A Review of Philosophies, Processes, Methods and Approaches that Protect In-Service Aircraft from the Scourge of Fatigue Failures

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Abstract: The paper describes the USAF aircraft structural integrity program (ASIP) and the key processes for controlling the risks associated with external threats and evolving damage. The ASIP exists to provide the systems framework for preventing structural failures, however one might define failures. The paper reviews the underlying philosophy and the systems framework, processes, methods and approaches used to protect aircraft against structural failures. The ASIP evolved from an initial focus on preventing catastrophic loss of aircraft and fatalities due to evolving fatigue damage in metallic structures. Today, the leadership expects ASIP to meet all the demands for ensuring airframe safety associated with the collection of threats resulting from different damage mechanisms, modes of failure and operating conditions that cause the structure to degrade as a function of time and service. While the ASIP systems framework and its processes allow the structures community to react to new problems, the overall intention is to anticipate times when future risks become too high to manage the fleet cost-effectively. While the limited number of structural accidents has demonstrated ASIP effectiveness, significant challenges exist for protecting the structural integrity for aging fleets. The paper suggests approaches for addressing these serious issues by further evolving the ASIP systems framework.

INTRODUCTION

Systematically attacking structural integrity cracking problems created by airframe operational environments requires a systems framework. Such a framework exists as defined by the USAF Aircraft Structural Integrity Program (ASIP) and its processes. The requirements for the ASIP had its genesis in the late 1950's as a result of in-flight failures of multiple B-47 aircraft. These failures resulted from fatigue cracks that had reached critical size well before the aircraft had reached what was estimated to be the operational lifetime [1, 2].

The initial structural integrity program was initiated in 1958 and was issued as a technical memorandum that defined the requirements for protecting airframe structure against damage nucleated and grown under operational cyclic loading conditions (referred to as fatigue damage or fatigue). The ASIP standard (MIL-STD-1530) was first published in 1972 and then revised in 1975 [3]. The 1975 revision came almost six (6) years after an undetected forging defect led to a catastrophic failure in a relatively new F-111 aircraft (that failed after only 105 hours of operation). Also in the late 1960's, the C-5A aircraft was found to have significant wing cracks during its full-scale fatigue test. For the F-111, the lack of material crack resistance in the D6AC high strength steel made it possible for the undetected forging defect to cause the failure at low operating conditions (~4 g) for a fighter aircraft. The cracking problems associated with the C-5A wing were attributed to the lack of modeling capability for addressing the potential for the onset of widespread fatigue damage (WFD), a multiple cracking scenario which rapidly led to the loss of residual strength capability in what was thought to be a fail-safe aircraft. These problems caused the USAF to change from a safe-life fatigue methodology to a damage tolerance methodology that addressed crack behavior. The 1975 approach required that potential crack damage be anticipated at fatigue critical locations and that the risks of failure due to the evolution of this crack damage be controlled [4].

Figure 1. The outer wing section of the F-111 aircraft that failed due an undetected forging defect (rogue flaw) in the D6AC high strength steel pivot fitting under a 4 g loading.

Over the last 45 years, the requirement to have an ASIP has resulted in approaches for systematically attacking the causes for structural failures and has maintained structural safety in a cost-effective manner. The ASIP exists today to ensure that we don't repeat the painful lessons learned in the late 50s through mid-70s. Experience has demonstrated that the lack of a structural integrity program may obscure true aircraft condition and cause unwelcome surprises in the form of accidents or of increased maintenance, or of unanticipated repairs and replacement costs. And even when the ASIP can not anticipate an unexpected structurally related event, it provides the framework, methods and approaches for rapidly addressing new findings. Historically, structural failures were viewed as resulting in fatalities and the catastrophic loss of the aircraft, but today, Leadership views any unanticipated structural problems as the failure of the ASIP, even though no catastrophic failures have occurred.

Figure 2 describes the aircraft loss rates from non combat causes for all USAF aircraft. These rates are calculated based on aircraft losses occurring over a 5 year period, since there may be multiple years when there were no structural losses. Note that the aircraft structural loss rate is approximately 2 percent or less of the overall loss rates and that both loss rates are decreasing.

Today, with a downward trend in the number of catastrophic airframe failures, structural failures are viewed by Leadership as the sudden increase in high structural maintenance costs and as unplanned structural maintenance efforts that impact availability and operational tempo. The new types of structural failure (as defined by Leadership) are largely the result of operating an aging fleet, which results in new classes of structural integrity issues.

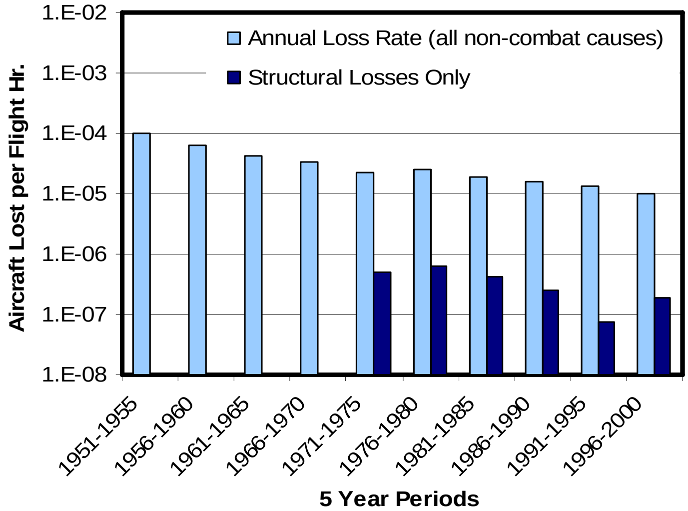

Figure 2. Annual loss rates for USAF aircraft resulting from structurally related causes compared to total loss rate of USAF aircraft resulting from all non-combat causes

Changing Leadership perspectives and requirements as well as the condition of aging fleets stimulated efforts in 2004 and 2005 to update the USAF ASIP standard to address a broader class of structural integrity issues, i.e., beyond those associated with catastrophic failure and fatalities. The updated ASIP Standard (MIL-STD-1530C) published in Nov 2005 [5] drives the structures community to collect data required to determine when the airframe might reach unacceptably high levels of structural risk (associated with catastrophic loss of aircraft, substantial increases in maintenance actions and major loss in availability associated with the fleet aircraft not able to perform their missions).

Figure 3 describes the evolution of ASIP philosophies and underlying methods as they have been adapted by the USAF. So while the ASIP initially evolved to develop the framework that provided approaches for solely preventing accidents and fatalities, today the emphasis has been expanded to ensure that structural performance also meets planned cost and availability targets. Thus, the concept of structural failure is more broadly defined in terms of lack of structural performance (includes the inability to safety perform defined missions, the

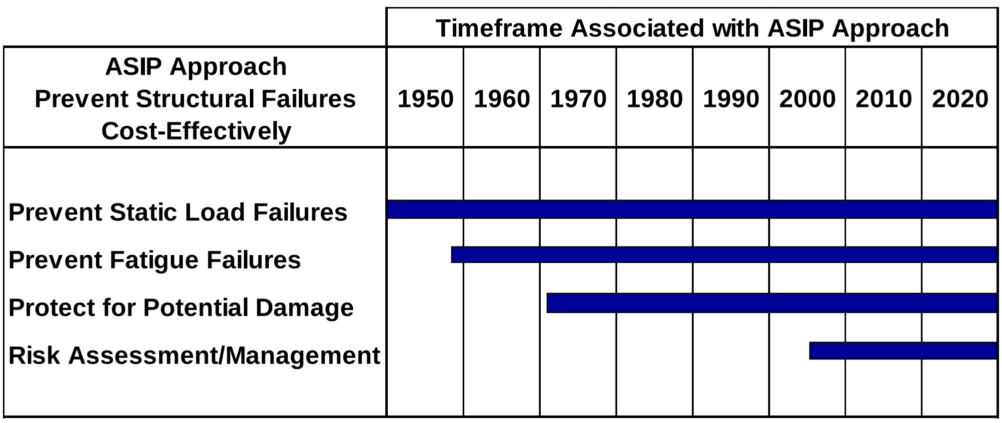

Figure 3. Evolution of the USAF's ASIP philosophies and approaches illustrated as a function of time.

inability to meet availability goals, and in the inability to anticipate major increases in unplanned maintenance).

The ASIP has kept pace with threats to structural integrity resulting from new modes of failure (e.g., delamination/debonding of structural composite and adhesively bonded structures) and associated triggers of damage (e.g., high-temperature, high-humidity environments, toolbox drops, hail impacts) from different mechanisms of failure (e.g., stress corrosion cracking, material loss due to corrosion, temperature-induced material property changes), from new material/manufacturing processes (e.g., welding and casting due to their defect populations and challenges to process quality control) and new structural concepts (e.g., unitized construction and hybrid-layered structures) that save weight and manufacturing costs.

Collectively, the ASIP Standard (MIL-STD-1530C), the policy directive (AFPD 63-10), the policy instruction (AFI 63-1001), the Joint Service Specification Guide (JSSG 2006) and the certification handbook MIL-HDBK-516 provide direction and guidance for ASIP [5-9].

RECENT ASIP STANDARD CHANGES

Today, the ASIP, as documented in the Department of Defense (DoD) Standard Practice – MIL-STD-1530C, provides direction for precluding structural failure using a systems framework adaptable for addressing any structural integrity concern. Principal concerns result from the evolution and growth of damage that degrades the structural performance characteristics resulting in a failure. The highest priority is given to managing and controlling risks associated with any damage which has the potential to evolve and threaten the safety of the structure during both design and sustainment. The standard covers the breadth of aircraft procured and operated by the USAF to perform its mission.

Table I defines the ASIP objectives; these objectives are aligned with the expanded scope of the ASIP, and give increased emphasis to certifying the airframe, airframe sustainment and assuring that airframe activities enhance the USAF's ability to better anticipate risks of potential structural failures (for safety problems, unplanned maintenance, loss in availability).

Table I. ASIP Objectives Defined

ASIP OBJECTIVES
Define the structural integrity requirements associated with meeting Operational Safety, Suitability and Effectiveness (OSS&E) requirements
Establish, evaluate, substantiate, and certify structural integrity
Acquire, evaluate, and apply usage and maintenance data to ensure the continued structural integrity of operational aircraft
Provide quantitative information for decisions on force structure planning, inspection and modification priorities, risk management, expected life cycle costs and related operational and support decisions
Provide a basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft systems and modifications

Figure 4 defines the five tasks of the updated ASIP Standard, where it will be noted that Tasks IV and V have been renamed from previous versions to clarify their function relative to the activities that support these tasks. Also, note that Task IV involves airframe certification. Figure 4 identifies which tasks primarily support the acquisition and sustainment phases of the aircraft life cycle.

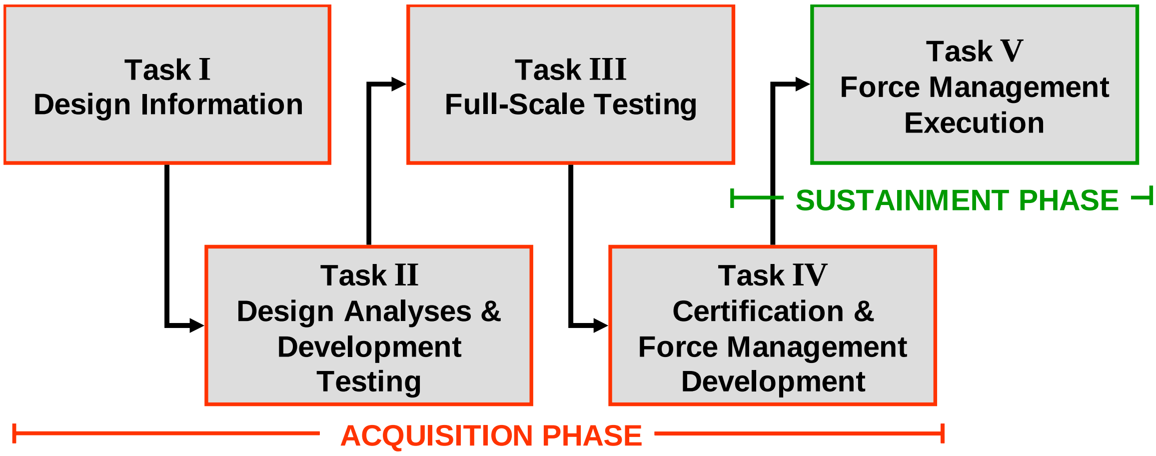

Figure 4. The five tasks link acquisition activities with sustainment activities. The ASIP goal is to ensure that the desired level of structural safety, performance, durability, and supportability is achieved with the least possible economic burden throughout an aircraft's service life.

Table II provides additional detail on changes that have been made during the updating of the ASIP Standard. As indicated previously, one reason for updating the Standard was to minimize the impact of structural integrity failures on availability and life cycle costs. The table identifies numerous new tasks that provide more emphasis to meet Leadership requirements. Note that Tasks IV & V have been extensively modified and renamed to cover the functions associated with these tasks. To summarize, the ASIP Standard was updated to 1) institutionalize risk management, 2) more formally incorporate requirements for structural corrosion management, 3) strengthen the role of analysis in airworthiness certification, and 4) increase the emphasis on durability and sustainment. The update also ensured that the USAF had one Standard that ensured the structural integrity of all its aircraft weapons systems.

Many updated ASIP Standard changes leverage the new emphasis on institutionalizing risk management, so whether a decision is made on a material choice for corrosion resistance, or for airframe certification, or loads and environment stress survey instrumentation, or for the evaluations of operational threats and the consequences of a failure, the decision is made with respect to structural risks. The ASIP Standard is directly tied to the DoD Safety Standard (MIL-STD-882, [10]) by references and the need to effectively communicate risks to program management to improve their decision-making. The updated Standard takes advantage of years of risk research and probability-based experience reported by J.W. Lincoln [11-15].

Risk Management

The ASIP Standard provides the overarching framework for assessing and managing the impacts associated with any kind of structural failure. More emphasis is now placed on including surveillance requirements (to measure the effects of aging mechanisms on structural integrity risks). In fact, the use of surveillance techniques by targeting aircraft that have been

Table II. Task and Subtask Summary of Updated ASIP Standard (1 Nov 05)

Task I	Task II	Task III	Task IV	Task V
Design Information	**Design Analysis & Development Tests**	**Full-Scale Testing**	**Certification & Force Management Development**	**Force Management Execution**
ASIP Master Plan Design Service Life and Design Usage Structural Design Criteria Damage Tolerance & Durability Control Program Corrosion Protection and Control Program Nondestructive Inspection Program Selection of Materials, Processes, Joining Methods & Structural Concepts	Materials And Joint Allowables Load Analyses Design Service Loads Spectra Design Chemical, Thermal & Environment Spectra Stress Analysis Damage Tolerance Analysis Durability Analysis Corrosion Assessment Sonic Fatigue; Vibration; Aeroelastic, & Aeroservoelastic Analyses Mass Properties Analysis Survivability Analysis Design Development Tests Production NDI Capability Initial Risk Analysis	Static Tests First Flight Verification Ground Tests Flight Tests Durability Tests Damage Tolerance Tests Climatic Testing Interpretation & Evaluation of Test Results	Certification Analysis Strength Summary & Operating Restrictions Force Structural Maintenance Plan Loads/ Environment Spectra Survey Development Individual Aircraft Tracking Program Development Rotorcraft Dynamic Component Tracking Program Development	Individual Aircraft Tracking Data Rotorcraft Dynamic Component Tracking Program Loads/ Environment Spectra Survey ASIP Manual Aircraft Structural Records Force Management Updates Recertification

New Subtask

severely used (for the loading conditions or for time in a corrosive environment) provides key information for evaluating the accuracy of the complete structural integrity model.

<u>Structural Corrosion Management</u>

The ASIP Standard leverages the improved basis for managing risks to require that the structural designer prevent corrosion damage from occurring by anticipating and assessing potential corrosion problems. By assessing the potential for, and consequences of, corrosion damage, the correct approaches can be taken to control the onset of corrosion damage in design. Another key part of the corrosion management thrust is the requirement to utilize surveillance to gain early recognization of the occurrence of corrosion. Surveillance lead-the-fleet concepts ensure the rapid identification of locations, times and causes for the onset of corrosion. Then based on the determined consequences of such corrosion, surveillance generated information facilitates the early development of plans that address potential fleetwide problems that are uncovered in service.

<u>Analysis Supporting Certification</u>

The ASIP Standard has two new subtasks in Task VI and Task V that address certification and recertification. Task IV subtask refers to MIL-HDBK-516 [9], which provides guidance on certification requirements and suggested approaches. The ASIP Standard requires that design analyses be correlated to ground and flight testing to establish structural certification. The certification analyses provide the engineering source data for the Technical Orders (TOs) that document the operational limitations/restrictions, procedures, and maintenance requirements to ensure safe operation. The ASIP Standard directs that approval of the certification analyses constitutes aircraft structural certification, a critical step in achievement of airworthiness certification for the aircraft in accordance with procedures outlined in MIL-HDBK-516. Should significant deviations from the certification baseline occur during sustainment, Task V requires performing a recertification. Such deviations may include changes to usage, damage, and/or service life expectancy. Recertification analyses provide the updated engineering source data for revising Technical Orders to ensure continuing safe operation. Recertification efforts should consider all ASIP tasks and elements and may require additional full-scale static and/or durability tests to validate the recertification effort.

Increased Emphasis for Durability and Sustainment

In an overall sense, the longevity of an airframe depends on its ability to resist the development and growth of damage created during operations as well as the effort required to control this damage. Fatigue, corrosion, wear, composite delamination, and debonding represent damage mechanisms which can lead to the loss of residual strength and unplanned major investments in maintenance to ensure safety and availability goals are met. The surveillance requirement puts increased emphasis on measuring the amount of aging damage that an individual airframe has experienced.

Tailoring Clarification

The ASIP Standard now covers all USAF aircraft and types of procurements (e.g., UAVs, spiral acquisition strategies, helicopters, commercial aircraft buys). This change was made to provide a complete and integrated document that could be used as part of any new procurement and to correct past practices where structural integrity requirements were ignored because the document was a handbook (which provides guidance only) rather than a Standard (which provides direction and can be incorporated into a contract by reference).

OVERVIEW OF ASIP PROCESSES

The USAF ASIP provides the engineering discipline and management framework associated with establishing and maintaining structural safety in the most cost-effective manner through a set of defined inspections, repairs, modifications and retirement actions. The ASIP is based on a preventative maintenance strategy that starts in acquisition and continues until retirement. ASIP systems framework and its processes involve engineers and managers working together to control the risks of structural failure. See Butkus, et al. [16], for additional information.

Figures 5 and 6 describe engineering processes associated with developing and sustaining airframe structural integrity, respectively. Figure 5, while less detailed than Figure 6, identifies several key process elements that are part of the acquisition activities. Both figures illustrate the importance of feedback loops in developing and sustaining the airframe. The key process elements of the acquisition (Tasks I-IV) and sustainment (Task V) engineering processes must deliver 1) a robust airframe design that meets acquisition performance goals and 2) an airframe that can be effectively maintained throughout its operational lifetime, without “structural failure.” Figure 5 emphasizes the importance of the acquisition tasks on reducing the risks associated with initially fielding the aircraft and then operating it. Figure 6 defines the ASIP engineering process as well as shows the relationships between the various data collection process elements and the analysis, planning and execution process elements. The aircraft ASIP Manager is responsible for the adequacy of the ASIP engineering process.

Figure 7 defines the ASIP management process and summarizes its key process elements. Note that the management process incorporates the engineering process as one of its major features. The ASIP management process thus drives and controls the activities of the engineering process. In essence, the ASIP management process: defines the performance requirements, develops plans that ensure that these requirements are met within the available budgets, and defines the information required to support decision-making. The process maintains a level of communication that ensures all managers are working to achieve common goals. System requirements drive the ASIP engineering processes to develop sufficient information to support decision making. Key personnel supporting the ASIP management process in the Program Offices are the Program Manager, Chief Engineer, and the ASIP Manager.

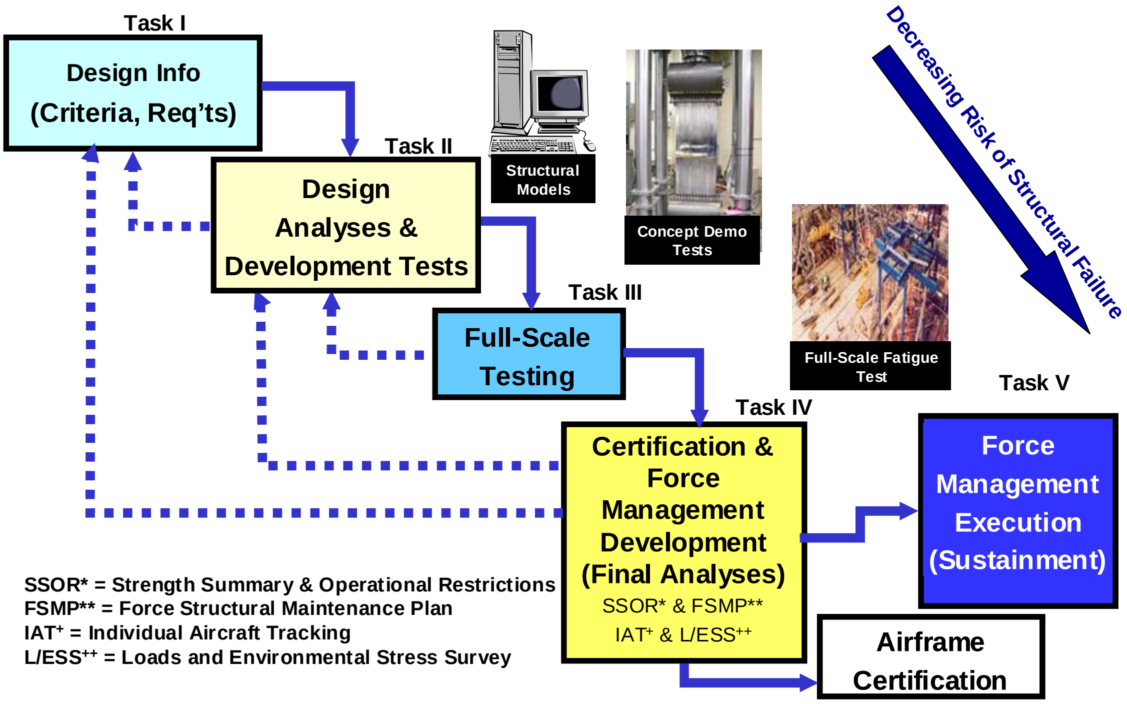

Figure 5. The ASIP engineering process emphasizing Task I-IV activities leading to a fielded structure certified to meet performance goals and delivering a structural maintenance plan.

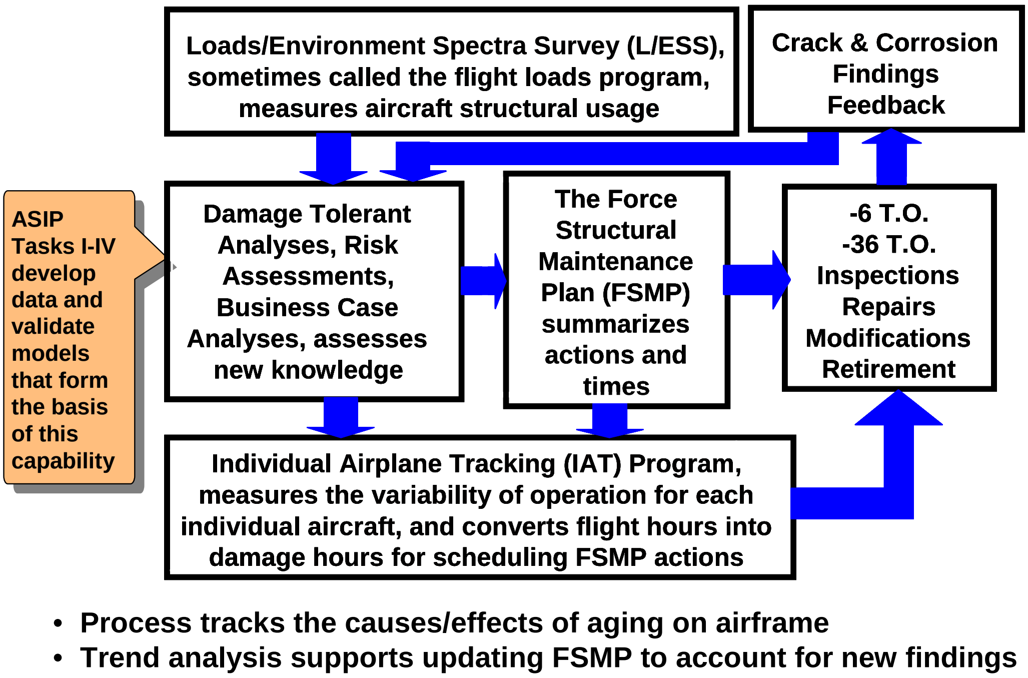

Figure 6. The ASIP engineering process emphasizing Task V activities and its closed-feedback-loop that collects/analyses usage and aging-related information to support 1) evaluating the current and future structural health and 2) updating the force structural maintenance plan (FSMP) to account for new damage findings and for changes in operations.

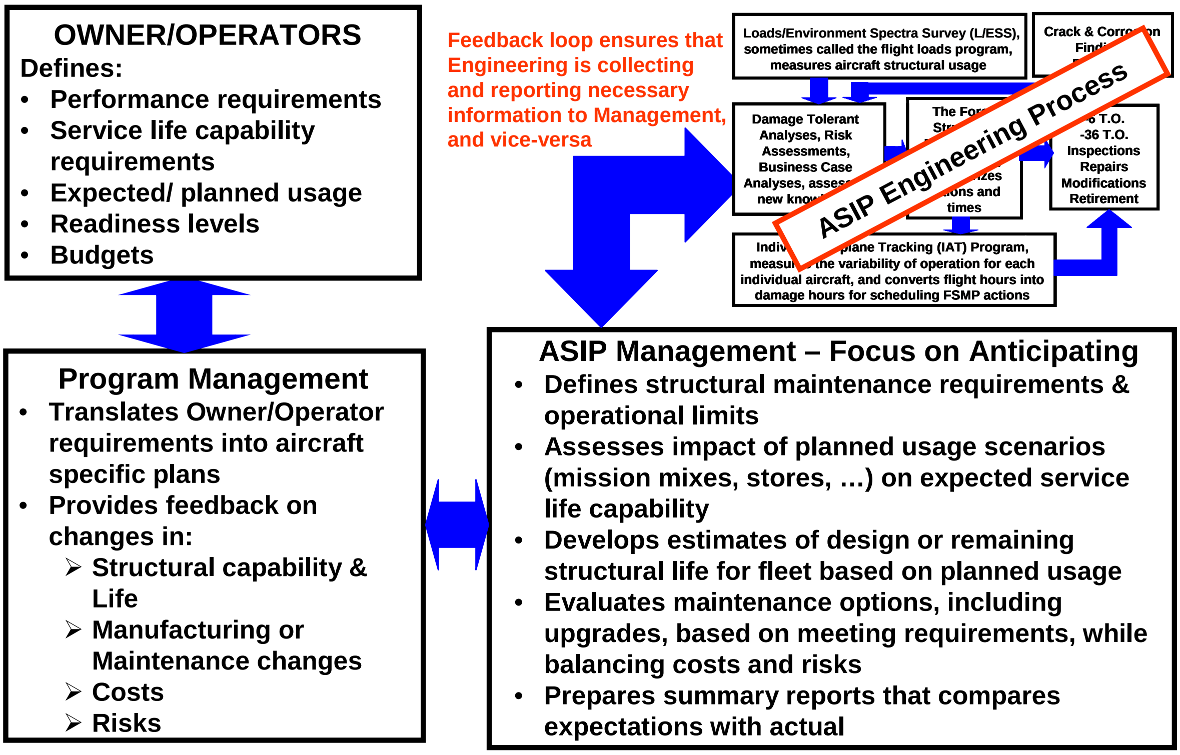

Figure 7. The ASIP management process utilizes the engineering process (Figure 5 or 6) to generate information essential for decision making. The figure emphasizes the interactions between the engineering process, the ASIP Manager, the Program Manager, and the Owner/ Operator and those actions involved in the management decision-making process.

REVIEWING INDIVIDUAL AIRPLANE ASIP PROCESSES

Scope and Objectives of Reviews

To ensure that the ASIP framework and its engineering and management processes are effectively addressing Leadership requirements, the USAF ASIP Manager conducts annual reviews of the aircraft inventory. The initial reviews started in 1997 and initially concentrated on identifying issues associated with the health of the individual weapon systems as a follow up to the findings of the National Materials Advisory Board's Aging Aircraft report [17]. As it became obvious that the health of aging aircraft was significantly being underestimated by the lack of execution of ASIP requirements, the reviews shifted to cover the evaluation of the health of the ASIP systems framework/ASIP processes as well of as the structural health of individual aircraft fleets. The ASIP engineering process reviews started in 2004 and the corresponding management processes started in 2006. It is the responsibility of the USAF ASIP Manager to report the findings to USAF Leadership.

There are a series of secondary objectives associated with the annual ASIP reviews. These objectives are associated with: 1) enhancing ASIP systems engineering and system management elements (by identifying best practices), 2) determining the technology needs associated with aircraft structures and the ASIP processes (supporting the Air Force Research Laboratory (AFRL) programmatic needs), and 3) enhancing communication between organizations supporting airframe structural integrity (ensuring improved networking for problem solving).

The annual evaluation review and reporting of ASIP processes and airframe health utilizes a 30 June cutoff for accomplishments, changes and findings. Every attempt is made to review all the aircraft in the inventory, and to include those both in acquisition and sustainment. Table III summarizes the aircraft fleets subjected to the evaluation review in the year that closed on 30 June 2006. Note that some mission design series (MDS) aircraft fleets were considered separately, i.e., F-16A/B and F-16C/D and RQ-4A and RQ-4B, due to either difference in known age (F-16 fleets) or because one MDS was in sustainment while the other was in acquisition (RQ-4).

Table III. Listing of USAF 50+Aircraft Fleets Evaluated in the 2006 Review

Mission Type	**Aircraft Fleets**
Bomber	B-1, B-2, B-52
Cargo	C-5, C-9C, C-12C/D/F, C-12J, C-17, C-20B, C-20H, C-21, C-26, C-32, C-37, C-38A, C-40, C-130, C-130J
Communication/Control	E-3A, E-4B, E-8C, E-9A
Fighter/Attack	A-10, F-15A-D, F-15E, F-16A/B, F-16C/D, F-22, F-35, F-117
Helicopter	UH-1N, MH-53, HH-60
Special	U-2, UV-18, VC-25
Tanker	KC-10, KC-135
Trainer	C-150, T-1, T-6, T-37, T-38 , T-41, T-43, TG-10A-D, TG-14, TG-15A/B
UAV	MQ-1, RQ-4A, RQ-4B

Evaluation Criteria and Scorecard Development

For each fleet evaluated, the evaluation review report summarizes results based on a scorecard concept. The USAF ASIP Manager creates one scorecard for the ASIP engineering process and one scorecard for the ASIP management process. Each key process element in these ASIP processes is evaluated and given a score that is measured in terms of metrics. The scores on any card can be evaluated using the information in Table IV. Note that a Green score does not imply that the process element is perfect, just that it is performing at a satisfactory level.

The evaluation criteria used to establish the scores are derived from the ASIP Standard and from past best practices. Some of these criteria are quantitative, while others are qualitative. Table V describes the evaluation criteria for the ASIP engineering process that supports acquisition (review Figure 5 for some of the process elements) and Table VI describes the evaluation criteria for the ASIP engineering process that supports sustainment (review Figure 6 for as summary of the process elements and how these interact). The concept of using scorecards grew from early ASIP engineering process evaluations conducted in 2002 and

2003 on several aging fleets, and was found to be a convenient form for communicating with senior managers and USAF Leadership on the health of ASIP processes in a state of failure.

Tables V and VI were constructed to provide not only the criteria on individual process elements, but also to include guidance on what was expected from the overall process. The first nine rows in each table describe the criteria for the individual process elements, the last row in the table describes the criteria for overall process effectiveness. The information on process evaluation criteria was provided to the program offices and owner/operators prior to the review.

Table IV. ASIP Process Element Metric Categories (Grading Levels)

Graphic	Metric Category	Description of Metric Category
Red	Critical	The process element is not functioning satisfactorily; immediate corrective action is required to protect integrity and airworthiness
Orange	Serious	The process element is not functioning satisfactorily; near term corrective action is required; overall ASIP process can protect safety today
Yellow	Caution	The process element is not functioning satisfactorily; corrective action is required to address concerns
Green	Effective	The process element satisfies the ASIP requirement for this airframe

Table V. ASIP Task I-IV Engineering Process Elements and Associated Evaluation Criteria

ASIP Element	Criteria
ASIP Master Plan	- The ASIP Master Plan (MP) is current, approved, and is being followed. - Tailoring is appropriate for The weapon system
Structural Design Criteria	- Criteria defined for loads, strength, flutter, vibration, durability, damage tolerance, weight and balance, etc. using JSSG 2006
Material and Joint Allowables	- Testing is adequate to understand the modes of failure for the material or joint in the configurations utilized in the weapons system and environments to which it will be exposed
Design Analysis	- Design analysis tools have been verified through prior experience
Development Testing	- Sufficient coupon, element, subcomponent and component tests exist to evaluate new structural concepts, new materials, new manufacturing processes and new joining methods
Full-Scale Ground Testing	- Static full-scale test verifies strength capability and the internal loads and stress models. - Durability full-scale test uses realistic loading spectrum and verifies design service life will be achieved
Full-Scale Flight Testing	- Flight tests verifies external loads, dynamic response, flutter, vibration and aeroelastic analyses
Final Analysis	- All design analyses are updated and correlated with the development and full-scale tests
SSOR, FSMP, IAT and L/ESS	- Documents describing the strength limitations, the maintenance requirements, and usage monitoring requirements are established and the results are incorporated into the Technical Orders
Overall Engineering Process Effectiveness	- Anticipates damage based on knowledge of usage and aging information. - Has a limited number of unanticipated damage events. - Communicates schedules ($, Manpower, readiness impacts to customer) for major structural events

Table VI. ASIP Task V Engineering Process Elements and Associated Evaluation Criteria

ASIP Element	Criteria
Force Structural Maintenance Plan (FSMP)	- FSMP is current, represents cracking scenarios & usage, and is followed
Inspection Procedures	- Documented by T.O.s (schedule & requirements) - Links to FSMP; focus on keeping risks of structural failure low - Inspection procedure development process responds to new damage
L/ESS (Loads and Environmental Stress Survey) Fleet Usage	- 10-20% of Fleet are instrumented, instruments work - High capture rate of accurate data reflecting average fleet usage
IAT (Individual Aircraft Tracking) Airplane Usage	- Data collected for all aircraft - High data capture rate (>90%) - Program accurately estimates the level of damage
Flaw Size Data (from inspections, ACIs, teardowns)	- Data collection processes exist - Data are stored and used to trend aging behavior - Data are used to support future maintenance actions
Corrosion Data	- Data collection processes exist; - Data stored and used to support maintenance decision-making
Durability and Damage Tolerance Analysis	- Models are current for predicting: external and internal loads, stress, damage growth, and residual strength - Models account for current usage and address observed damage scenarios at all critical structural locations
Risk Analysis	- Quantitative procedures exist for estimating risks per MIL-STD-882 - Evaluation of risks is a basic (formal) part of decision-making
Business Case Analysis	- Process proactively conducts cost-benefit evaluations to reduce costs of major planned structural actions
Overall Engineering Process Effectiveness	- Anticipates damage based on knowledge of usage and aging information - Has a limited number of unanticipated damage events - Communicates schedules, funding, readiness impacts, etc. to customer for major structural events

In 2005, the ASIP management processes for a limited number of airframe fleets were evaluated, but not reported to Leadership as the criteria were still evolving. In 2006, the ASIP process evaluation review included both the engineering and management processes. The corresponding ASIP management elements and criteria are summarized in Table VII (Review Figure 7 for a description of the key management process elements).

Table VII. ASIP Management Process Elements and Associated Evaluation Criteria

ASIP Element	Criteria
MAJCOM-SPO Communication	- Periodic evaluation reviews occur to address plans & deviations from plans covering structural integrity issues: -- Service life capability defined in terms of expected time in service and numbers (Force Structure issues) -- Usage (activity and capture rates) and aging damage findings -- Prioritizing budgets
MAJCOM Support	- MAJCOM has instructions on implementing ASIP standard & AFI 63-1001 - MAJCOM has processes for collecting and reporting usage data - MAJCOM maintains plans that summarize expected force structure & usage for comparison with current usage
Program Execution	- ASIP Master Plan is being followed - Single Manager, Chief Engineer and SPO ASIP Manager have clear understanding of their respective roles - Processes anticipate problems and maintenance is cost-effective
Program Planning	- ASIP Master Plan is current, accurate and focused - FSMP guides future efforts to control maintenance costs - Decision-making is based on risks to structural integrity
Quality of Decision Information	- Engineering process generates information essential for SPO and MAJCOM decision-making - Engineering process generates accurate information - MAJCOM provides planning data to support SPO
Usage, Life, Force Structure Defined	- MAJCOM provides this planning information - SPO uses this planning information to anticipate structural integrity problems
SPO Oversight on ASIP Process	- Chief Engineer and Single Manager periodically review structural integrity issues with the SPO ASIP Manager - SPO periodically performs self-assessments
Attention to ASIP Process Deficiencies	- Deficiencies of process elements are evaluated relative to their impact on the effectiveness of the overall process - Deficiencies are dispositioned
Budget Sufficient to Control Risks	- MAJCOM and SPO work collaboratively to ensure sufficient funding exists for the ASIP process to anticipate, identify and control the risks for structural integrity failures that impact safety, availability and life cycle costs
Overall Process Effectiveness	- Collects, interprets and communicates near and long term risks of structural integrity failures - Manages structural health of weapon system to meet its ORD - Is proactive in terms of converting new information into decisions of potential risks of structural integrity failures - Communicates schedules ($, manpower, readiness impacts to customer) for major structural events

Aircraft Fleet Scorecards for Evaluating ASIP Processes

Collecting Information: Each aircraft fleet listed in Table III received ASIP process health scorecards. One scorecard summarized the health of the ASIP engineering process, the other the health of the ASIP management process. As discussed above, the program phase dictated the choice of key process elements and criteria used for evaluating each aircraft's ASIP engineering process.

The information on the features, capability, performance and effectiveness of each key process element for the ASIP engineering process is developed through interactions with the program office associated with managing either the development or sustainment of the aircraft fleet. Similarly, the information on each key process element for the ASIP management process is collected through interactions with the program office. However, for the ASIP management process, the information collected from program offices is considered preliminary until it is vetted with the owner/operator, since within the USAF it is necessary for both the program office and owner/operator to communicate and interact to support the ASIP process.

Engineering Process Evaluation: For establishing the ASIP engineering process scorecard, the interactions are between the USAF ASIP Manager and the program office, since the program office is responsibility for managing the engineering process. After initial information is acquired on the engineering process and its elements, the USAF ASIP Manager provides the program office with a preliminary assessment of the process health and requests concurrence or additional information to justify changes. Normally only one iteration is required to agree on the status of process health. Figure 8 provides an example ASIP engineering process scorecard.

Management Process Evaluation: Preliminary ASIP management process scorecards are developed based on interactions between the USAF ASIP Manager and the program office. The program office is asked to collect information by interacting with the owner/operator and to report this information to the USAF ASIP Manager for an evaluation. As with the engineering scorecard, an initial evaluation is provided to the program office and iterated to ensure collective understanding/agreement. With this preliminary assessment, the ASIP management process scorecard becomes the basis of interactions with others outside the program office until it could be reviewed and vetted with the owner/operator responsible for the specific airplane fleet. Figure 9 provides an example ASIP management process scorecard.

Structural Health Evaluation: During the evaluation period, the USAF ASIP Manager collects information from the program office on airframe aging issues experienced by the individual aircraft fleets. The focus is on determining if structural aging issues are isolated and anticipated (or not). The biggest aging concerns result from the occurrence of previously unknown and now detected damage that can not be linked back to design, surveillance, or previous in-service experience. Such damage normally causes unplanned actions and unscheduled maintenance that affect aircraft availability. It is also important in these reviews to discern if the occurrence of aging damage is increasing at multiple locations in a given component. Aging damage due to fatigue cracking, stress corrosion cracking and corrosion (various types) are of primary concern.

Vetting Scorecard Evaluations: Subsequent to the vetting interactions with the program offices, the USAF ASIP Manager meets with commanders to whom the individual Weapon

System Program Managers report. These commanders are those responsible for managing 1) a group of program offices (typically a Wing Commander) and 2) all acquisition program offices at a Center or all sustainment program offices at a Center (the Center Commander). These interactions increase awareness of local best practices, common process deficiencies and aging issues of concern that require the attention of these commanders.

ASIP Element	*Metric*	*Remarks*
FSMP	Green	Plan update to be released in Sept 2006 and being followed.
Inspection Procedures	Green	NDI procedures being developed for Fatigue Critical Locations as requirements come due; tested in ACIs.
L/ESS – Fleet Usage	Green	The capture rate for year 2006 update is 34.9% which is greater than the 20% required.
IAT – Airplane Usage	Yellow	Valid data captured continues to average ~73% < required 90%; SPO working w/ Lead Command to address problems.
Flaw Size Data	Yellow ↑	Data are now being captured from individual inspections and are being stored in EXCEL databases.
Corrosion Data	Green	Limited corrosion observed and being effectively man-aged. Developing potential best practice on Identifying.
Durability & Dam Tolerance Analysis	Green	DADTA was updated to account for weight changes, rough runways, and refueling loading.
Risk Analysis	Green	The Program Office continues to use MIL-STD-882A safety analysis to establish structural risks.
Business Case Analysis	Green	Strong working group focusing on reducing production costs, gaining value.
Overall Engineering Process Effectiveness	Green	Adequately tracks aging and its causes/usage variability; aircraft recently fielded. Several Best Practices.

LEGEND: Red – *Critical*; Orange – *Serious*; Yellow – *Caution*; Green – *Effective*

Figure 8. Example ASIP Engineering Process Scorecard for an Aircraft Fleet in Sustainment.

ASIP Element	*Metric*	*Remarks*
MAJCOM-SPO Communication	Green	Periodic reviews are held with all operators at a bi-annual ASIP Working Group (WG).
MAJCOM Support	Green	Lead Command has drafted Instruction (I63-1001) to implement ASIP for active duty Command units.
Program Execution	Green	Master Plan identifies all necessary maintenance activities required to ensure structural integrity.
Program Planning	Green	ASIP MP is current, accurate, and is updated annually. A major FSMP revision is in-work.
Quality of Decision Information	Green	Process anticipates structural problems before they adversely impact mission readiness or availability.
Usage, Life, Force Structure Defined	Green	MAJCOM provides feedback on usage trends/plans, coordinates force planning, thru ORD & ASIP WG.
SPO Oversight on ASIP Process	Green	Periodic reviews with leaders occur at ASIP WG, Reqts WG (RWG) and Reqts & Planning Council.
Attention to ASIP Process Deficiencies	Green	Identified deficiencies & solutions are coordinated with the Program Director, Staff, WG, and OEM.
Budget Sufficient to Control Risk	Green	Funding has not been a limiting factor in managing structural concerns. Budget is sufficient.
Overall Management Process Effectiveness	Green	The ASIP process is very effective in maintaining structural integrity, reliability, and availability.

LEGEND: Red – *Critical*; Orange – *Serious*; Yellow – *Caution*; Green – *Effective*

Figure 9. Example ASIP Management Process Scorecard for an Aircraft Fleet in Sustainment.

Owner/Operator Vetting: Another key part of the vetting is to review the findings with the owner/operators to finalize the ASIP management process scorecards and to determine if there are other structural health issues about which they either are aware of, or have some concern. Normally, the interactions with senior Leaders of the owner/operator involve summarizing the health (processes and structural) of the aircraft fleets for which they are responsible. Leader presentations concentrate on presenting the bottom line process effectiveness scores from the individual scorecards. In 2006, as a result of interaction with the USAF owner/operator community, no management scorecards were changed; however, additional information on airframe aging issues was identified for several aircraft fleets. Key element deficiencies are reviewed with the owner/operator to support Program Managers' justification for additional systems engineering support and for recommended maintenance actions.

Interactions with USAF Leadership: Subsequent to the finalization of the scorecards and agreements on weapons system structural health, the USAF ASIP Manager presents a status of the inventory to the Air Force Materiel Command's (AFMC's) Logistics and Engineering Leaders. AFMC is responsible for managing all aircraft weapon system acquisition and sustainment activities, for Air Force research and development, and for establishing/maintaining the ASIP infrastructure. The AFMC Leadership interactions focus on identifying ASIP process deficiencies and airframe aging issues, as well as recommending actions on cooperative cross-cutting efforts that systematically attack weapon system process deficiencies and research needs.

The meetings with AFMC Leadership are followed with meetings with acquisition and logistics Leaders who report to the Secretary of the Air Force. The meetings with these Air Staff Leaders increase their awareness of structural health issues as well as the challenges associated with anticipating future health issues. Recommendations are provided for investments in the collection of information that could improve the USAF's ability to anticipate health issues that impact availability and future maintenance.

Collectively, the meetings with the AFMC and Air Staff Leadership increase awareness of important information that compels action for addressing both the near term and longer term process and structural health issues. The next two subsections describe summary information on the ASIP engineering and management process issues, respectively.

<u>Key Common ASIP Engineering Process Issues</u>

During the 2004-2006 ASIP engineering process reviews, it was found that there were four common process issues: 1) Inspection reliability, 2) Usage data collection, 3) Collection of aging damage data, and 4) Currency of airframe structural models. Table IX identifies the common process issues (seen on multiple aircraft fleets) and their potential impact. Additional discussion of these issues and suggested approaches for addressing them is covered in the next section.

<u>Key Common ASIP Management Process Issues</u>

During the 2006 ASIP management process reviews, it was found that there were five common process issues: 1) Communicating requirements, 2) Program office planning, 3) Decision-making data accuracy, 4) Budgets to support sustainment, and. 5) Resources for the Aircraft ASIP Manager. Table X identifies the common process issues (seen on multiple aircraft fleets) and their potential impact. While some of these issues are expected to exist in other country's aircraft fleets, the USAF's solution approaches will probably differ due to the different infrastructures, and thus are not further discussed in this paper.

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Table IX. Common ASIP Engineering Process Issues and Their Impacts

Key Process	Common Process Issue	Impact
Inspection Reliability	Quality of field and depot inspections may be unknown	Inspections may not ensure airframe safety when cracks are present
Usage Data (L/ESS & IAT programs)	Critical fleet and tail number usage data not being fully/accurately collected	Lack of fidelity in estimating effects of operations on aging (and thus remaining life)
Flaw & Corrosion Information (Aging Damage)	Incomplete/nonexistent data from field & depot level maintenance describing damage	Improper "sight picture" of health of inventory
Currency of Structural Models	Sustaining engineering budgets are insufficient to update models or to evaluate accuracy of models for predicting failures	Limited ability to anticipate structural problems from aging

Table X. Common ASIP Management Process Issues and Their Impacts

Key Process	Common Process Issue	Impact
Communicating Requirements (Owner/Operator & Program Office)	Facilitating communication on future force structure and usage	Fidelity of usage and force structure info is key to planning
Program Office Planning	ASIP Master Plans not up to date, thus not defining future needs	Limited ability to address ASIP deficiencies or to define strategies that focus on minimizing life-cycle sustainment costs
Decision-Making Data Accuracy (Program Offices, ASIP Managers)	Inattention to collecting, organizing, storing and reporting key data	Key sustainment decisions made without input
Budgets (investment strategy for sustainment)	Sustaining engineering budgets are insufficient to anticipate or to explore potential future threats to structural integrity	Limited ability to anticipate structural problems from aging
Resources to Support the Aircraft ASIP Manager	Emphasis on the day to day activities (engineering requests for support)	Limits activity for prime responsibility (anticipate/plan)

Self Evaluations: As a result of this formal review process, many aircraft weapon system program offices conduct self evaluations, normally on a semi-annual schedule, to address process issues and to gage progress made during the course of the year.

ADDRESSING COMMON ENGINEERING PROCESS PROBLEMS

Inspection Reliability Issue

Contrary to popular belief, the damage tolerance (DT) design approach was not created to support the development of an inspection program to maintain safety. The objective for DT design was to minimize the potential for cracks to become a threat to structural safety during the expected design lifetime of the aircraft. However, if during design after the configuration becomes fixed, it is determined that cracks will likely occur in service and that a rogue flaw could grow to critical size before two design lifetimes, the designer/manufacturer and procuring organizations have several options for addressing this threat. If the business case assessments justify the inspection option as cost-effective and practical, then the DT designer/analyst defines inspection actions as part of the force structural maintenance plan (FSMP) requirement to maintain aircraft structural integrity.

Initial Inspection Interval: Figure 10 illustrates a typical fatigue crack growth curve for a slow crack growth structure category DT design. The structure for this crack growth curve is a safety-of-flight structure, that is, should a crack grow to critical size ($a_{\mathbf{cr}}$), the element, the component and then the aircraft will catastrophically fail. When the inspection option is chosen, USAF policy requires that inspections occur at half the crack growth life associated with growing the crack from its initial rogue size ($a_{\mathbf{0}}$) to the critical crack size ($a_{\mathbf{cr}}$). This requirement continues as part of MIL-STD-1530C. The first half-life inspection also establishes where other damage exists in these locations or if the cracking scenarios used in design adequately describe what is occurring in-service. Note that the half-life inspection decision gives the inspectors a minimum of two chances to find rogue flaw type cracks.

Repeat Inspections: What has been become known as the inspection reliability issue is more associated with repeat inspections and, in many cases, their associated relatively-short inspection intervals. If the size of the $a_{\mathbf{ASIP}}$ is larger than the target crack size shown in Figure 10, then the inspection interval associated with subsequent inspections will be less than the initial first-half lifetime ($T_{\mathbf{1}}$). Every attempt is made to justify the smallest post-inspection "rogue" flaw-size ($a_{\mathbf{ASIP}}$), since this flaw size controls the period between inspections. Figure 11 describes the growth of a crack from the $a_{\mathbf{ASIP}}$ size to a_{cr}, this crack growth interval is then used to determine the repeat inspection interval ($\Delta T = 0.5^* (T_{\mathbf{3}} - T_{\mathbf{1}})$), so that the next planned inspection will occur at $T_{\mathbf{2}}$. Prior to the recent past, the USAF used results from inspection probability of detection (POD) studies to provide data for defining this post-inspection flaw size [18]. In fact, numerous papers in the literature [19-21] refer to the post-inspection flaw size as $a_{\mathbf{NDE}}$, a crack size determined from POD experiments.

Inspection Misses: The inspection reliability issue became recognized from investigations required by Leadership to determine the causes for missing detectable cracks during safety investigations. Such cracks were initially found during subsequent inspections which occurred shortly after a required safety inspection occurred. When it was established that these initial missed fatigue cracks were present during the required safety inspection, Leadership required that several safety inspections be repeated.

a_0 = rogue crack size; establishes initial inspection interval

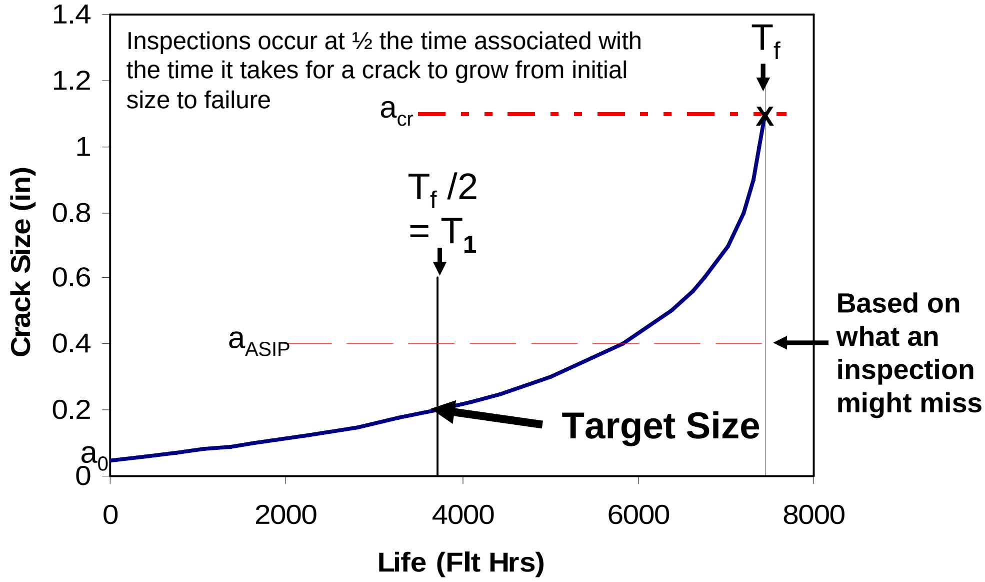


Figure 10. Initial safety inspections are planned to occur at one-half the crack growth life (T_f) associated with growth from the initial rogue flaw (a_0) to critical crack size (a_{cr}). Also shown in the figure is the time period (T_1) and the target crack size associated with the first one-half crack growth life inspection, as well as a crack size associated with the post-inspection "rogue" flaw size (a_{ASIP}).

a_{ASIP} = potential miss-crack size; establishes repeat inspection interval

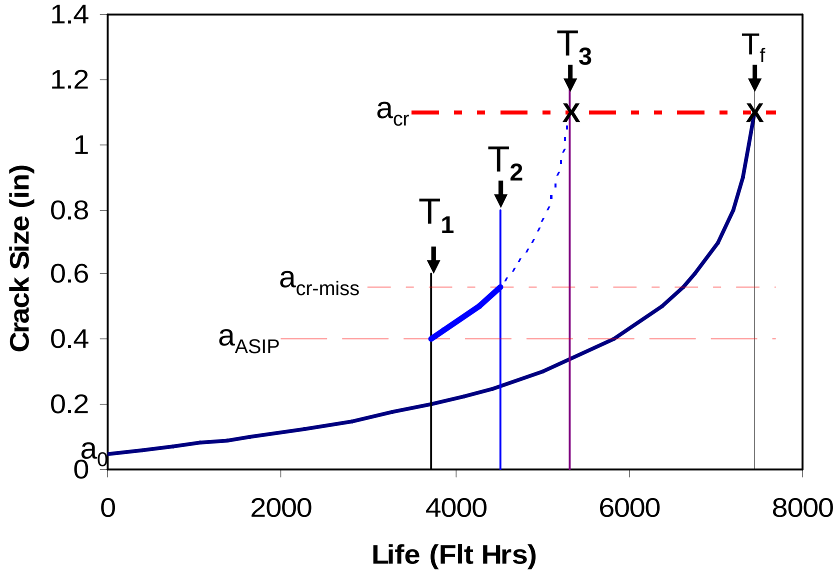
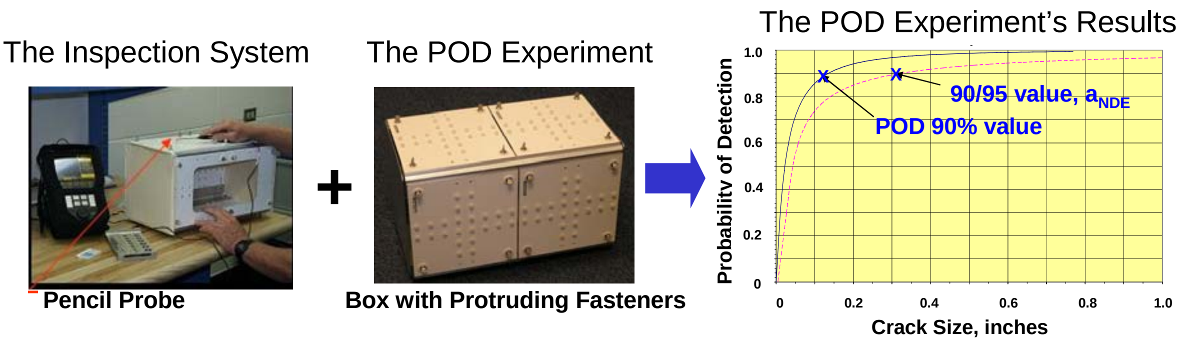


Figure 11. Repeat safety inspections are planned to occur at one-half the crack growth life associated with growth from the post-inspection rogue flaw (a_{ASIP}) to critical crack size (a_{cr}). The figure also shows the time period (T_2) and the critical-miss crack size ($a_{cr\text{-}miss}$) associated with the crack that will grow to failure before the next inspection period if missed during a repeat inspection. The $a_{cr\text{-}miss}$ crack size is the SIGNIFICANT crack size.

During these Leadership-required repeat-safety inspections, numerous additional missed cracks were detected, some of which were larger than the SIGNIFICANT crack size ($a_{cr\text{-}miss}$), associated with a size that, if missed, will cause failure prior to the next scheduled inspection. The root-causes for the inspection misses were numerous and included: ineffective/confusing Technical Order documents and instructions, lack of training/proficiency associated with inspection method for specific inspection location, human factors issues, equipment deficiencies, and management oversight, to name a few.

Confidence Shakers: The structures community's confidence in the inspection system's capability to detect cracks was further reduced when the results from the evaluation of several POD studies were summarized. Figure 12 summarizes a POD study conducted using laboratory feature test articles to evaluate standard high frequency eddy current (HFEC) inspection capability in a depot environment. Shown in Figure 12a is the collection of equipment, shown in Figure 12b is one of the laboratory feature test articles and in Figure 12c, the experimental results. The typical inspection system characteristic, i.e., the 90/95 crack size estimate (= a_{NDE}) from these POD experimental results, is associated with the 95% confidence bound on the POD curve evaluated at the 90% POD level. This 90/95 crack size estimate (0.322 inch, 8.2 mm) was a factor of 2 to 3 larger than what the structures community was typically using to establish inspection intervals using this kind of inspection system. Additional information on the POD and its interpretation relative to inspection interval setting can be found in [18-21].



a. b. c.

a. **The equipment, instructions, probe, calibration and inspector are parts of the inspection system.**
b. **The experiment utilizes multiple POD structural feature test articles (only one article shown) which have numerous details representative of aircraft hardware; some of the fastener holes are cracked but most are not cracked.**
c. **The results are portrayed in a probability of detection (POD) chart (fraction of cracks of a given size that are detected vs. the size associated with the cracks present in the experimental elements). POD curves describing the average POD response are established through statistical methods and confidence bounds are placed on these curves.**

Figure 12. Characterizing the capability of an inspection system with laboratory experiments that simulate aircraft structural configurations. (1-inch = 25.4 mm) [18]

Interpretation of Inspection Misses and POD Experiments: The principal conclusion resulting from the several years of investigating the inspection miss issue and evaluating results from laboratory-feature-test-article POD experiments is that the USAF must 1) baseline its inspection capability and 2) carefully evaluate all situations where inspections are **solely** being used to protect safety-of-flight structure when significant crack populations exist in a particular component. Steps are being taken to develop baseline inspection capabilities for high frequency eddy current inspections and other high value inspection techniques.

Approaches for Addressing the Inspection Reliability Issue: When the number of cracks sites is few so that inspectors can focus on these zones with validated procedures, the USAF believes that the inspection option continues to be justified for protecting safety. The concern comes from the potential for overwhelming the capability of the inspection system when multiple sites are experiencing cracking events.

The USAF ASIP Manager recommends that risk assessments be accomplished whenever cracks are being found (especially at multiple locations) to support plans for developing alternate means for protecting airframe safety. If it is determined that the inspection option will result in high risk if continued, then the inspection option should be considered as temporary until other actions can be implemented. Such actions could include imposing flight restrictions, modifying the aircraft, replacing the component, and retiring the aircraft. The choice of action is dictated by the level of interim risk and the need for the aircraft fleet to meet mission requirements.

Usage Data Collection Issue

One challenge associated with managing an aging aircraft fleet is maintaining an effective system for collecting usage information that defines how the aircraft fleet is being operated. This is not only important for measuring the overall life capability expended, but for determining the remaining life capability of the fleet.

Fundamentals: The usage monitoring system is composed of the individual aircraft tracking (IAT) program and the loads and environmental spectrum survey (L/ESS) program – see Figure 6 which describes these key process elements in the ASIP engineering process. The methods and instrumentation used to support these two usage monitoring programs vary. Aircraft that have been developed over the last 10 years or so have chosen to integrate the on-board IAT & L/ESS usage data collection function and process the data off-board to determine individual aircraft maintenance schedules and to determine fleet-wide usage statistics, respectively. However, most of the existing USAF aircraft fleets use two separate methods for collecting usage data that emphasizes limited instrumentation for the IAT that applies to all aircraft in the fleet and more extensive instrumentation that better characterizes the usage operation of a limited number of aircraft in the fleet (~10-20%, per MIL-STD-1530). Some of the older transports and bombers in the USAF inventory utilize a forms-based IAT monitoring system that depends on individuals summarizing individual aircraft operations for each flight. Typically, the older USAF fighter/attack aircraft utilize a vertical accelerometer (Nz) recorder to support their IAT program.

For an aging fleet, it is most important that the IAT program effectively captures the usage associated with each aircraft in the fleet. For fighter aircraft which tend to change missions and roles as they mature, the other usage monitoring process element (the L/ESS program) provides essential information for determining if 1) the aircraft is being utilized differently than previously planned and 2) the usage basis for assessing remaining aircraft life needs to be changed.

IAT Data Collection Issue: Several aircraft fleets evaluated in the 2004-2006 ASIP reviews did not meet the required 90% data collection level (per MIL-STD-1530) for accurate data capture. Sometimes the issue resulted from the limited data collection efforts occurring at several operating bases and sometimes the issue was related to the reliability of the IAT recorders. Recommendations for addressing the issues included 1) having the aircraft ASIP

Manager take a more active role in interacting with those bases showing less than a 90% accurate data capture rate, 2) engaging the owner/operator Leadership in encouraging their bases to meet requirement levels, 3) developing web-based access that facilitates data transfer between bases and the data capture organization, and 4) replacing recorders with updated systems that rely on the on-board flight control system to provide the necessary usage data. Solutions varied depending on the type of IAT program and its current instrumentation as well as budgets requirements for various options.

L/ESS Data Collection Issue: Typically, the reliability of the recorder equipment represents the greatest challenge to maintaining the L/ESS program at satisfactory levels as the aircraft age. For older fleets, the equipment is plagued with the loss of manufacturing suppliers who can provide replacements for failed elements; so, many program offices overseeing aging aircraft fleets use recorders taken from retired aircraft to support their near-term needs. The updated MIL-STD-1530C allows the aircraft ASIP Manager to decide on the total number of aircraft where active L/ESS recorders must be maintained to provide the capability for collecting required L/ESS data to support that fleet. It is expected that those program offices associated with aging bomber or cargo fleets will exercise this option. As the issues with IAT data collection, similar recommendations are made to address L/ESS data collection requirements.

Collecting, Storing and Using Damage Information Issue

As aircraft age, the cracks (i.e., the damage) population start to become visible, i.e., cracks are detected at multiple sites and typically found to be physically larger. To control the risks associated with the loss of structural integrity from this threat, one must have a clear understanding of the size and locations of the cracks that could jeopardize structural integrity.

Figure 13 provides a schematic that illustrates several individual flaw contributors to the overall fatigue crack population. On the far right of the figure is the rogue flaw (anomalous material/manufacturing defects) contribution, in the center is the flaw contributor resulting from other in-service damage mechanisms (corrosion, fretting, etc.), and on the far left is the flaw population created by applying typical quality control to material microstructures and manufacturing processes. Protecting the aircraft using rogue flaw concepts ensures that the aircraft is also protected from the other flaw contributors as long as the crack growth scenarios correctly represent the behavior of cracks in service.

Figure 14 illustrates how the crack population at a specific location compares to the DT crack growth analysis conducted during design and to a subsequent crack growth analysis that ignored the initial manufacturing cold-work assumption. The initial design assumption was based on a typical cold-working hole-crack starting rogue corner flaw (this is the lower curve) while the upper curve was associated with the typical DT rogue corner flaw assuming no hole-cold-working. Neither crack growth curve was developed considering the effect of residual stresses generated by a cold-working process. This residual stress effect was estimated based on a change in the initial flaw size assumption, and validated with experiments.

Figure 14 includes both the inspection results: detections (above the axis) and no detections (on the axis). As can be noted most of the crack size data are typically upper bounded by the original design assumption. Note that two cracks were found to be substantially larger than what might be characterized by the original design assumption and are truly considered "rogue." The typical safety based analysis provided an upper bound to these two cracks size results.

The larger cracks in the population are those that are most likely to cause premature structural failure

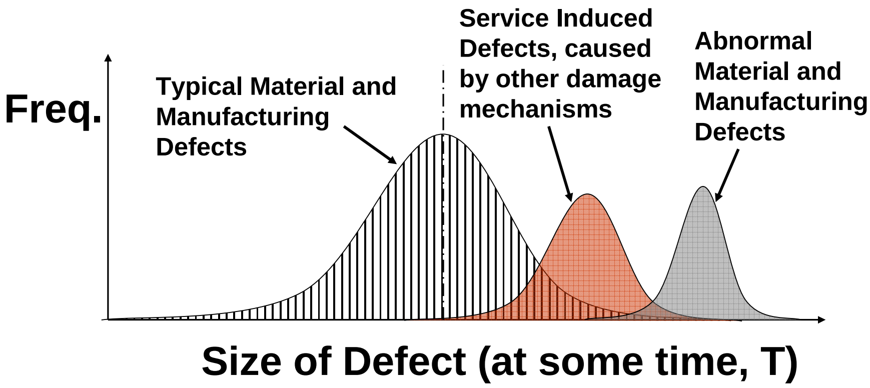


Figure 13. Schematic illustration of the principal probability density function (PDF) contributions associated with the crack size population at a fatigue critical location. These individual defect PDFs evolve as a function of time. The abnormal material and manufacturing defect PDF characterizes the rare rogue flaw behavior.

Evidence that larger (rogue) cracks do exist comes from comparison to Anticipated Crack Growth Life Curves

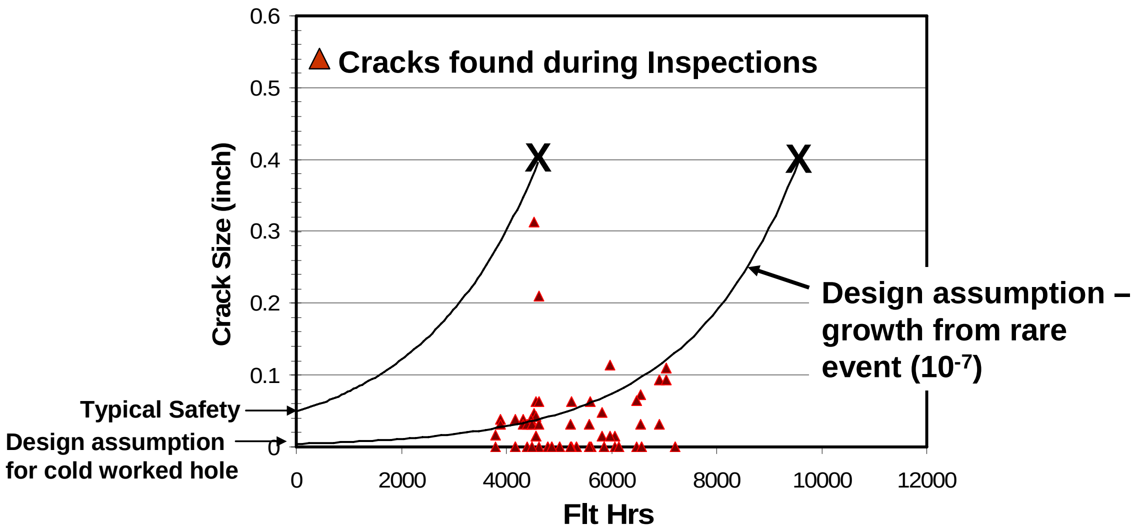


Figure 14. Comparison of observed damage to anticipated damage for crack behavior at a fatigue critical location. Shown are curves based on two different assumptions; the lower curve (the design curve) assumes that the hole was cold-worked during production and has a small rogue flaw (0.127-mm = 0.005-inch corner crack), the upper curve assumes that cold-work was inadvertently not performed and the crack starts at the traditional surrogate USAF rogue flaw assumption (1.27-mm = 0.050 inch corner crack). (1-inch = 25.4-mm)

Risk Assessments using Crack Data from In-Service Inspections: By extrapolating the crack size data in Figure 14 both forward and backwards to a common time (say 5000 hours), one can establish the estimate of the equivalent flaw population for subsequent risk assessments.

In fact having crack size data such as described in Figure 14 is a key requirement for conducting risk assessments. When data such as shown in Figure 14 appear (especially at multiple locations in a component), this is a reminder that continuing to protect safety by inspections for safety-of-flight structure is a high risk proposition given that such cracks might overwhelm the inspection system. Planning must be in place to protect the future safety using alternate means.

Over the years, numerous efforts have been made to support evaluations of the crack size population with aircraft teardowns that initially start with evaluations of damage that occurred during the full-scale fatigue-test article (Task III) and subsequently with evaluation of high time aircraft to support service life extension efforts. Additionally, efforts have been made using surveillance programs to collect detailed information at specific suspected "hot spot" regions (using localized teardowns) to identify potential types of damage (cracks, corrosion, wear, etc.) as well as after an aircraft fleet has experienced extensive service.

Recording and Storing Damage Information: The updated MIL-STD-1530C requires that program offices collect information on damage that could impact the structural integrity of their airframes. Task IV requires that the structural maintenance database be designed and Task V requires that the program office record all significant damage findings in this database. Significant findings include detailed information on cracks, corrosion, and/or delaminations discovered during program depot maintenance, analytical condition inspections, time compliance technical order (TCTO) structural inspections, teardown inspections, and normal operational maintenance. Figure 15 describes the types of observed damage data which are expected to be stored in the structural maintenance database as a function of the aircraft (tail number), the aircraft location (with sufficient detail that the location can be identified relative to fatigue critical locations/analysis zones), flight hours expended and calendar time when observed in service, type of action/equipment that found the damage, and an estimate of size fidelity. Additional information on the structural maintenance database and data collection requirements can be found in the MIL-STD-1530C.

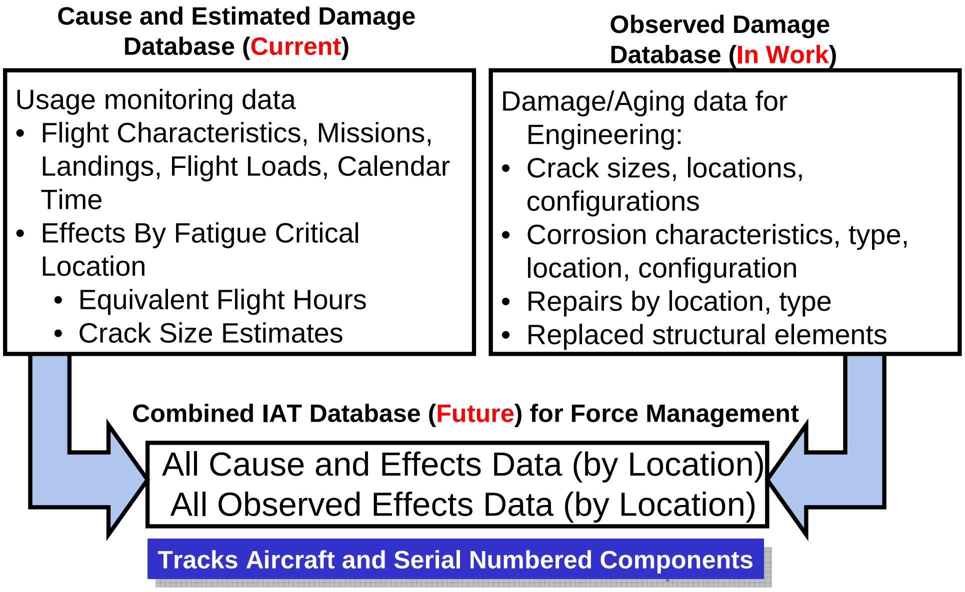


Figure 15. USAF plans for an Individual Aircraft Tracking (IAT) database for managing aircraft in sustainment. This approach integrates all the usage monitoring (virtual sensor) data with the maintenance data which describe the state of structural health of each airframe [22].

What can be noted in Figure 15 is that the USAF plans to integrate its current individual aircraft tracking (IAT) program that stores usage information on each aircraft with the structural maintenance database so that all the information on the causes and effects of aging damage are available to program decision makers and to USAF Leadership.

Having a database such as illustrated in Figure 15 that stores usage and damage data individually required by MIL-STD-1530C leads to the following outcomes; the database:

- Improves the accuracy of anticipated aging damage, the scheduling of effective maintenance and clear definition of which aircraft by serial number should be retired
- For new corrosion and cracking locations, rapidly identifies the causes
- Builds confidence in anticipated structural maintenance requirements (including retirement) to address aging issues.

Having all these data in an integrated database not only facilitates improvements in information for anticipating risks associated with future aircraft structural integrity issues and for developing cost-effective maintenance plans to address these issues, but allows the structural analyst the opportunity to determine the accuracy of the overall models for predicting the remaining structural life capacity.

Conducting Risk Assessments: Since (per MIL-STD-1530C defined requirements) risk-driven decision-making is a key element of the USAF strategy in anticipating structural integrity issues, it is essential that the structural analysis models be sufficiently accurate to provide confidence in the information generated by any risk assessment. Figure 16 summarizes a software package (PROF) that is frequently used by the USAF to estimate the probability of failure for cracked structure [20, 23-28].

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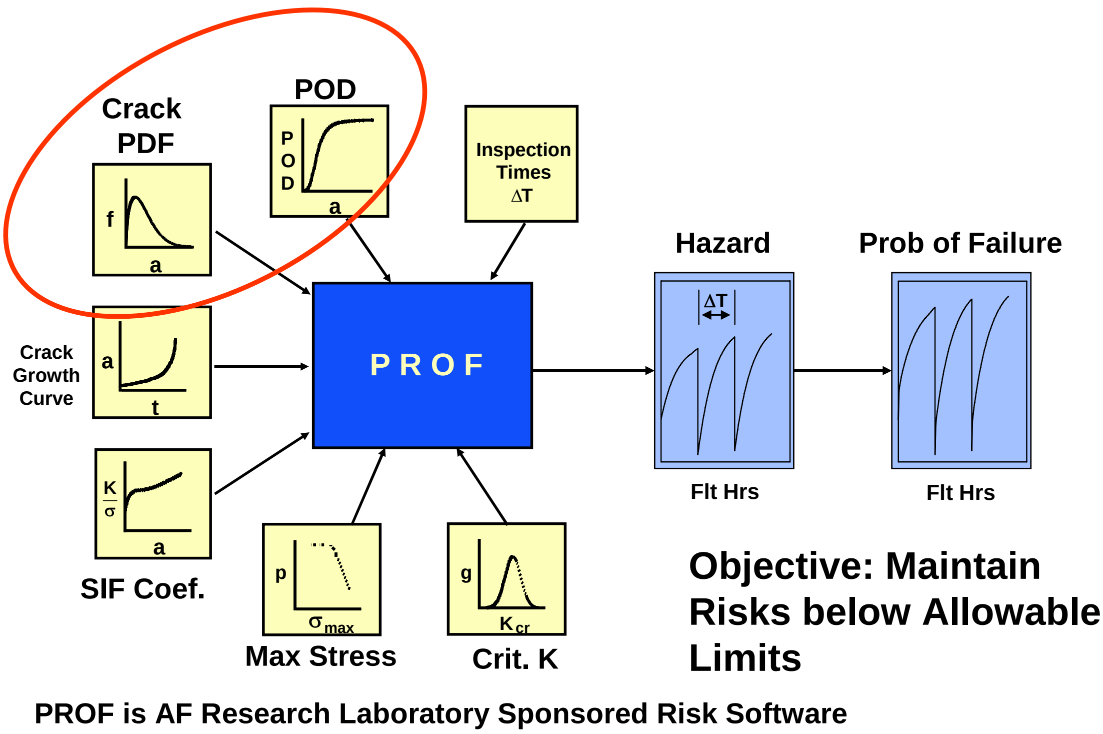

Figure 16. The schematic shows various inputs and outputs available from risk analysis tools. USAF frequently utilizes PROF to calculate structural risks for cracked structure.

The two circled inputs in Figure 16 are associated with the crack growth population (expressed as a probability density function in the figure) at the location of interest and a inspection system's capability as characterized by the probability of detection (POD) associated with for the structural location of interest. The creation of an integrated IAT database such as shown in Figure 15 could be interfaced directly with risk analysis software to rapidly assess structural integrity issues and thus would facilitate conducting risk assessments.

As outlined in the updated MIL-STD-1530C, the USAF requires that airframes be operated below a risk level associated with a $1x10^{-7}$ per flight probability of failure and that no aircraft be operated above $1x10^{-5}$ per flight probability of failure. Between these two limits, the ASIP Standard requires that aircraft be limited in exposure to this level of risk. A diagram that summarizes these risk thresholds is provided by Figure 17.

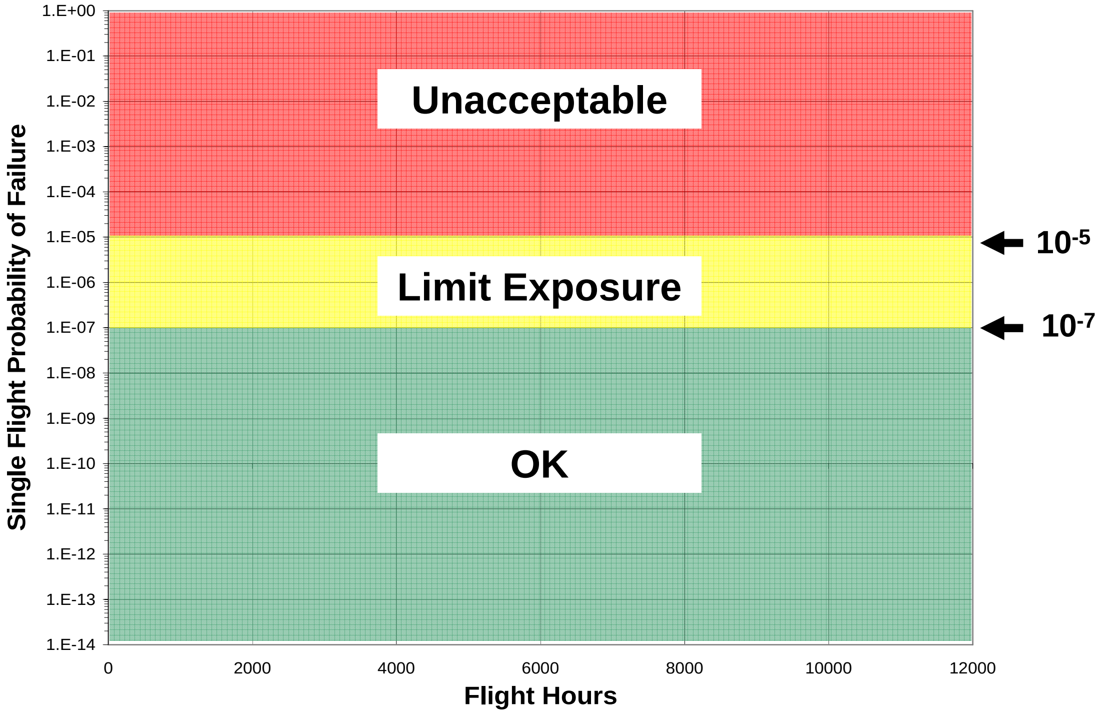

Figure 17. Risk thresholds defined by MIL-STD-1530C

Currency of Structural Model Issue

The 2004-2006 ASIP engineering process review uncovered a number of issues associated with estimating the remaining structural life capability of the USAF aging fleets. Because many aircraft utilized design models, which in some cases date to 1950s pencil and paper methods, the design models (e.g., external and internal loads models, stress analysis models, and life prediction models), do not have the accuracy existing in currently available structural models. Many of the older structural models were updated to conduct the DT analyses required by the 1975 ASIP Standard (MIL-STD-1530A) requirements and these models then date from the late 1970's to the late 1980's.

This currency issue is important in a global sense when one attempts to confidently estimate the remaining life capability of the airframe. The USAF recognizes that some structural models might not have much of an impact on the risk analysis results for a local region where detailed structural models can be developed and then demonstrated and validated by historical data, whereas in other situations these older models could have a significant impact on the confidence of even the local analysis.

As indicated above in the discussion of risk assessment tools (See for example, Figure 16), it is essential that the structural models associated with creating input for the risk analysis model be sufficiently accurate so that high confidence will exist in the risk analysis results. Thus, it is important that program offices be diligent in establishing confidence in the accuracy of all their structural models. One method for evaluating the accuracy and variability in structural models is shown in Figure 18.

Figure 18 describes the collection of crack growth life comparisons where the ratios of predicted crack growth lives to experimental measured crack growth lives for a series of variable amplitude fatigue crack growth experiments are presented using a log-normal cumulative distribution function. As can be seen from the figure, approximately 62% of the ratios fall below 1 (perfect correlation indicator) and are therefore conservative. Furthermore the variability of the life predictions are such that one could state that approximately 80% of the life predictions fall within a factor of two of the experimental results. Understanding both the accuracy and variability of the individual structural models that are used to develop risk assessments (or durability and damage tolerance assessments) is key to making engineering decisions with confidence.

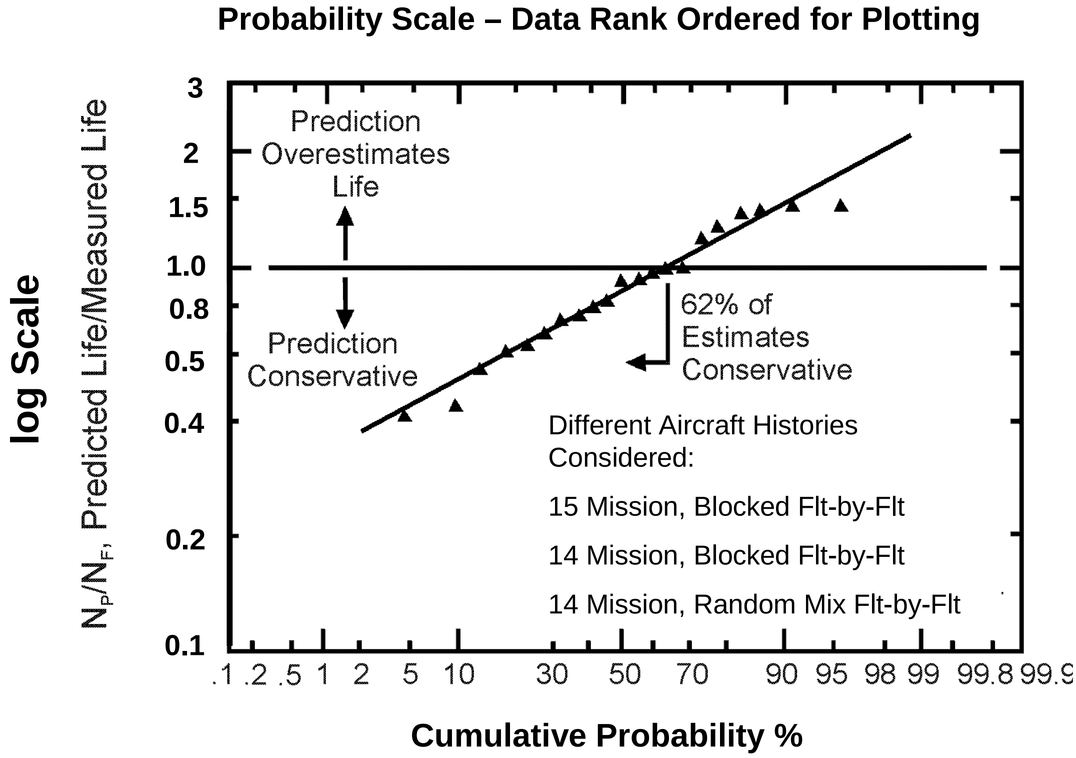

Figure 18. Use of Log-normal Probability diagrams to conventially assess the accuracy of fatigue crack life predictions and the variability associated with such predictions for a given life prediction method [29].

The use of probabilistic tools for presenting the accuracy and variability of structural models is both convenient and general. Various probabilistic approaches have been used, normal distributions (suitable for stress analysis, loads analysis and strength model validations), log-normal distributions and Weibull distributions (useful for describing usage variability and life prediction methods). These methods can be utilized to validate individual modules of a total structural life prediction method as well as to define the overall capability to estimate the occurrence of damage.

THE FUTURE OF STRUCTURAL INTEGRITY

There are several other issues that require discussion because they could lead to substantially improved airframe structural integrity for future aircraft.

Favoring fail-safe redundancy in design

The USAF institutionalized damage tolerance (DT) analysis with the 1975 ASIP Standard requirements, and provided several options for designers/manufacturers to demonstrate compliance with these requirements. The designer/manufacturer could choose to demonstrate compliance using two different design concepts referred to as: slow-crack-growth design and fail-safe design concepts. The slow crack growth design concept must be used for single-load-path safety-of-flight structure. For this design concept, the designer/manufacturer was required to show that rogue flaws would not grow to failure during two lifetimes of service loading.

Fail-safe structure required that the design demonstrate either a period of un-repaired usage prior to detection of element failure or by crack arrest capability. While the 1970 compliance requirements do not impose restrictions on today's analytical capability, they were challenges for the 1970 vintage structural analysis tools. So an opportunity was given to the designer/manufacturer which allowed them to qualify their fail-safe design concepts in the same way as that of the single-load-path structure, i.e., by using the slow crack growth requirement.

Unfortunately, over time, the slow-crack-growth concept was accepted for routinely designing structures and this has resulted in less redundant (less fail-safe) designs. The USAF intends to re-emphasize and favor fail-safe redundant design concepts in its future airframe programs. We plan to work with industry to develop approaches that guarantee damage tolerance capability using designs that don't favor single-load-path design concepts.

Considering alternate (multiple and variable) design mission usage

Typically, Fighter and attack aircraft operate to support missions and roles beyond those envisioned during design. Experience has demonstrated that alternate mission usage can have a significant impact on the aging damage accumulation rates (as well as sites where damage is experienced). Changes in roles and missions often lead to aircraft capability enhancements that change the stores and weapons, lead to aircraft weight growth, and require the aircraft to operate in different operational environments.

Given today's analytical modeling capability, it seems logical to suggest future aircraft structures be designed to thoroughly evaluate the structural sensitivity to loading that includes more than the contractual required design load mission spectrum. Sensitivity evaluations would focus on uncovering locations which are prone to fatigue damage when the aircraft is subjected to alternate missions. For those fatigue sensitive locations, risk assessments could be then conducted to determine if a local redesign is appropriate to minimize durability related problems in service.

Careful of optimizing airframe design based on one choice

Design/Manufacturing organizations optimize the choices of structural material (e.g., metallic alloy, composite, etc.), manufacturing process (e.g., welding, casting, etc.) or structural configuration concept (e.g., unitized, layered hybrid, etc.) so that the structure satisfies a design performance objective (i.e., a weight target or an acquisition cost target). Frequently, the organization meets its design objective by primarily focusing on a single design criterion, i.e., static strength, damage tolerance resistance for a material. Optimizing the design using a single criterion can result in choices that lead to sustainment problems. For example, choosing a material to be more damage tolerant may lead to early fatigue cracking due to the lack of material resistance to fatigue or corrosion. We suggest that both the design/manufacturing organization and the procurement organization NOT take a too narrow view when working to meet design criteria, since such narrow view could result in additional life cycle costs. The objective would be to NOT optimize choices based on one property exclusive of others that could impact sustainment.

STRUCTURAL INTEGRITY RESEARCH AND DEVELOPMENT REQUIREMENTS

Structural integrity technologies have played a vital role in the design and certification of new aircraft as well as in the sustainment of legacy aircraft. Further advancements in predictive analyses, inspection techniques, damage prevention methods, and repair and part replacement technologies are required to ensure legacy aircraft meet their required operational lives. Fatigue cracking, corrosion (uniform, exfoliation, crevice, intergranular), stress corrosion cracking, and disbonding (honeycomb and composite) continue to represent the principal concerns for maintaining the structural integrity of fielded aircraft. An assessment of the needs and priority of research needs for the defined aircraft was based on interactions with the structures community. Research and development programs are recommended to provide the technology for existing and emerging ASIP challenges with ensuring flight safety, mission readiness, and cost effective, preventative maintenance. Future research and development programs should be aimed at cross-platform solutions and should address these existing and emerging ASIP challenges. The following secondary sections highlight major themes for future research and development.

NDI for Crack and Corrosion Damage

Nondestructive evaluation/inspection (NDE/I) is a key component of the maintenance and safe operation of USAF's Aging Fleet. Two types of research are required: 1) better methods for improving inspection reliability and 2) improved NDI methods for identifying, characterizing, and quantifying hidden cracks and corrosion in aging aircraft structures.

For improving the inspection reliability, it is recommended that additional attention be given to the interaction between crack size distributions and the probability of detection (POD) used to characterize the inspection capability. This would include additional focus on quantitative NDE methods. Probabilistic analysis methodology should be used as the basis for this evaluation to define the key parameters which can be used to continuously re-evaluate the actual inspection capability.

The requirement for POD methods and NDE calibration improvements are increasing with the waves of new inspection procedures and NDI equipment systems that have to be developed to support the aging fleet. This evaluation should include a comparison of the predicted vs. actual crack size distribution discovered during the inspection (See Figure 19 [18, 30, 31]). Research is needed to reduce sample preparation and testing efforts involved in POD studies while improving the confidence of their results. While the NDI system POD is normally generated under laboratory conditions for the expected range of cracks expected to exist in a particular structural region, it is not always possible to capture the effects of the operator or environmental conditions on the POD evaluation. Furthermore, it is recommended that attention be given to defining and integrating the impact that human factors have on the accuracy of the inspection results.

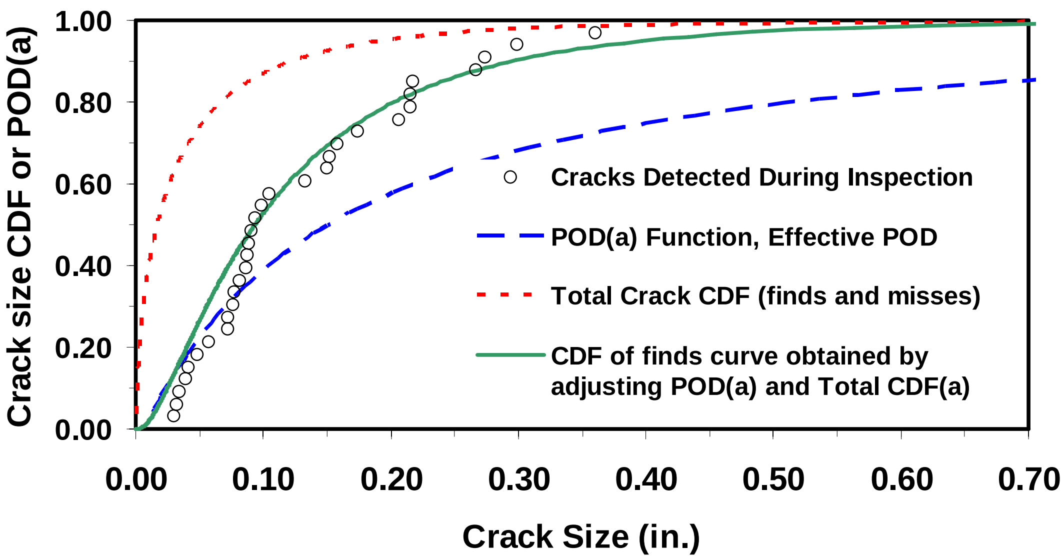

Figure 19. Iterating function parameters for POD and crack size distribution functions can provide best fits to inspection crack detections. Beren's approach allows for estimates of the Effective (or Operational) POD for aircraft at a specific location [18].

To reduce the inspection burden associated with maintaining aging airframes, research and technology support should be directed at investigating advanced methods for interrogating thick aerospace structures (e.g., wing) and multilayer structures for fatigue cracking and corrosion damage.

Typically, the most challenging inspections involve complicated geometries such as multilayer wing, joints of multiple structural elements (skins, spar caps, attachment fittings), wing-carry-through structure, and bulkhead-longeron connections. Some of the multilayer structures involve multiple materials (aluminum, steel and titanium layers with dissimilar metallic bushings). Typically, individual aircraft local area solutions are developed for each today. Enhanced understanding is required to generalize some key geometrical and materials features are required to support technology development for this class of problems.

The focus of NDE/I research should be on minimizing the structural disassembly required to conduct the inspection, and especially to minimize fastener removal. Extension of the operational lives of most USAF aircraft requires the inspection of integral structural members to provide the ASIP community an assurance of the integrity of these components. These complex structures require technology development beyond the capabilities of existing NDI technologies to enable the inspection of thick regions or to inspect subsurface layers where the interfaces disrupt the inspection signal.

Improved NDI methods are also needed for smaller defect detection capabilities, penetration into deep structures, ability to inspect without coating removal, and the ability to discriminate between preexisting or repaired corrosion and new corrosion. These new inspection techniques must also be capable of rapid corrosion detection over large areas. In addition to the above, enhanced understanding is required of the ability of any particular inspection system to detect damage present in the structure.

Risk Management

Over the last several years, aircraft ASIP Managers have become increasingly familiar with the use of risk assessment methods for enhancing the interpretation of current ASIP deterministic analyses. However, the lack of airplane specific databases prevents the routine use of these tools for many serious structural integrity problems. The databases that are required contain damage findings generated from inspections that are part of normal or urgent maintenance actions (See Figure 15). Several weapon systems are building damage findings databases in cooperation with their depot engineering organizations. This will facilitate the application of quantitative risk assessments by providing one key input to any risk analysis– the crack size distribution.

Off-the-shelf risk assessment tools focus on fatigue crack growth behavior and fracture mechanics approaches rather than on how aging processes in general degrade the residual strength. To generalize existing models, we must develop relationships between residual strength and each aging process (fatigue, corrosion, wear, etc.) that results in the loss of residual strength as a function of time in service. This approach would leverage the kind of modeling accomplished using crack growth behavior; it would also utilize the probabilistic foundation provided by many of the early aircraft reliability studies (See for example [32]).

For widespread acceptance of a reliability-based design approach for new aircraft, it will be necessary to develop confidence in the basic risk assessment methods as they are applied to fielded systems. Additional attention must be given to developing a risk quantified life prediction methodology to support aircraft both in design and sustainment. This methodology then becomes the basis for a broader risk quantified fleet management approach at the inventory level. Additionally, the technical foundation of this methodology can also be used to supplement vehicle health monitoring systems to provide near real-time system evaluation, thereby improving availability.

IT Integrated ASIP Fleet Management System

The primary purpose of ASIP is to prevent structural failures. Another purpose of ASIP is to anticipate degradation requiring maintenance action and to mitigate this potential using a preventive maintenance strategy. Most weapon systems have the structural tools to address crack and corrosion findings and to provide information that defines the structural maintenance decisions. Unfortunately, these tools, even when they have been periodically updated, are not organized to take advantage of the application of IT that allow coupling information concerning those factors that affect aging with indications of where aging has already occurred. New types of aging problems require more extensive structural modeling, such as improved stress analysis, new stress intensity factor analysis, and assessments of nonlinear structural and geometrical behavior. Furthermore, the existing tools are not integrated with fleet management decision-making, and the framework is not in place to integrate new tools into the tool box for convenient and routine application.

To anticipate damage found in service, and to update an aircraft's preventative maintenance plan to address this damage, it is necessary to have a modern integrated IT supported structural analysis tool set, which allows for a rapid assessment of structural risk. This tool set should have the capability to facilitate conducting updated damage-tolerance analysis (DTA) which provides data that are the foundation of structural maintenance planning. Most of the basic structural analysis tools reside with the original equipment manufacturer and the data resulting from applying these tools to fatigue and fracture critical locations could provide the basis for Owner/Operator and program Office fleet management decision making.

The tool set should be able to rapidly assess: a) usage severity effects, b) risk of catastrophic structural failure, c) new cracking/corrosion scenarios, d) the impacts of residual stresses on fatigue lives (especially those which involve the use of processes that create deep surface compressive residual stresses), e) the probability of failure given situations where the onset of widespread fatigue damage (WFD) may occur or where the single manager is trying to determine the best approach for managing the fleet within defined budgets, and f) estimate the remaining service life of the principal structural components (wing, fuselage, etc.).

The ultimate object of the IT-based structural tool set is to provide the operating customer with the data necessary to react to new cracking problems and to support budget decisions that ensure continuing airframe structural integrity. The collection of individual tools also support: the development of reliable business case models that have the capability for assessing solution choices (repair, replace, inspect, retire…) and that can be used to assist in making intelligent decisions when addressing structural problems. Business case models are fueled by fleet management data that currently are not conveniently stored in on-line databases that take maximum advantage of information technology.

This requirement exists to apply an improved, cost-effective, fleet management tool set, one which combines data that describe the severity of usage with data that define the extent of the aging processes and their impact to the structure. Multiple weapon systems requested this kind of improved capability to support their depot needs. All other fielded weapon systems would also benefit from a modular IT-based fleet management system which provides an integration of those data that describe the causes of aging with those data that describe the effects of aging.

There are immediate requirements in this arena (high priority assistance today for the Depots and for the fielded fleets), near/mid term requirements (where technology transition and/or manufacturing technology programming is needed for the implementation of new science and technology developments) and long term requirements (where essential laboratory/academia programming is defined based on the recommendations from the systems engineering and sustaining engineering communities).

The R&D community should develop and validate analytical approaches that can be used both in design and sustainment that builds an integrated, modular, IT-based, structural tool set that incorporates a database that stores information associated with both usage and aging damage. While advances to any number of structural tools are required, the R&D focus should be on those tools which are less mature and would have a significant impact on fleet management.

In particular, we recommend concentrating on enhanced risk assessment tools for decision making and improved life prediction tools that account for crack damage in the presence of residual stresses, as well as determining limits for corrosion damage.

An essential part of the modular system is a broadened risk analysis capability for assessing risks of structural failures that could result from any of the potential aging processes important to a particular weapon system and its structural materials. The risk assessment module should be able to address tradeoffs of various maintenance actions with force structure and readiness needs to establish the most cost effective strategy for maintaining structural integrity. The risk assessment module should have the capability to utilize aircraft specific damage findings and usage information to project risk of structural failure as a function of remaining time in service.

Furthermore, to facilitate life extension decisions, the structural tool set should have the capability for estimating the crack growth life in the presence of residual stresses created by coldworking and surface treatment processes (e.g., laser shock peening and low plasticity burnishing). For the residual stress analysis capability, improvements in finite element methods that deal with localized yielding and cyclic plastic deformation are required along with the capability for addressing crack damage in the presence of residual stresses.

To address the impact of corrosion damage to the strength capability of a structural element, the structural model must be able to address the various types of corrosion damage that can exist in the structure. We recommend that the modeling focus on the impact of exfoliation damage and localized pitting damage.

Corrosion Prevention

New approaches to corrosion prevention are needed for reducing aircraft maintenance burden. Effective methods for corrosion prevention will mitigate many current issues with respect to corrosion repair and management. Figure 20 describes a systems engineering approach based on the ASIP framework to synergistically attack the structural corrosion issues.

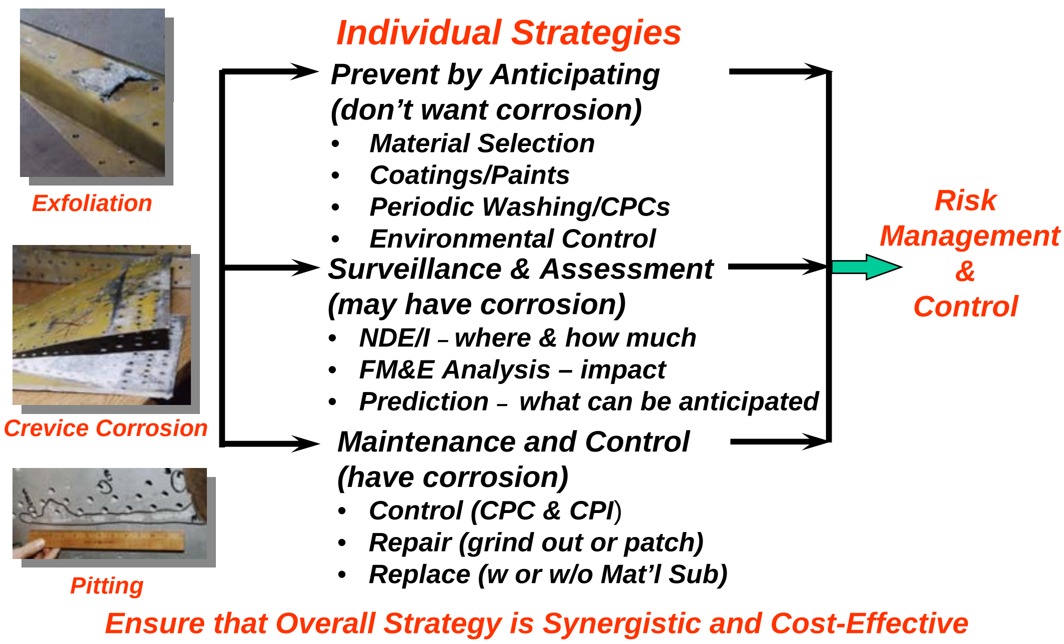

Figure 20. Overall Scheme to support managing structural corrosion

Innovative corrosion prevention schemes will involve the development of corrosion-resistant materials; advanced manufacturing process and design; and improved paints, coatings, sealants and corrosion-prevention compounds (CPCs). Research should be aimed at developing alloys with a combination of improved mechanical and corrosion resistance properties. These efforts are not limited to improved alloys but also include the development of affordable processing methodologies that will enable, for example, titanium alloys to be cost competitive. Additionally, improved material process and design applications should be developed that eliminate the requirement for welds and fasteners where moisture intrusion typically occurs and/or allow for moisture drainage.

New paints, coatings, sealants and CPCs should be formulated to improve corrosion protection while still being environmentally and worker friendly. Advancements in nonchromated primers indicate progress is being made to provide comparable corrosion preventive properties of chromated primers, but further testing and research is needed to ensure equivalent protection across all applications. Topcoat and appliqué finishes play a large role in corrosion prevention and require durability specifications that will satisfy appearance expectations of end users. Performance improvements in CPC technology will advance prevention as part of field level maintenance.

Although longer term, research should also be aimed at developing improved tools and prognostic models to detect and predict corrosion. Prognostic models and corrosion analysis tools that will 1) allow the fast and rapid identification of aircraft zones that might be susceptible to environmental attack, 2) allow the measurement of structural corrosion growth rates, and 3) predict corrosion rates and the associated degradation in component properties will eventually result in further reductions in inspection and maintenance requirements. Some of the recent work by Saff, et al. [33] might prove useful in this regard.

CONCLUDING REMARKS

To adequately satisfy Leadership for anticipating future structural integrity issues, the USAF must ensure that the ASIP systems framework and its engineering and management processes generate the information required to make sustainment decisions. The types of information requested by senior Leaders are presented at the bottom right of Figure 21. The information shown in the usage diagram summarizes for program managers whether usage is more severe than planned so that they can better anticipate when they need to change existing maintenance plans and budgets for addressing future structural integrity issues Similarly, if a program manager knows the anticipated impacts on current maintenance resources and associated maintenance purchases he/she can strive to maintain minimum depot cycle times. The projected maintenance plan resources information could also be converted to an indication of availability impacts associated with structural integrity issues and ultimately defines any impacts to the aircraft fleet’s economic life or to anticipated structural risks for catastrophic failure.

While managing fleets of aging aircraft is challenging, the USAF’s structural integrity track record is good, but there are major challenges ahead, and as discussed in the paper, the USAF is working to address these challenges.

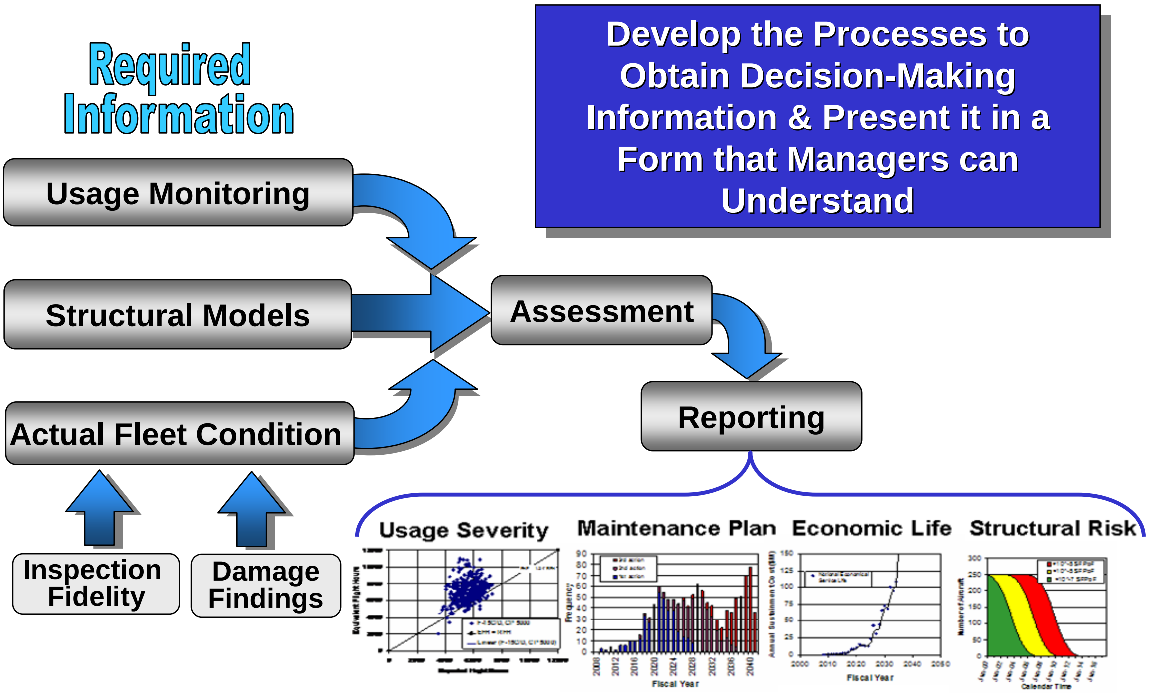

Figure 21. Schematic describing the type of information required to develop a structural integrity assessment and to produce required decision-making information for USAF Leaders.

The USAF uses an annual review of the ASIP systems framework and its engineering and management processes to identify process issues or situations that might inhibit the development of information required to maintain structural integrity and to anticipate structural failures. Structural failures as defined by USAF Leadership not only include catastrophic structural failures resulting in loss of aircraft and fatalities, but failures to anticipate major impacts to unscheduled maintenance and to availability.

The ASIP reviews have identified key common: 1) process issues which directly impact our ability to anticipate and control the risks of structural failures, 2) best practices being employed by various aircraft weapon system program offices, and 3) technology needs that enhance the process elements and the overall integrity program.

The USAF has instituted an ASIP focus that utilizes risk-driven decision making. This focus was institutionalized as a key element of the updated ASIP Standard (MIL-STD-1530C). The risk-driven approach provides an improved framework for addressing and controlling risks resulting from the growing crack populations (i.e., that grow both physically and at multiple locations) associated with aging. The growing fatigue crack (more generally damage) population significantly contributes to the risks of structural failure. And as part of its overall risk-driven method, the USAF now requires that aging-related damage information be collected, stored and used to assess structural health and the risks of failure. To be effective, the ASIP must define and mitigate these aging risks.

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