flaws detected**
  - Surface or near-surface cracks, pores, inclusions
  - Balance between frequency and resolution
- **Advantages/Disadvantages**
  - Rapid, clean, complex geometries, holes, portable
  - Requires baseline, parts must be conductive, parts must be smooth, relatively thin

10

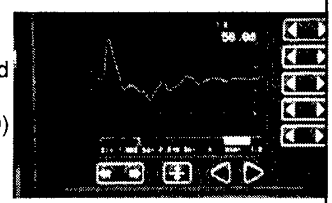
Field/Deployed Units

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Ultrasonic: A-Scan**
- **Tools Required**
  - Inspector
  - Ultrasonic Testing Equipment (AF T.O. 1-1-36)
  - Testing Standard for particular configuration



- **Operation**
  - Hi Frequency (100,000 Hz +) pulse transmitted through part
  - Sensors (piezoelectrics often used)
    - Pulse-Echo
    - Through Transmission
    - Good coupling (grease, water, gel) required
  - Displays
    - A-scan (reading from a single position, 0-D)
    - B-scan (reading along a line, 1-D)
    - C-scan (reading of an area, 2-D)



11

Depot Level

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

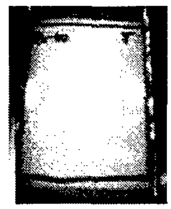
- **Types of Flaws Detected**
  - Internal
  - Thickness variations
  - Disbonds, delaminations
  - Corrosion
  - Chem mils
- **Advantages/Disadvantages**
  - Any material, versatile, automated
  - Messy (wet sometimes), complicated
  - Flat, smooth parts

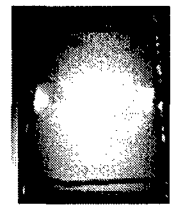
Depot: C-Scan

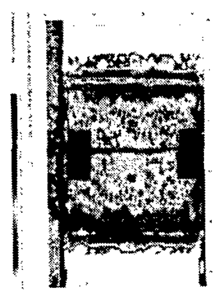
12

Depot Level

- **Thermography**
- **Tools Required**
  - Inspector
  - Heat Gun
  - Heat Flash
  - Infrared Camera or Device
- **Operation**
  - Apply heat to the specimen
  - Monitor heat dissipation using infrared spectrum
- **Types of flaws detected**
  - Excellent for determining disbonds/delaminations
  - Adequacy of insulation
- **Advantages/Disadvantages**
  - Fast, noncontact, nonintrusive
  - Still in infancy, subjective, expensive, sensitive
- **Uses**
  - Electrical industry (transmission lines)
  - USAF (disbonds in bonded repairs)
  - NASA (space shuttle leading edge NDI)

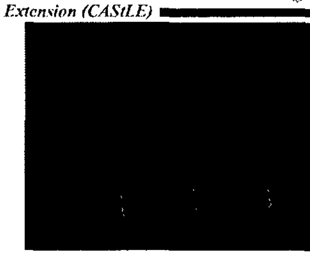






Depot Level

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

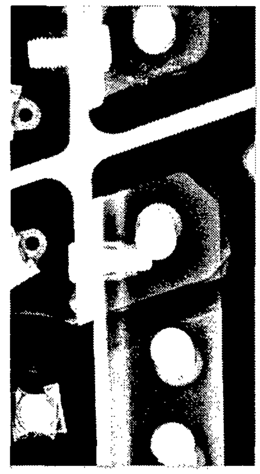


- **Magnetic Particle Inspection**
- **Operation**
  - Apply particles (in slurry) to surface
  - Apply magnetic field
  - Look for discontinues
- **Types of flaws detected**
  - Surface or near-surface cracks, pores, inclusions
- **Advantages/Disadvantages**
  - Entire surface in one shot, low cost, portable
  - Crack must be perp. to flux lines, only magnetic materials, messy

Depot Level

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **X-Ray (radiography/tomography)**
- **Operation**
  - Part exposed to X-rays
  - Film placed in back of part
  - Transmitted x-rays expose film (flaws don't transmit)
- **Types of flaws detected**
  - Volumetric flaws (moisture, corrosion)
  - Sub-surface flaws (cracks, inclusions)
- **Advantages/Disadvantages**
  - Rapid, clean, gives entire picture of part (CAT scan)
  - Not portable, expensive, dangerous, complicated
- **Uses**
  - Large parts, complex shapes
  - Castings, welds
  - Honeycomb parts



15

Other NDI Techniques

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Acoustic Emission**
- **Operation**
  - Listening
  - Monitoring elastic waves in a material
  - Use of piezoelectric materials (converts mechanical energy into electrical energy, and sometimes into sound)
- **Type of Flaws Detected**
  - Flaws "in process"; i.e., cracks while they are happening
- **Advantages/Disadvantages**
  - Passive, nonintrusive, real time, accurate (order of magnitude more sensitive than any other method, cracks ≈ 25 microns)
  - Sensitivity, interpretation of results, complicated
- **Uses**
  - Pressure vessel proof testing
  - Leakage detection & control
  - Weld monitoring

16

Other NDI Techniques

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Shearography**
- **Operation**
  - Applies small strain to part—often by applying vacuum or ΔT
  - Measures changes in strain in part
- **Types of Flaws Detected**
  - Disbonds between skin and core
  - Delamination in composite lay-ups
- **Advantages/Disadvantages**
  - Fast, accurate, precise
  - Expensive equipment, lots of training required

17

This Page Intentionally Left Blank

Lesson 20

Nondestructive Inspection II

Lesson Goals & Objectives

- After this lesson, engineers will better understand what nondestructive inspection (NDI) is, and know how NDI affects failure analysis and prevention. They will also be able to identify common AF NDI techniques and applications.

- Objectives
  - **Define** basic NDI terms such as POD, POFA, POI and a_{NDE}
  - **Differentiate** between an indication and a Defect or finding
  - **Discuss** the reasonable expectations of various NDI techniques

- **INDICATION**: In nondestructive inspection, a response or evidence of a response, that requires interpretation
- **NON-RELEVANT INDICATIONS**: An indication due to misapplied or improper inspection. Also, an indication caused by an actual discontinuity in the material that does not affect the usefulness of the part (such as a change of section).
- **DISCONTINUITY**: An interruption in the normal physical structure or configuration of a part such as cracks, laps, seams, inclusions, porosity. A discontinuity may or may not affect the usefulness of a part. See DEFECT.

NDI Definitions

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **DEFECT**: a discontinuity that interferes with the usefulness of a part. A fault in any material or part detrimental to its serviceability. Note that all cracks, seams, laps, etc. are not necessarily defects as they may not affect serviceability of the part in which they exist.
- **RELEVANT DISCONTINUITY**: a discontinuity that is detrimental to the intended use of a part or material.
- **FINDING**: when NDI equipment detects a true flaw of some type (crack, corrosion, disbond, etc.)

NDI Definitions

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **PROBABILITY OF DETECTION** (POD): the probability that a given inspection technique and inspector will find a true flaw of a given size with a given confidence, usually given in terms of POD/Confidence, example 90/95
- **PROBABILITY OF FALSE ALARM** (POFA): the probability that a given inspection technique and inspector will get a false positive
- **PROBABILITY OF INSPECTION** (POI): the probability that a given inspection will be properly accomplished
- **MINIMUM DETECTABLE FLAW SIZE, a_{NDE}:** the smallest flaw that a given inspection, inspector, and instrument can find in a given part, under certain geometrical, environmental, and working conditions for a given POD/Confidence, example .250" 90/95

5

Possible NDI Outcomes

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Inspection response	Inspection stimuli: Positive, a	Inspection stimuli: Negative, n
Positive, A	**True positive** (flaw detected) M(A,a) P(A,a) (no error)	**False positive** (false alarm) M(A,n) P(A,n) (type II error)
Negative, N	**False negative** (undetected flaw) M(N,a) P(N,a) (type I error)	**True negative** (no flaw) M(N,n) P(N,n) (no error)

Fig. 2 Matrix of four possible outcomes from an NDE procedure for flaw detection

6

Factors Influencing POD and POFA

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- POD and POFA are influenced by:
  - Technique
  - Operator
  - Material
  - Part Configuration
  - Accessibility of Part
  - Environment
  - Inspector's State of Mind

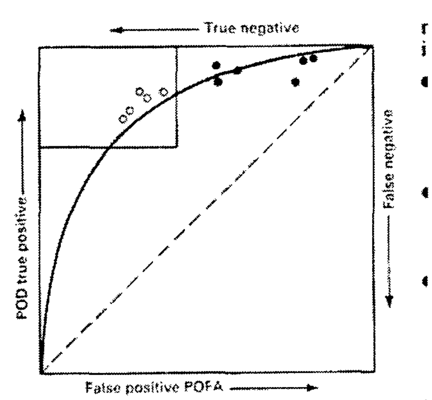
- **The Current USAF NDI Focus:** *What is the largest size flaw that a technique will miss?*

7

Expertise of the Inspector

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Relative Operating Characteristic (ROC) Curves
  - Operators inspect test articles with known flaws
  - Best operators should be nearer to the upper left corner



8

Threshold Acceptance Criteria

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Basis for detection is in sensing a signal above a <u>predetermined threshold</u>
  - If threshold criteria is too high—flaws will be missed
  - If threshold criteria is too low—result in false positives
- **Bottom Line: Inspection Standards need to be developed for each new inspection, material, environment, etc.**

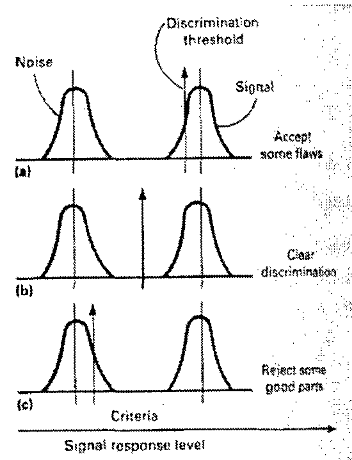


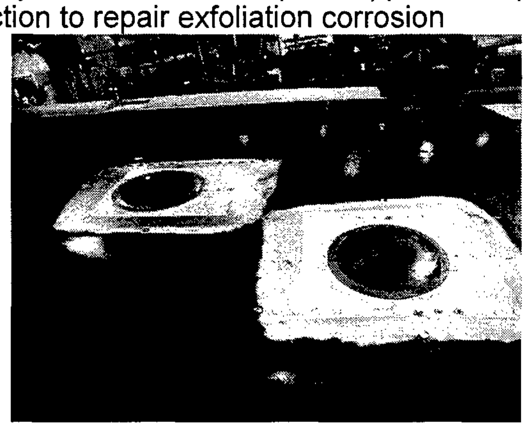
Fig. 3 Influence of acceptance criterion (vertical arrow) on process discrimination. (a) Acceptance criterion too high. (b) Acceptance criterion at proper level. (c) Acceptance criterion too low

9

Topic Teaser: A-10 Boron Repairs

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Adhesively Bonded Boron Repairs applied to top skin, outer wing section to repair exfoliation corrosion



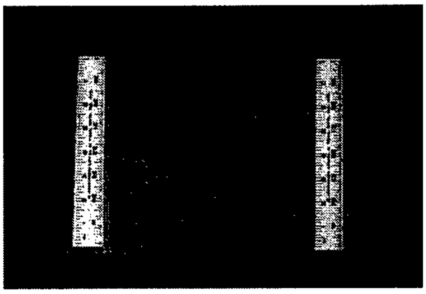
- Problem—Barnes ANGB had never inspected Boron patch adhesion before

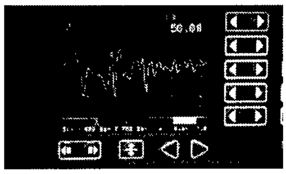
10

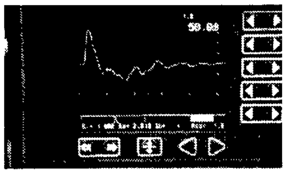
Topic Teaser: A-10 Boron Repairs

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- An inspection standard needed to be developed that called out:
  - Equipment Type(s)
  - Equipment Settings
  - a_{NDE} for the inspection method
  - Inspection steps







11

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 22

Composites Failures

1

Lesson Goals & Objectives

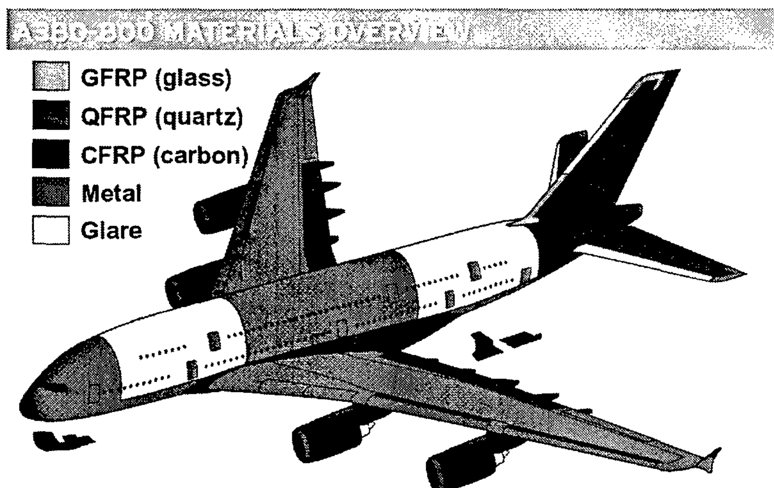
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers should understand the nature of composites failure and failure prevention.
- Objectives
  - **Define** a composite material
  - **Identify** the various types of failure in composite materials
  - **Identify** common manufacturing errors and their impact
  - **Identify** which NDI techniques are applicable to composites

2

Composites in Aircraft Structure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



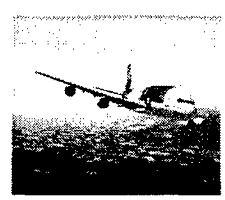
FLIGHT INTERNATIONAL

http://www.flightglobal.com/assets/getAsset.aspx?ItemID=9116 3

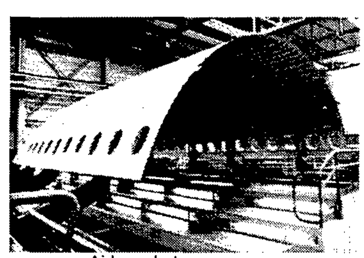
Glare: A fiber-metal laminate

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

http://www.cytec.com/business/EngineeredMaterials/FML.shtm



http://www.storkaerospace.com/fokker/Images/Aerospace/StorkFokker/Glare3.jpg

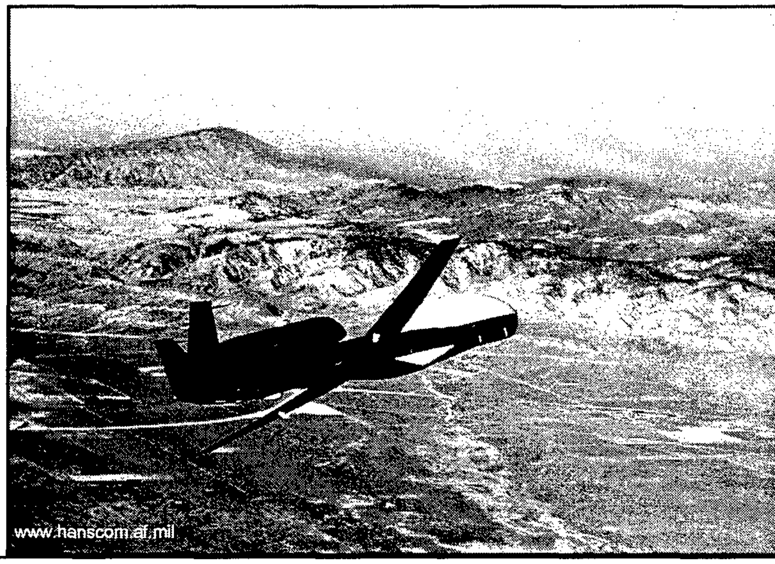


Airbus photo

4

Composites in Aircraft Structure

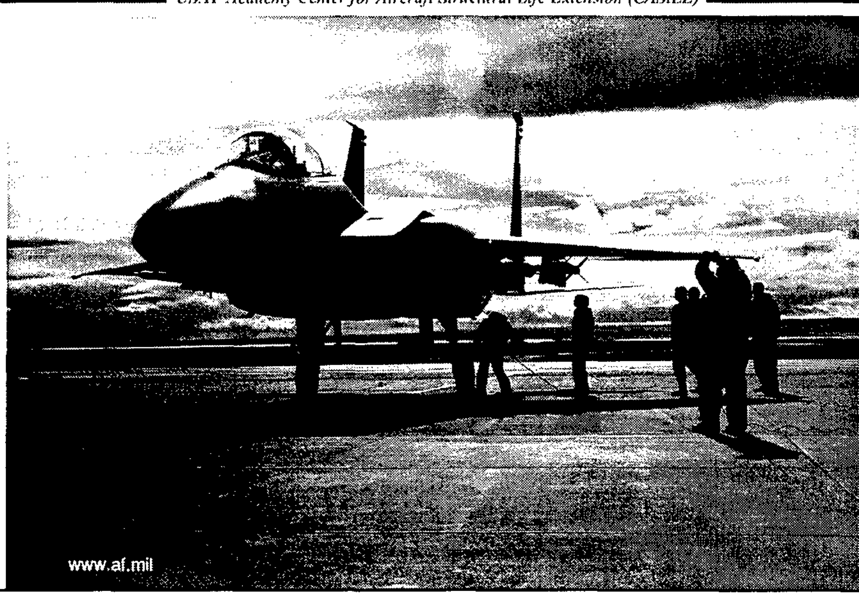
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

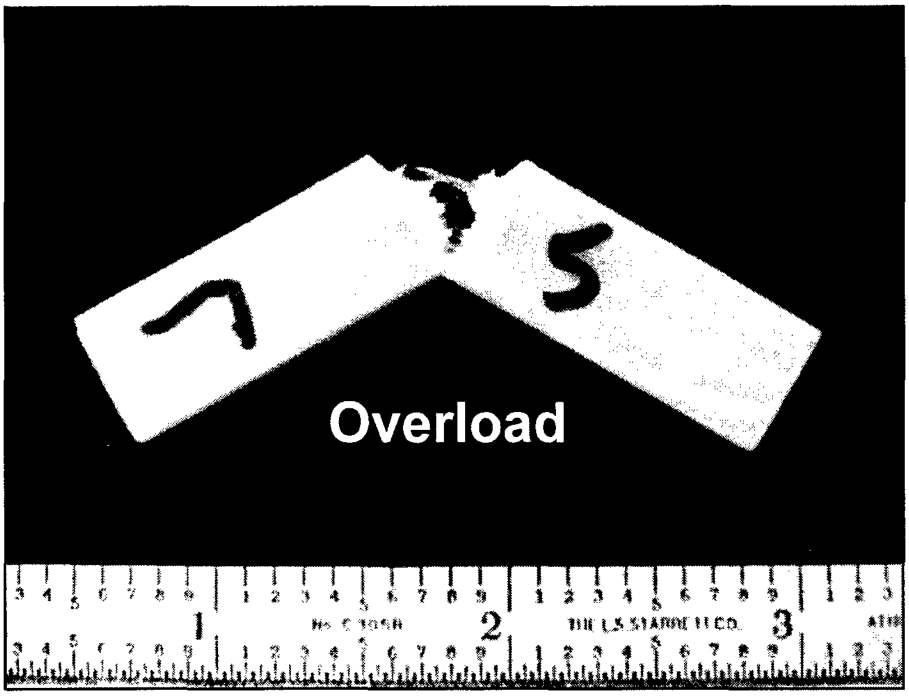


5

Composites in Aircraft Structure

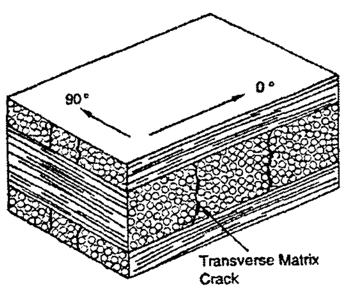
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



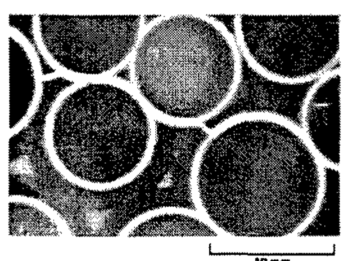


Overload Failure: Matrix Cracking

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



http://www.nap.edu/openbook/NX006900/html/images/p20003245g24001.jpg

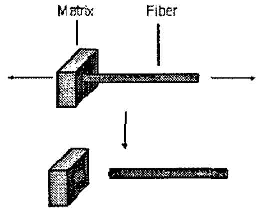


http://www.nasatech.com/Briefs/Oct00/LEW16864.html

8

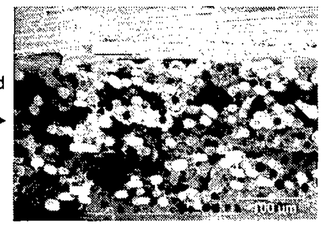
Overload Failure: Fiber Pullout

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



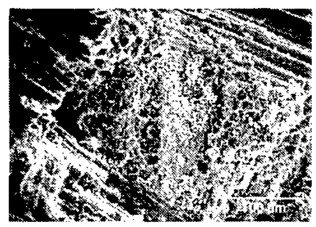
http://www.pslc.ws/macrog/mpm/composit/bio/images/pull01.gif

Fibers de-coupled from matrix



Fiber Pullout

Hurst, J.B.; Freedman, M.R.; Kiser, J.D.: Fracture Surface Observations for SiC Fiber/SiC Matrix Composites. Paper presented at the 20th Annual Conference on Composites, Materials & Structures, Cocoa Beach, Florida, Jan. 1997.



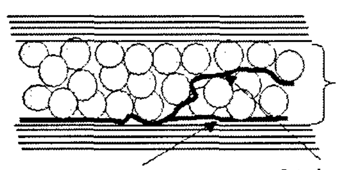
Brittle Fracture

Fibers adhere to matrix through fracture

9

Overload Failure: Delamination

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

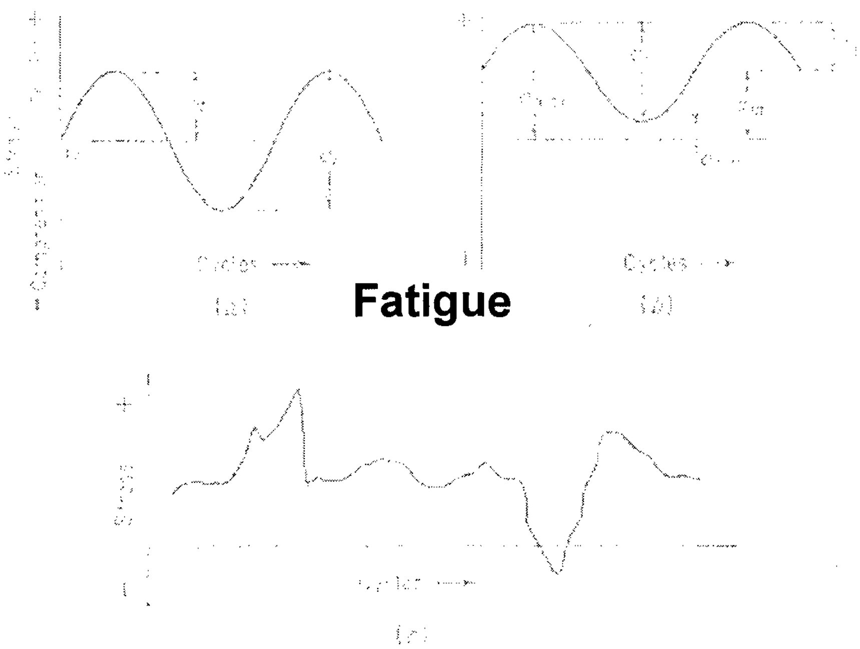


http://rutgersscholar.rutgers.edu/volume01/pelestra/fig2.jpg

http://www.ktc.uky.edu/structures/img/s2.jpg

Concrete/FRP bridge deck beam. The FRP reinforcement has delaminated from the concrete beam.

Fatigue

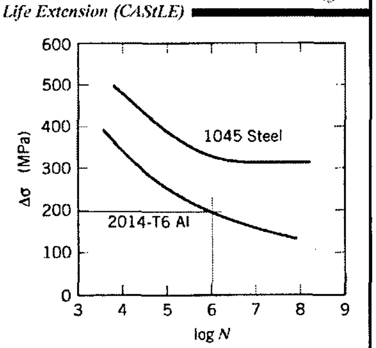


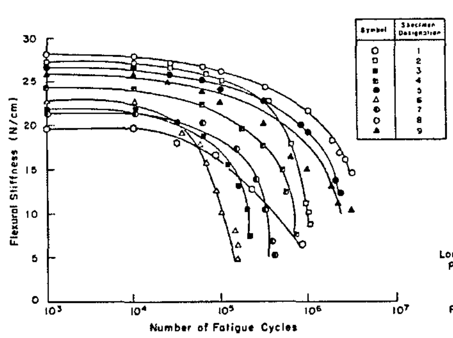
Composite Fatigue

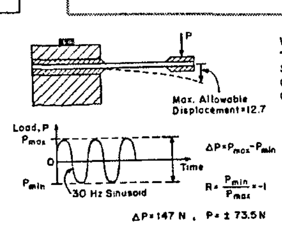
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

"In the area of fatigue, however, ***no generalized methodology*** has yet been devised to predict laminate behavior from unidirectional specimen data. Hence, the development of fatigue design values becomes ***a unique problem for each application lay-up.***"

MIL-HDBK-17-1F, 17 Jun 2002





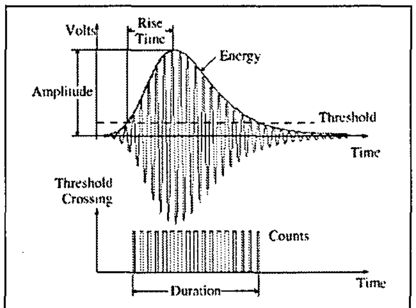


Williams, Yuce, Lee, "Characterizations of Fatigue States of Graphite Epoxy Composite Laminates," NASA-CR-3504, MIT, 1982.

12

Composite Fatigue

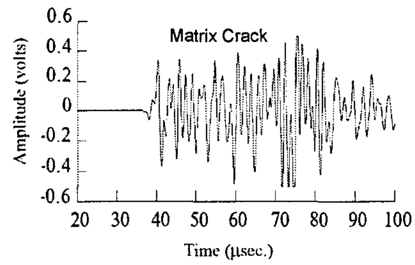
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

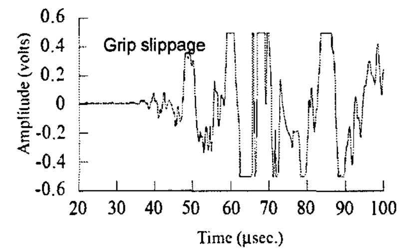


http://www.tms.org/pubs/journals/JOM/9811/Huang/Huang-9811.fig.1.lg.gif

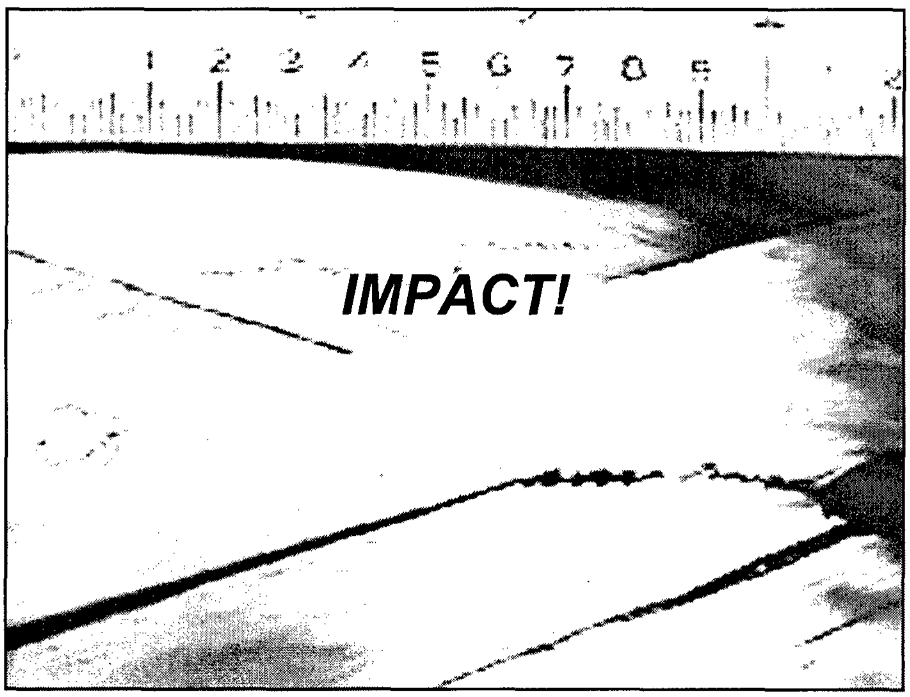
Listening for cracks...

Waveform Based Acoustic Emission Detection and Location of Matrix Cracking in Composites
W. H. Prosser
NASA Langley Research Center
MS 231
Hampton, VA 23681-0001





13



Impact Damage

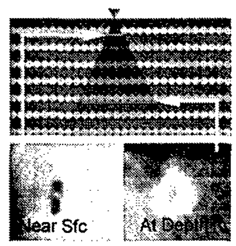
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

"With sufficient kinetic energy, these impacts can damage the composite ***without readily visible evidence*** and can ***significantly reduce the strength***. Current regulations require composite structures to carry ***ultimate load*** with nonvisible impact damage." —NASA Langley

Visible Impact Damage

http://www.tsb.gc.ca/en/reports/rail/1999/r99t0256/figure_10.jpg

Cone-shaped propagation of an impact in a CFRP-laminate



Invisible Impact Damage

http://www.edevis.de/quality/boundary_defects_en.php

15

Corrosion (Environmental Attack)

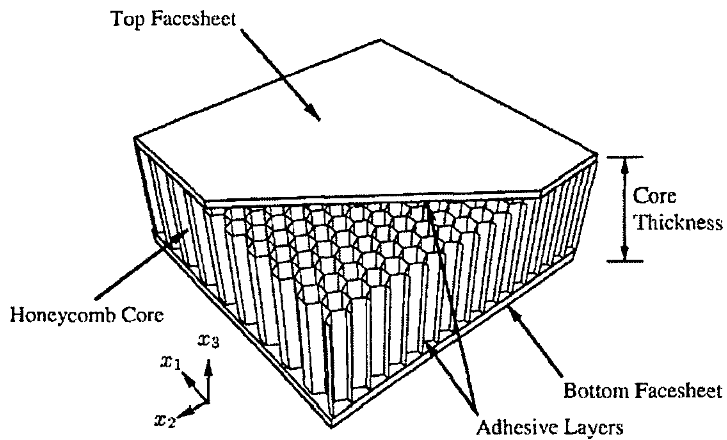
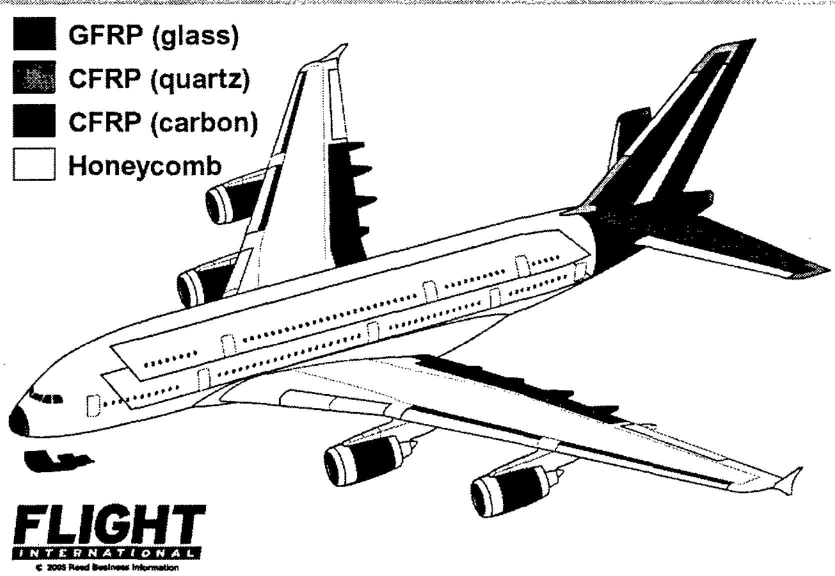


Figure 1. Honeycomb sandwich panel.

Source: Han, T.S., Ural, A., Chen C.-S., Zehnder, A.T., Ingraffea, A.R., and Billington, S., "Delamination buckling and propagation analysis of honeycomb

A380-800 SANDWICH AND COMPOSITE APPLICATIONS



18

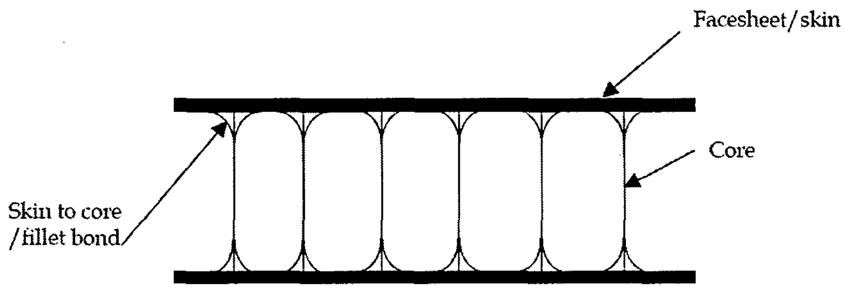


Figure 1 Schematic of honeycomb sandwich structure (side view)

Source: T.C. Radke, A. Charon, R. Vodicka, "Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Flatwise Tension Strength," Technical Report DSTO-TR-0908, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, Sep 1999.

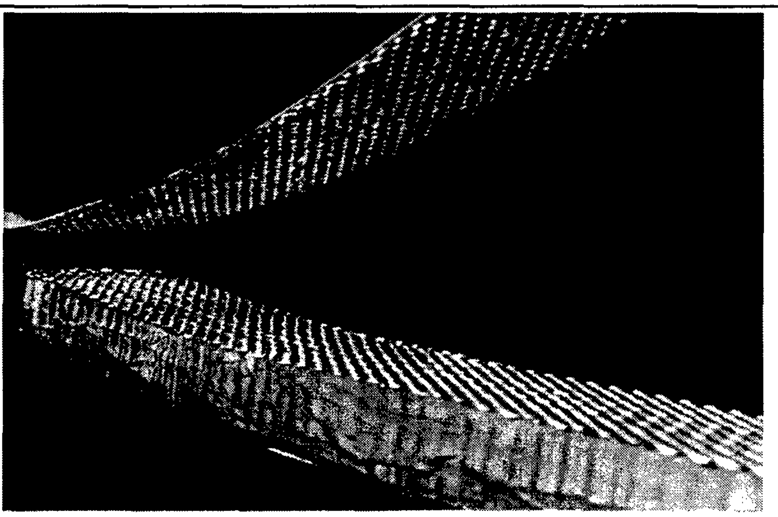


Figure 1 Honeycomb sandwich beam recalled from AMRL-Q showing the carbon skin (top) disbonded from the core and a light brown colour of fillet adhesive at this part of the beam. The failure mode between the core and skin is purely adhesive.

Source: Aaron Charon, "Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Discolouration of Cytec FM-300 Adhesive," Technical Note DSTO-TN-0263, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, May 2000.

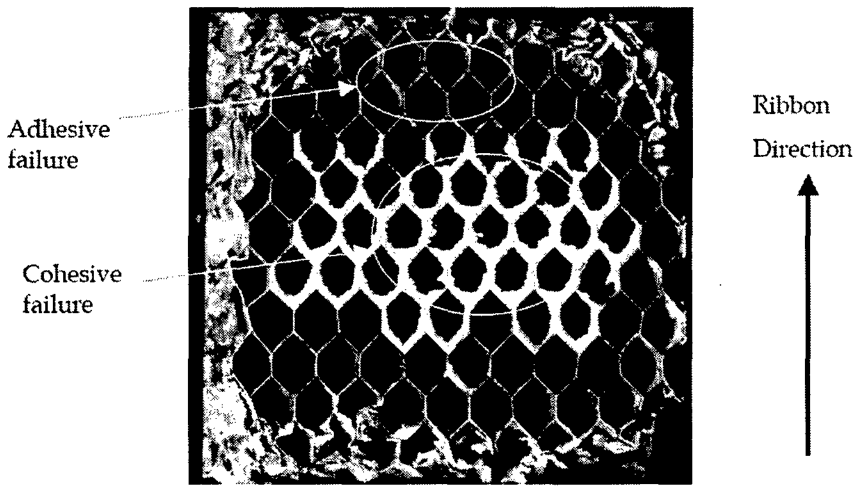


Figure 3 Degradation of fillet bonds (effect of ribbon direction)

Source: T.C. Radke, A. Charon, R. Vodicka, "Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Flatwise Tension Strength," Technical Report DSTO-TR-0908, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, Sep 1999.

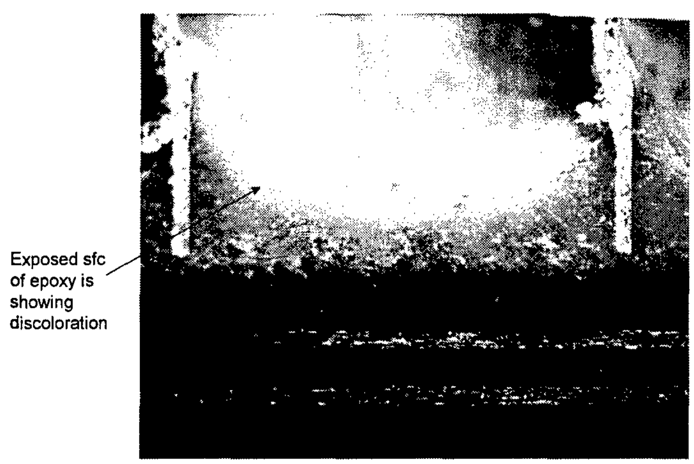


Figure 9 Cross sectional view of the adhesive fillet bond on a newly manufactured panel showing the thin green layer of discoloured adhesive.

Source: Aaron Charon, "Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Discolouration of Cytec FM-300 Adhesive," Technical Note DSTO-TN-0263, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, May 2000.

Hot/Wet Effects on Epoxy Adhesive

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Source: Aaron Charon, "Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Discolouration of Cytec FM-300 Adhesive," Technical Note DSTO-TN-0263, Airframes and Engines Division, Aeronautical and Maritime Research Laboratory, May 2000.

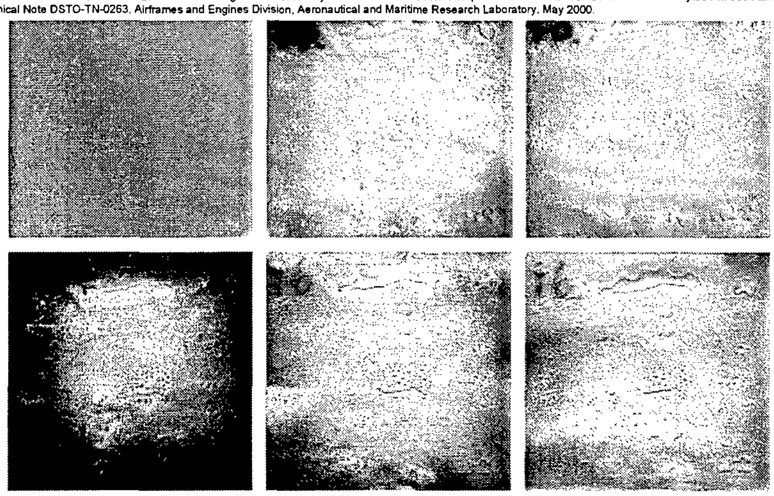
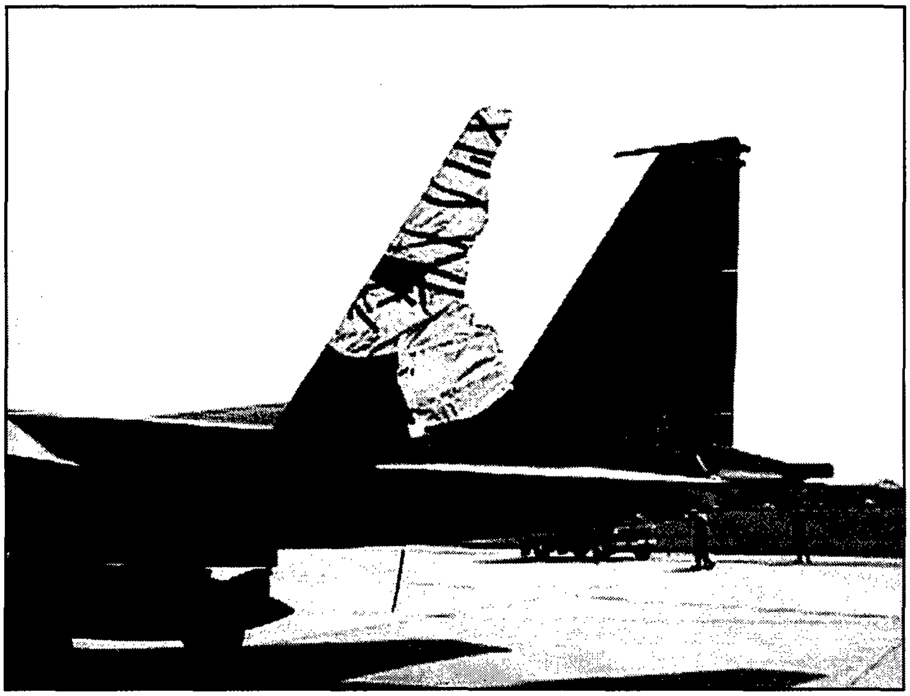
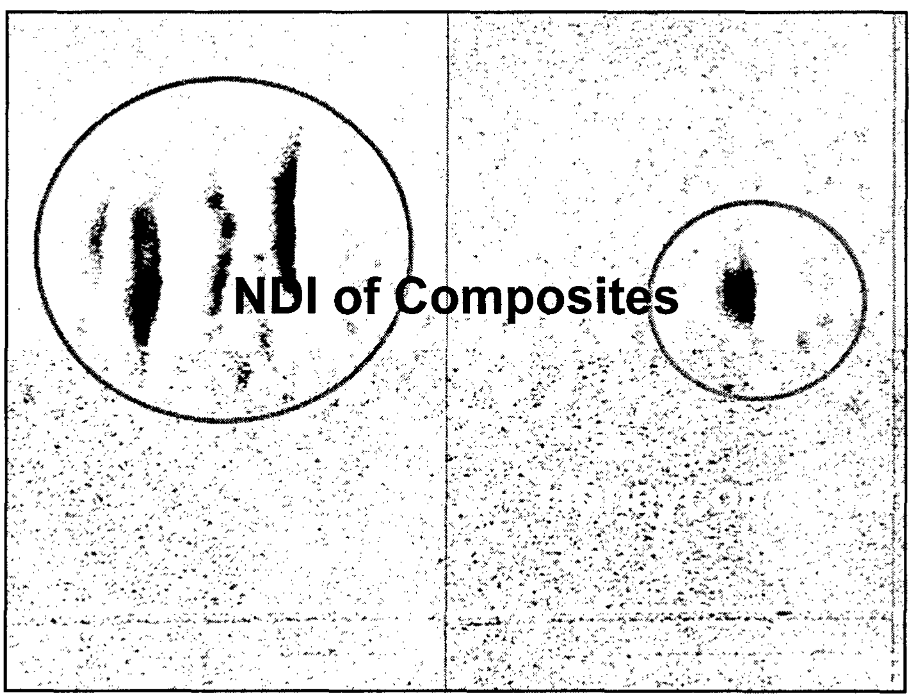


Plate # 16 Exposure to 90 °C, 95 % RH: (Clockwise from top left) Reference, 4 weeks, 8 weeks, 16 weeks, 25 weeks & 36 weeks.

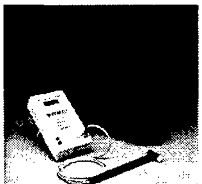
23




NDI of Composites

NDI

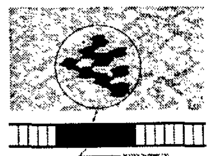
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

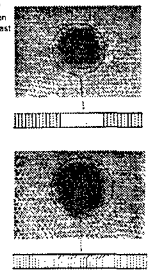


Source: Wichitech Industries, Inc.

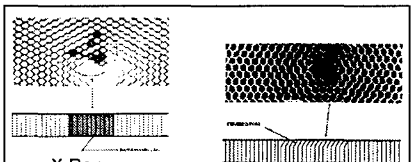
Tap Hammer: Disbonds

Source: A. B. Doyum, M. Durer, "Defect Characterization of Composite Honeycomb Panels by Non-Destructive Inspection Methods," Department of Mechanical Engineering, Middle East Technical University Ankara 2002



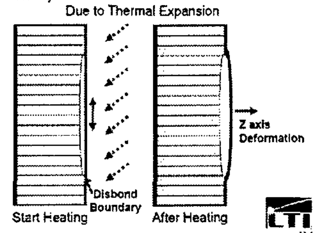


Through-transmission C-Scan
- Water entrapment
- Corrosion
- Crushing



X-Ray
- Water entrapment
- Crushing

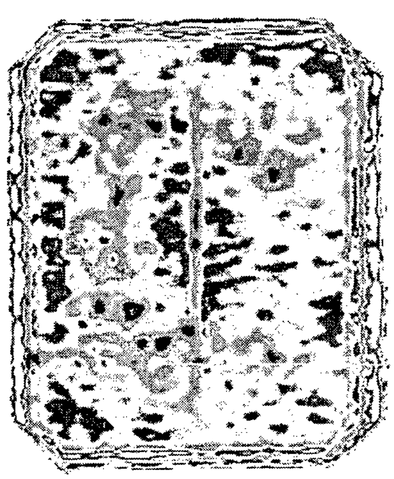
Honeycomb Panel – Face Sheet Deformation Due to Thermal Expansion

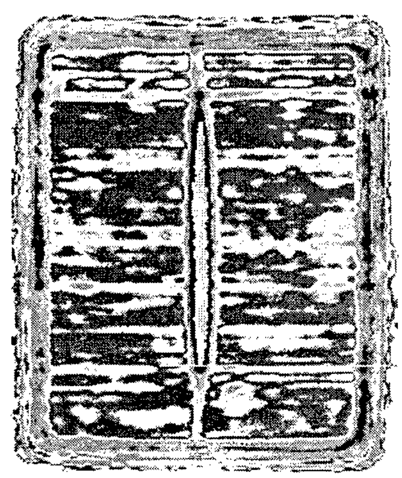


27

NDI

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)





C-Scan of Boron Epoxy Patches

28

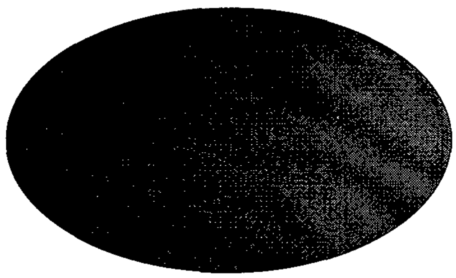
Processing Quality vs. Strength & Life

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Problems are often due to poor:
- Temperature control
- Pressure control
- Surface preparation
- Fabrication process control

Failure prevention in composites lies in addressing these.

...which result in:
- Disbonds
- Voids
- Porosity
- Warping

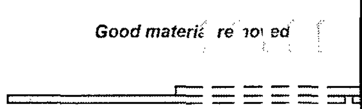


29

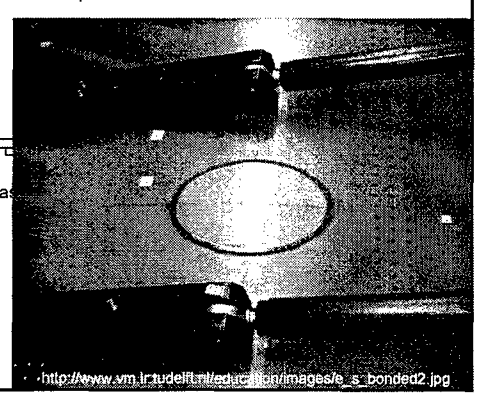
Composite Bonded Repair

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Adhesively Bonded Repair



Additional "damage" Mechanically Fa



Bonded Repair Short Course Fall 2006!

This Page Intentionally Left Blank

Lesson 23
Manufacturing Failures

Lesson Goal and Objectives

- **Goal**: At the end of this lesson, engineers should comprehend how manufacturing processes could impact structural life.
- **Objectives**
  - **Discuss** how mechanically fastened joint quality impacts failure and/or life
  - **Describe** how material processing quality impacts failure and/or life
  - **Describe** how bonded joint quality impacts failure and/or life

Manufacturing Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Definition: Failure of the manufacturing process to reflect the design
- When do they happen
  - OEM
  - During a repair
  - During an inspection
- Can also lead to false indication of a crack
- Common types in USAF aircraft structure

3

Mechanical Manufacturing Failures

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

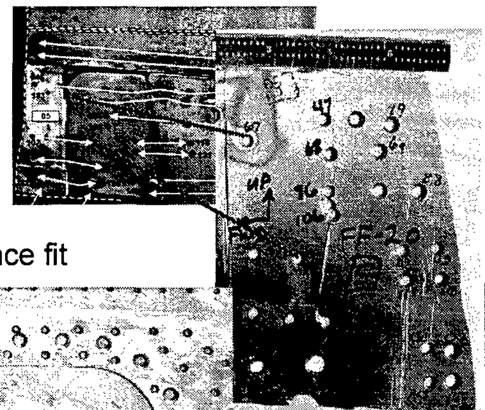
- Double Drilled Holes
- Low Edge Distance
- Poor Hole Quality
- Fastener Issues
- Assembly Technique Issues

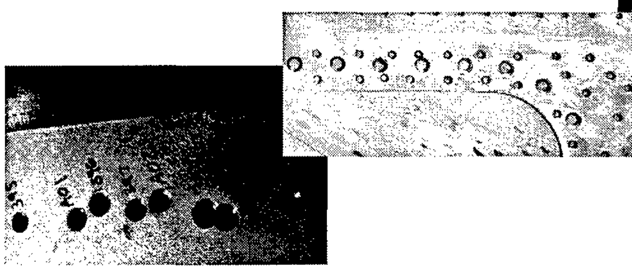
4

Double Drilled Holes

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- "Binocular Holes"
  - Not joined
    - Open hole
    - Low edge distance
  - Joined
    - Sharp edge
    - Precludes interference fit



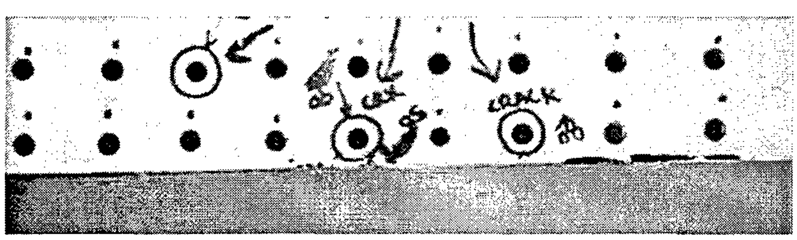


5

Low Edge Distance

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Design practice calls for 2D (1.5D possible)
- Lower than requirements means
  - Drives region to new MS_{MIN}
  - To some NDI can look like a crack

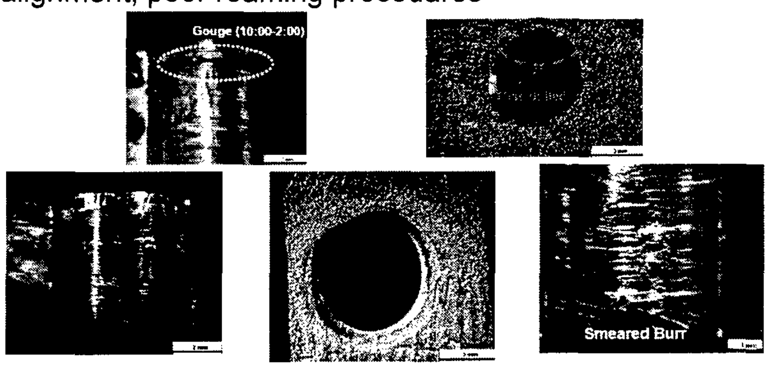


6

Poor Hole Quality

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- What: Gouges, Burrs, Scratches, out-of-round
- Where: Circumferentially or down the bore
- How: no pilot hole, dull drills, improper drill speed or alignment, poor reaming procedures



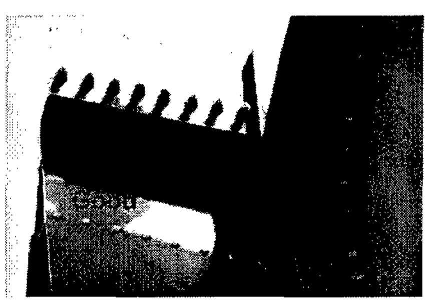
NOTE: All of these were 50% FSH or greater BHEC indication

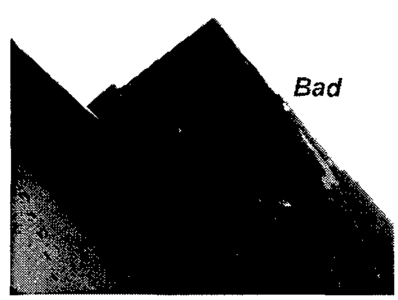
7

Fastener Issues

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Less than desired interference
- More than desired interference
- Fasteners "installed" in their original packaging (missing)





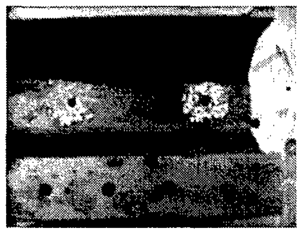
NOTE: Crack formed at fasteners which adjoin the missing fastener region

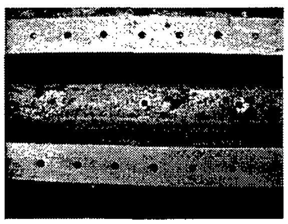
8

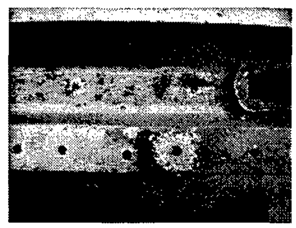
Assembly Issues

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Wet assembly techniques
- Not really a manufacturing failure but can throw off NDI







9

Assembly Issues

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Out of spec grind-outs
  - Corrosion removal, fit-up
  - Reduced section size (higher stress)
- Poor blending
  - Increased stress riser
- Fit-up
  - Residual stress
  - Drilling parts as an assembly can help but....

10

Material Processing Issues

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

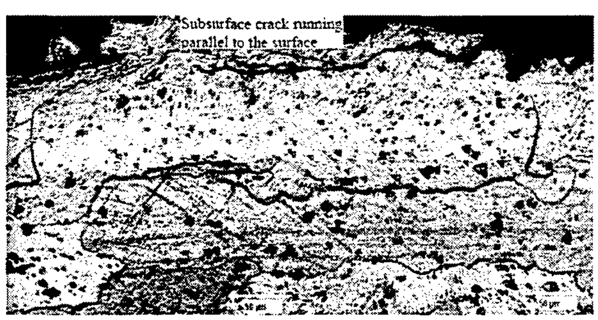
- Excess Shot Peen
- Excess Cold-Working in Holes
- Casting/Forging/Rolling/Extrusion Flaws
- Improper Alloy/Heat Treat Condition
- Coating Failures

11

Excess Shot Peen/Cold-Work

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Tensile–to–compressive transition > F_{TU}
- Subsurface cracks form
- Crack grow by fatigue or SCC
- Excess cold-working in holes has same effect on bore

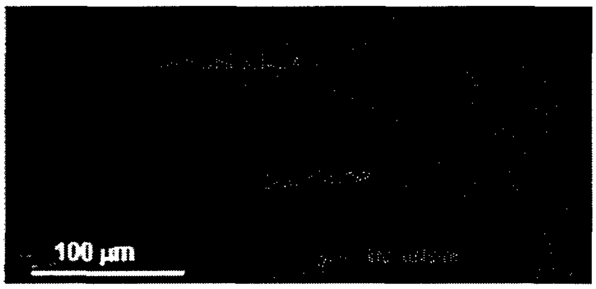


12

Casting/Rolling/Forging/Extrusion Flaws

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Porosity
  - Pores are initiation sites
  - Pores can line up to look like a crack
- Inclusions
  - Hard particles create residual stress
  - Crack initiation sites



13

Other

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Improper Alloy and/or Heat Treat Condition
  - Not per design
  - Aging effects?
  - Record keeping
- Coating Failures
  - In-service damage
  - Contaminants during coating process
  - All are corrosion initiation sites

14

Case Study

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

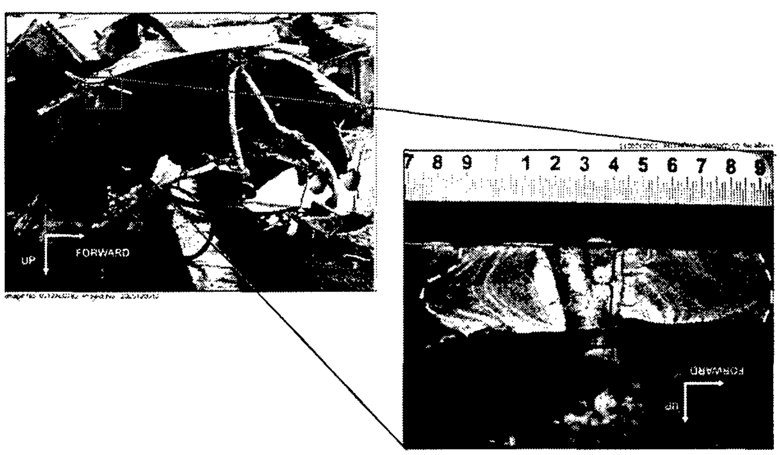
- Chalk Airways, flight 101, 19 December 2005
  - Large explosion hear immediately after TO
  - Fire seen from area of right engine
  - Some witnesses believed right wing separated
  - G-78T, built in 1947, TT>31K hrs, >39K takeoffs

15

Investigation Details

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Right wing separated in-flight near fuselage connection
- Light corrosion found on previous inspections



16

Preliminary NTSB Results

- Preliminary metallurgical examination has located evidence of fatigue cracking in:
  - the lower rear wing spar cap
  - along the lower wing skin
  - on an internal z-stringer
  - corresponding areas on the left wing
- NTSB Identification: DCA06MA010
- From NTSB Investigator (Bill English) to AP:

  Finding such damage would require "very sophisticated testing," such as a special dye that penetrates the aluminum structure.
- "Investigation" also progressing in the legal world

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 24

Material Substitution for Failure Prevention

1

Lesson Goals & Objectives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

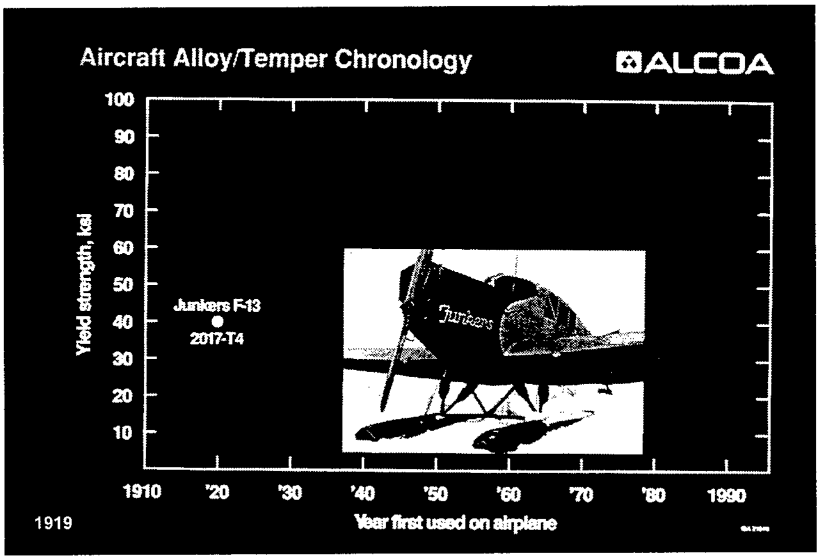
- After this lesson, engineers should understand the development and limitations of legacy material and the substitution options available to replace them.

- **Objectives**
  - **Describe** the life cycle of alloy development
  - **Discuss** how seemingly "poor" alloy choices may be made by manufacturer
  - **Discuss** how material substitution, without geometric redesign can prevent failure

2

Aluminum Alloy Development

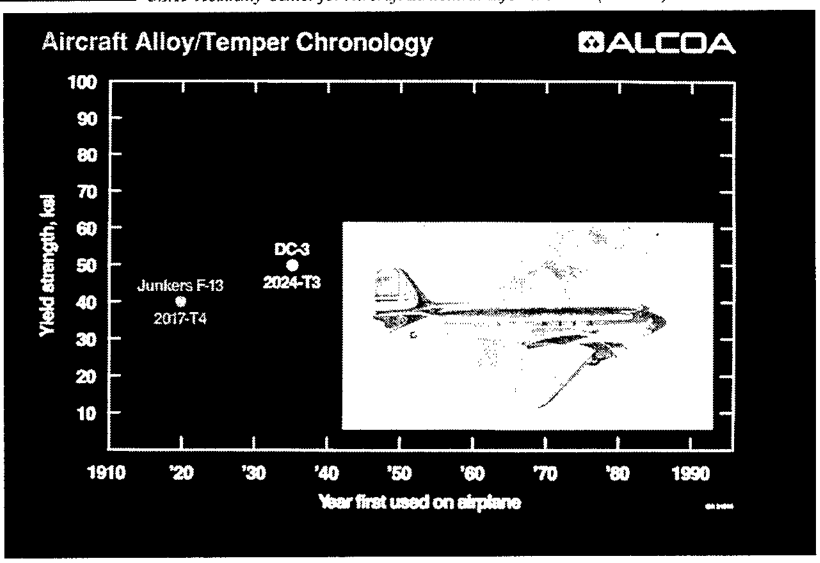
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



3

Aluminum Alloy Development

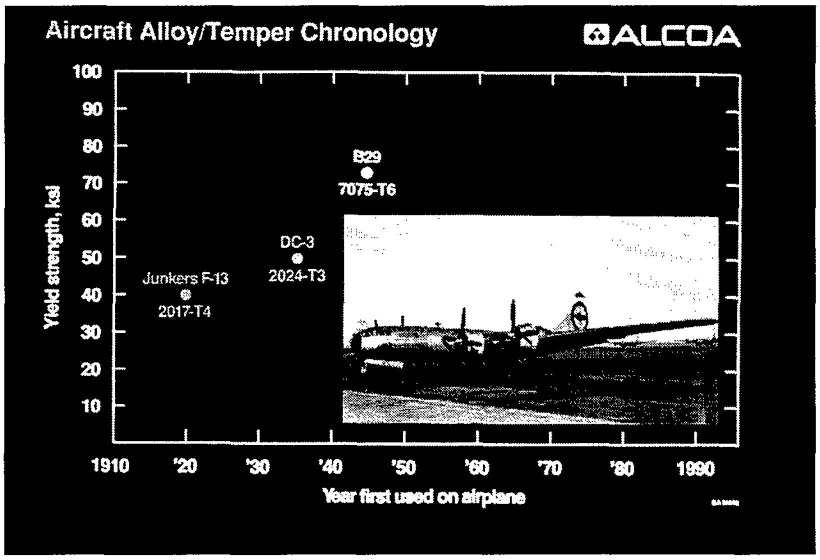
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



4

Aluminum Alloy Development

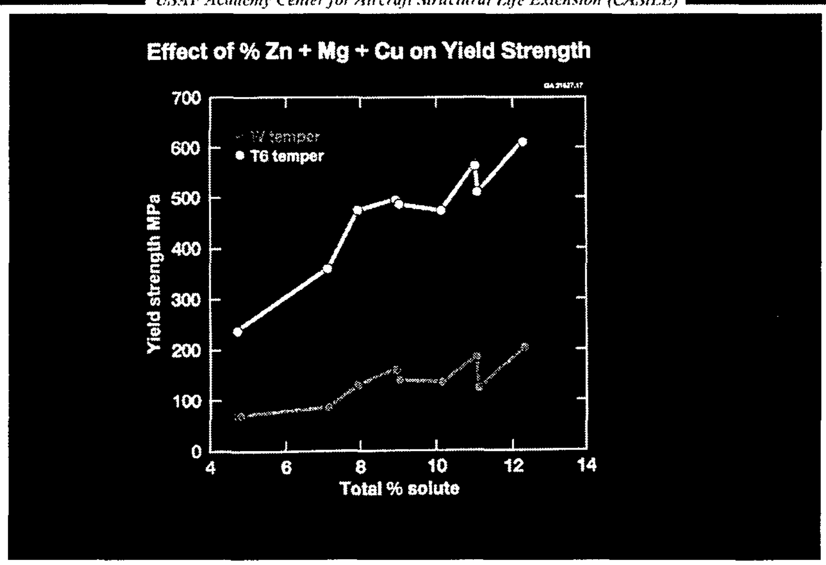
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



5

Aluminum Alloy Development

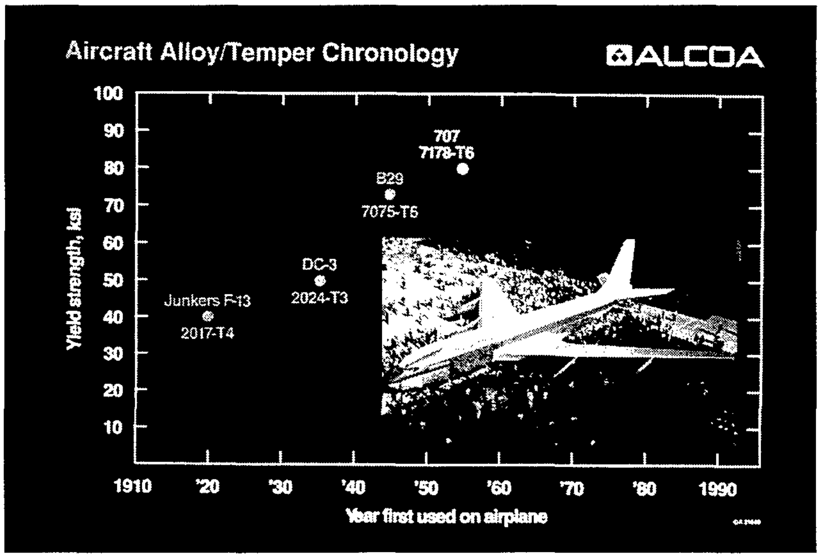
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



6

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



7

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

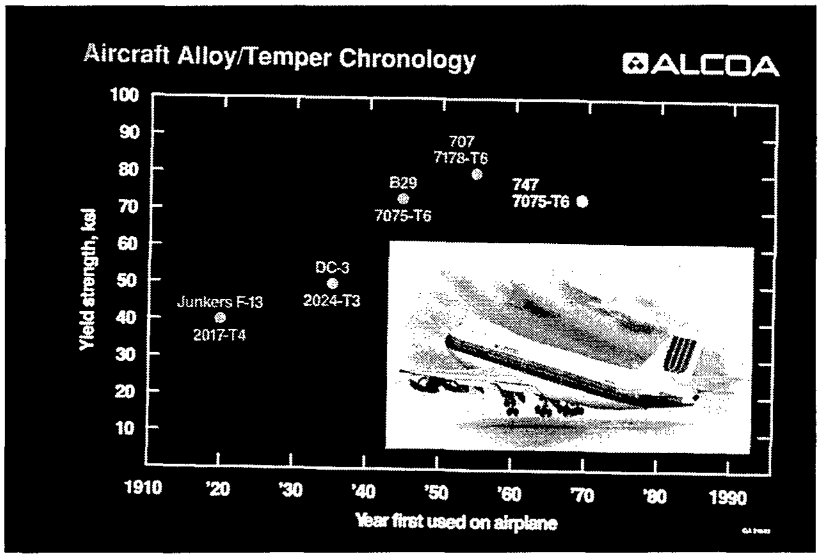
Materials Developed Up to the 1950s

- Driver:
  - Weight savings
- Materials:
  - 2017-T4
  - 2014-T6
  - 2024-T3, T8
  - 2124-T8
  - 7075-T6
  - 7178-T6
  - 7079-T6
  - 2219-T6, T8
  - 2020-T6

8

Aluminum Alloy Development

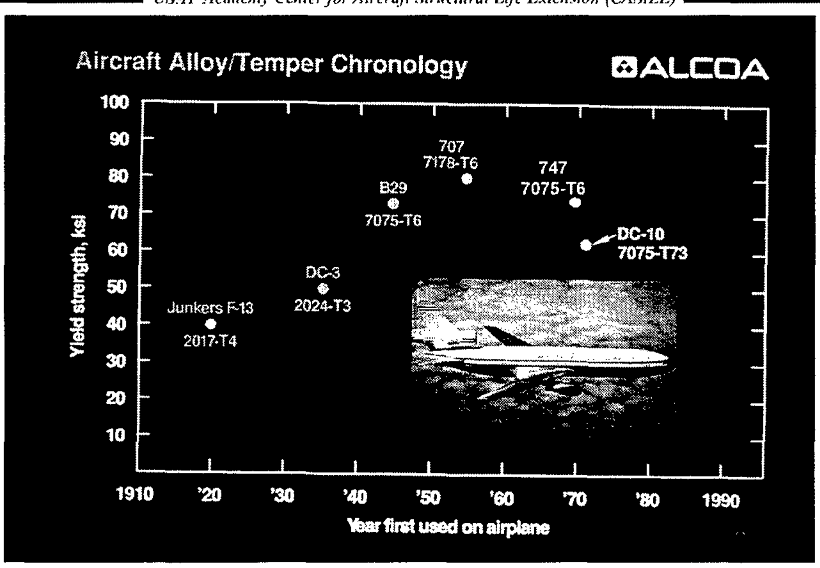
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



9

Aluminum Alloy Development

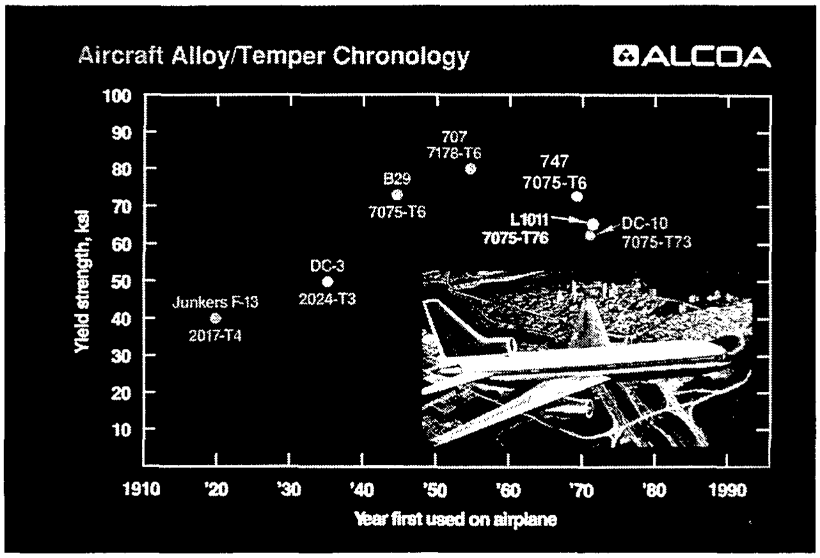
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



10

Aluminum Alloy Development

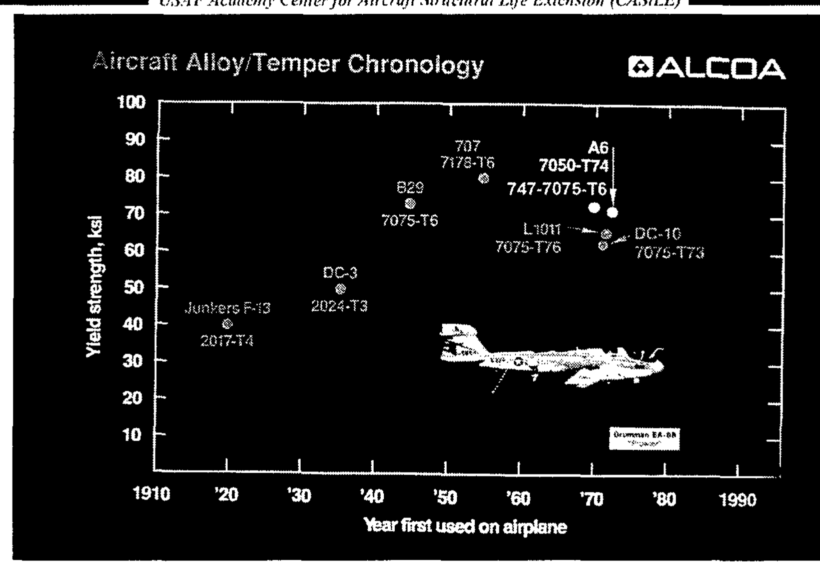
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



11

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



12

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

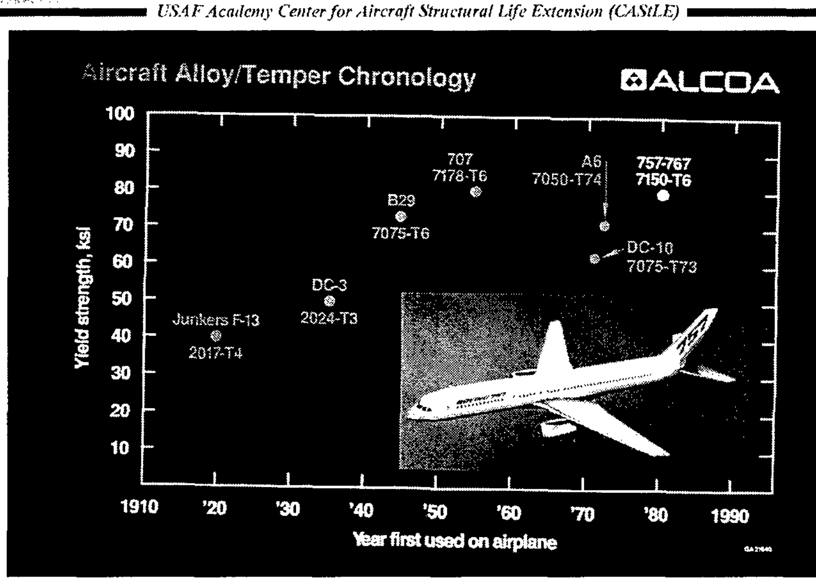
Materials Developed in 1960s and Early 1970s

- Driver:
  - Durability and damage tolerance
- Materials:
  - 7075-T76, T73
  - 7475-T76, T73
  - 7050-T74, T76
  - 7049-T73
  - 7010-T74, T76

13

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



14

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Materials Developed in the Late 1970s

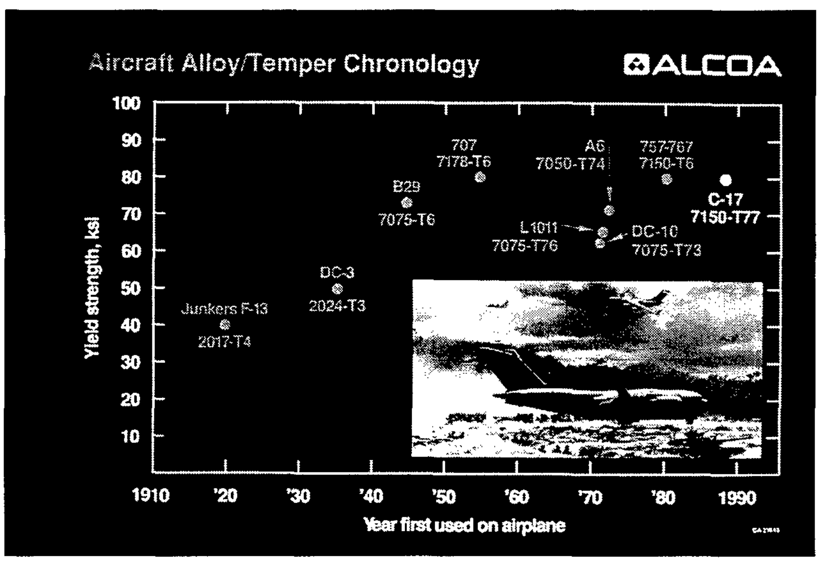
- Driver:
  - Focused weight savings for particular applications
- Materials:
  - 2224-T3
  - 2324-T39
  - 7150-T6, T61

5

15

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



16

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Materials Developed During the 1980s

- Drivers:
  - Generic weight savings because of jet fuel price
- Materials:
  - 2090, 2091, 8090
  - GLARE® and ARALL®
  - Wrought P/M 7093
  - Al-Fe-X
  - Mechanically alloyed
  - Metal matrix composites
  - 7150-T77

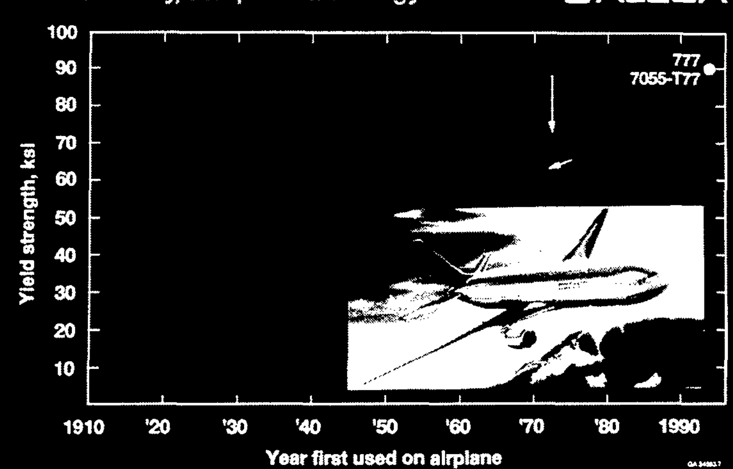
6

17

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Aircraft Alloy/Temper Chronology



18

Aluminum Alloy Development

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Materials Developed Most Recently

- Drivers:
  - Weight savings
  - Durability and damage tolerance
- Materials:
  - Alclad 2524-T3 sheet
  - 7055-T77 plate and extrusions
  - 2195-T8 plate
  - 2097 plate

7

19

Need For Materials Substitution

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Legacy Aircrafts of 50s and 60s

Material Related Problem:

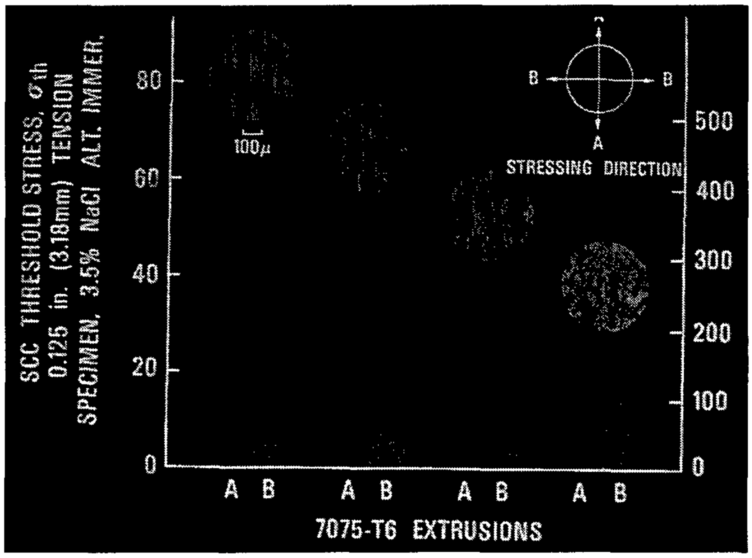
- Driver was weight saving so high strength alloy
- Poor Corrosion Resistance
- Poor Damage Tolerance
- Processing Defects
- Compositional and Microstructural Inhomogeneities.

Or they have just aged more than their design life.

20

Corrosion of High Strength Alloys

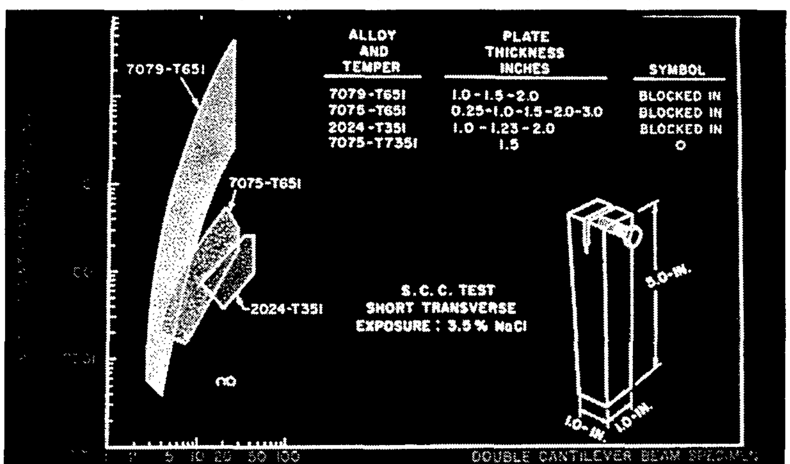
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



21

Corrosion of High Strength Alloys

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



STRESS-CORROSION PERFORMANCE OF PRECRACKED DOUBLE CANTILEVER BEAMS OF VARIOUS HIGH STRENGTH ALUMINUM ALLOYS. (BOEING-ARPA).

22

Factors Affecting Corrosion

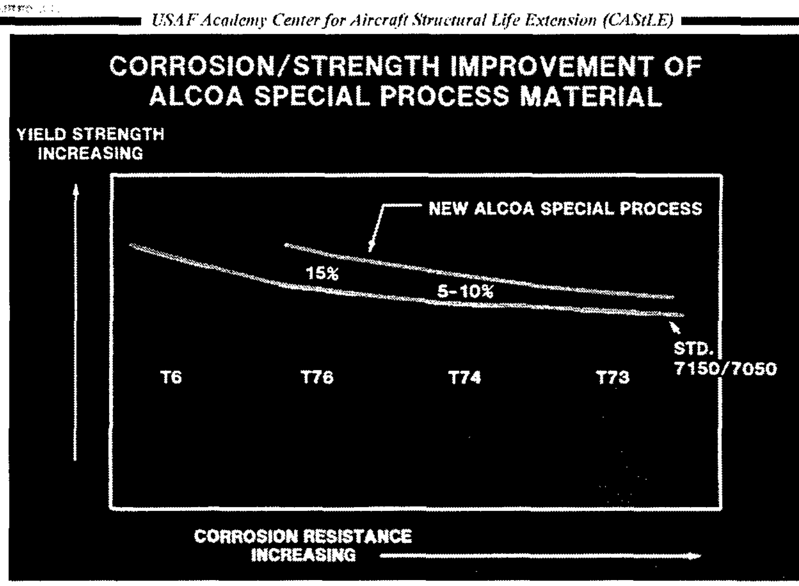
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- SCC and exfoliation corrosion occur in the precipitate free zones (PFZ) that are adjacent to grain boundaries in aged material.
- Zn and Mg in solution make the electrochemical potential more negative than aluminum while Cu in solution makes it more positive.
- The degree of overaging required to develop good corrosion characteristics decreases with increasing Cu content in the alloy.
- Overage tempers such as T7 prevents Cu from precipitating in eta phase during first aging step.

23

Improved Tempers for Corrosion Resistance

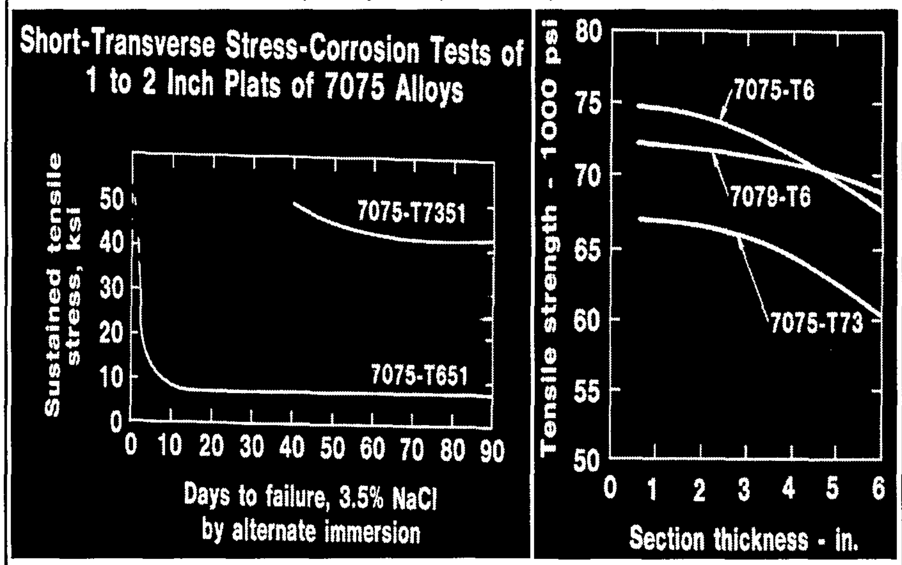
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



24

Improved Tempers for Corrosion Resistance

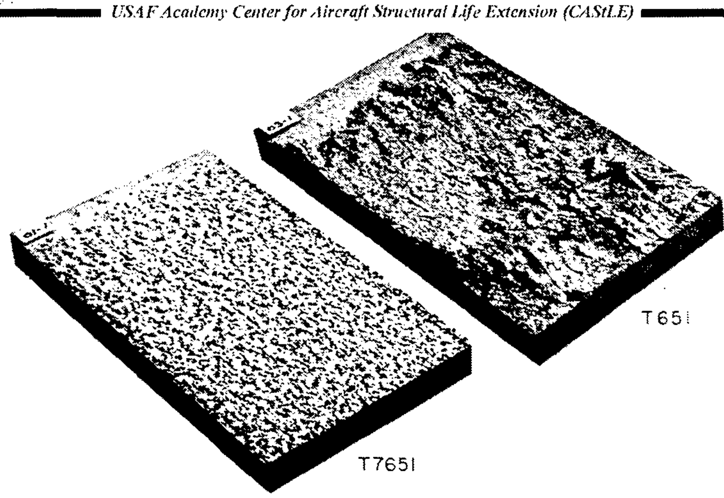
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



25

Improved Tempers for Corrosion Resistance

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

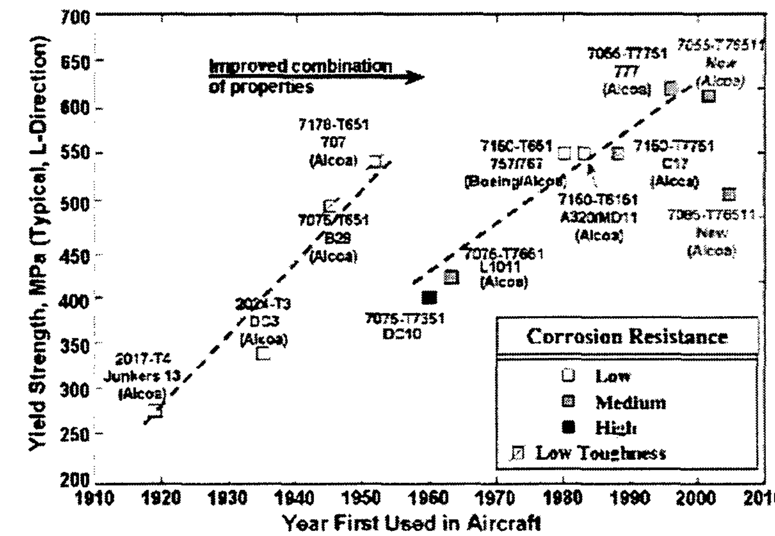


0.5-IN. 7075 PLATE EXPOSED TO SALT-SPRAY EXFOLIATION TEST

26

Strength & Corrosion Resistance

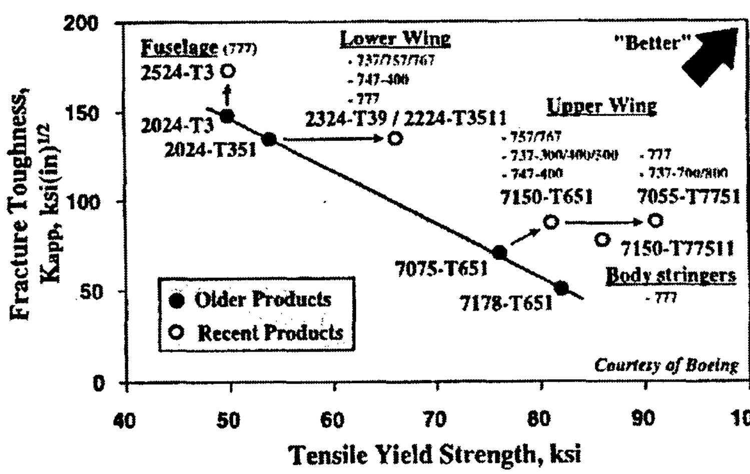
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Bucci et al. *Journal of Aircraft*, **37** [1] 122-9 (2000) 27

Damage Tolerance New and Old Alloys

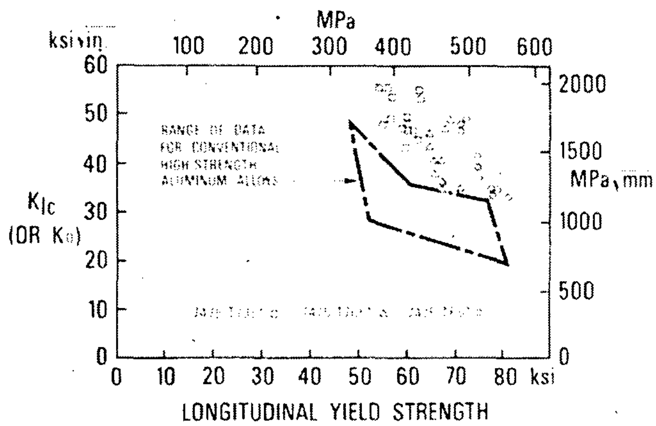
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Bucci et al. *Journal of Aircraft*, **37** [1] 122-9 (2000) 28

Damage Tolerance New and Old Alloys

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



K_{Ic} of new alloy 7475 plate relative to commercial alloy plate

29

Ideal Structure for High Toughness

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Grain Structure
- Unrecrystallized (Plate, Forgings, Extrusion)
- Fine recrystallized grain size (Sheet)

Intermetallic Constituent Particles
- None

Dispersoid Particles
- Fine, Coherent
- Widely dispersed if incoherent

Precipitate
- None on grain boundaries
- No PFZ
- Finely Dispersed

Inclusions
- None

Porosity
- None

30

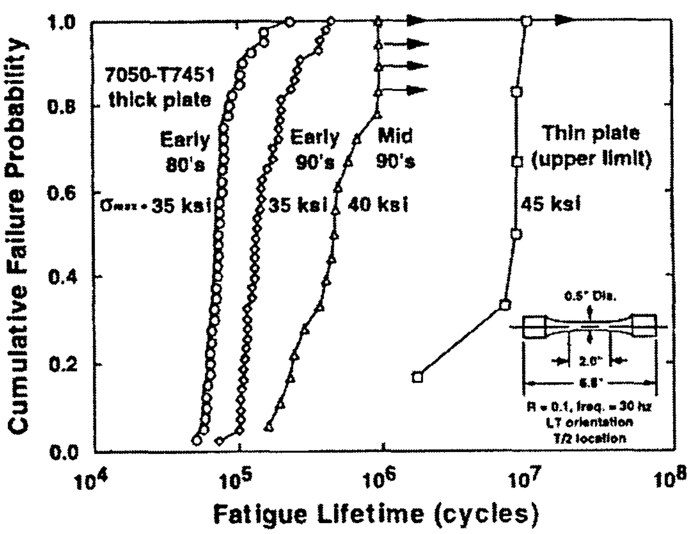
Comparison of K_{IC} For Two Applications

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

APPLICATION:	FUSELAGE	UPPER WING SKIN
REQUIREMENTS:	MODEST STRENGTH HIGH TOUGHNESS	HIGH COMPRESSION YS USEFUL TOUGHNESS
FRACTURE MODE:	TRANSGRANULAR OR INTERGRANULAR	HIGHLY TRANSGRANULAR
METAL PURITY	LARGE EFFECT IF TRANSGRANULAR NO EFFECT IF INTERGRANULAR	EFFECT DECREASES AS YS INCREASES
GRAIN STRUCTURE:	FINE RECRYSTALLIZED	UNRECRYSTALLIZED
QUENCH RATE:	NOT HIGHLY SIGNIFICANT	HIGH AS POSSIBLE
COLD WORK:	MEET YS REQUIREMENT	HIGHEST FOR 2XXX MINIMUM FOR 7XXX
AGING:	NATURAL AGED 2XXX UNDERAGED Al-Li PEAK AGED 6XXX OVERAGED 7XXX	PEAK STRENGTH
EXAMPLES:	2024-T3 2091- 8090 6013-T6 7475-T76	7150-T6, 7150-T77

Better Processing – Better Properties

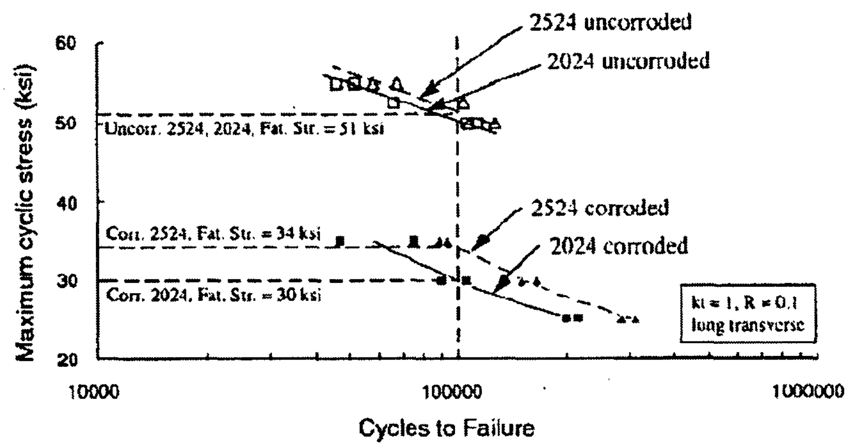
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Bucci et al. *Journal of Aircraft*, 37 [1] 122-9 (2000) 32

Composition and Microstructure Control

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Bucci et al. *Journal of Aircraft*, **37** [1] 122-9 (2000) 33

7XXX Series Replacement Alloys

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Table 1 Longitudinal property comparisons for various 7xxx series aluminum alloy products

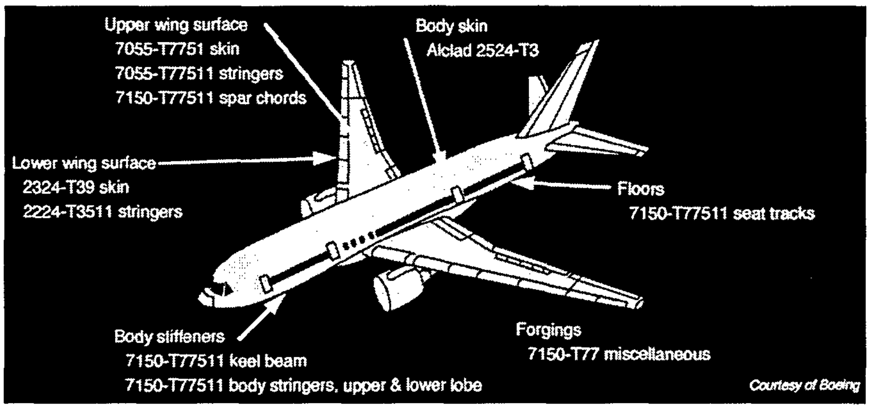
Alloy/temper	Ult. tens. strength, ksi (Mpa)	Tens. yld. strength, ksi (Mpa)	Compr. yld. strength, ksi (Mpa)	Elong. %	Kic, L-T toughness, ksi (in)$^{1/2}$	Exco rating ASTM G34	SCC thresh. stress ST, ASTM G47, 20 days, ksi
Plate, 1.00 in (25.2 mm)							
7075-T651	79 (545)[a]	72 (497)[a]	70 (483)[a]	7	26 (typical)	ED (typical)	10 (typical)
7178-T651	84 (580)[a]	73 (504)[a]	73 (504)[a]	5	<18 (typical)	ED	<10 (typical)
7055-T7751	91 (628)[a]	88 (607)[a]	88 (607)[a]	7	26 (typical)	EB	15 (min)
7150-T7751	84 (579)[b]	78 (538)[b]	77 (531)[b]	8	27 (typical)	EB	25 (min)
7050-T7651	80 (552)[a]	71 (462)[a]	68 (441)[a]	9	31 (typical)	EB	20 (min)
7050-T7451	76 (524)[a]	67 (462)[a]	64 (442)[a]	10	32 (typical)	EB	35 (min)
7475-T7351	72 (497)[a]	62 (428)[a]	60 (414)[a]	10	50 (typical)	EA	40 (min)
Extrusion, 0.500 in (12.7 mm)							
7075-T6511	85 (587)[a]	76 (524)[a]	76 (524)[a]	7	27 (typical)	ED (typical)	10 (typical)
7178-T6511	90 (621)[a]	81(559)[a]	79 (545)[a]	5	<18 (typical)	ED (typical)	<10 (typical)
7055-T77511	95 (656)[a]	93 (642)[a]	94 (649)[a]	9	30 (typical)	EB	15 (typical)
7150-T77511	88 (607)[b]	83 (572)[b]	83 (572)[b]	9	27 (typical)	EB	25 (min)
7050-T76511	79 (545)[b]	69 (476)[b]	69 (476)[b]	7	40 (typical)	EB	17 (min)
Die-forging, 4.00 in (102 mm)							
7075-T6xx	73 (504)[b]	62 (428)[b]	—	7	29 (typical)	ED (typical)	10 (typical)
7055-T76xx	74 (511)[a]	65 (449)[a]	—	4	25 (typical)	—	35 (typical)
7055-T74xx	72 (497)[a]	62 (429)[a]	—	4	29 (typical)	—	35 (typical)
7050-T74xx	70 (483)[b]	60 (414)[b]	—	7	27 (typical)	EB	35 (min)
7175-T74xx	73 (504)[b]	63 (435)[b]	—	7	30 (typical)	—	35 (min)
7075-T73xx	64 (442)[b]	53 (366)[b]	—	7	—	—	42 (min)

[a]MIL-HDBK 5 Minimum "B" basis value. [b]MIL-HDBK 5 Minimum "S" basis value.

Bucci et al. *Journal of Aircraft*, **37** [1] 122-9 (2000) 34

Use of New Alloys in Boeing 777

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

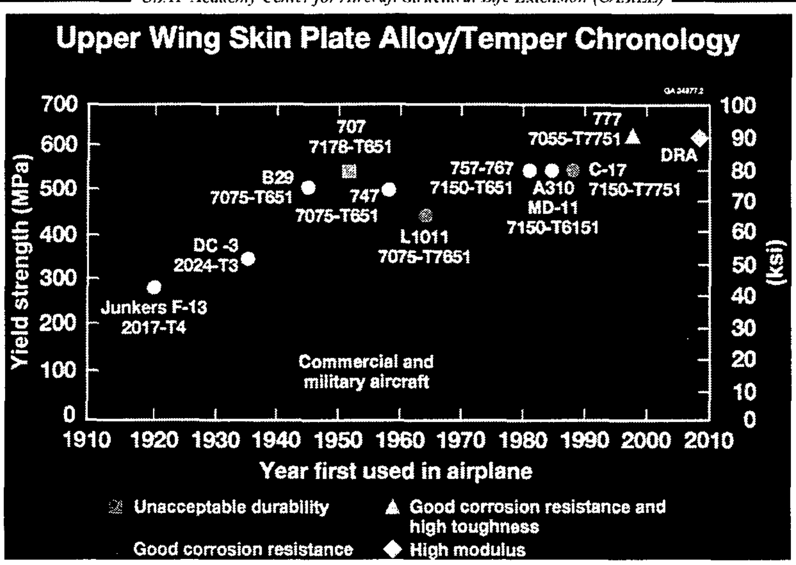


Higher Combinations of Strength, Durability and Damage Tolerance

35

Material Development for Wing Skin

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



36

Economics of Materials Substitution

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

New Material

Cost of material development, characterization and certification for substitution

Legacy Material

- Inspection intervals
- Repair costs
- Downtime
- Procurement of new material
- Engineering efforts to adapt
- Administrative – logistics, inventory
- MISSION IMPACT

37

Lower Cost Structures

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Integral structures**
- **Low residual stress forgings**
- **New generation alloys and composites**
- **Ultra large castings**
- **Functionally graded materials**
- **GLAREs**

38

Acknowledgements

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Dr. Ralph W. Bush, DFEM, USAFA
- Dr. James Staley, ALCOA
- Craig Brice, Lockheed Martin

39

Lesson 25

USAF ASIP

Lesson Goals & Objectives

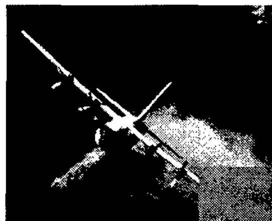
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- After this lesson, engineers will comprehend the roles of the USAF Aircraft Structural Integrity Program (ASIP) in failure prevention and fleet management.

- Objectives
  - **Distinguish** between the safe-life, fail safe, and damage tolerant approaches to design
  - **Define** the USAF's Aircraft Structural Integrity Program (ASIP)
  - **Comprehend** the magnitude of the USAF's "Aging Aircraft" problem
  - **Understand** the relationship between ASIP and failure prevention

Topic Teaser – C-130A Fire Bomber Crash

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Date: 17 JUN 02
Weather: VFR
Airframe: C-130A
Production # 3146 / 56-538
Owner: Hawkins & Powers Aviation
Certification: Dec 1988

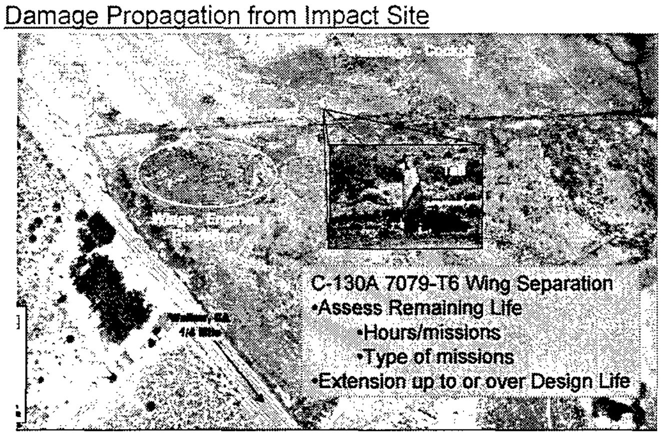
A/C Age: LMAS estimate 58,000 hrs
History:
- Delivered to USAF 1957
- Retired by USAF 1978
- In storage 1978-1988
- Started with Parks Service 1988
- Fire fighter since late I988

Structural Data:
- Original C-130A config
-No center wing upgrade
-Wing repair in 98 "cracks from rivet hole on the underside on the wing"

C-130A Fire Bomber Crash

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Damage Propagation from Impact Site

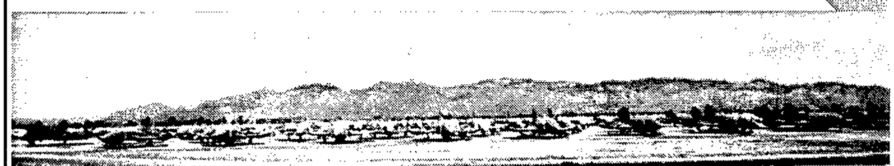


4

History of the subject C-130A

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- USAF
- CIA
- Grounded & Mothballed
- Traded to Department of the Interior



5

C-130A – Structural Info

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- In service 1956, TN 56-0538
- Designed for static strength, 7079-T6 wing
- Problems with SCC and subsequent fatigue
  - Grounded in 1970s
  - Re-winged, just like C-5A
  - Bonded Repairs (RAAF)

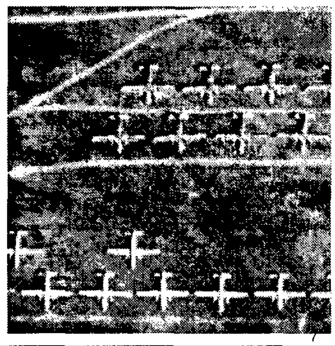
6

CIA Service of the C-130A

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

"Those kind of airplanes basically don't exist records-wise."
George Petterson, air safety investigator

- Electronic surveillance *somewhere* in the world
- Number of hours?
  - Void in maintenance history
  - 3000 up to 20,000 hrs?
- Mothballed in 1978



7

Interior Department Service of the C-130A

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- "Acquired" 1988
- Fire-fighting mission
  - Missions & Loads changed
  - Fire retardant (corrosive)
- Operated by Hawkins & Powers
- Crashed, Walker CA, June 2002

8

Aftermath – FAA Directive

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

"An unsafe condition has been identified that is likely to exist or develop on other Lockheed C-130A airplanes"

- A fact well known to the USAF
- The initial reason for mothballing
- Aircraft traded to obtain museum quality aircraft
- Illegal nature of exchange in 1988
  - 1996; Federal indictments, two men in fed prison
  - Conspiracy to steal 22 aircraft
  - DOJ maintains ownership but does not reposes
  - Aircraft are still flying

Similar C-130A crash happened in 1994!

Contributing Factors

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

C-130A:

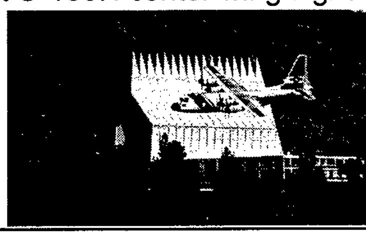
- Unknown usage in hours and loads
  - Massive inspections should have been performed, especially on FCLs
  - Might have prevented this disaster
- Unknown maintenance history
- Changed mission
  - Low-level, dropping fire-retardant, high thermals
  - Flight loads changed dramatically, with no subsequent analysis performed
  - Prediction of crack-growth unknown

10

C-130 Center Wing Instrumentation

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

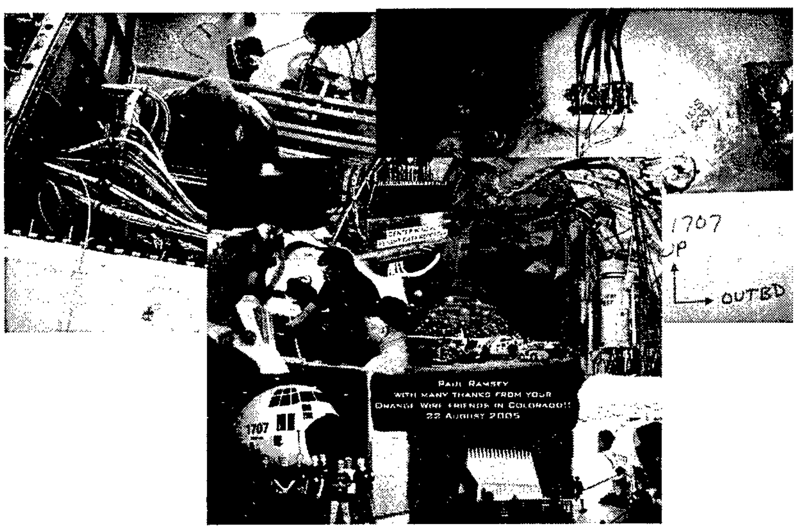
- Widespread fatigue damage (WFD) concern in current fleet of C-130's
  - Numerous a/c grounded or restricted
  - Update of loads/mission severity needed
- June 2005-CAStLE instruments C-130 center wing at Elizabeth City CGB
  - Currently recording center wing flight loads/environment parameters
  - Only current C-130H center wing flight data program



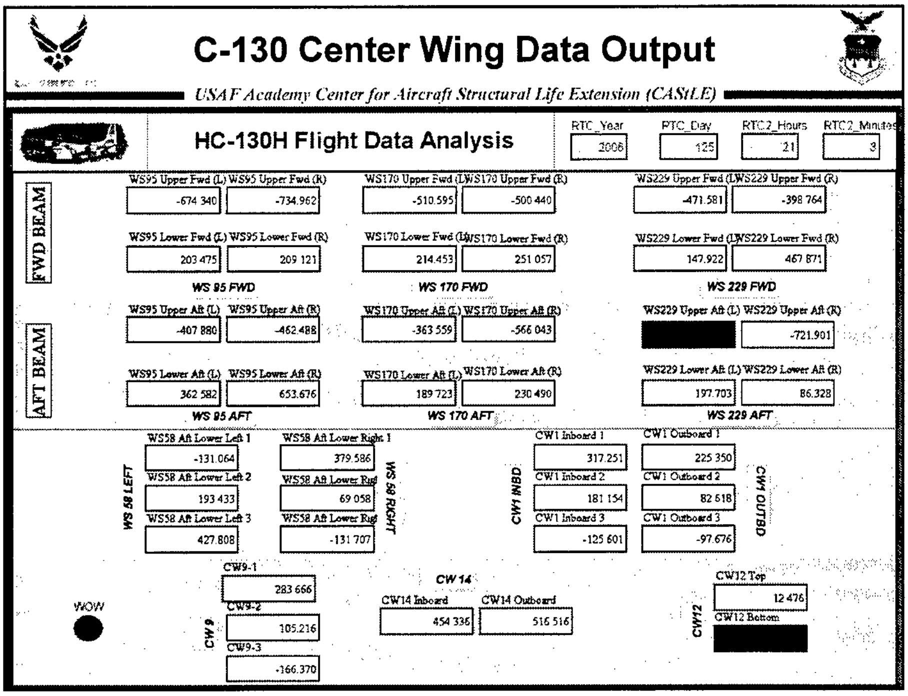
11

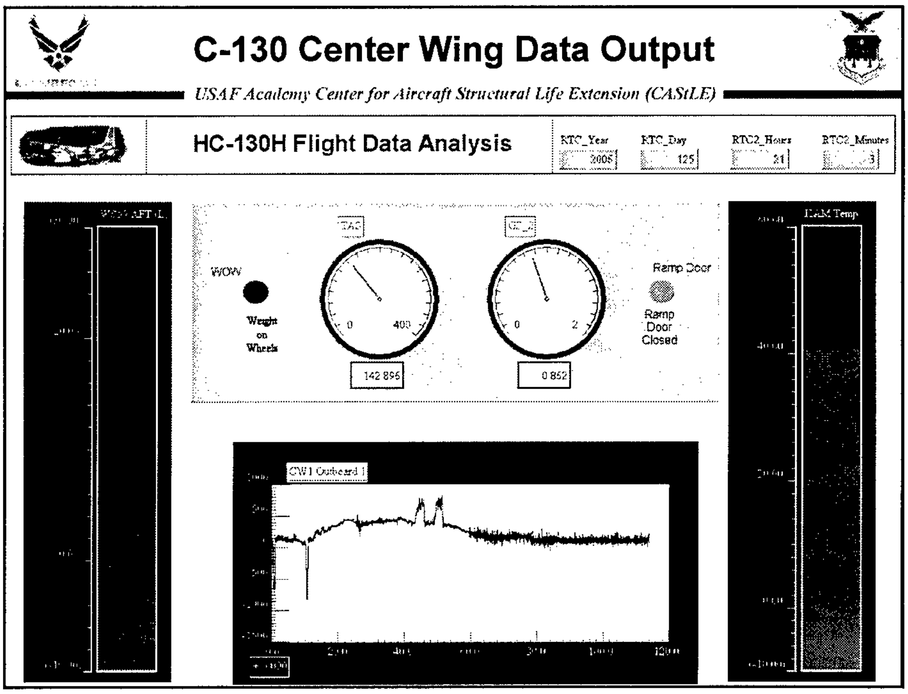
C-130 Center Wing Instrumentation

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



12

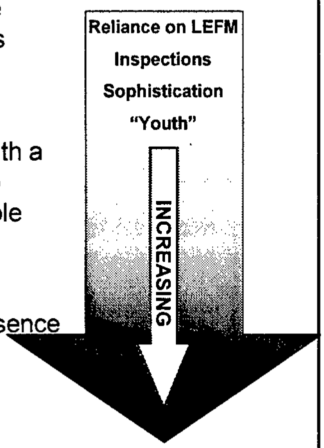

C-130 Center Wing Data Output
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)
HC-130H Flight Data Analysis
RTC_Year 2005
RTC_Day 125
RTC2_Hours 21
RTC2_Minutes 3
FWD BEAM
AFT BEAM
WS95 Upper Fwd (L) -674.340
WS95 Upper Fwd (R) -734.962
WS170 Upper Fwd (L) -510.595
WS170 Upper Fwd (R) -500.440
WS229 Upper Fwd (L) -471.581
WS229 Upper Fwd (R) -398.764
WS95 Lower Fwd (L) 203.475
WS95 Lower Fwd (R) 209.121
WS170 Lower Fwd (L) 214.453
WS170 Lower Fwd (R) 251.057
WS229 Lower Fwd (L) 147.922
WS229 Lower Fwd (R) 467.871
WS 95 FWD
WS 170 FWD
WS 229 FWD
WS95 Upper Aft (L) -407.880
WS95 Upper Aft (R) -462.488
WS170 Upper Aft (L) -363.559
WS170 Upper Aft (R) -566.043
WS229 Upper Aft (L)
WS229 Upper Aft (R) -721.901
WS95 Lower Aft (L) 362.582
WS95 Lower Aft (R) 653.676
WS170 Lower Aft (L) 189.723
WS170 Lower Aft (R) 230.490
WS229 Lower Aft (L) 197.703
WS229 Lower Aft (R) 86.328
WS 95 AFT
WS 170 AFT
WS 229 AFT
WS 58 LEFT
WS58 Aft Lower Left 1 -131.064
WS58 Aft Lower Left 2 193.433
WS58 Aft Lower Left 3 427.808
WS 58 RIGHT
WS58 Aft Lower Right 1 379.586
69.058
-131.707
CW1 INBD
CW1 Inboard 1 317.251
CW1 Inboard 2 181.154
CW1 Inboard 3 -125.601
CW1 OUTBD
CW1 Outboard 1 225.350
CW1 Outboard 2 82.618
CW1 Outboard 3 -97.676
WOW
CW 9
CW9-1 283.666
CW9-2 105.216
CW9-3 -166.370
CW 14
CW14 Inboard 454.336
CW14 Outboard 516.516
CW12
CW12 Top 12.476
CW12 Bottom


C-130 Center Wing Data Output
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)
HC-130H Flight Data Analysis
RTC_Year 2005
RTC_Day 125
RTC2_Hours 21
RTC2_Minutes 3
WOW
Weight on Wheels
142.896
0.852
Ramp Door
Ramp Door Closed
CW1 Outboard 1
RAM Temp

Design Approaches to Failure Prevention

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Safe Life**
  - Structure is designed not to fail during the service life (and if they do fail, the result is usually catastrophic)
- **Fail Safe**
  - Structure will support designated loads with a single member failed or partial damage to extensive structure (usually implies multiple load paths)
- **Damage Tolerance**
  - Structure has ability to function in the presence of damage



15

Additional Design Issues & Failure Prevention Tools

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Durability**
  - ability to function without sustaining damage
- **(Durability &) Damage Tolerance Analysis [DA]DTA**
  - in depth study to:
    - determine if critical components were designed correctly
    - determine if service conditions are as predicted
    - find (un)anticipated locations of cracks and corrosion
- **Teardown Inspection (often part of a [DA]DTA)**
  - laborious disassembly of a large portion of an entire aircraft conducted to find cracks or corrosion that have accumulated during service and which may not be visible without a disassembly
- **Widespread Fatigue Damage (WFD)**
  - Characterized by the simultaneous presence of cracks at multiple structural details that are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirements

16

Loads & Lives

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **(Design) Limit Load [DLL]**
  - maximum load projected during an aircraft's anticipated service life
- **Ultimate Load**
  - limit load multiplied by a factor of safety (typically 1.5 to 2.0 for manned aircraft)
- **(Design) Service Life [DSL]**
  - Anticipated length of time or # of flight hours an aircraft will be in service

17

Aircraft Structural Integrity Program (ASIP)

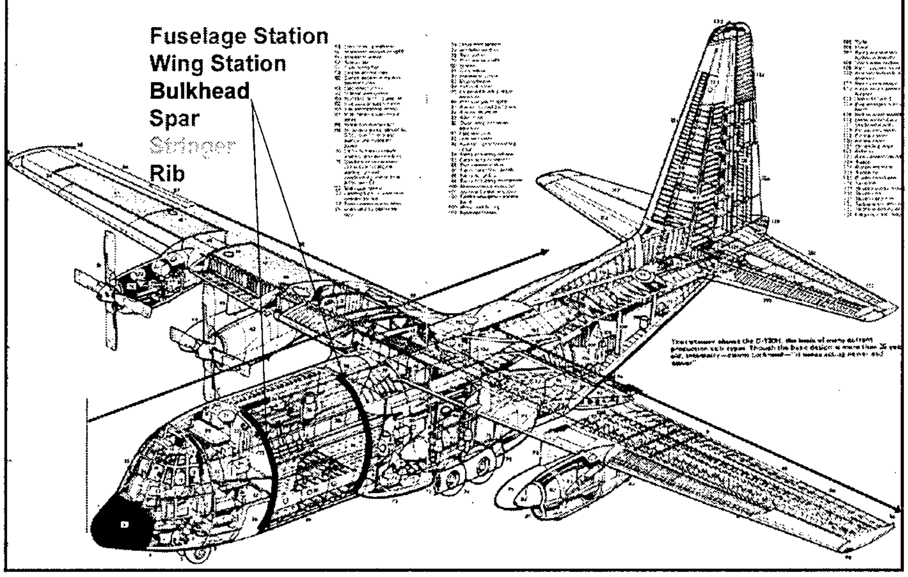
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **ASIP [Aircraft Structural Integrity Program]**
  - USAF program to ensure aircraft remain structurally sound throughout their life (regardless of whether they are in service longer than the design service life); components include inspection protocols and schedules, identification of critical components, periodic assessments ([DA]DTAs or partial [DA]DTAs)
- **ASMP [Aircraft Sustainment Master Plan]**
  - Governs how an entire aircraft will be maintained
- **FSMP [Force (Fleet) Structural Maintenance Plan]**
  - Dictates the structural maintenance that must be accomplished, the schedule that must be kept, and any additional studies/schedules required to keep an aircraft structurally sound

18

Structural Features

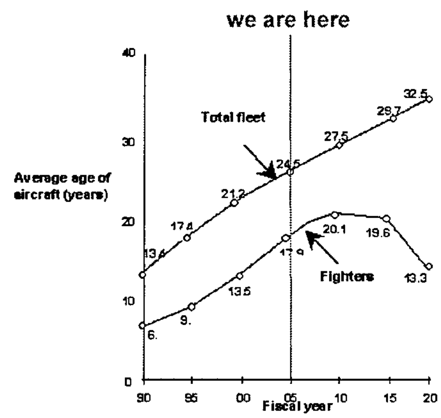
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



The Aging USAF Inventory

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- USAF operates 4,284 aircraft
- Average age
  - **22.8 years**
- Percent older than 24 years
  - **39%**
- Percent older than 21 years
  - **47%**
- Percent older than 18 years
  - **56%**
- Percent younger than 9 years
  - **12%**

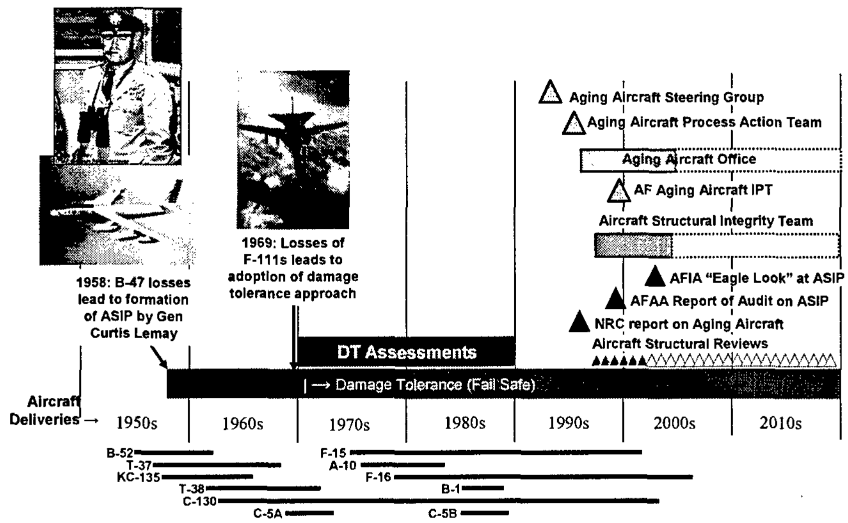


Source: *Air Force Magazine*, May 2005

20

History in Relation to ASIP

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



21

Five Tasks of ASIP

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Per MIL-STD-1530C

TASK I	TASK II	TASK III	TASK IV	TASK V
DESIGN INFORMATION	DESIGN ANALYSES & DEVELOPMENT TESTING	FULL-SCALE TESTING	CERTIFICATION & FORCE MANAGEMENT DEVELOPMENT	FORCE MANAGEMENT EXECUTION
5.1.1 ASIP Master Plan	*5.2.1* Material and Joint Allowables Testing	*5.3.1* Static Tests	*5.4.1* Certification Analyses	*5.5.1* Individual Aircraft Tracking (IAT) Program
5.1.2 Design Service Life & Design Usage	*5.2.2* Loads Analysis	*5.3.2* First Flight Verification Ground Tests	*5.4.2* Strength Summary & Operating Restrictions (SSOR)	*5.5.2* Rotorcraft Dynamic Component Tracking (RDCT) Program
5.1.3 Structural Design Criteria	*5.2.3* Design Service Loads Spectra	*5.3.3* Flight Tests	*5.4.3* Force Structural Maintenance Plan (FSMP)	*5.5.3* Loads/Environment Spectra Survey (L/ESS)
5.1.4 Durability and Damage Tolerance Control Program	*5.2.4* Design Chemical/Thermal Environment Spectra	*5.3.4* Durability Tests	*5.4.4* Loads/Environment Spectra Survey (L/ESS) Development	*5.5.4* ASIP Manual
5.1.5 Corrosion Prevention & Control Program (CPCP)	*5.2.5* Stress Analysis	*5.3.5* Damage Tolerance Tests	*5.4.5* Individual Aircraft Tracking (IAT) Program Development	*5.5.5* Aircraft Structural Records
5.1.6 Nondestructive	*5.2.6* Damage Tolerance	*5.3.6* Climatic Tests	*5.4.6* Rotorcraft Dynamic	*5.5.6* Force Management

continued....

22

ASIP Discussion

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Why can we consider ASIP to be a failure prevention tool?
- How effective has ASIP been?
- Specific examples from the:
  - F-16
  - JSTARS (707)
  - KC-135
  - C-141
  - C-130A (fire fighting aircraft)

  } ***What actions may have prevented problems encountered on these aircraft?***
- What changes may affect ASIP in the future?

23

APPENDIX C: Case Study Scenario Handouts

This Page Intentionally Left Blank

Case Study 1

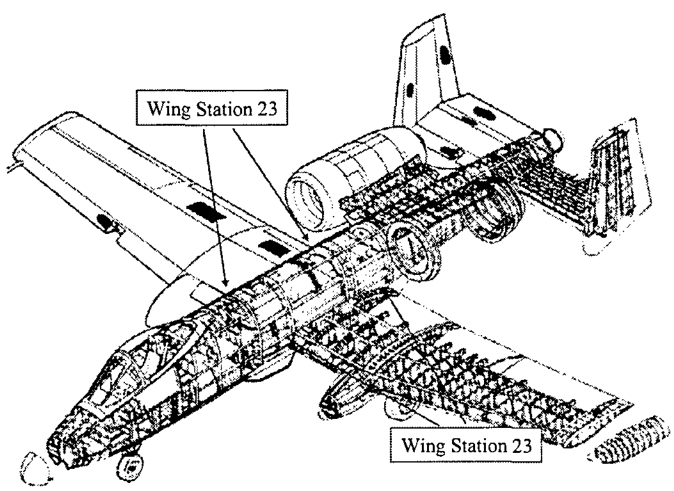
A-10 Wing Station 23 "Hog Up" Program

Adapted From: "A-10 WS-23/Hog Up Scheduling and Funding Summit"
Ogden ALC, 18 July 02

1

Airframe WS23 Location

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



2

Fleet Inspection History

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- FSMP inspections were not accomplished as required
- ACI and TCTO inspection program
  - 62 Aircraft received WS23 Inspection
    - ACI - Oct 1994-97 (WS23 inspection terminated)
      - **All but 1 A/C displayed expected crack indications**
      - **1 Rogue Crack (.36")**
    - TCTO 1438 (Sep 2001 - Present)
      - **All aircraft inspected displayed expected crack indications**

3

Expected Findings

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

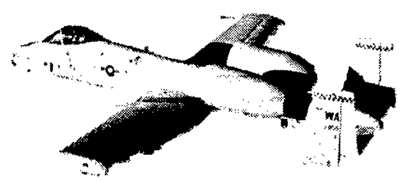
- **Based on Previous Inspection Results:**
  - 10% Failure – 25 A/C
    - Requires replacement wing
  - 33% No Cold Work Repair – 81 A/C
    - Re-inspect after 370 Flying Hrs or replace wing
  - 30% Cold Work Repair – 74 A/C
    - Re-inspect after 750 Flying Hrs
  - 27% No Defect – 67 A/C
    - Re-inspect after 1500 Flying Hrs

4

A-10 History

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- 1977: 8,000 Flight Hours
- 2028: 16,000 Flight Hours
- 363 Active Aircraft in Inventory
  - 247 Thin Skinned
  - 116 Thick Skinned



5

Hog Up

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Wing and fuselage structural repair
- Extends design life to 16,000 hrs
- Applies to all 363 A-10 aircraft
- Original Plan
  - 10 Yr program begins FY02 3rd Qtr
  - 5000+ Man-hours per aircraft
- Now a Service Life Extension Program (SLEP)

6

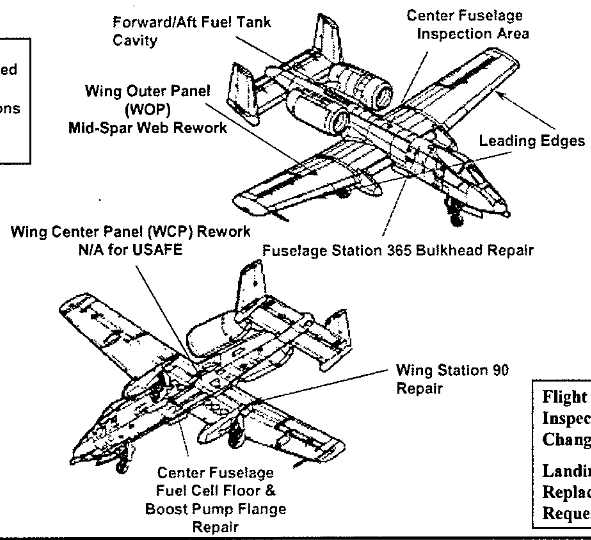
A-10 Structural Rework Locations

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Service-Life Related

Existing Inspections

Improved Item



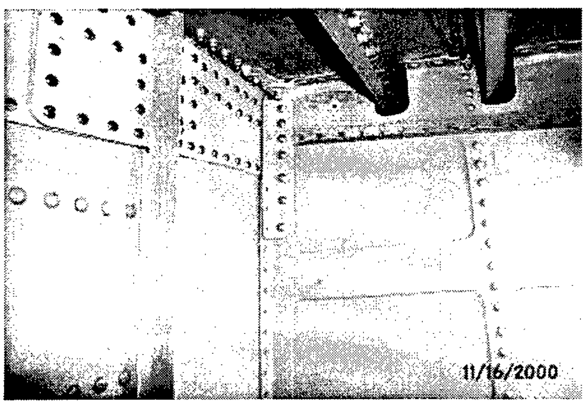
Flight Controls Inspection and Time Change

Landing Gear Replacement (103 Request)

Mid-Spar Repair

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Typical repair of mid-spar at WS110.
- Improvements identified by Hog Up technicians are being incorporated into drawings.

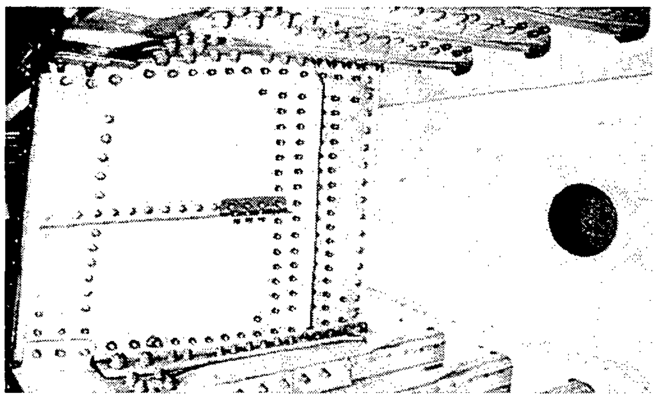


8

Front Spar Repair

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Typical repair to front spar.
- Not part of Hog Up, however, anticipate cracks will be discovered during routine inspection.

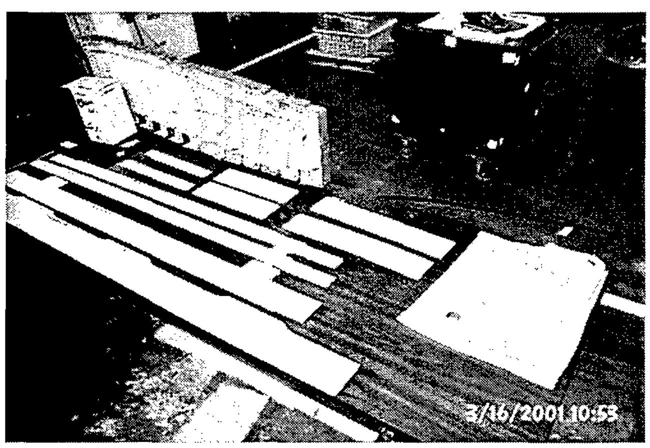


9

WCP Repair Parts

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

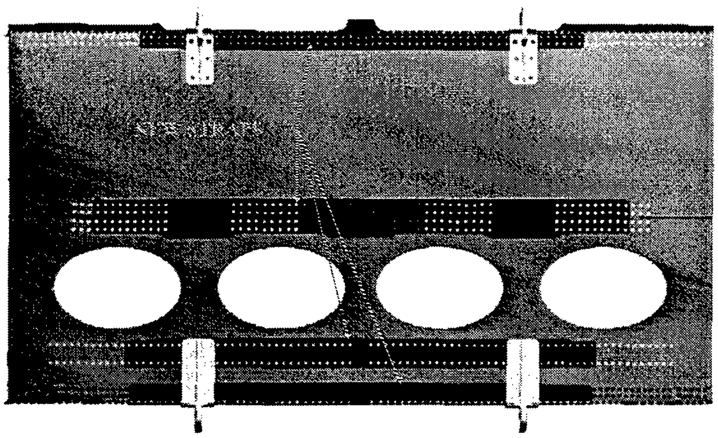
- Stainless steel straps and aft attach fittings used to repair wing center panel



10

Wing Center Panel Repair

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

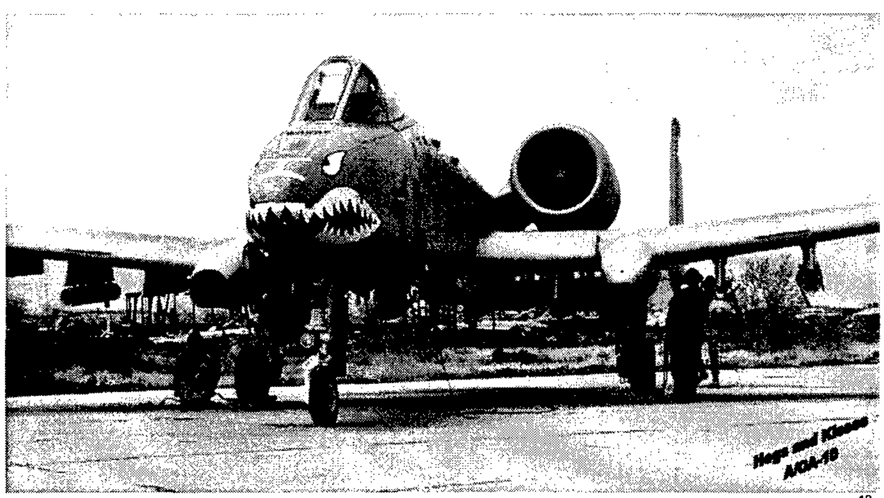


VIEW LOOKING UP AT WING CENTER PANEL

11

Questions?

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



12

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

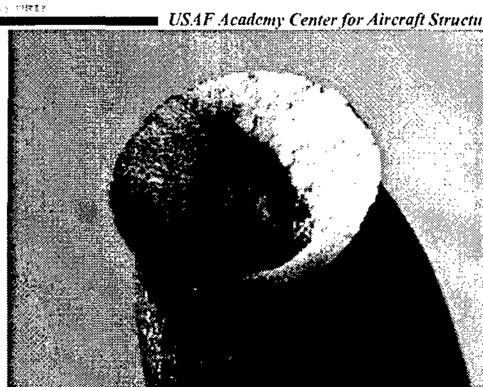
Case Study 2

Failure Modes

1

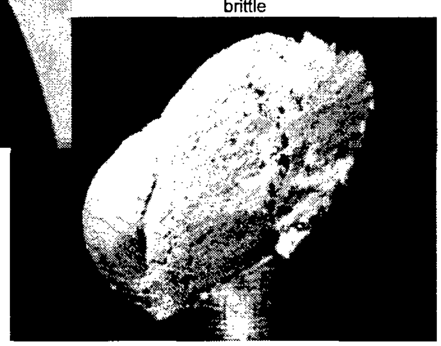
Aluminum in Tension

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



ductile

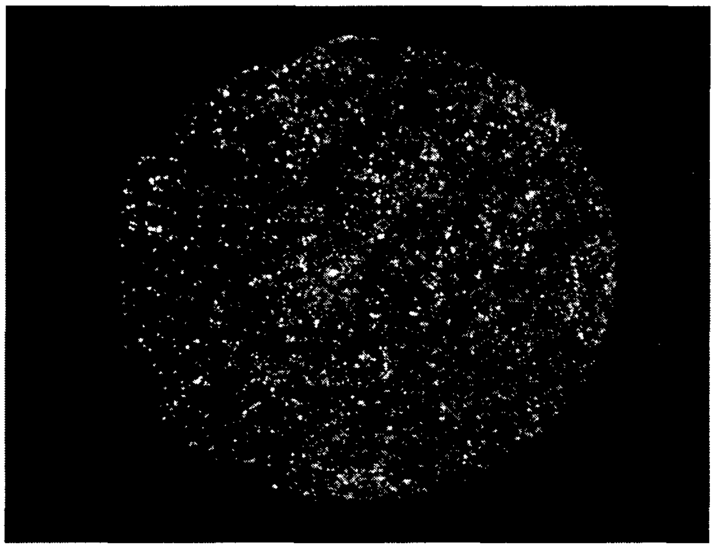
brittle



2

Another Brittle Tension Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



3

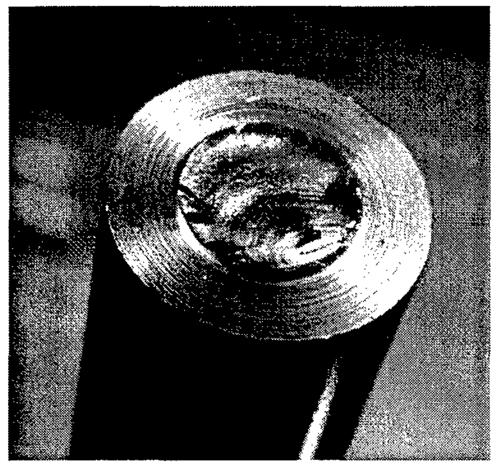
Compression Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

4

Bucking Bar Fatigue

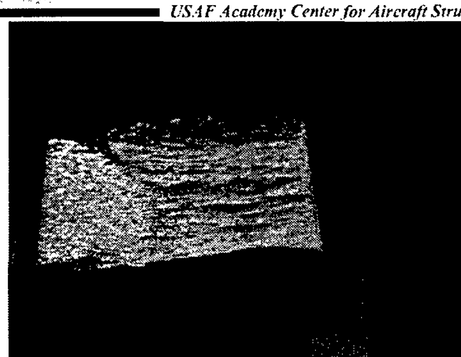
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



5

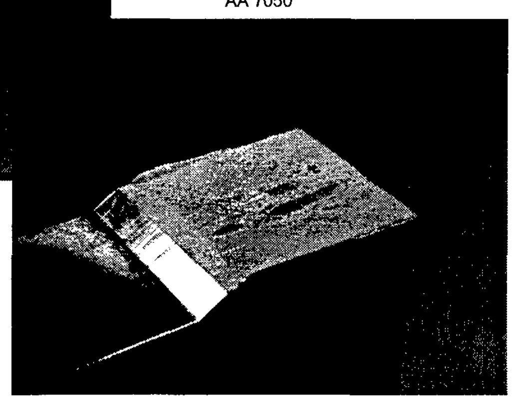
Delamination

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



aluminum lithium alloy

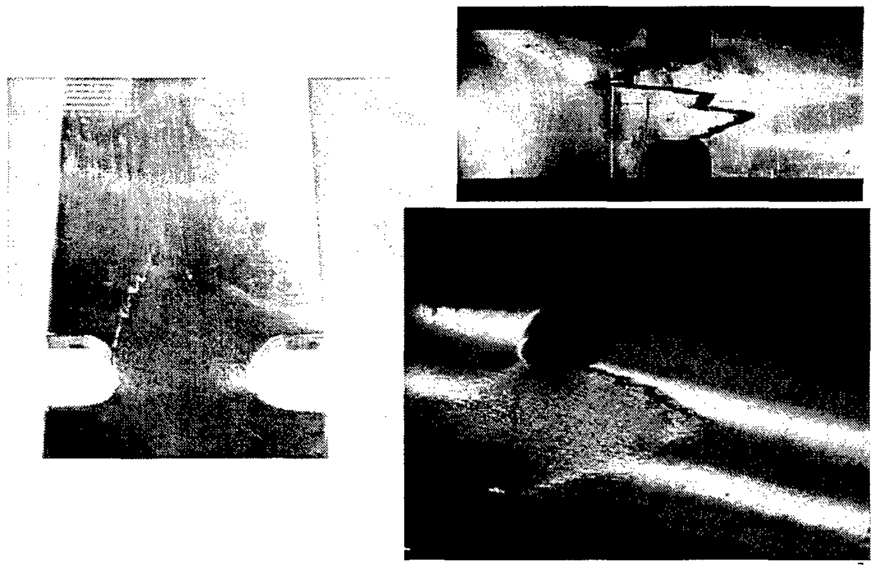
AA 7050



6

Delamination

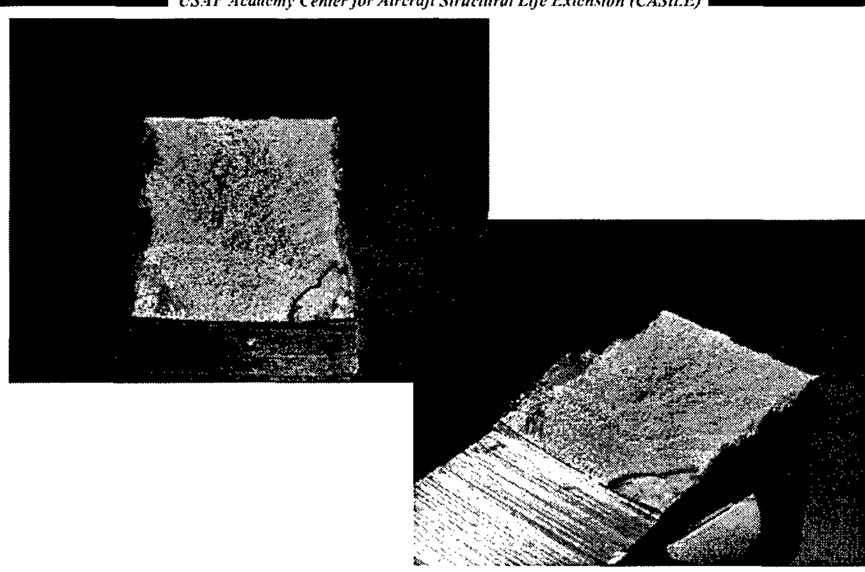
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



7

Fatigue to Fast Fracture

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



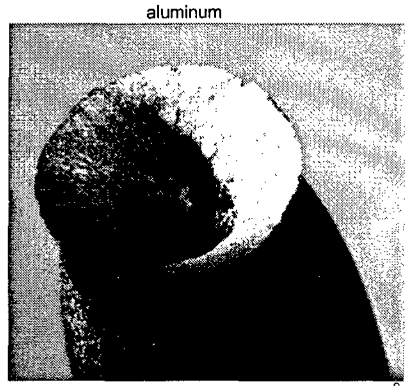
8

Ductile-Tension Failure

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

steel

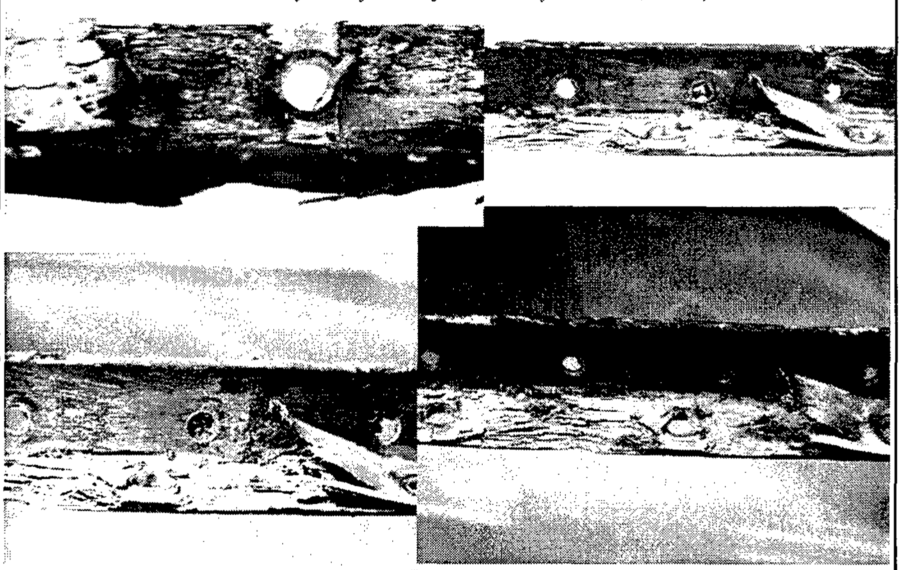
aluminum



9

Mild Corrosion

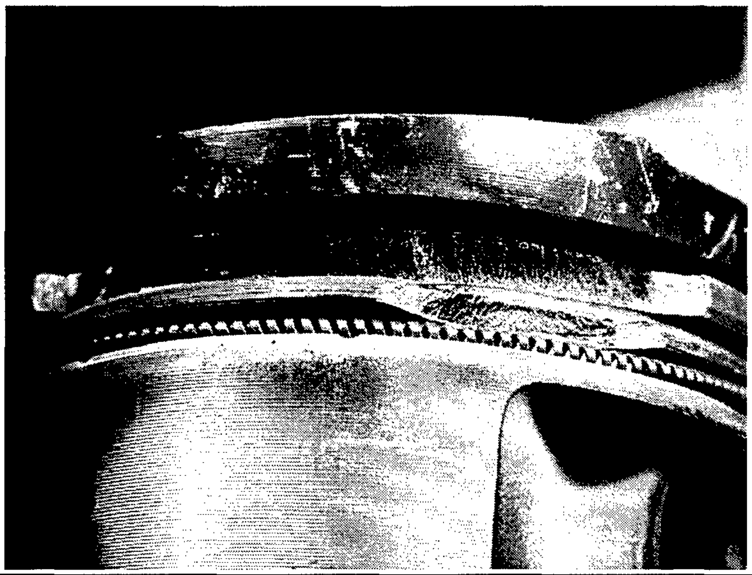
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



10

Something for the Gear Heads

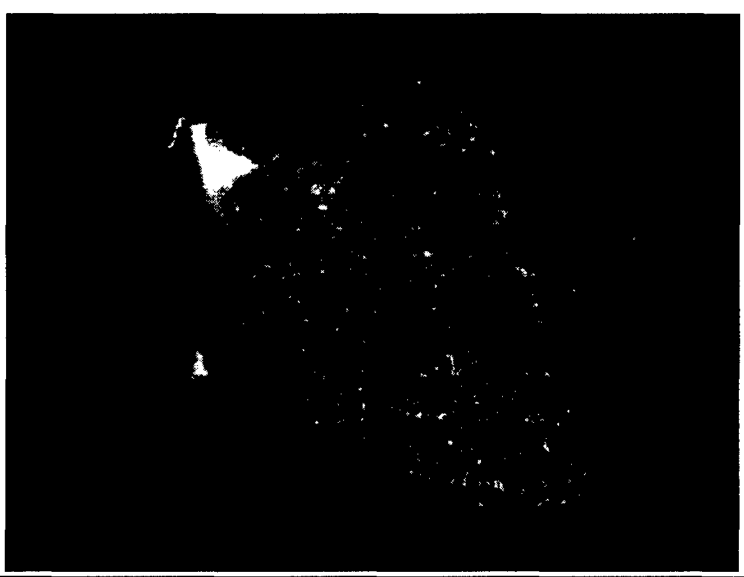
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



11

The End (mill)

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



12

Case Study 3

Scenario:

You are assigned to a large strategic cargo aircraft. A crack with an outer surface length of more than ½ inch was discovered at a fuselage fastener hole during a scheduled inspection. For various reasons, the panel was removed and replaced. You have been assigned to report on the root cause of failure so that the problem might be better understood. Figure 1 is a close-up photograph of the failed area in the panel.

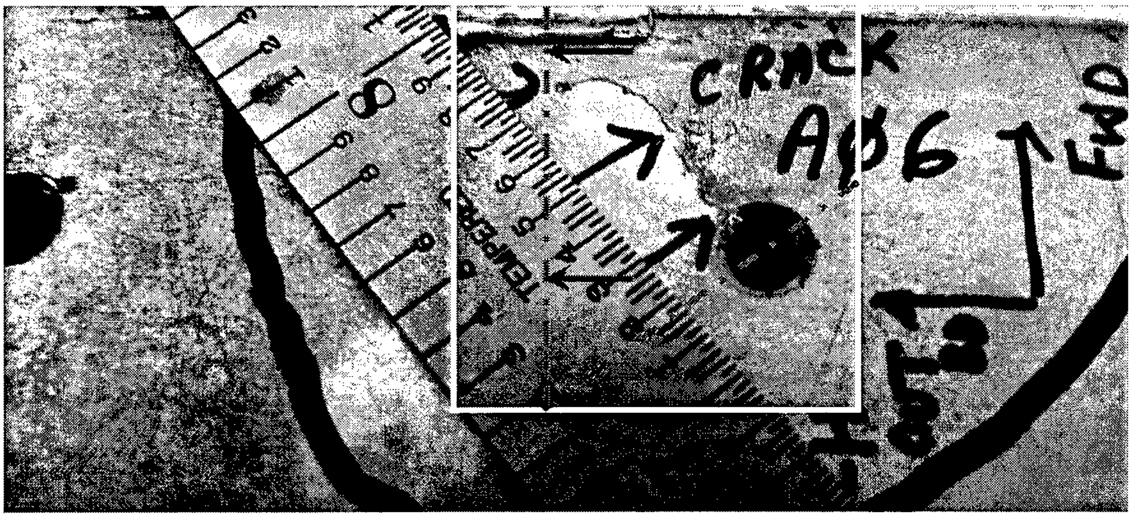


Figure 1: Macroscopic photograph of crack in panel.

Method and Data:

Working with the failure analysis lab's metallurgist you first excise the finding from the panel per the white lines in Figure 1. After examination you notice that the crack is through the part and, judging by the top and bottom surface, seems to take a path through the thickness which is not perpendicular to either surface (as shown in Figure 2) You determine to open the crack via an applied shear load (also as shown in Figure 2).

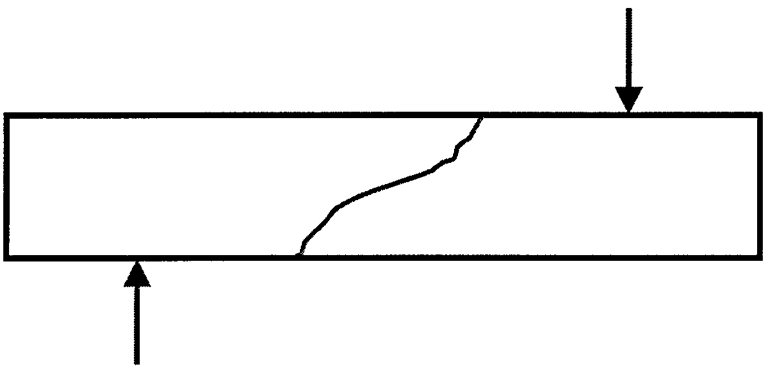


Figure 2: Schematic of through thickness crack and direction of shear load applied to open the crack.

Figure 3 is a macroscopic photo of both halves after opening showing one of the fracture surfaces.

Figure 3: Macroscopic photo of both halves after opening.

Figure 4 is a microscopic image of both fracture surfaces which show a fibrous woody structure with a rough surface and dull luster.

Figure 4: High magnification image of a) right half of fracture surface as shown in Figure 3 and b) the opposite of the same fracture surface.

The metallurgist notes from the examination that a clear initiation site is evident in an area of pitting corrosion at the intersection of the countersink and the bore of the hole. This initiation site is noted in the high magnification scanning electron microscope (SEM) image of Figure 5.

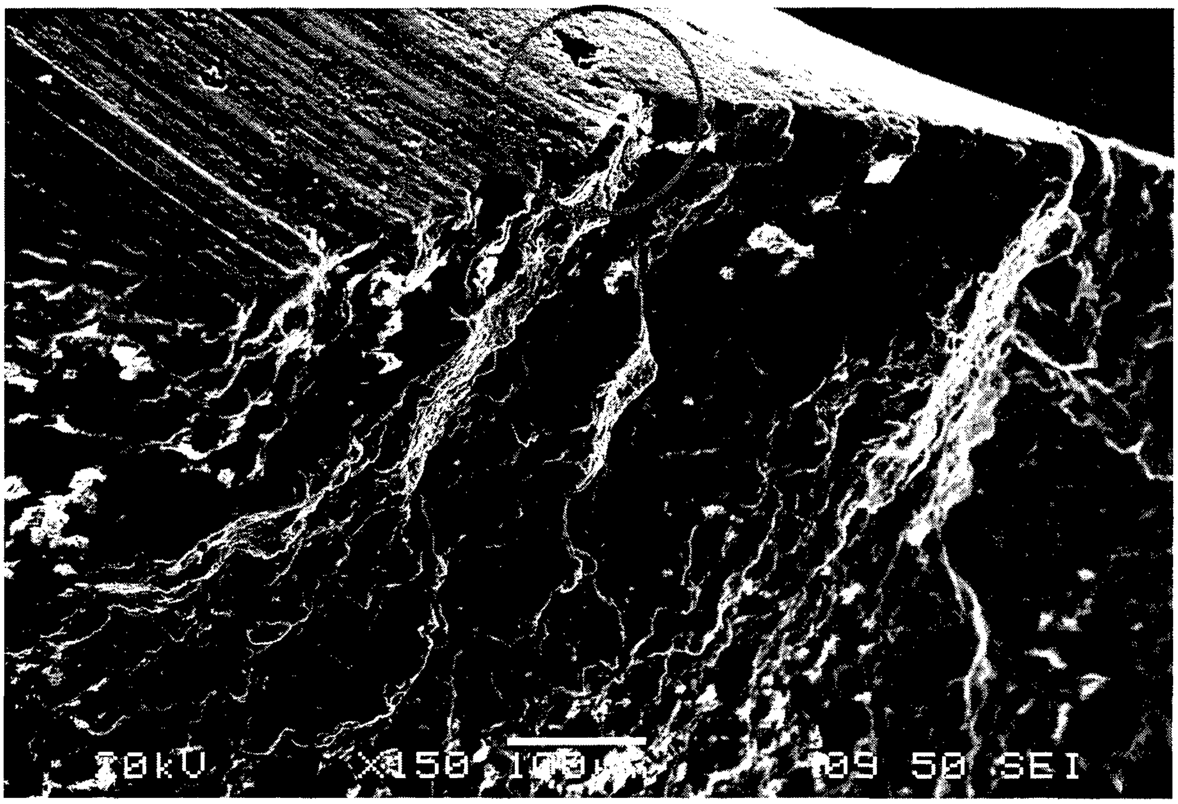
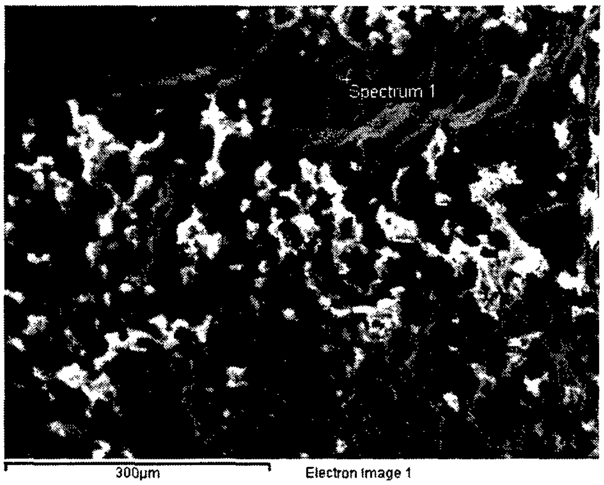


Figure 5: SEM image with the initiation site noted by the red circle.

Since you noted a rough surface and a dull luster in portions of the fracture surface you ask that an elemental analysis be performed of these areas. Figure 6 is a typical elemental analysis performed in these areas which shows electron image, elemental analysis and energy spectrum.



Element	Weight %	Atomic %
C K	25.46	35.61
O K	45.69	47.98
Al K	21.39	13.32
Si K	0.35	0.21
P K	1.33	0.72
S K	2.06	1.08
K K	0.33	0.14
Cr K	0.97	0.31
Zn K	2.42	0.62
Totals	100.00	

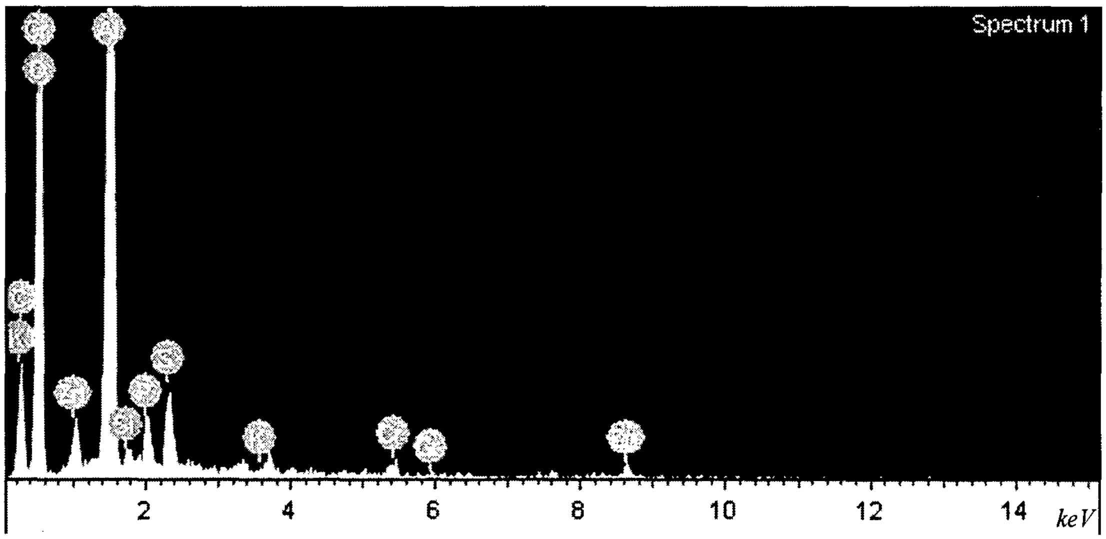
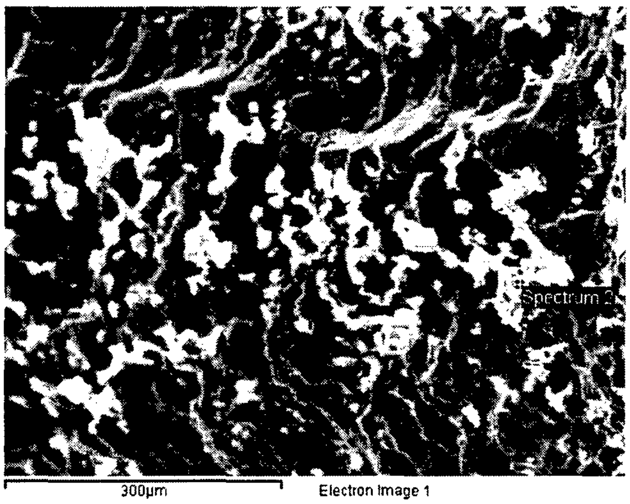


Figure 6: Elemental analysis from location 1 of the fracture surface with electron image, elemental composition and energy spectrum.



Element	Weight%	Atomic%
C K	22.21	29.76
O K	57.81	58.28
Na K	1.68	1.12
Al K	15.93	9.49
P K	0.15	0.35
S K	1.79	0.86
K K	0.43	0.14
Totals	100	

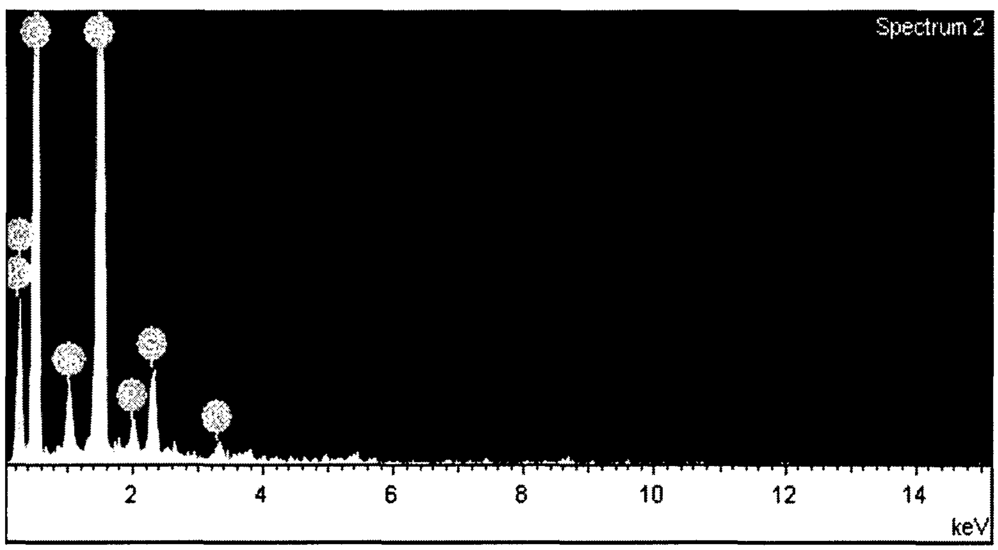


Figure 7: Elemental analysis from location 2 of the fracture surface with electron image, elemental composition and energy spectrum.

Finally, you have the region just ahead of the visible surface crack front (as noted by the blue arrows in Figure 1) polished and etched for detailed SEM observation. Figure 8 shows the resulting SEM images of this polished surface as a composite of the entire surface through the thickness and a higher magnification close-up of an area of in-plane cracks near the mid-thickness.

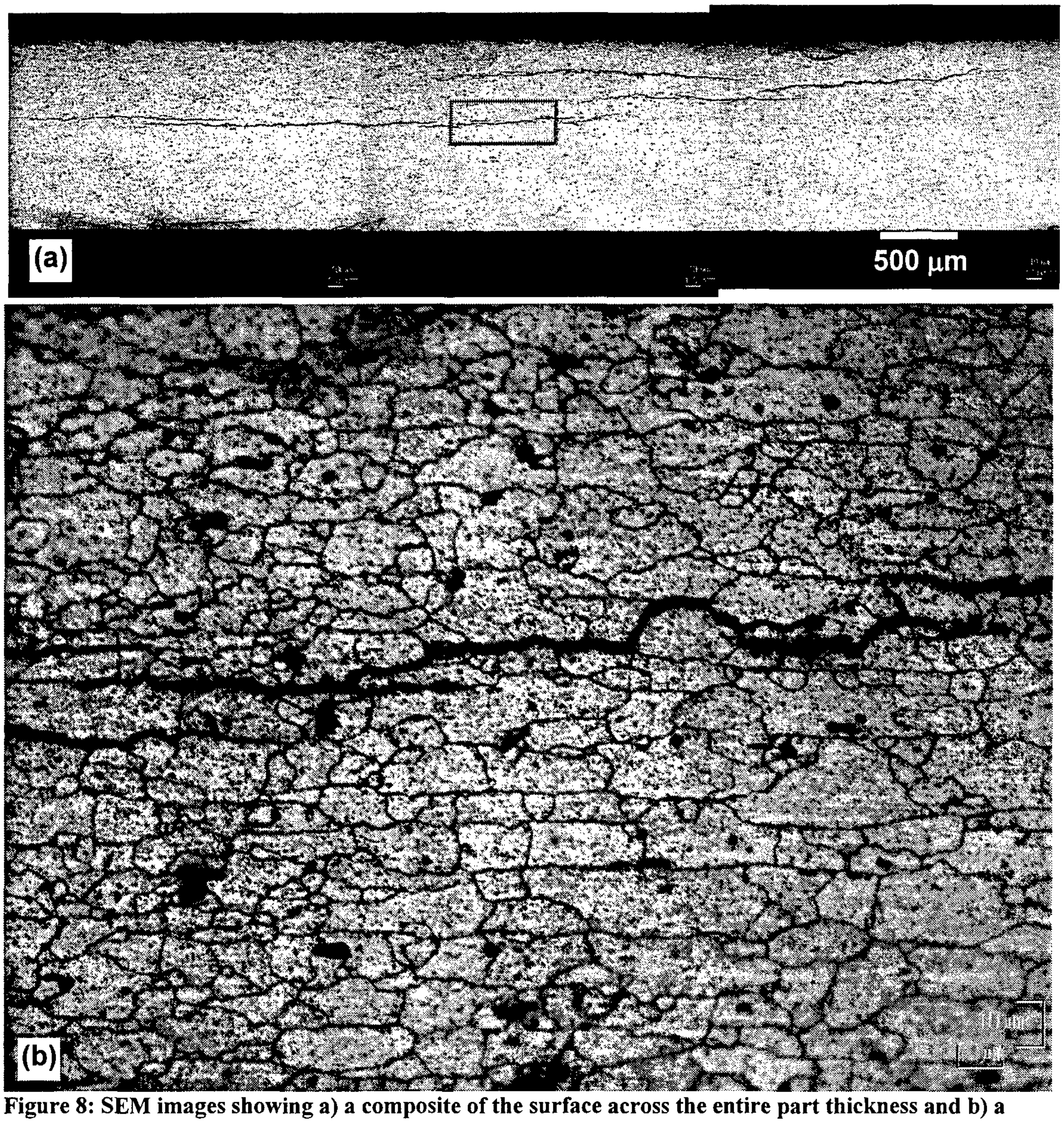


Figure 8: SEM images showing a) a composite of the surface across the entire part thickness and b) a close-up of the area shown by the red box in Figure 8a.

Notes:

This Page Intentionally Left Blank

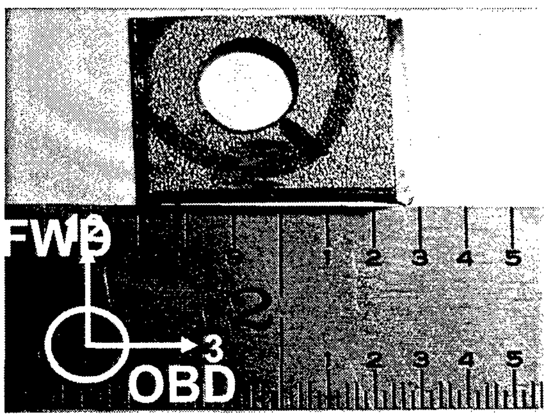
Case Study 4

Scenario:

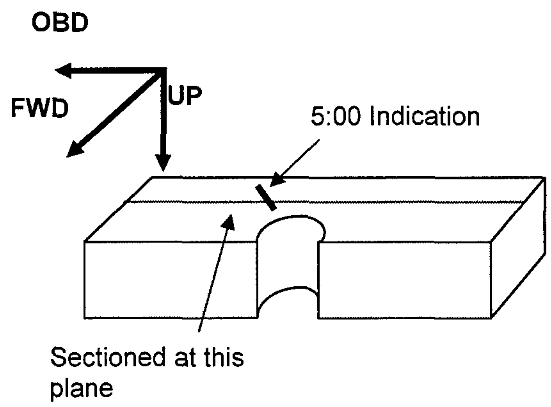
You have received a skin panel which was replaced on a tactical cargo aircraft. This panel had been inspected by bolt hole eddy current (BHEC) and several indications were found. All BHEC indication showed good signal to noise ratios with dominant peeks at the orientations noted. You have been tasked to determine the source of these NDI indications. To accomplish this task you have the following metallographic evaluation data. Comment on any additional details which you deem relevant in each finding and suggest any further testing you feel would be necessary to support your conclusions.

Method and Data:

<u>**35% BHEC Indication at the 5:00 Orientation**</u>

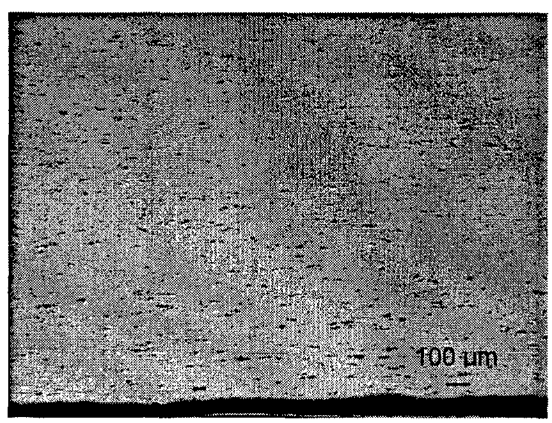


Specimen as removed from skin panel



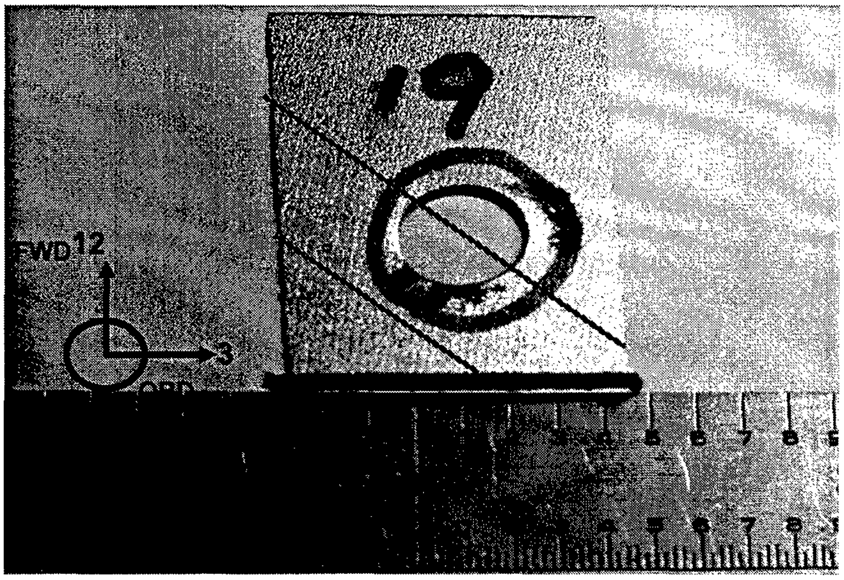
Schematic of hole sectioning

Stereo micrograph of hole bore near indication

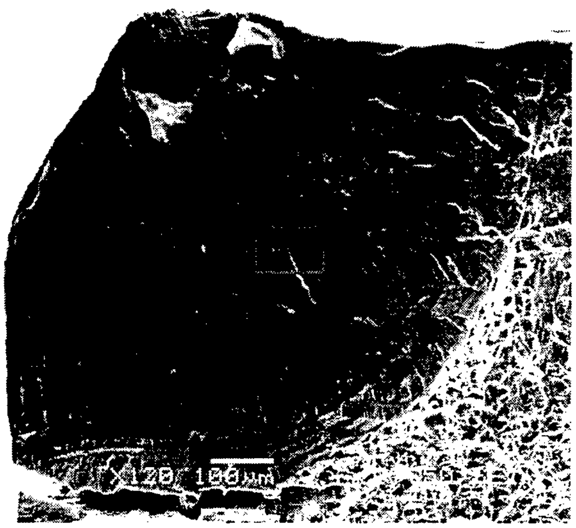


Typical micrograph of polished surface from 5:00 indication. Surfaced polished to within ~250 microns of the hole bore with similar results.

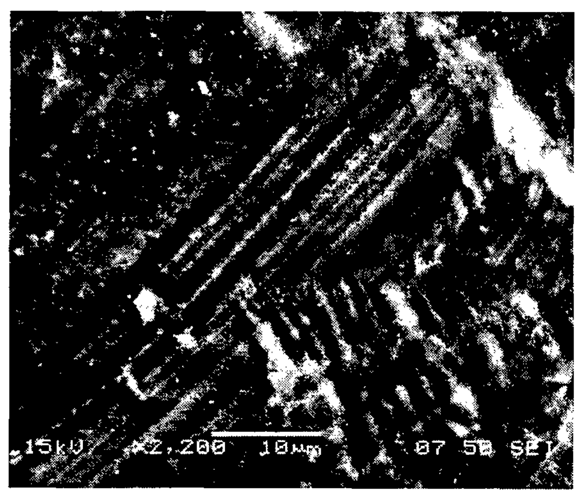
100% BHEC Indications at the 7:00 and 8:00 Orientations



Specimen as removed from skin panel. The blue lines indicate section cuts made for opening at the indication location.

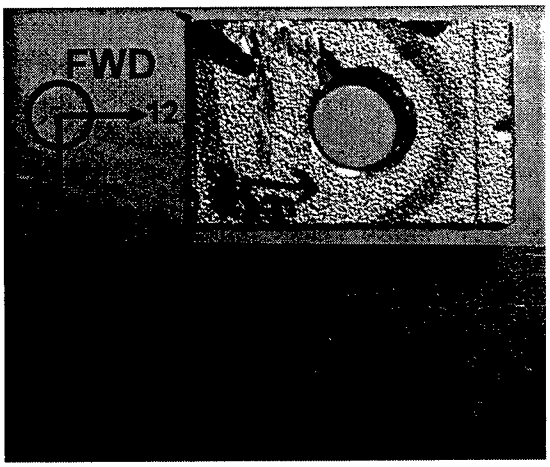


SEM of opened fracture surface

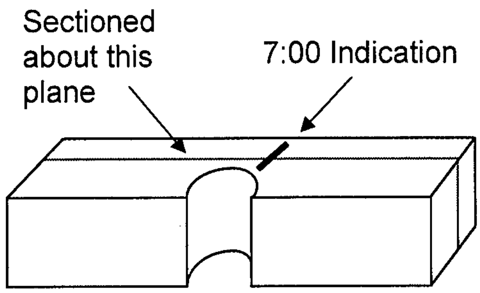


Close up of area shown by red box

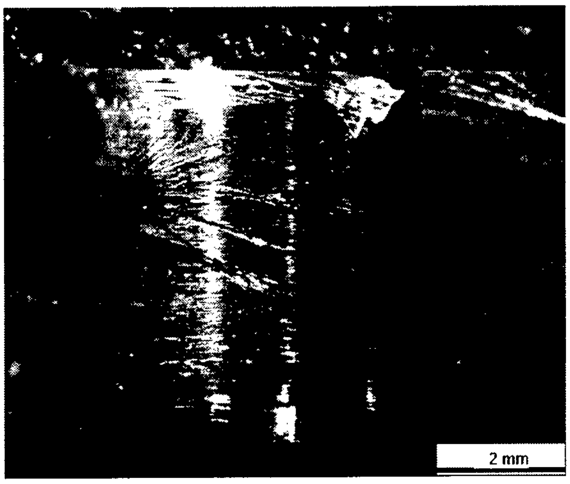
80% BHEC Indication at the 7:00 Orientation



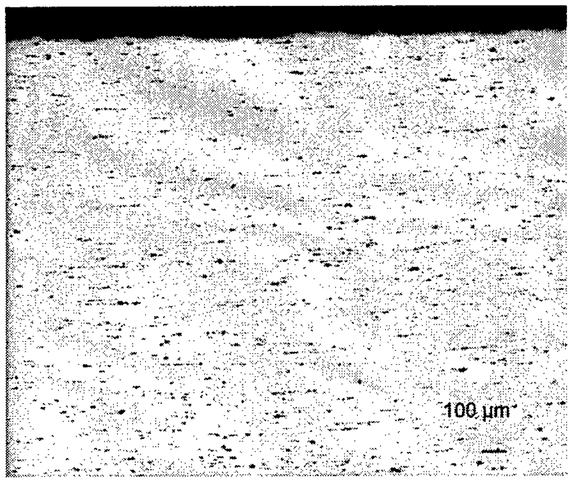
Specimen as removed from skin panel



Schematic of hole sectioning



Stereo micrograph of hole bore



Typical optical micrograph of polished surface from 7:00 indication. Surfaced polished to within ~250 microns of the hole bore with similar results.

This Page Intentionally Left Blank

Notes:

This Page Intentionally Left Blank

Case Study 5

Scenario:

A crown skin panel has been removed from a large strategic air lifter after finding numerous crack indications. As shown in Figure 1, the subject skin panel is between the fuselage stations 1844 and 1884 and stringers 72 and 96

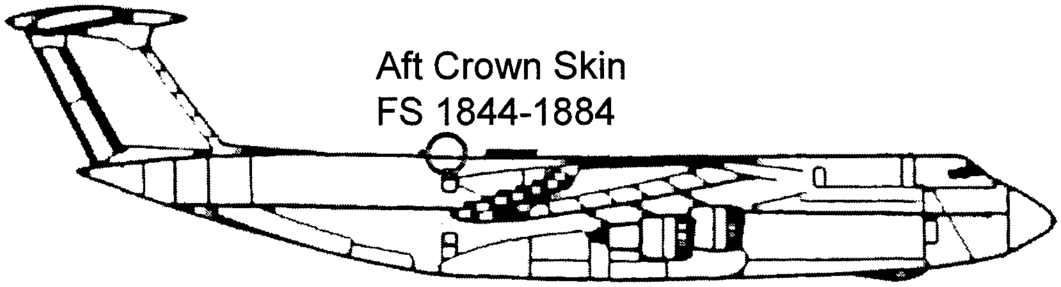


Figure 1: Subject crown skin panel location.

The crack indications (findings) are primarily on the forward and aft edges of skin panels. The numbers overlaid on this panel in Figure 2 show the rough locations of the findings in the subject panel. Determine the failure mode of finding 29.

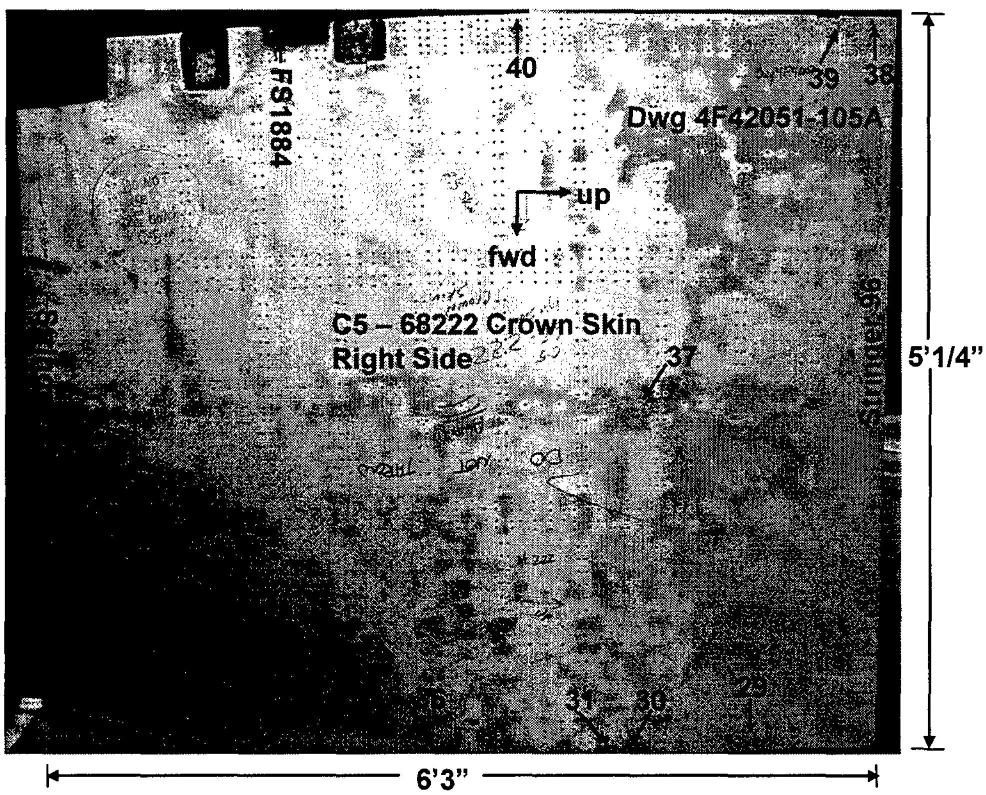


Figure 2: Location of crack indication in crown skin panel.

Method and Data:

After making some judgment as to the likely loading environment you move on to detailed metallurgical and fractographic evaluation of the finding. Figure 3 shows a close up view of the finding and the section made for studying the crack cross section. The resulting polished cross-section is shown in Figure 4. The images shown in Figure 5 are SEM close-ups of various locations in Figure 4.

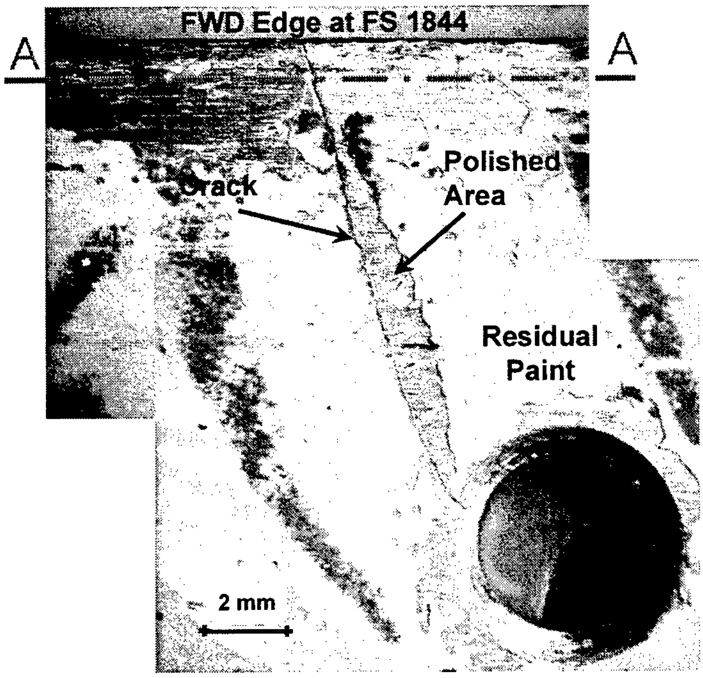


Figure 3: Finding 29 with red line indicating section made to study the crack cross-section.

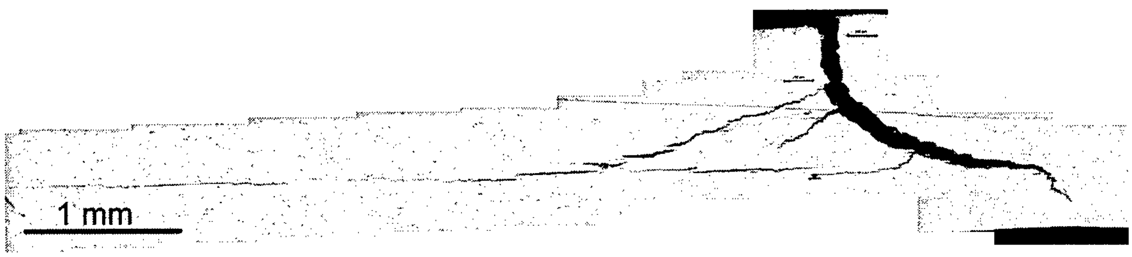


Figure 4: Composite SEM images of polished cross section A-A from Figure 3.

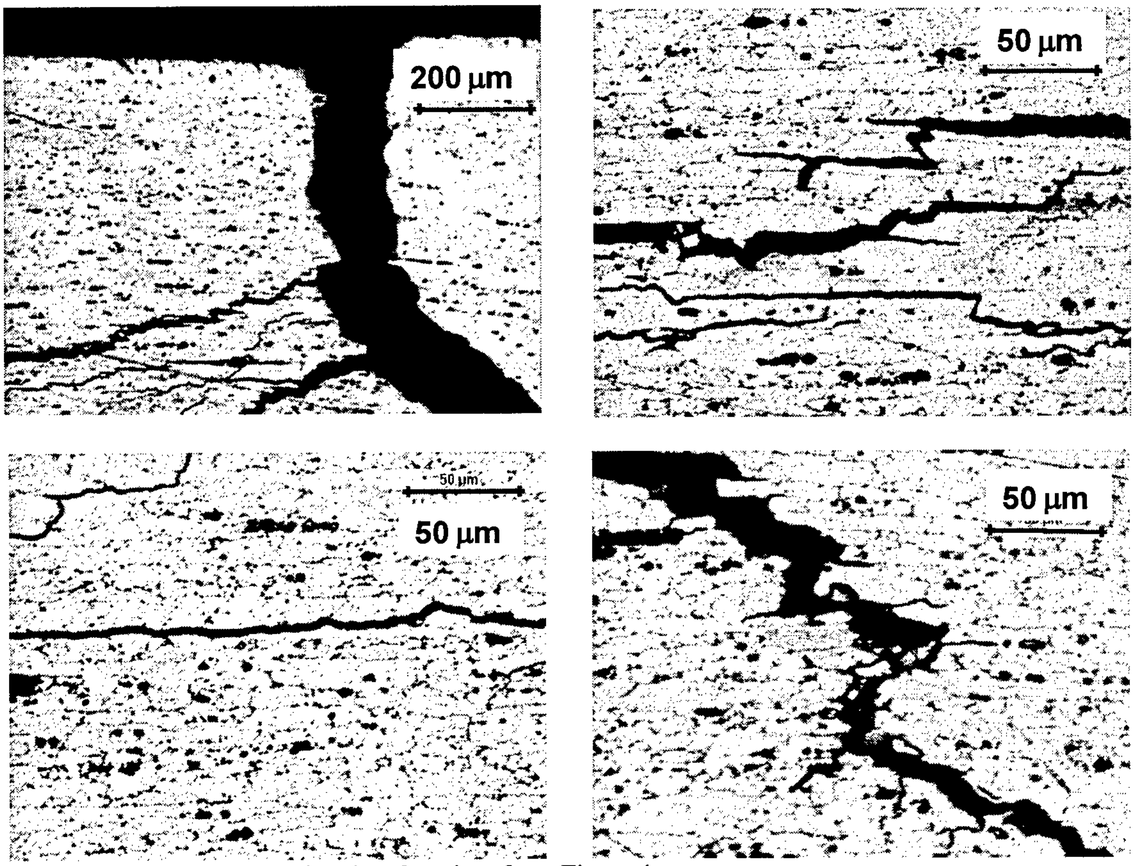


Figure 5: Close up images of various locations from Figure 4.

An investigation of the fracture surface by the metallurgists revealed the initiation site to be a pit on the forward edge (Figure 6). Also noted during the metallurgist's examination of the fracture surface was extensive corrosion damage. Accordingly you have an elemental analysis (EDAX) performed of this region. A typical EDAX result is given in Figure 7.

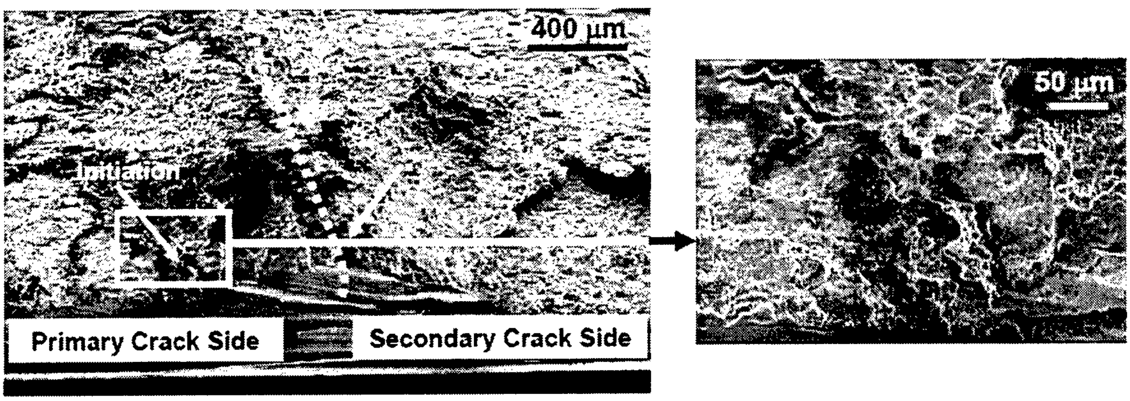
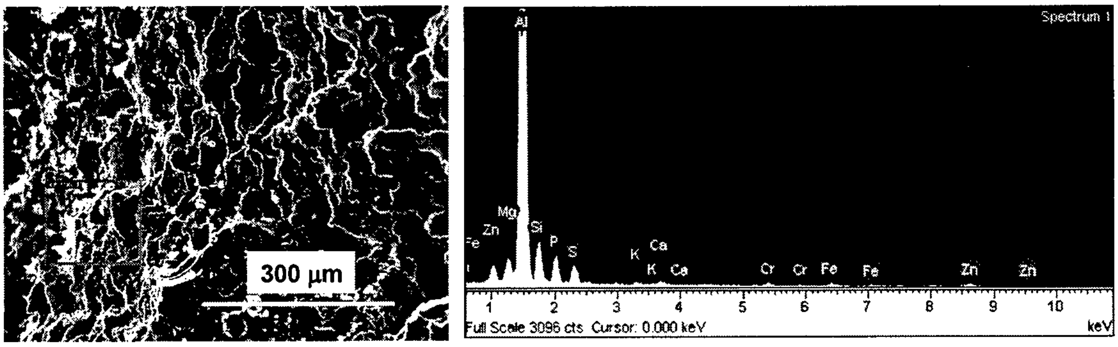


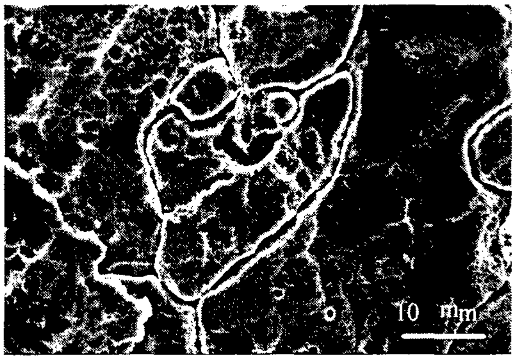
Figure 6: SEM image of the initiation site at a pit on the forward edge of the panel.



Element	Weight (%)	Atomic (%)
O	49.5	63.4
Al	39.3	29.8
Mg	1.1	0.9
Si	3.1	2.2
P	2.5	1.6
S	1.5	0.9
K	0.2	0.1
Ca	0.3	0.1
Cr	0.5	0.2
Fe	0.6	0.3
Zn	1.5	0.5
Total	100	100

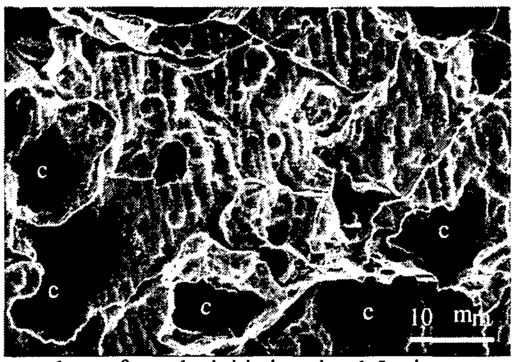
Figure 7: Typical elemental EDAX analysis of the fracture surface with electron image, energy spectrum and elemental composition.

Finally you conduct a detail examination of the fracture surface. Figure 8 shows samples of images taken from these surfaces. Images are given from both the primary and secondary crack surfaces.



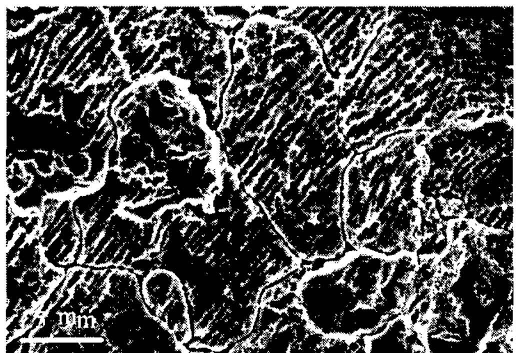
0.4 mm from the initiation site

1.5 mm from the initiation site



1 mm from the initiation site, 1.5 micron striation spacing

Primary Crack Surface



3.5 mm from the initiation site, 0.5 micron striation spacing

Secondary Crack Surface

Figure 8: Images taken from the fracture surface. Note that the primary crack at 1mm from the initiation site is also characterized by quasi cleavage planes denoted by "c" indicating brittle failure.

This Page Intentionally Left Blank

Notes:

This Page Intentionally Left Blank

APPENDIX D: Graphical Material used to Present Guest Lectures

This Page Intentionally Left Blank

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Lesson 13
Guest: USAF Corrosion Prevention and Control Office (AFCPCO)

Major Robert Reed

Chief, AFCPCO

1

Major Robert Reed

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Experience:
  - Chief, Air Force Corrosion Prevention and Control Office
  - Engineering Exchange Officer, Aerospace Composites (Paris)
  - 463rd Airlift Group XP Chief
  - 463rd Airlift Group Assistant XO
  - F22 Engine Operations and Production Engineer
  - C17 Pollution Prevention Program Manager
  - Environmental Engineer
- Education:
  - M.S. Engineering Management, Southern Methodist University
  - B.S. Engineering Mechanics, USAFA
  - A.A. French Language, DLI
  - Air Command and Staff College
  - Squadron Officer School

2

Overview

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Mission
- Organization
- Program Efforts
  - Technical Orders
  - Cost of Corrosion
  - Command Surveys
  - Information Management, Dissemination, Feedback
  - USAF Corrosion Managers' Conference
  - Corrosion Prevention Advisory Boards
- What to Remember...

3

Air Force Corrosion Prevention and Control Office

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Mission

Ensure the Air Force has an effective program to prevent, detect, and control corrosion and minimize the impact of corrosion on Air Force combat capability.

Directed by HQ USAF: Manage AF Corrosion Maintenance Program

(AFI 21-105, Air and Space Equipment Structural Maintenance, Apr 03)

- Engineering and Technical Assistance
- Engineering Responsibility for 5 Technical Orders
- Corrosion Surveys of Major Commands and Weapon Systems
- Weapon System Corrosion Prevention Advisory Boards
- Host Annual USAF Corrosion Conference
- Support Corrosion Training
- Facility Requirements for Corrosion Maintenance
- Cost of Corrosion Studies
- Transition Corrosion Technologies to Users

Customers:

- Field Units
- Major Commands
- System Managers
- Air Logistics Centers
- AF Research Laboratory

4

AFCPCO Personnel

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Government
  - Major Robert Reed — Office Chief
  - Dick Kinzie — Senior Materials Engineer
  - Dave Ellicks — Materials Engineer
  - Kim Andrews — Materials Engineer
  - CMSgt Ronald Allison — AF Corrosion Program Manager
  - SMSgt T. "Hutch" Hutchins — AF Corrosion Program Manager
  - Issie Kennedy — Management Assistant
- Engineering and Technical Support Contractors (S&K Technologies)
  - Owen Jett (CMSgt Ret) — Senior Project Manager
  - Wes Barfield — Senior Materials Engineer
  - Mac McKenna (CMSgt Ret) — Senior Maintenance Analyst
  - Mark Foley (SMSgt Ret) — Senior Maintenance Analyst
  - Kevin Wilson (MSgt Ret) — Senior Maintenance Analyst
  - Ruth Jett — Senior Corrosion Technician
  - Jeff Hatfield — Senior IT Systems Engineer
  - Beverly Dillard — Administrative Assistant
- Liaison contractors
  - Jerry Powell (SMSgt Ret) — Air National Guard Liaison
  - Larry Cornwell (Cmdr Ret, USCG) — US Coast Guard Liaison

5

Technical Orders

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- We manage five AF general series corrosion-related technical orders
  - Pervasive -- apply to all systems
  - Referenced by all other corrosion T.O.s
- Primary means to transition technology to AF-wide use
- Continual effort to update as needed
  - Ensure maintainers use best materials and processes-- increase combat capability, reduce maintenance time & cost, protect people & assets, comply with environmental restrictions
- Available publicly at

6

Technical Orders

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- T.O. 1-1-8, Application and Removal of Organic Coatings, Aerospace and Non-Aerospace Equipment
- T.O. 1-1-686, Desert Storage Preservation and Process Manual For Aircraft
- T.O. 1-1-689, Avionics Cleaning and Corrosion Prevention/Control
- T.O. 1-1-691, Aircraft Weapon Systems Cleaning and Corrosion Control
  - All updates available at
- T.O. 2-1-11, General Corrosion Control of Engine Parts During Overhaul & Field Level Maintenance
- T.O.s for vehicles & support equipment
  - WR-ALC/552 SEVSG is engineering authority; AFCPCO provides technical support

7

Cost of Corrosion Study

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- AFCPCO conducted Air Force-wide collection/analysis of corrosion cost
  - Aircraft, vehicles, equipment, munitions, space systems
  - Not real property (AF OPR is Civil Engineering)
- Cost of documented, direct corrosion control maintenance
  - Repair, treatment, washing, painting, depainting, sealing (conservative--only costs that could be captured)
  - Not intangibles (availability, readiness, training, safety)

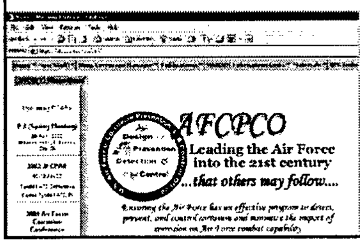
Total Costs, Then Yr Dollars				AF O&M Budget, Then Yr Dollars			
1990	1997	2001	2004	1990	1997	2001	2004
$720	**$795**	**$1,139**	**$1,497**	**$25,160**	**$22,728**	**$29,328**	**$38,406**
Total Costs, Adjusted to 2004 $'s				AF O&M Budget, adjusted to 2004 $'s			
1990	1997	2001	2004	1990	1997	2001	2004
$926	**$857**	**$1,175**	**$1,497**	**$32,342**	**$24,512**	**$30,246**	**$38,406**
Corrosion Cost Growth as a Constant Compounding Rate				Corrosion Proportion of AF O&M Budget			
				1990	1997	2001	2004
5.23%				**2.86%**	**3.50%**	**3.88%**	**3.90%**
Fleet Size Study Year							
8,722	**5,991**	**6,075**	**6,066**				

8

Information Management, Dissemination, Feedback

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Biggest hurdle is communication
  - Many corrosion needs have some known answers
  - Many unauthorized or damaging processes being used
- Customer feedback and needs identification via:
  - Surveys, CPABs, conferences, direct contact (phone/e-mail)
  - Quarterly corrosion telecon with MAJCOM managers
  - Corrosion newsletter to SPOs
- Best dissemination tool is Web site:
- Publicly releasable info on



- Survey & project reports
- Cost of Corrosion Studies
- Qualified Product Lists
- Technical Orders
- Message traffic
- Material selection Info
- Event schedules
- Specifications
- Points of contact
- Links to partner organizations
- Meeting minutes
- Training & technical info

9

Command Corrosion Surveys

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- Surveyed AMC & AFSPC in 2005
- Assess <u>overall health of programs</u> -- NOT inspection
- Provided on-site assistance
- Briefed base and MAJCOM maintenance leadership, published final reports
- Planning for ANG, PACAF, AFMC (Operational Units)

10

Air Force Corrosion Managers' Conference

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Purpose: crossflow & resolve issues across <u>entire Air Force</u> corrosion prevention and control community**
- **Around 500 participants: all MAJCOMs, ALCs, SPOs, over 120 field units, all sister services, HQ USAF, AFRL, industry**

11

Corrosion Prevention Advisory Boards

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

- **Each aerospace system required to establish CPAB, hold annual meetings**
- **Purpose: bring system designer, program office, MAJCOM corrosion managers, field corrosion representatives together to discuss and resolve corrosion issues unique to their weapon system.**
- **SPO chairs CPAB and directs corrosion program for its system (SPO is engineering authority)**
- **AFCPCO is technical support, advising on most effective methods, materials, and processes for that specific system.**
  - **We participate in approximately 15 CPABs/year**

12

What to remember…

USAF Academy Center for Aircraft Structural Life Extension (CAStLE)

Visit our web site!

(We also post PA-reviewed info on
www.dodcorrosionexchange.org)

Call us!

DSN 468-3284

478-926-3284

afcorr@robins.af.mil

13

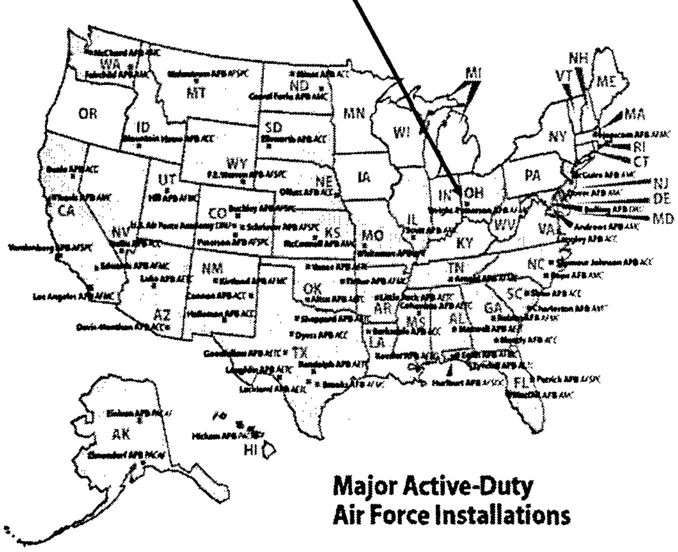
This Page Intentionally Left Blank

AFGROW

James A. Harter
Robert Reuter

Air Vehicles Directorate
Structures Division
Wright-Patterson Air Force Base
Dayton, OH

WPAFB

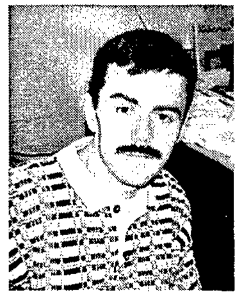


Major Active-Duty Air Force Installations

2

The People Currently Behind AFGROW:

- Jim Harter Lead Engineer
- Alex Litvinov Lead Programmer
- Robert Reuter Support



3

Day #1

- Introduction
- Layout and Flow of AFGROW
- Spectrum
- Beta / K Solutions
- Stress Intensity / Fatigue Crack Growth

4

Day #2:

- Geometry / Beta
  - Beta
  - Beta Correction
  - Geometry Solutions
  - Loading Conditions
- Stress State
- Failure Criteria
- Retardation
- Residual Stresses

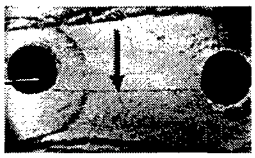
5

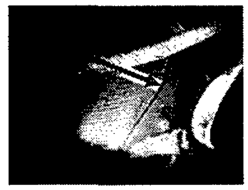
Day #3

- COM
- Plug-Ins
- Composite Patch Repair
- Initiation
- Environmental Data
- Closing
  - Q&A session

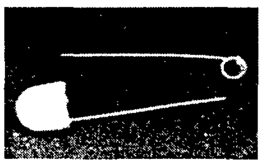
6

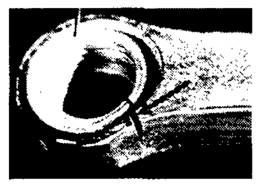
Examples of Problems in Fatigue





Fatigue is problem for many types of structures



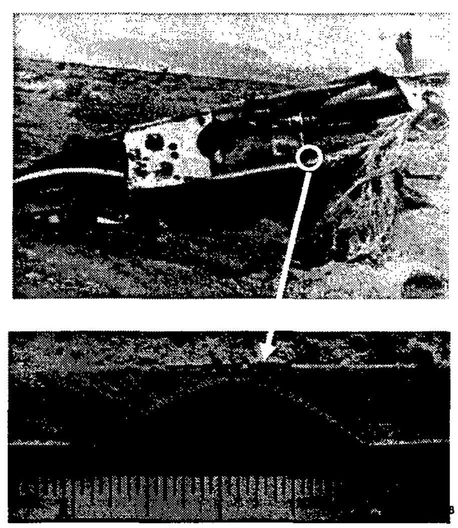


7

F-111 Fatigue Failure

1969 Accident

- Forging defect in wing attachment
- Caused fatigue failure after 100 flight hours
- Promoted advances in damage tolerant design

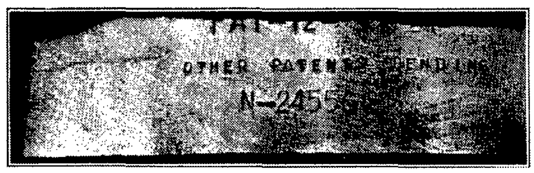


8

Fatigue Failure of Aircraft Propeller

- Failed after 115 flight hours
- Ran "rough" next to last flight
- Failed 1 minute into last flight
- Design/material sound
- Fatigue origin at "patent pending" stamp

Fracture Surface



Fatigue origin

Ref: *Prevention of the Failure of Metals Under Repeated Stress,* Bureau of Aeronautics, Navy Department, 1941

9

What is AFGROW?

- AFGROW is a fatigue crack growth life prediction code created in Visual C++ which uses Linear-Elastic Fracture Mechanics (LEFM) on metallic models

10

Sales Pitch

- AFGROW is the most comprehensive life prediction code available on the market
- AFGROW has a user-friendly Windows interface
- AFGROW has become the industry standard in life predictions
- AFGROW is free

11

When should I use AFGROW?

- You have discovered an unwanted crack in a structure and wish to determine its remaining life
- You are designing a new component and desire to know the expected life
- You are changing the configuration of a structure and wish to determine the effect

12

Who uses AFGROW?

- Prime Contractors
- Government Entities
- Academia

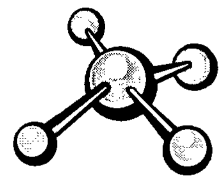
13

AFGROW's Dark Side

14

AFGROW's Inadequacies

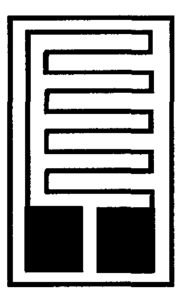
- The user must choose a representative model



15

AFGROW's Inadequacies

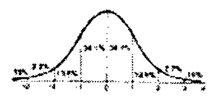
- The user must estimate the loading conditions present on the structure



16

AFGROW's Inadequacies

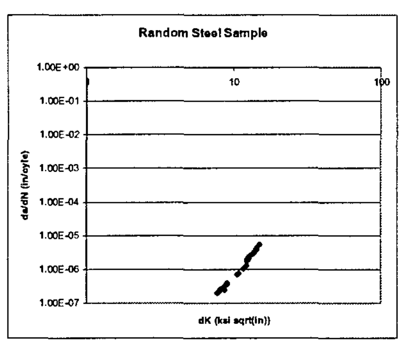
- **FCG data is seldom validated for statistical significance**



17

AFGROW's Inadequacies

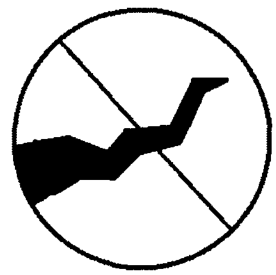
- **Fatigue Crack Data is seldom available in complete sets. (Partially solved by the Harter-T Method)**



18

AFGROW's Inadequacies

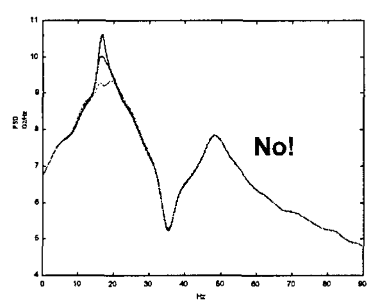
- There is a disjuncture in initiation and fatigue crack growth theories



19

AFGROW's Inadequacies

- Dynamic effects are basically ignored – rate at which the loads are applied



20

AFGROW's Inadequacies

- AFGROW's scope...

Geometries

Cube Maple Leaf Cone
Foil Rhombus Sphere
Taurus

Environments

Low-Temperature Bacteria
Acidic Vacuum Basic Water
Wild Animals High-Temperature

Loading Conditions

Bearing Compression
Bending Tension
Frequency Effects
Fretting Mixed-Loading

Materials

Cobalt Polystyrene
Chocolate Steel
Titanium Boride
Transparent Aluminum

21

AFGROW's Inadequacies

- Version Discrepancies
  - After modifications have been made to solutions or bug fixes, values sometimes change
    - Solutions are complex

22

AFGROW's Inadequacies

- Predictions are usually only accurate to a factor of two.

X2

23

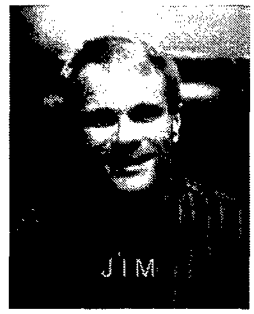
...however

- For estimating fatigue life in metallic components, there is no better solution

24

AFGROW's History

- Ed Davidson (Early 1980's)
- ASDGROW
- MODGROW
- AFGROW (1998)



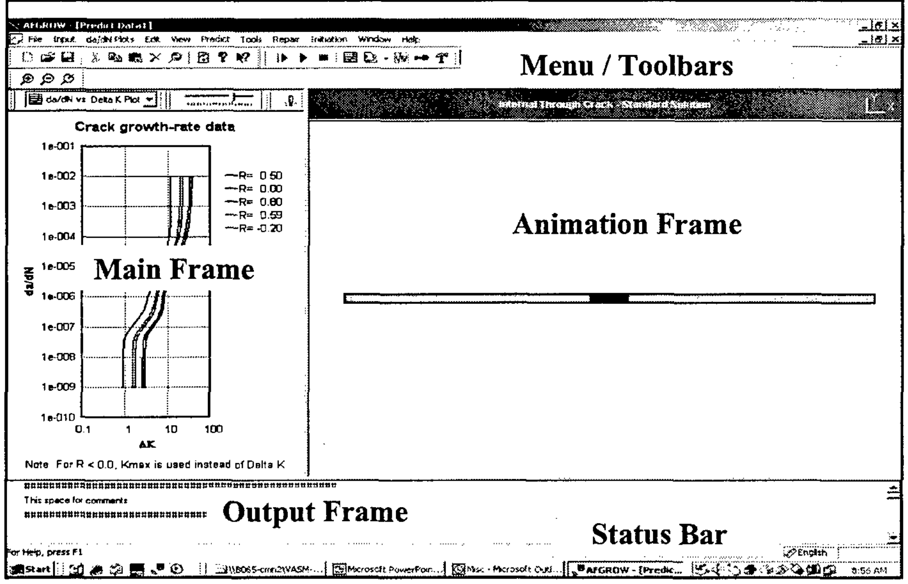
25

Layout and Flow of AFGROW

James A. Harter
Robert Reuter

Air Vehicles Directorate
Structures Division
Wright-Patterson Air Force Base
Dayton, OH

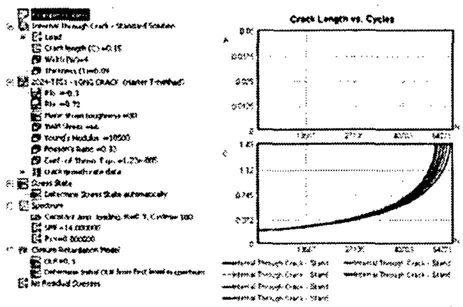
Layout of AFGROW

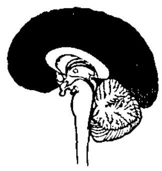


Layout: Main Frame

Views Include:

- Status
- Crack Plot (a vs. N)
- da/dN vs. DK Plot
- Repair Plot
- Initiation Plot





3

Fatigue Crack Growth Plot da/dN vs. ΔK

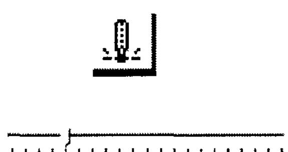
- Displays your fatigue crack growth plot
- Numerous options to modify your graph
  - Slider Bar
  - Freezing a curve
  - Overlaying fatigue crack growth data
  - Quickly switching material Data
  - Erasing your data
  - Copying and pasting your data

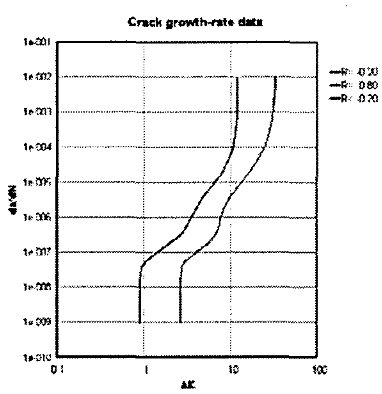
4

Slider Bar

5

Freezing a Curve





6

da/dN vs. ΔK Viewer

- **Default Filename:** **[filename].cgr**
- **File Format**

  [Title]

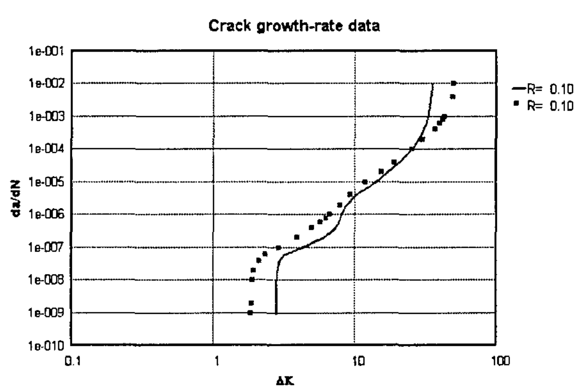
  [R]

  [Delta K][da/dN]

Sample: test.cgr

7

da/dN vs. ΔK Viewer: Overlaying Data

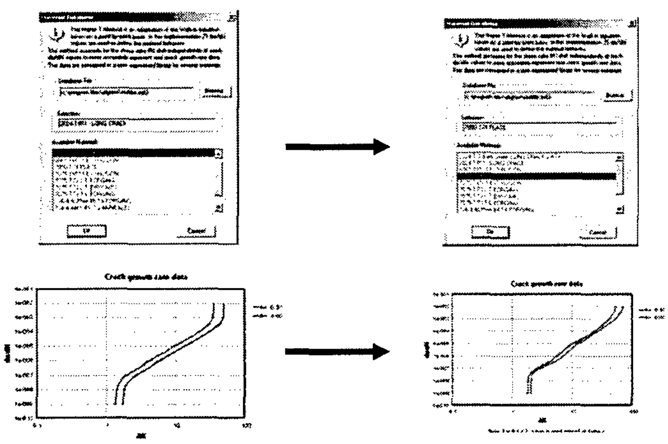


Note: For R < 0.0, Kmax is used instead of Delta K

8

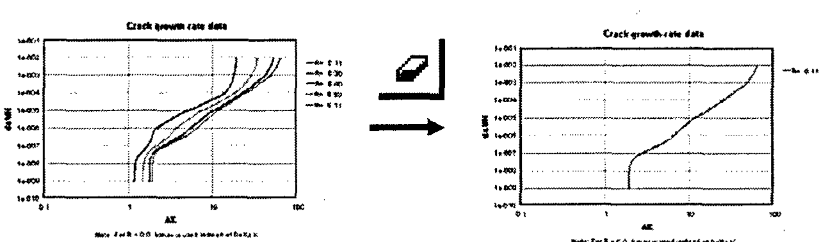
Material Data

- **Hot Key to change material data more quickly**



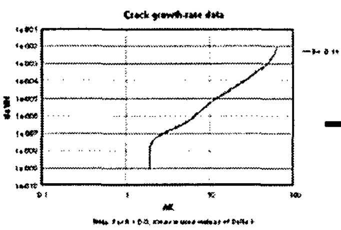
9

da/dN vs. ΔK Plot: Erasing



10

da/dN vs. ΔK Plot: Copying and Pasting Data

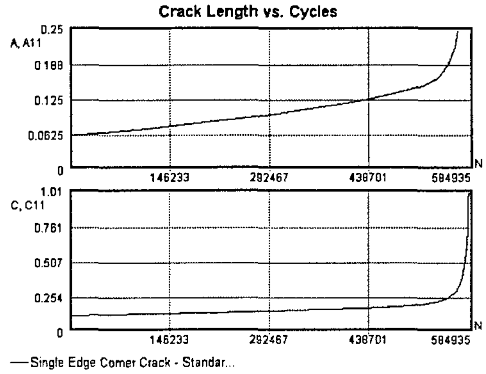


1.92455	1e-009	11.3488	1e-005
1.94379	4e-009	14.6227	2e-005
1.96533	1e-008	18.3567	4e-005
1.98923	2e-008	22.0037	7e-005
2.08583	4e-008	24.9028	0.0001
2.32837	7e-008	30.3198	0.0002
2.69751	1e-007	37.169	0.0004
3.65331	2e-007	43.9668	0.0007
4.93058	4e-007	48.1505	0.001
5.84576	7e-007	59.4908	0.004
6.42914	1e-006	63.7691	0.01
7.6959	2e-006		
9.0851	4e-006		
10.2571	7e-006		

11

Crack Growth Plot (a vs N)

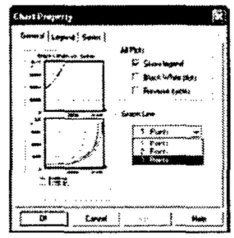
- VIP
- Plots:
  - a vs. N
  - c vs. N

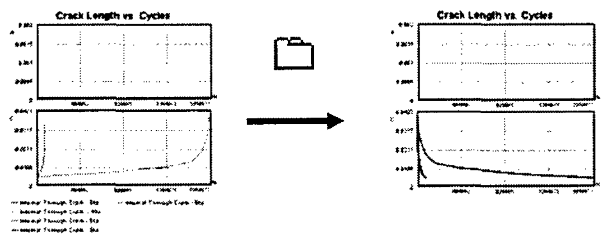


12

Crack Growth Plot: Plot Properties

- General
  - Show Legend
  - Black and White Plots
  - Reversed Cycles
  - Line Thickness (Graph Line)

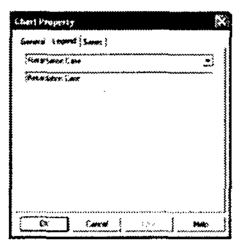


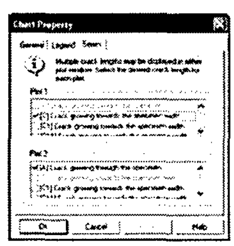


13

Crack Growth Plot: Plot Properties

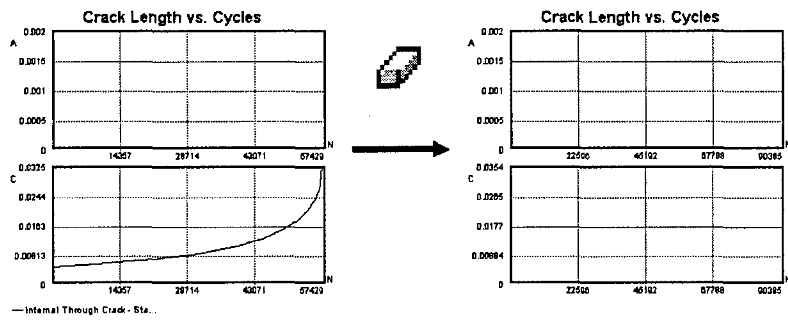
- Legend
  - Use *after* a run
- Series
  - Plot any crack in either plot
  - More important for advanced or custom models
  - One case in either plot





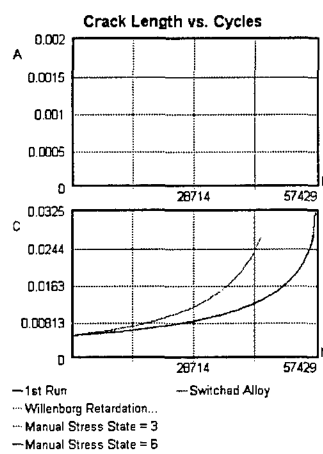
14

Crack Growth Plot: Erasing



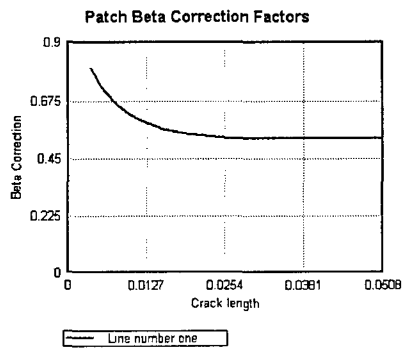
15

Crack Growth Plot: Overlay



16

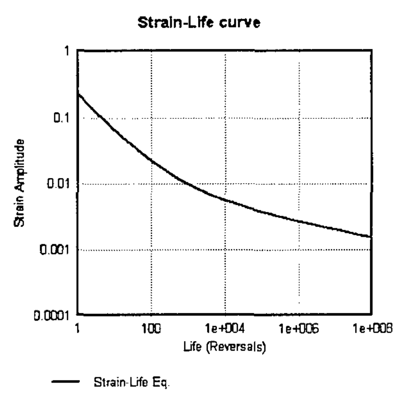
Repair Plot



17

Initiation Plot

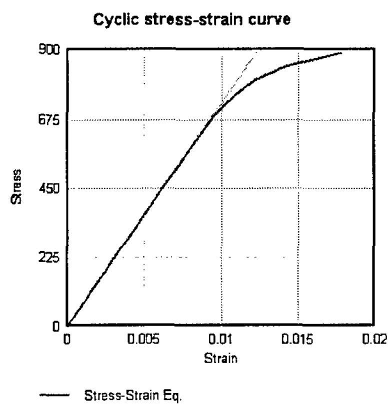
- **Strain-Life Curve**



18

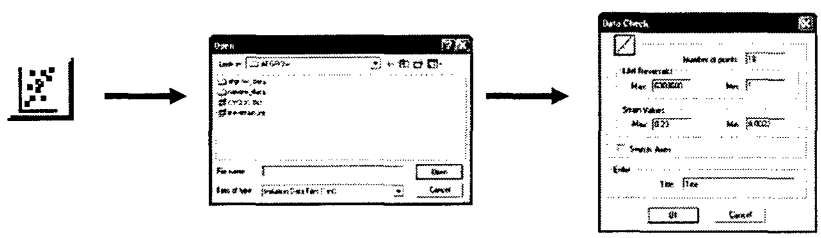
Initiation Plot

- **Stress Strain Curve**



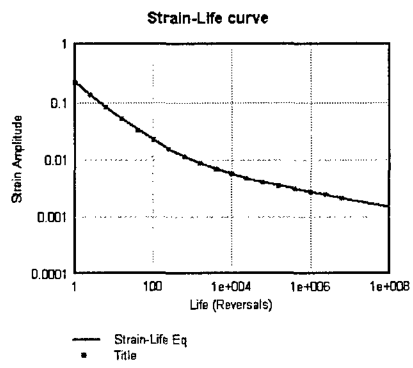
19

Initiation Plot: Read Test Data



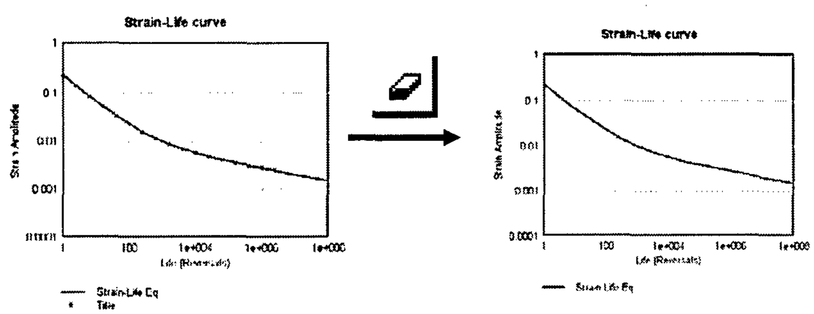
20

Initiation Plot: Data Overlay



21

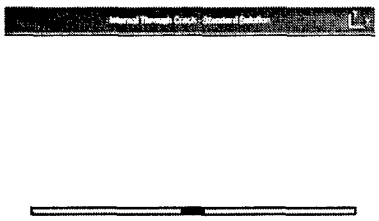
Initiation: Erase



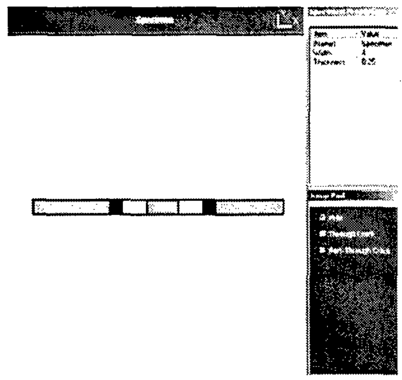
22

Layout: Animation Frame

Classic or Weight Function Geometries



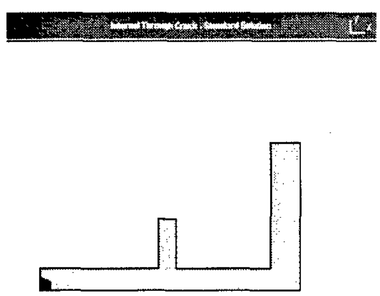
Advanced Geometries



23

Layout: Animation Frame

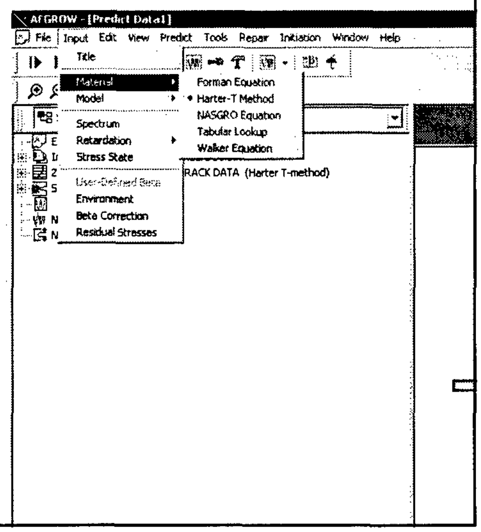
Plug-In Models



24

Layout: Menu and Toolbars

- Input Dialogs
- Preferences
  - Output Intervals
  - Calculation Increments
  - Transition Options
  - Failure Options
- Misc. Visual Tools
  - Rainflow analysis
  - Cycle Counting
  - Others…
- Help
  - Menu (F1)
  - Link to S.I. Research



Layout: Toolbars

Handout

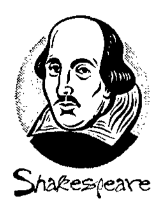
26

Flow of AFGROW

27

How do we simulate?

- We choose:
  - Loading Environment
  - Model Geometry
  - Material
  - Others…
- During the simulation:
  - Start: Initial Conditions
  - Move: Crack Growth Increment (da)
  - Finish: Failure Criteria



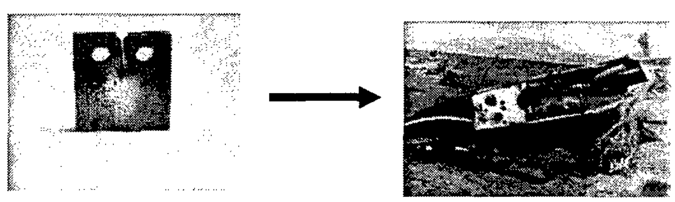
28

Our goal…

TOTAL LIFE

29

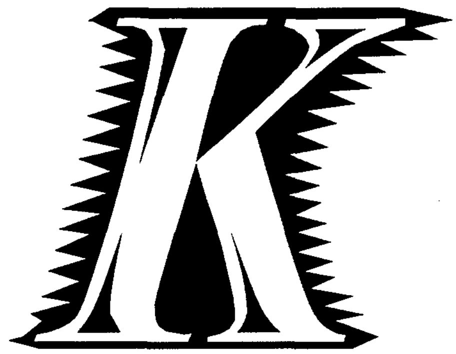
Setting the ‘Stage’



- Geometry
- Loading
- Crack Length

30

Stress Intensity Factor



31

Methods for Calculating K

- Stress-displacement method
- Weight function method
- Crack closure method
- Contour integral method

32

What's Wrong with K?

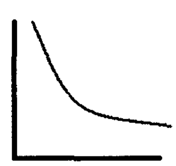
- Various Forms / Dimensions
  - 'applied'
  - 'apparent'
  - 'closure'
  - 'propagation'
- K has dimensions
  - Inconsistent between unit systems

33

Why not just stress?

- Stress at the crack tip is *infinite* for LEFM

Stress in 'Y' Direction

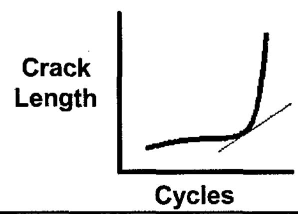


Distance to Crack Tip

34

Creating da/dN vs dK Curves

- From laboratory:
  - Measure Crack Length and Cycles (a vs. N)
  - Applied load is known
- On paper:
  - da/dN – tangent line of a vs. N
  - dK = change in stress * beta * SQRT (Pi * a)
  - Tabulate da/dN with dK



35

da/dN

36

$$da = da/dN * dN$$

We know this from K !

We can pick this!

37

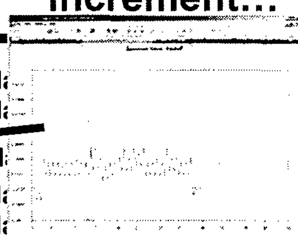
Going back to our story…

38

Summing up each growth increment...

da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+ 39

Summing up each growth increment...



da+da+da+da+da+da+d ... la+da+da+da+da+da+da+
da+da+da+da+da+da+d ... la+da+da+da+da+da+da+
da+da+*DA*+da+da+d ... la+da+da+da+da+da+da+
da+da+da+da+ a+da+d ... la+da+da+da+da+da+da+
da+da+da+da+d da+d ... la+da+da+da+da+da+da+
da+da+da+da+da+d +da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+ ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da ... la+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+
da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+da+

Summing up each cycle increment...

dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+
dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+
dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+
dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+
dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+
dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+d
N+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN
+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+dN+

Our goal...

TOTAL LIFE

42

The Big Picture:

See Handout

43

This Page Intentionally Left Blank

Engineering Inspections for Fatigue Critical Structures

More Science, **Less Art**

21 April 2006

- John Brausch
- AFRL/MLSA
- Lead NDI Engineer
- Air Force Research Laboratory

Definition

Nondestructive Testing (NDT)

or

Nondestructive Inspection (NDI)

Process of testing to detect internal and/or concealed defects in materials/structures using techniques that do not damage, alter or destroy the items being tested.

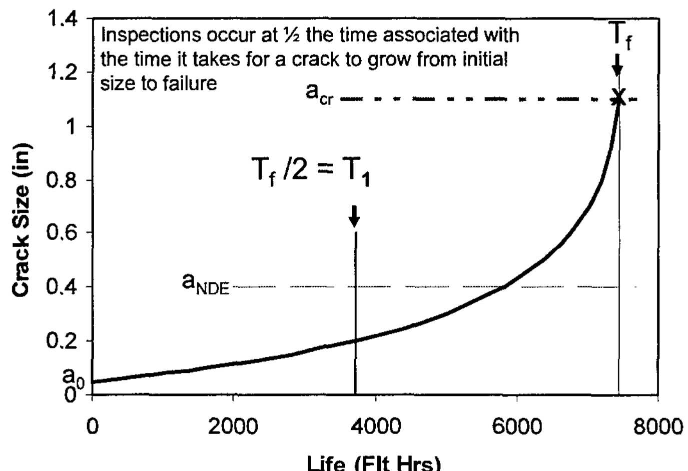
Why NDI?

- Process control
- Quality Assurance
- Reduce/Mitigate Fracture
- Reduce/Mitigate Failure
  - Manage safety of fielded assets after unexpected incident, or previously undetected variance discovered
- Life extension / life cycle management

Reduce Risk

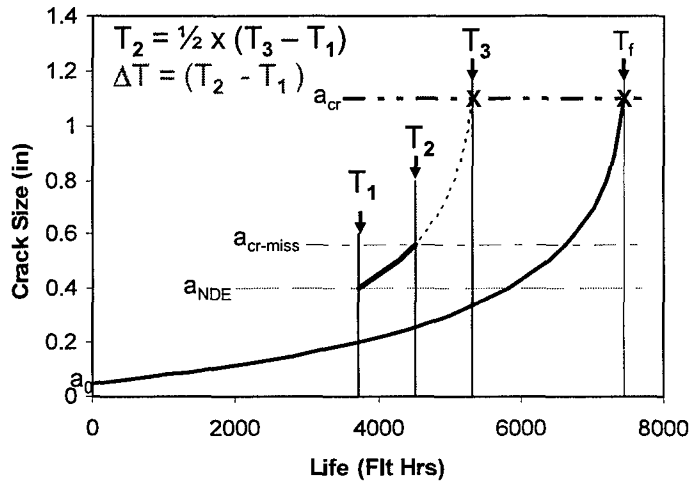
Establishing Initial Inspection for Fatigue Critical Locations

Traditional DT Inspection Philosophy

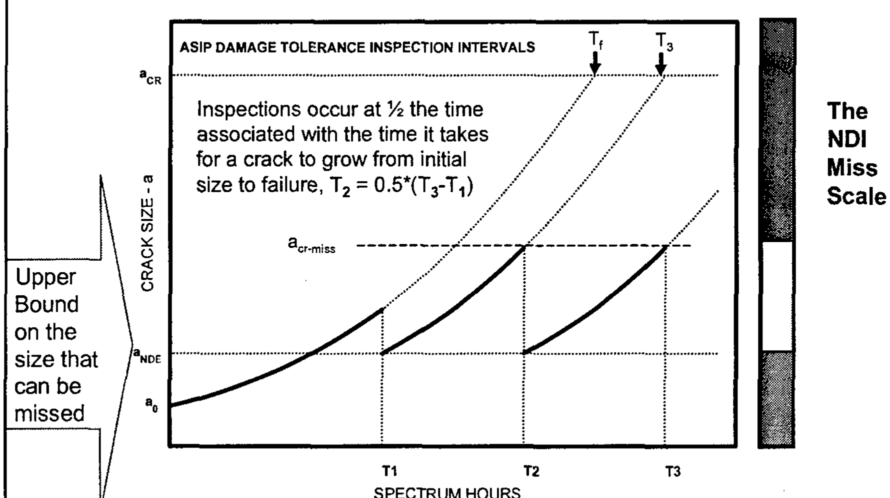


Reference: MIL-STD-1530C

Establishing the In-Service Inspection Interval



ASIP Inspection Philosophy



Damage Tolerance Design Based Inspections

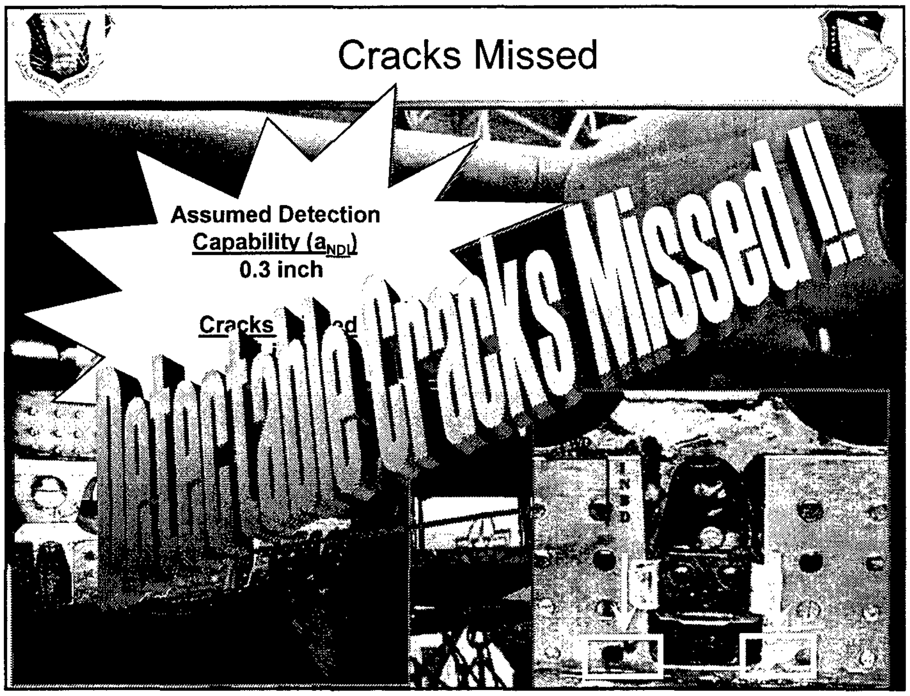
Summary
a_{NDE} and $a_{cr\text{-}miss}$

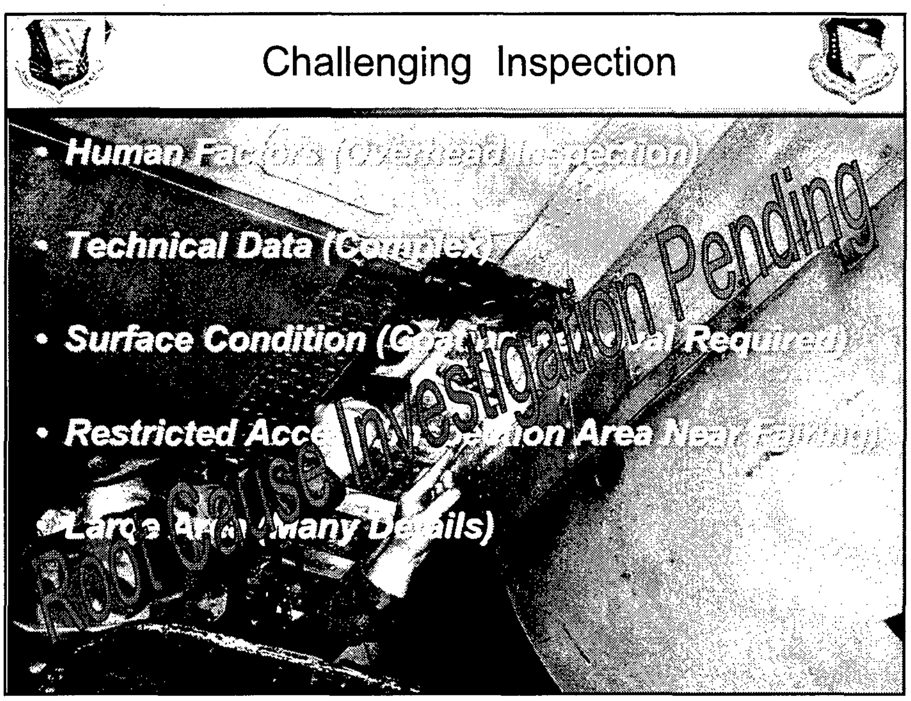
- a_{NDE} represents the starting point for in-service crack growth analysis, so the smaller this crack size value, the bigger the in-service inspection interval
- $a_{cr\text{-}miss}$ represents the crack size condition, where a missed crack will grow to failure before the next inspection
- Approach based on design, then improved when actual crack behavior/scenarios are observed
  - Bigger than expected => serious problem
  - Cracks not always where anticipated

Recent Challenges

- In March 2005, a restricted aircraft at experienced moderate turbulence, violated the restriction, and was re-inspected
  - Two cracks were found only 24.3 hours after depot inspection
  - Other re-inspected aircraft also had cracks
  - Misses at other field and depot locations
- Investigation findings: "these cracks were missed during initial inspection"
- AFMC/CV directed Tiger Team (TT) to analyze issue
  - TT collected data, published findings/recommendations

Tiger Team Conclusion: *AF has an institutional inspection problem*


Cracks Missed
Assumed Detection
Capability (a_NDI)
0.3 inch
Detectable Cracks Missed !!


Challenging Inspection
• Human Factors (Overhead Inspection)
• Technical Data (Complex)
• Surface Condition
• Restricted Access
• Large Area (Many Details)
Root Cause Investigation Pending

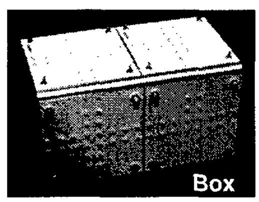
What Are The Root-Causes?

- Root-Cause Analysis not routinely accomplished unless mishap occurs
  - Fortunately only one Mishap (Class B) in past ten years related to NDI misses in safety of flight structures
- Effective Corrective Actions not implemented

Have We Been Lucky??

Probability of Detection (POD) *Findings*

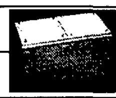
- **NDI Program Office study**
- **Focus was High Frequency Eddy Current (HFEC) surface inspections**
- **Depot and Field locations surveyed**
- **Results (from Box-Plate Study)**
  - Depot detectable flaw 0.322 inch
  - Field detectable flaw 0.551 inch
- **Required detectable size varies from 0.05 to 0.25 inches**



Detectable flaws size exceeds requirement
Protection of safety of flight structure reduced

Summary of POD Results

High Frequency Eddy Current Surface Inspections

Test Condition	Location	$a_{90/50}$ (inch)	$a_{90/95}$, a_{NDE} (inch)
Plate 	Depot	0.135	0.322
"	Field	0.271	0.561
Angles 	Depot	0.432	>0.982
"	Field	Indeterminate	Indeterminate
Lug w/ 	Depot	0.084	0.148
fixture	Field	0.125	Indeterminate
Lug w/ 	Depot	0.146	0.284
template	Field	0.165	Indeterminate
Lug 	Depot	0.161	0.268
"	Field	0.215	Indeterminate

Impact of NDI "Misses"

- Increased risk of catastrophic failure on aircraft experiencing cracking in critical locations
  - Re-inspection interval set based on historical detectable flaw size per inspection technique
  - Cracks missed far exceed expected NDI capability

INCREASED SAFETY RISK ON SOME AGING PLATFORMS

- Risk mitigation options:
  - Inspections (more frequently, multiple, oversight, etc)
  - Modify structure
  - Alter operational flight envelope
  - Improve NDI techniques and processes

Establishing Effective Inspection Solutions

What Makes For an Effective Inspection?

- Well Trained People
- Empowered People
- Motivated People
- Well Engineered Inspections
  - Clearly Defined Requirements
  - Suitable Equipment (Instruments, probes standards)
  - Human Factors Considered in Inspection Development
  - Clear Guidance and Documentation
  - Capability Meets Requirement
- Strong Organization
  - Employee Feedback
  - Strong Proactive Management
  - Effective Oversight

Defining Inspection Requirements

Structures Engineers Must
Define and **Understand** Quantifiable Requirements

- Flaw Type
- Flaw Size – **BE REALISTIC**
- Flaw Location
- Flaw Orientation
- Surface Condition
- Flaw Nearest Neighbor
  - local geometry variations
  - local material variations
- Configuration changes
  - Material/geometry between systems
  - MRB's, modifications, repairs

Structures Engineers Must

Develop clear and complete inspection requirement definitions for each control point.

- Definition of general structural location and access restrictions

- Clear identification of specific details requiring inspection

- Identification of probable crack location and direction of propagation

NDI Engineers Must

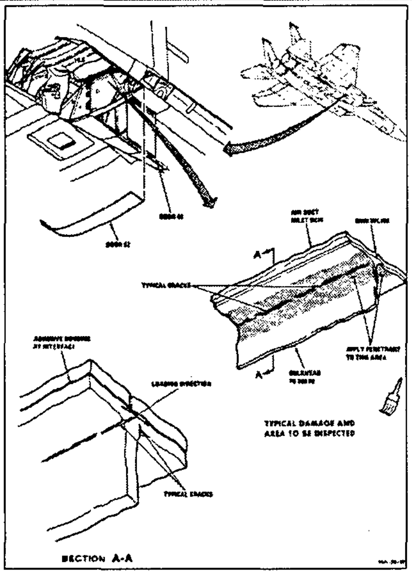
Chose inspection method most suitable for application considering

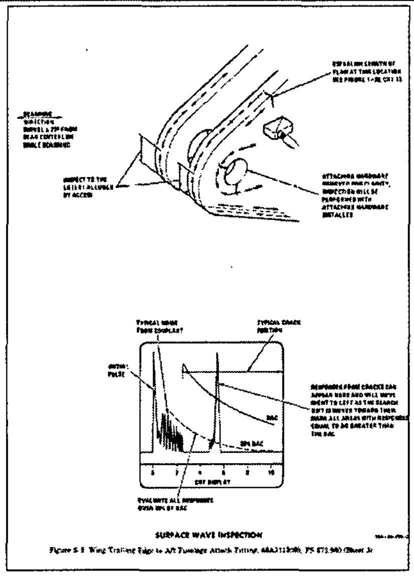
- Capability - flaw detection expectation
- Reproducibility - calibration
- Repeatability - process control
- Decision threshold levels quantified and useful
- Insensitive to non-relevant variances in material and geometry
- Logisitics - supportable, deployable
- Training - standard training, task certification
- Cost

NDI Engineers Must

- Develop procedures that are
  - Clear
  - Concise
  - Trainable
  - Effective
- Validate procedures through performance
- Verify inspection capability
- Ensure traceability of inspection methods and results

Tech Data Examples





ULTIMATE GOAL
NDI RELIABILITY

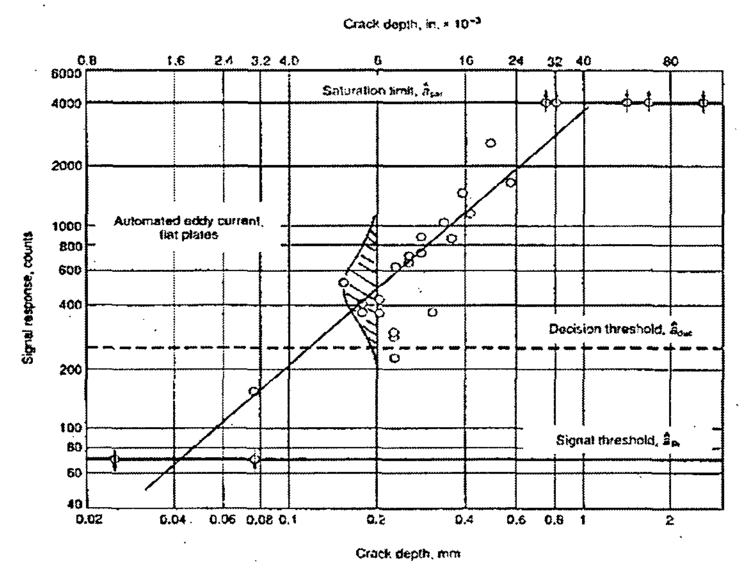
- **CAPABILITY-**
  Probability of Detection (POD)
- **REPRODUCIBILITY**
  Calibration
- **REPEATABILITY**
  Process Control

POD

- POD is a metric based on a sampling test (representative of application population)
  - Population:
    - Inspectors
    - Measurement variables

- Probabilistic based on the test sample set used

Beren's Model
Probability (*a-hat vs. a*)



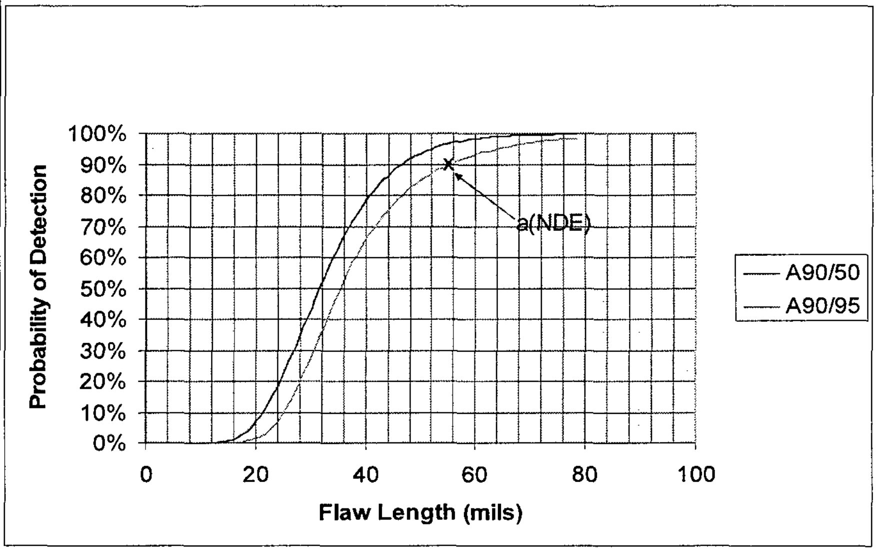
Two Approaches for POD Estimation

- Hit/Miss – Use of maximum likelihood estimator
- *a vs. a-hat* - Scalar and quantitative
  - Useful for NDE methods providing a quantitative response
  - Data may be fit to a straight line function
  - Requires less data

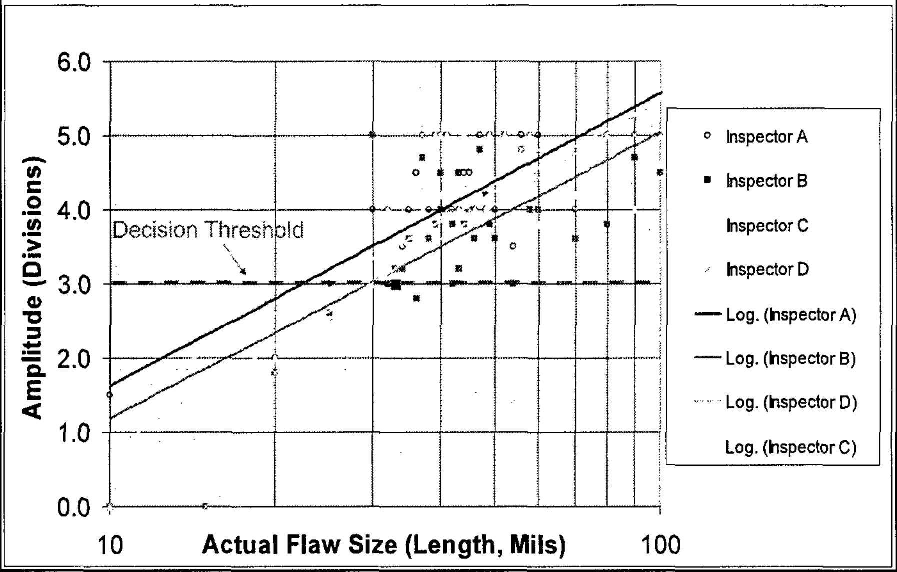
Reference: MIL-HDBK-1823

POD Calculation

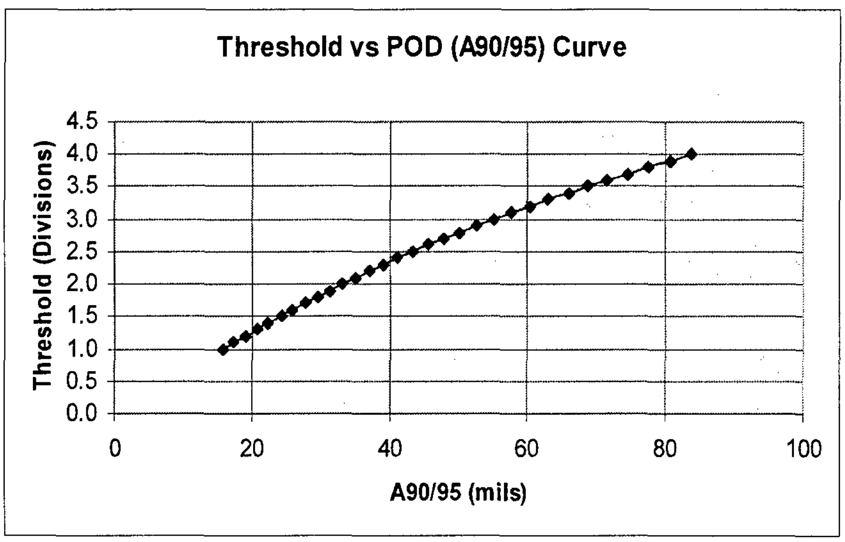
Log Odds Model Based



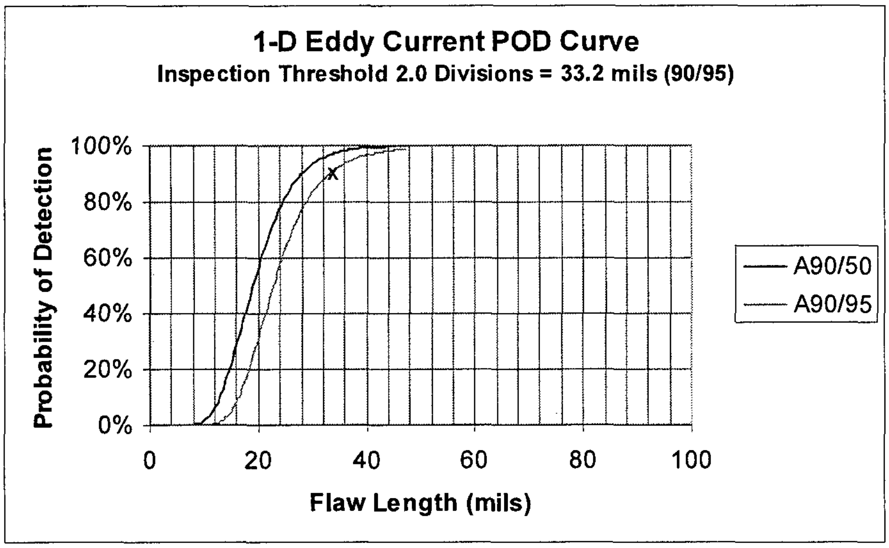
a vs. a-hat Example



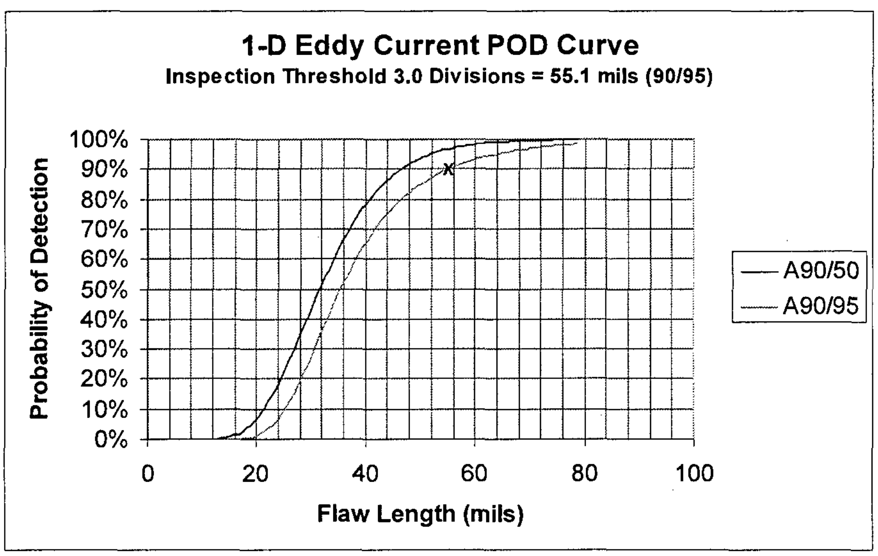
Example Threshold vs. POD



Acceptance Criteria/Decision Threshold



Acceptance Criteria/Decision Threshold

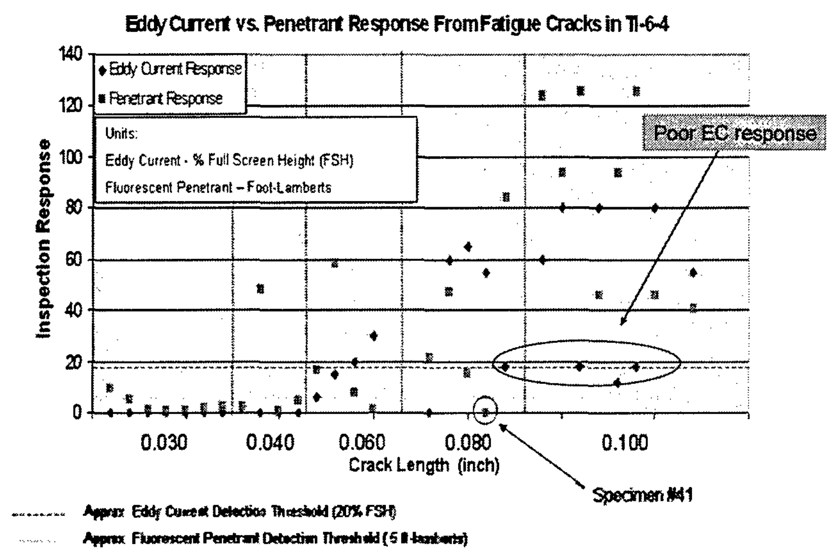


Variables Affecting Capability

- Flaw (Artificial vs. Natural)
- Test Object (Geometry, Material)
- NDI Method
- NDI Materials
- NDI Equipment
- NDI Procedure
- NDI Process
- Calibration
- Acceptance Criteria / Decision Basis
- Human Factors

Example: Crack Response Variability

Eddy Current and Fluorescent Penetrant

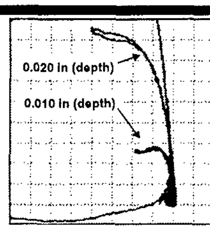


Variables Affecting Capability

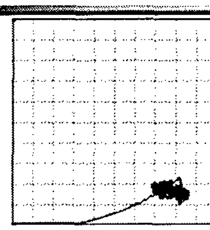
- **Flaw (Artificial vs. Natural)**
- Test Object (Geometry, Material)
- **NDI Method**
- **NDI Materials**
- **NDI Equipment**
- **NDI Procedure**
- **NDI Process**
- **Calibration**
- **Acceptance Criteria / Decision Basis**
- **Human Factors**

Example: Material Variability

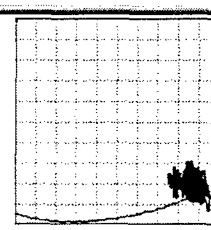
Eddy Current Noise Comparison: Forging vs. Casting



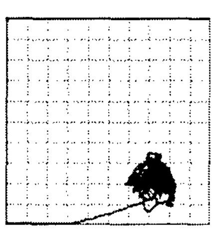
Ti-6-4 Reference Standard



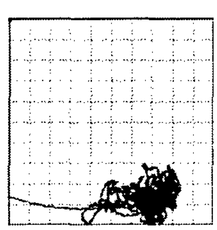
Ti Forging
Machined Surface
~ 32 RMS



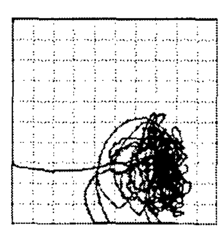
Ti Casting
Machined Surface
~ 32 RMS



Ti Casting
As Cast Surface
Flat – Moderate Texture



Ti Casting
As Cast Surface
Radius – Moderate Texture

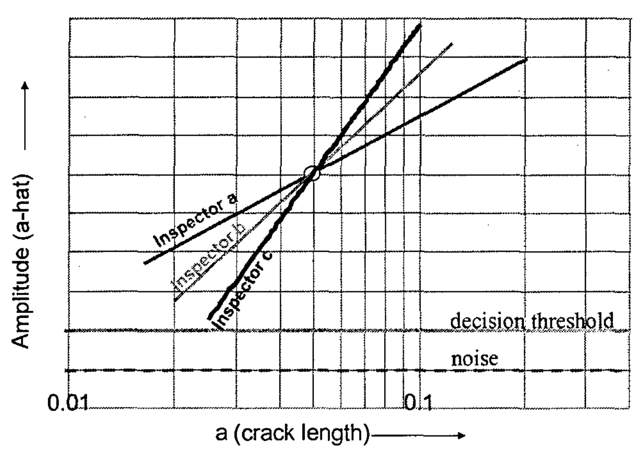


Ti Casting
As Cast Surface
Radius – Course Texture

Variables Affecting Capability

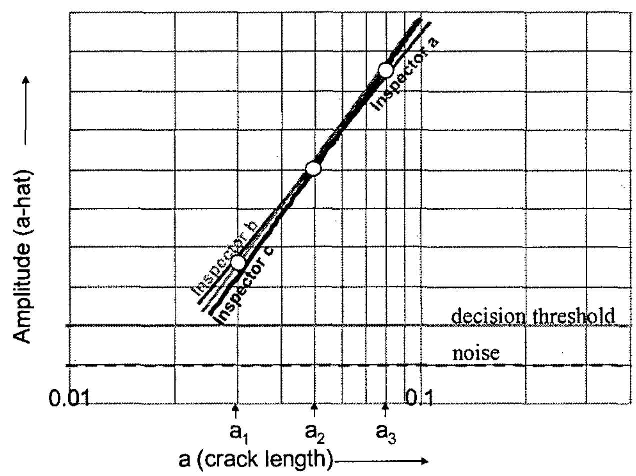
- Flaw (Artificial vs. Natural)
- Test Object (Geometry, Material)
- NDI Method
- NDI Materials
- NDI Equipment
- NDI Procedure
- NDI Process
- Calibration
- Acceptance Criteria / Decision Basis
- Human Factors

Single Point Calibration Scenario



Same calibration can lead to different POD's

Multiple Point Calibration Scenario



Multi-point Calibration Can Improve Reproducibility

Traceability To a POD Baseline

Inspections Cannot Be Traceable to a POD Baseline Unless...

- **"Calibration" Method Established**
  - **Example: 3-point Calibration**
- **"Calibration" Artifacts are Traceable**
- **Instrument, Cable, Probe Variables are Understood and Controlled**
- **Procedures are Validated and Stable**

Variables Affecting Capability

- **Flaw (Artificial vs. Natural)**
- **Test Object (Geometry, Material)**
- **NDI Method**
- **NDI Materials**
- **NDI Equipment**
- **NDI Procedure**
- **NDI Process**
- **Calibration**
- **Acceptance Criteria / Decision Basis**
- **Human Factors**

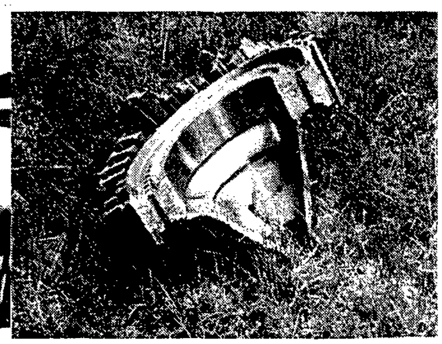
Reducing Inspection Variability
For Fatigue Critical Locations

- Institute 3-point calibration where possible
  - Tests instrument, probe and cables
- Institute reference standard traceability
  - Ensures consistent inspection results field wide
- Institute effective initial and refresher training
- Implement task certification with proficiency testing
  - Measure of individuals competency to perform task
- Design inspections to reduce human factors

When Inspections Fail

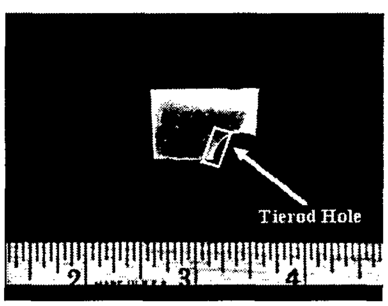
MD-88 Engine Failure, Pensacola, Florida

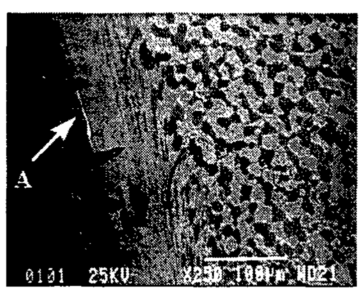
- Uncontained engine hub failure killed passengers upon ground run-up
- Titanium hub fails in fatigue initiating from a tie-bolt hole



MD-88 Engine Failure

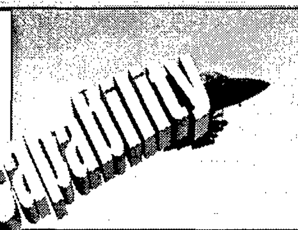
- Disturbed layer identified to have been overheated during manufacture
- Evidence of tool breakage discovered
- Alpha layer resulted in reduced fatigue properties
- Ammonium bifluoride inspection during manufacture missed alpha layer
- Periodic penetrant inspection missed resulting service crack
- Bolt-hole eddy current implemented for all future periodic inspections

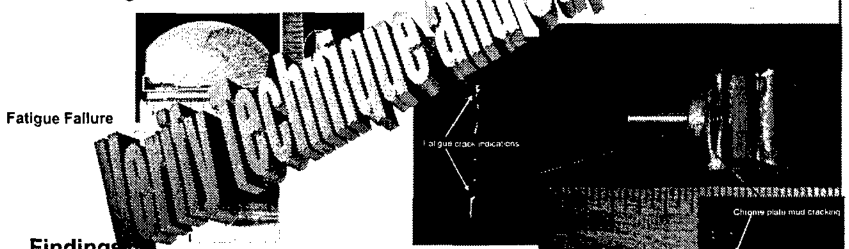


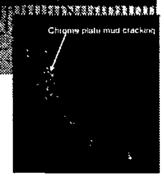


F-15 Pylon Hook Inspection

Problem:
- Chrome plated D6AC pylon hooks failed in service resulting in three Class B mishaps.
- Fatigue failure attributed to stress concentrations in hook radii from machining marks and corrosion pitting.
- TCTO Magnetic Particle failed to detect cr...







Findings:
- Magnetic Particle Procedure found to be ineffective due to part geometry and chrome plating
- Alternate fluorescent penetrant procedures developed, validated and fielded.

Closing Thoughts

- NDI Reduces Risk
- Inspection Development is a Critical Engineering Process
- Structures Engineers must understand and clearly define realistic inspection requirements
- NDI Engineers must translate the requirements into effective inspection solutions that are:
  - Capable
  - Repeatable
  - Reproducible

Top 10 Ways You Know You've Been in the Aging Aircraft Business Too Long

6. As years go by, more pages in your flight manual turn-up missing.
7. Your crew chief has observed recent crack growth in your lower rear bulkhead...stop drilling is not an option.
8. Your buddies call you "Hangar Queen"
9. Heavy usage, exceeding original design requirements, has resulted in excessive unplanned maintenance.
10. Weight penalty from conformal fuel tank mods. has negated enhanced endurance goals.

Top 10 Ways You Know You've Been in the Aging Aircraft Business Too Long

1. Two words...INFERIOR AERODYNAMICS
2. Your arresting hook does not deploy as quickly as it use to...sometimes not at all.
3. The frequency of required borescope inspections has increased dramatically.
4. Your bilge requires constant draining.
5. Even with optics upgrades your night vision capability is limited.

Backup Slides

F-15 FSMP NDI Assumptions

IN-SERVICE FLAW SIZES RELIABLY DETECTED BY STATE-OF-THE-ART NDI

EDDY CURRENT	
• FROM HOLE WITH FASTENER REMOVED – EMBEDDED CRACK	0.050 x 0.025
• FROM HOLE WITH FASTENER REMOVED -- CORNER CRACK	0.050 x 0.050
• FROM HOLE WITH FASTENER IN PLACE -- EMBEDDED CRACK	0.125 x 0.100
• FROM HOLE WITH FASTENER IN PLACE -- CORNER CRACK	0.100 x 0.100
• SURFACE CRACK	0.050 x 0.025
• EDGE CRACK	0.050 x 0.050
ULTRASONIC	
• FROM HOLE WITH FASTENER IN PLACE -- EMBEDDED CRACK	0.100 x 0.050
• FROM HOLE WITH FASTENER IN PLACE -- CORNER CRACK	0.100 x 0.100
• SURFACE CRACK	0.100 x 0.050
• EDGE CRACK	0.070 x 0.070
• EMBEDDED CRACK	0.100 x 0.050
PENETRANT	
• SURFACE CRACK - MEDIUM SENSITIVITY (LEVEL 2)	0.100 x 0.025
• EDGE CRACK - MEDIUM SENSITIVITY (LEVEL 2)	0.050 x 0.050
• SURFACE CRACK - ULTRAHIGH SENSITIVITY (LEVEL 4)	0.030 x 0.015
• CRACK - ULTRAHIGH SENSITIVITY (LEVEL 4)	0.015 x 0.015
MAGNETIC PARTICLE	
• SURFACE CRACK	0.050 x 0.025
• EDGE CRACK	0.050 x 0.050

F-16 FSMP NDI Assumptions

NDI CAPABILITY:

The assumed NDI capability shown in the detailed maintenance requirements summaries, and summarized in Table 2.2-3, was used to compute the reinspection interval. The MIL-A-83444 specified value (0.25" uncovered length at holes and edges, and 2c = 0.50" for surface flaws) was not assumed since the ability to detect smaller flaws has been demonstrated in a production environment for various NDI techniques. For most locations, eddy current inspection techniques have been recommended with an assumed capability of detecting a 0.03" corner flaw and a 0.05" length surface flaw. Should depot or base level NDI operations prove to be incapable of detecting the assumed NDI flaw size documented herein, the resulting reinspection interval should be reduced. The referenced figure provided for each maintenance summary can be used to determine the reinspection intervals corresponding to other levels of NDI capability.

F-16 FSMP NDI Assumptions cont...

TABLE 2.2-3 (continued)

AIRFRAME STRUCTURAL MAINTENANCE REQUIREMENTS
STRUCTURAL MAINTENANCE SUMMARY

MAINTENANCE AREA	IAT OR RELATED NO.	REFERENCE FSMP SECTION	INITIAL INSPECTION (FLT HRS)	REINSPECTION INTERVAL (FLT HRS)	REQUIRED NDI DETECTION CAPABILITY (INCHES)
Vertical Stabilizer Area:					
16T7228 Vertical Tail Center Attach Fitting	T7228BA	3.6.1	12,000	6,000	2c = 0.05
16B6224 Upper Bhd at FS 479, Web Fillet Radius near Flange Step	B6224BA	3.6.2	10,080	6,000	2c = 0.05
16B6224 Upper Bhd at FS 479, Vertical Tail Attach Pad Radii	B6224AC	3.6.3	TBD	TBD	2c = 0.05
Horizontal Tail Area:					
16T7467 Horizontal Tail Pivot Shaft Bolt Hole #7	T7467AA	3.7.1	10,110	6,000	0.03
16T7467 Horizontal Tail Pivot Shaft Root Radius	T7467BA	3.7.2	10,250	6,000	2c = 0.05

This Page Intentionally Left Blank

APPENDIX E: End-of-Course Survey Raw Data

***Note:** All data provide herein has been transcribed precisely as it was received. Answers from individual respondents are separated by a space.*

1. What did you like about this course?

The instructors were knowledgeable with experience.

I liked the info on failure types and causes. More info on this would have been help full.

Instructors were easy to understand and made the course relevant with practical experiences.

All the information provided about the fracture mechanics, specificall condition of failure, Residual stress, corrosion, & Fatigue.

New material helped me understand problems outside my job.
Case studies
It put pieces together

It was well organized and executed with good pacing.
The case studies really helped grow my understanding. I also like the use of equations to describe relationships between contributing factors.

Very informative. Well planned out. Each section is appropriate length.
The real life examples were great. I seem to relate better when examples come from aircraft we actually work on and are familiar with.

Case studies were helpful

The level of information was good. Wasn't over my head and it wasn't "dumbed" down. It's nice to have a class geared to AF engineers specifically.

Real world examples of common failure problems associated with AF aircraft

Lots of good real-world examples.

I liked the examples, pictures, and applications given in each lesson. It was helpful to see actual damages/failures, reasons why they probably occurred, how they were repaired, and how they could be prevented in the future.

I enjoyed how the class helped to put what I learned I school in context to my job.

Great info

- Geat content
- Information is directly related to day-to-day job.

It was a great review of materials and LEFM courses.
The course did a good job of providing a "Whole AF" view of current methodologies

I liked having ~~products~~ material and information directly related to work done at the ALC
Understanding (basic) of LEFM helps maintain aging A/C. I didn't get much of this at school.

The binder, cd, informative lectures and discussion, use of fear of embarrasment to help keep us focused, case studies and topic teasers, note pad, group work.

NdI fatige corrosion..everything case studies

Learning about NDI, methods for fixing cracks, exposure to common aircraft structural problems

Good setup. (50min/10min). Multiple instructors helped break things up- level of discussions was good.

Very relavent to Depot engineering

2. What did you dislike about this course?

1. Too much knowledge can be confussing and make it hard to understand the instructors. The 'open-ended' questions during instruction took a lot of assumption- that everyone had familiarity and prerequisite subjects.
2. the entire AFGROW presentation.

Although I thought the metallography & fractology was interesting, I thought as ~~an~~ a practical application for an engineer working on repairs was to indepth. The reports that are returned from failure analysis ~~was~~ are very important.

Nothing really comes to mind

I enjoyed the course a lot. I did not see anything I dislike.
This is a good course.

Pictures were too small
Local students probably used extra time to check ~~on~~ their jobs but for someone TDY I could have taken more information.

The level of the material seemed to oscillate. One lesson would be very simplistic while the next was ridden with equations. It would have been better had it steadily ramped up. I also thought there should have been more opportunities for interaction perhaps with mini case studies.

N/A ? the chairs

Some of the guest speakers were dry and took too much time.

The AFGROW demonstration was interesting but hard to follow.
I prefer to have a computer to follow along for software demos.

Time – I felt that sometimes we could have spent a little more time on certain issues and topics. I just feel like some of the info was jam-packed into the 50 minute sessions

Too repetitive. All of this material could easily be covered in 5 half days

Given the time constraint, it was sometimes hard to follow the lesson "completely" (fully comprehend) – if the course was a little longer (?) , perhaps the more difficult topics could be better understood.

I thought there could have been some more real world examples. Also, the guest presenters topics were a little too complex

- The orientation of some pictures & diagrams were difficult to discern. View directions should be clearly marked when showing multiple views.

Some of the guest lectures did not seem to be familiar with the idea of the course and previous topics covered

With people coming from different backgrounds, it is hard not to cover material that some people already have knowledge about. This may help for class discussions, but not enough to spend so much time reviewing.

On the case studies, it is hard to piece some of the pictures together, add more orientation labels on pictures.

The non technical briefs
To short

Repetition; often veered off topic; this course should be shorter timewise

Overall none – some areas had too much info and some not enough. Tough call on who needs what though

The AFGROW is not something the majority of engineers will use. The "working lunch" made for a very long day – no break.

3. Were having printed materials (your binder) an aid to your experience this week?

Absolutely.

the material in the ~~class~~ binder was very good.

Very helpful

Yes.

Yes with the case studies ofcource looking back helped
Not as much with lecture

Yes.

Yes. It is nice to be able to listen and concentrate on the lecture instead of worrying about taking notes. Plus, I can take the pictures with me.

Yes

Absolutely. Didn't feel like I had to take extensive notes, allowed better focus.

Yes, it was easier to follow along

Yes

Yes. Great reference to keep as well. Being as people sitting in front of me were blocking some of my view, it was great to have them directly in front of me.

Yes. I thought the materials were very helpful.

Yes

Yes.

Absolutly!

Yes because notes were not required to be duplicated.
It was a good reference for other lessons.

Oh yes, its great not having to write alot when you are trying to listen.

Yes, good for taking notes for future reference

Yes thanks

Yes – although having more details provided (ie what was said in class would help later on (months/years after course)

Yes, could easily turn to notes when projected pictures hard to see; also, could refer back

4. Do you think you will reference your book after this week? YES NO

YES	NO
22	0

5. Do you think you will reference your CD after this week? YES NO

YES	NO
22	0

6. Did the hour-long daily case studies support the course objectives?

Yes, working in groups helped my lack of knowledge and helped my learning and understanding.

Yes, I thought they were relevant to each course.

I think so. The only recommendations I have for the case study, is to provide the results from the lab at the end of the case study in order to use it as a reference in the future.

Yes add more of them when you go from 6 to 7 lessons/day

Yes.

Yes, they helped support what we were learning and made us "think." Many times I can listen to a lecture and understand all the concepts but it is not until I use this information before I really learn it and feel more comfortable with the material.
* Really enjoyed the Topic Teasers

Yes

Yes, without practice, this would have been much less effective. Pictures and real world examples always help.

Yes, it brought the course material to "light."
It made the course material relevant

Yes

Yes – these were very helpful. They teach lessons and support theory.

Yes.

Yes

Yes.

good – but they were very repetitive. They were all pretty much the same.

Yes, they were a good way to apply and reinforce material. Keep them

Yes.

Yes but more details would be helpful

Yes very much. Applying the material just learned always reinforces the learning process.

Yes.

Yes, they were good.

7. What changes or additions would you suggest to make this course better for future offerings?

Some added pages ~~with~~ for background information refreshment.
Include the speakers contact info in the reference book/binder.

I would like to see more short courses (week or so) that go into several of these topics more in depth.

I would have liked more time on LEFM

See #6.

Increase time 10% to 20% with additional case studies and real life examples
This is a great overview
Now develop additional follow on course just for corrosion and fatigue and NDI

The order of lessons should be rethought. The instructors referenced fatigue repeatedly & always followed that with "We'll discuss that [a few days] later." Rather than having topics grouped consecutively like Fatigue I, II, III being taught in a row, perhaps introduce the simple material early & return to the advanced discussion later.

Maybe work some real life examples from beginning to end. There were lectures that explained the theories and final result but not the details in "working" the problem. The lecture on AFGROW was informative but should not have been as in depth or should have started from the beginning with a problem and worked thru it.

1) Have more lessons during the week (M-Th) about 7 lessons per day. Get out early Friday.
2) Have little quizes at the end of each lesson to ensure we have learned everything. Immedialty go over the quiz.

More diverse practice problems. It seemed like all of them were scc's.

More time on topics

Compress the course, it shouldn't take 5 full days

Having more discussions/case studies as a class could initiate new ideas, good questions, and get your thoughts flowing.

More real world examples so that it can be related to our jobs better.

Have the students work example fatigue problems

- Add list of online references

- After each lesson, cite a reference (text, website, T.O., etc.) that class members can review for further study of the topic.

Get rid of some of the super basic stuff and talk more about "why" things fail

For a 5 day course, I would spend 3 days doing general review on basic concepts. Then, on the last 2 days, focus on more in depth topics.

More case studies and topic teasers. Not more than one per lesson, though. Make graphs more readable.

More time
Moe ndi an composites/bonded repairs

This course was thoroughly thought-out. Excellent.
-For the case studies, it would be helpful if the "Notes" page is separate, so we're not writing on the backs of needed figures.

8. Would you recommend this course to another ALC engineer? YES NO Why or why not?

YES	NO
22	0

It has plenty of relevance to the jobs of structural engineers.
Makes you aware of a lot of options for repairs as well as for seen problems.

as a good overview of a material. this is very helpful.

For me it was a great refresher to what I learned many, many years ago in college. I think others in my situation would benefit the same.

Because this is a good review material. also, as structure Enginer this class has a lot of information that will keep us up todate and we can apply to problems that we deal on daily basis. Note, I wished I would it have this class as soon as I got here (4 years ago).

Anyone in program office or ASIP related support design and acquisition

I grew a basic understanding of structural failure and analysis despite not having a structures background.

I was able to successfully evaluate all of the evidence in the final case study to produce a correct analysis.
This is attributable to strong instruction.

This course covers many topics that we see everyday. It will help engineers with the way the "think" about failures and ways to prevent them.

It helped me to understand what different kind of failures look like

All the information is pretty much ALC-specific. It's nice to get a perspective from all of airframes instead of just the one you work on. You could probably justify making this a mandatory class for AF structures eng'rs

It makes things we will need to one-day know as an engineer concerning the fleets of aging aircraft the AF has

I thought it was a good way to bring work & education together.

Condenses a wide range of information pertinent to a/c structural engineering that otherwise readily available to new engineers. This course & the provided book & CD are great resources for future reference.

Every ALC engineer should take this after 6 months of ALC work.

This is what we need here!
After getting a good understanding of the basics, the material substitution lesson was very ~~helpul~~ helpful. This should be elaborated on.
paul.hrad@robins.af.mil

I found this course to be very informative and enjoyable most of the time.

- Besides ABDR this is the only training that has be relivent and helpful to my Job
- I'm looking forward to future course offerings

Although mostly those in Aircraft spo or interested in moving to one in future.

New engineers will get excellent overview, old engineers get good refresher plus there's always something new to learn

This Page Intentionally Left Blank