Airframe Digital Twin

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Abstract: Airframe Digital Twin (ADT) is a concept for enabling the Condition-Based Maintenance Plus Structural Integrity (CBM+SI) process. The objective of Airframe Digital Twin Spiral 1 is to develop and demonstrate a probability, risk-based, flight-by-flight Individual Aircraft Tracking (IAT) framework to replace the baseline deterministic IAT framework currently used for legacy aircraft. Key uncertainty drivers and promising areas for future research will be identified. The feasibility of the approach for application to legacy fleets will be assessed.

The approach of Airframe Digital Twin Spiral 1 is to integrate technologies developed in Stick-to-Stress Real-Time Simulation, Hot Spots Structural Health Monitoring (SHM), and Risk-Informed Decision Making programs into a modular probabilistic framework for planning aircraft maintenance based on control-point-by-control-point, flight-by-flight risk analysis with uncertainty quantification (UQ) and Bayesian updating. The framework will be used to perform sensitivity analyses and identify technology gaps and opportunities for reducing uncertainty through technology development. The feasibility and benefits of ADT will be demonstrated by comparing its results to those of conventional IAT for (a) two "surrogate tail numbers" and (b) a complete legacy fleet.

The three primary demonstration goals of Airframe Digital Twin Spiral 1 are as follows: (1) Demonstrate an integrated "CBM+SI" process as a potential alternative to the current Aircraft Structural Integrity Program (ASIP) IAT Program process. The demonstration will include usage estimation, selected "hot spots" SHM, and frequently updated damage tolerance and risk analyses. Two full-scale fatigue tests of a real United States Air Force aircraft structural module will be used in lieu of a flight test. A "conventional" IAT Program approach and the associated full-scale fatigue tests will be carried in parallel to facilitate comparisons of the two approaches. (2) Enhance in-house expertise in CBM+SI Technology Focus Areas and ASIP engineering processes. Accomplishment of the goal will enable engineers to see where their technology fits into the ASIP process and understand how the multiple disciplines interact with each other. (3) Create an enduring analysis integration framework and test set-up procedures for the assessment of additional analysis and monitoring techniques as they mature. This will provide a CBM+SI "test bed capability" and a first-generation Airframe Digital Twin.

BACKGROUND

This section identifies the airframe sustainment strategic goal to be achieved, the United States Department of Defense Condition-Based Maintenance Plus (CBMI+) initiative established to achieve the goal, and the Condition-Based Maintenance Plus Structural Integrity (CBMI+SI) vision created to enable the successful execution of the CBMI+ initiative.

<u>Sustainment Strategic Goal</u>

The airframe sustainment strategic goal being addressed in this effort is to eliminate programmed maintenance and repair cycles. Rather than calendar-based maintenance and repairs actions that are performed for numerous aircraft at pre-determined times, condition-based maintenance and repairs would be performed at times that are determined based on the structural condition of the individual aircraft of interest. Hence, individual aircraft would be brought in for maintenance and repairs only when those actions are needed. This would result in a significant reduction in the maintenance burden and life cycle costs of the aircraft while significantly increasing the aircraft's availability.

Condition-Based Maintenance Plus (CBM+) Initiative

The Condition-Based Maintenance Plus (CBM+) initiative [1, 2] was established to achieve the sustainment strategic goal previously described. CBM+ consists of maintenance processes that are performed based upon evidence of need for maintenance from embedded sensors, nondestructive inspection (NDI) including human senses, and models. CBM+ requires decisions (e.g., when, where, who and how maintenance will be performed) to be made throughout the entire lifecycle of an aircraft. The focus of CMB+ is on improving maintenance practices.

The CBM+ initiative can be schematically described by the pyramid [3] shown in Figure 1. The height of the pyramid represents increasing complexity and cost; the breadth of the pyramid at any height represents its breath of applicability (e.g., number of applications). The portion of the CBM+ initiative that is complex and costly (i.e., near the apex) usually has very specialized and limited applications. However, the portion of the CBM+ initiative that is less complex and costly (i.e., near the base of the pyramid) is widely applicable.

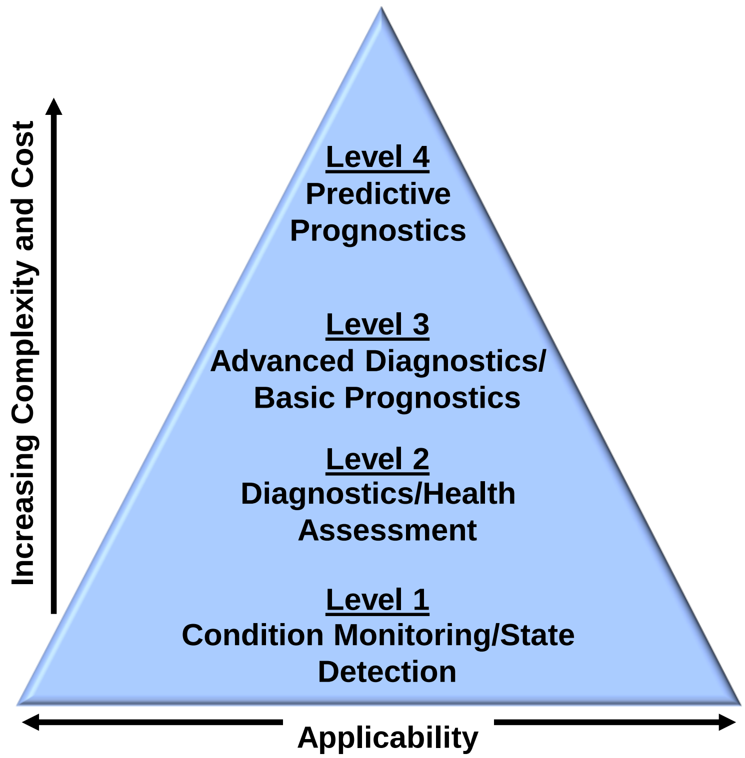


Figure 1. Complexity vs. Applicability Pyramid

Level 1: Condition Monitoring/State Detection: An aircraft's flight history is compared against expected values or operational limits. Loads/Environment Spectrum Survey (L/ESS) data are compared to either the design usage or the average usage spectrum. Individual Aircraft Tracking (IAT) Program data relate each aircraft's actual usage to the expected baseline usage. Additionally, the Aircraft Structural Integrity Program (ASIP) institutes a process for detecting structural anomalies. Regular nondestructive inspections (NDI) are performed to detect structural cracking and corrosion.

Level 2: Diagnostics/Health Assessment: Updates are required to the L/ESS, Durability and Damage Tolerance Assessment (DADTA), IAT, Force Structural Maintenance Plan (FSMP), corrosion assessment, and risk analysis.

Level 3: Advanced Diagnostics/Basic Prognostics: The probabilistic distribution of remaining useful life (RUL) for an aircraft is to be determined within one standard deviation based upon past usage and fleet-wide averages. Risk analyses are to be used to: (1) evaluate detected and anticipated aircraft structural damage, (2) evaluate economic and availability impacts associated with maintenance operations, and (3) determine the risk to structural integrity associated with operating beyond the design service life. However, structural risk analysis has been limited to crisis situations due to lack of data and knowledge.

Level 4: Predictive Prognostics: This level is limited to specific structural locations. Aircraft structures have wide varying times to reaching service life limit due to fatigue, corrosion, etc., as a result of inherent material property scatter and compounded by unknown and variable damage due to manufacturing and maintenance. Local sensors are required to determine RUL due to scatter. Aircraft structures have thousands of critical locations and it's not practical to place sensors in all of them.

ASIP employs the first three levels of CBM+ as currently implemented. However, a Predictive Prognostics (Level 4) capability is needed to successfully execute the CBM+ initiative. This is accomplished by the Condition-Based Maintenance Plus Structural Integrity (CBM+SI) vision described in the next subsection.

Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Vision

The vision of CBM+SI is to utilize the structural integrity concepts prevalent in the Aircraft Structural Integrity Program (ASIP) to successfully execute the CBM+ initiative. This requires extensive knowledge of the following four Emphasis Areas: (1) Damage State Awareness: current state of damage (e.g., fatigue cracking, corrosion, disbonds, delaminations, etc.), (2) Usage: loads and environment to which the airframe is subjected, (3) Structural Analysis: damage progression, residual strength, and remaining useful life, and (4) Structural Modifications: life enhancements, repairs and replacements. The required knowledge of these four emphasis areas can be provided by the nine Technology Focus Areas identified in Figure 2.

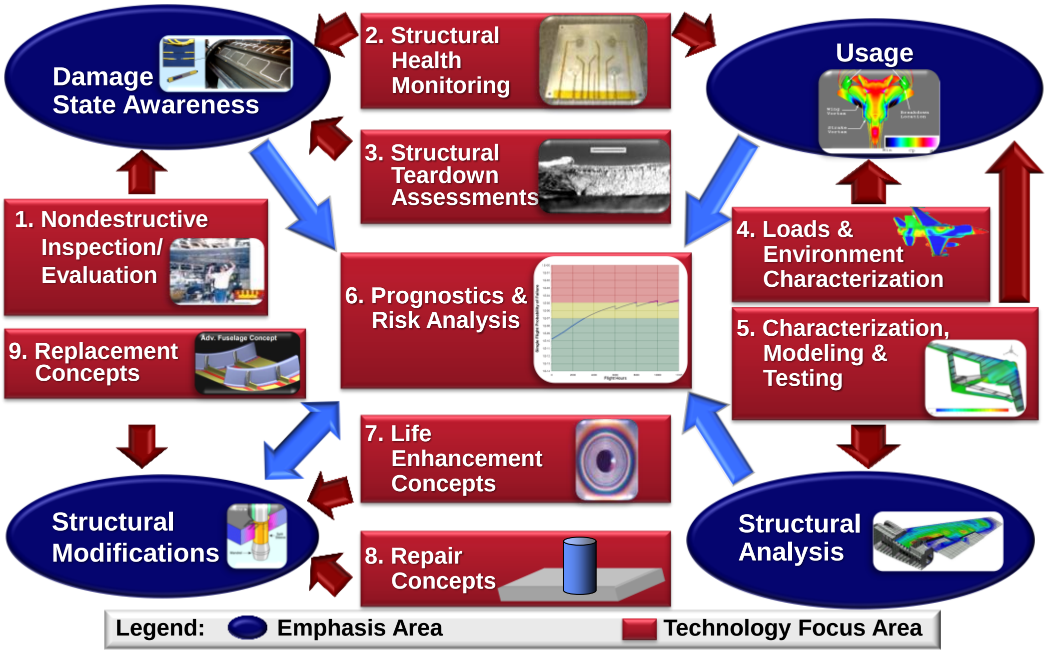


Figure 2. Contributions of Technology Focus Areas to Emphasis Areas

The CBM+SI mid-term (10-year) vision is described in the Air Force Research Laboratory's (AFRL's) Aerospace Systems Directorate's Vision 2009 document. The vision includes the realization of the following: (1) transformation of aircraft lifecycle management and maintenance practices that are efficient, standardized, integrated, and semi-autonomous, (2) structural capability of individual aircraft that is known and predictable: characterization of its current health, prediction of its future health, and planning of its future usage and maintenance actions, (3) quantification of risk of structural failure while enhancing safety, (4) reduction in the inspection and repair burden, (5) extension of the aircraft's remaining useful life, and (6) increase in aircraft availability and decrease in operational and support costs.

The CBM+ far-term vision was established in an AFRL CBM+SI workshop in February 2009. The vision included the development of the "Digital Twin" concept that would provide real-time, high-fidelity operational decisions for individual aircraft enabled by tail number health awareness. The vision includes the realization of the following: (1) delivery of a digital model at the time of delivery of a physical aircraft that is specific to tail number including deviations from nominal design, (2) digital model is flown virtually through same flight profiles as actual aircraft with the aid of a structural health monitoring (SHM) system, (3) modeling results are compared to sensor readings at critical locations to enable updating, calibration, and validation, (4) model reflects current state of actual aircraft including the addition of unanticipated damage that is found, (5) development of aircraft prognostics including "flying" the digital model through possible future missions, and (6) determination of when and where damage is likely to occur to determine when to perform maintenance. A more detailed description of the Airframe Digital Twin concept is provided in the following.

AIRFRAME DIGITAL TWIN CONCEPT

This section describes the Airframe Digital Twin (ADT) concept and the ADT Spiral 1 program including the contributions of the "SHM for Hot Spots" and "Risk-informed Decision Making" programs to the ADT Spiral 1 program.

Airframe Digital Twin (ADT) Description

Airframe Digital Twin (ADT) is an avatar for an individual physical airframe [3]. It is a cradle-to-grave model of an aircraft structure's ability to meet mission requirements. ADT represents the integration of data, models and analysis tools to form a "Digital Twin" of an individual aircraft. It's a high-fidelity model that incorporates knowledge of the physical condition, the physics operating at all scales (Figure 3), and how the aircraft has been flown in the past that together with projections as to how it will be flown in the future can be used to efficiently manage the aircraft throughout its service life. ADT, as an ultra-realistic model of the as-built and maintained airframe, is explicitly tied to the materials and manufacturing specifications, controls, and processes used to build and maintain the aircraft. In this way, the ADT is an integrated database of the history of the actual aircraft. It provides configuration control. It operates as a virtual damage sensor of the actual aircraft.

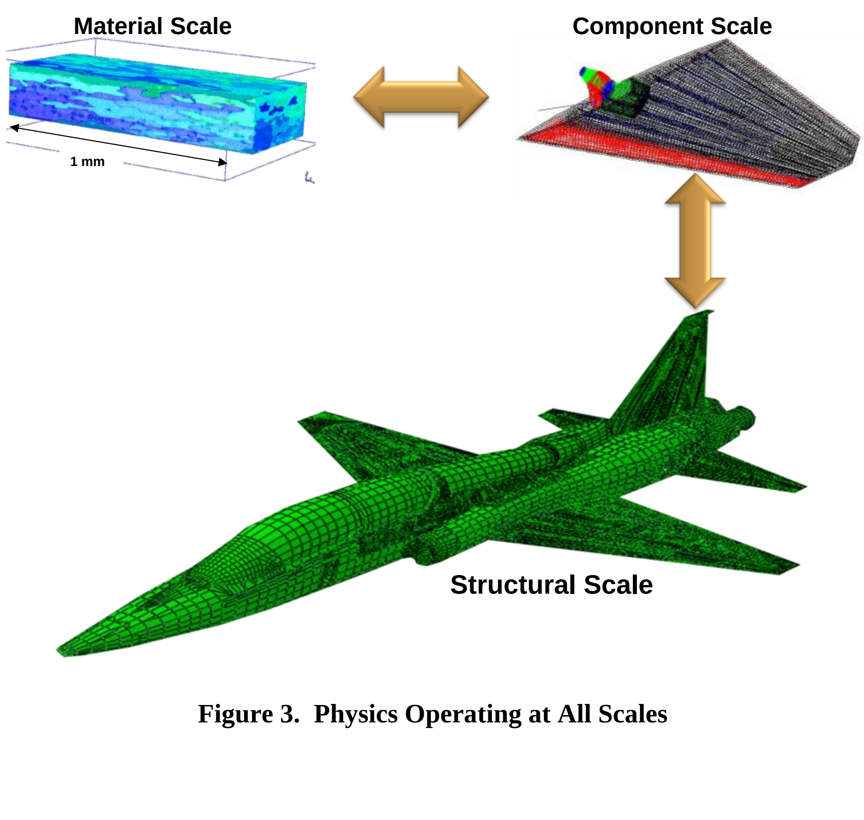


Figure 3. Physics Operating at All Scales

While talked of as a single model, the ADT is really an integrated collection of submodels as illustrated in Figure 4. These submodels are currently used separately with limited sharing of information between them. The major differences between the ADT and the current structural modeling process are the degree of integration between the submodels, the level of fidelity of the submodels, and the quantification of uncertainty in all calculations. All the submodels use the same tail number specific structural definition. The dimensions of all details of the physical airframe, along with the measurement error, are recorded in the structural definition of the ADT. The states of all materials and any uncertainty are also tracked throughout the aircraft's life. Any repairs of modifications to the physical airframe during service are also captured in the ADT. All of the submodels contain the best available physics for the given discipline. The output from any submodel (e.g., temperature, stress, or strain fields) is readily accessible by any other submodel. The output of each of the submodels is not a single number, but a probability distribution over the range of possible outcomes based upon the uncertainty in the inputs. As experience with a particular tail number accumulates, the objective is to update the ADT for that tail number using various proven statistical methods to reduce the uncertainty in the submodels so that over time the ADT becomes more representative of the aircraft [4].

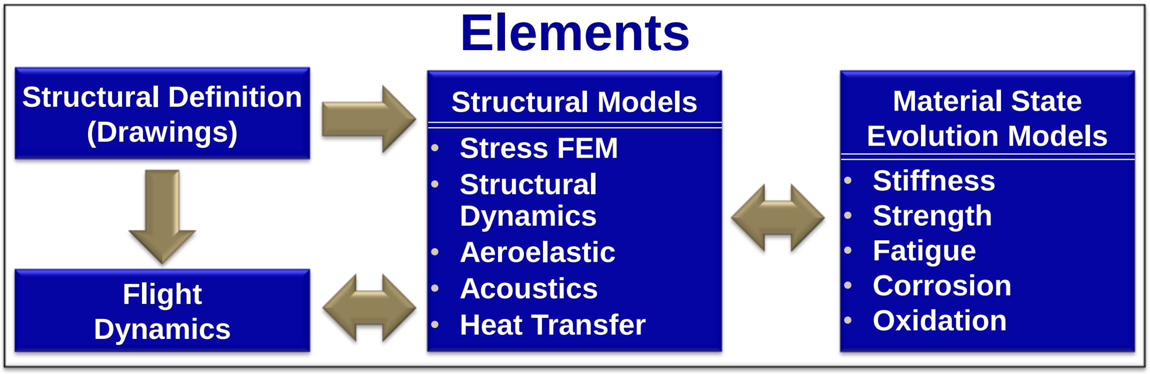


Figure 4. Elements of the Airframe Digital Twin

The shrinking defense budget and the increasing cost of the next generation of aircraft have resulted in fewer new aircraft being purchased. This means there will be fewer aircraft in the USAF inventory, and these aircraft will be kept in the inventory longer. These events have created a need for:

1) More efficient design and certification to reduce the acquisition cost,
2) Greater availability of aircraft, and
3) Decreased maintenance and support costs.

Specific goals that can help to satisfy these needs are:

1) Reducing the number of design changes after certification testing,
2) Minimizing the number and duration of certification tests,
3) Eliminating unanticipated cracking and failure, and
4) Minimizing the number and frequency of structural inspections.

With an ADT, a proposed design can be flown and tested virtually before any components are fabricated. Structural components that are unlikely to meet requirements can be redesigned before the aircraft is assembled and tested. As our ability to develop and utilize an ADT improves, there should be fewer surprises during testing and fewer redesigns required after testing. Airworthiness certification tests then become a means to validate the ADT, instead of the design. Certification tests can be efficiently planned for model validation using design of experiments. This will reduce the amount of certification testing required.

After aircraft are fielded, the ADT for individual tail numbers can be flown virtually to reproduce the flight history and estimate the damage currently in an airframe. In addition, the ADT can be flown any number of missions into the future in order to forecast the development of damage in the aircraft and anticipate the maintenance needs of the airframe. As uncertainty in the ADT decreases over the service life, the ADT can be relied upon to set inspection intervals so as to eliminate frequently repeated inspections during which no damage is found.

The ADT can be used throughout the life-cycle of a mission design series and of individual aircraft as illustrated in Figure 5. An overarching ADT (OADT) is created as the design of the aircraft model takes shape. The OADT contains the nominal design and designed in uncertainty, i.e., part tolerances, material property variation, etc. The probability of producing an individual aircraft that does not meet requirements can be determined with the OADT. Those design parameters which are most responsible for a failure to meet design requirements can be identified and the design modified prior to a single aircraft being built.

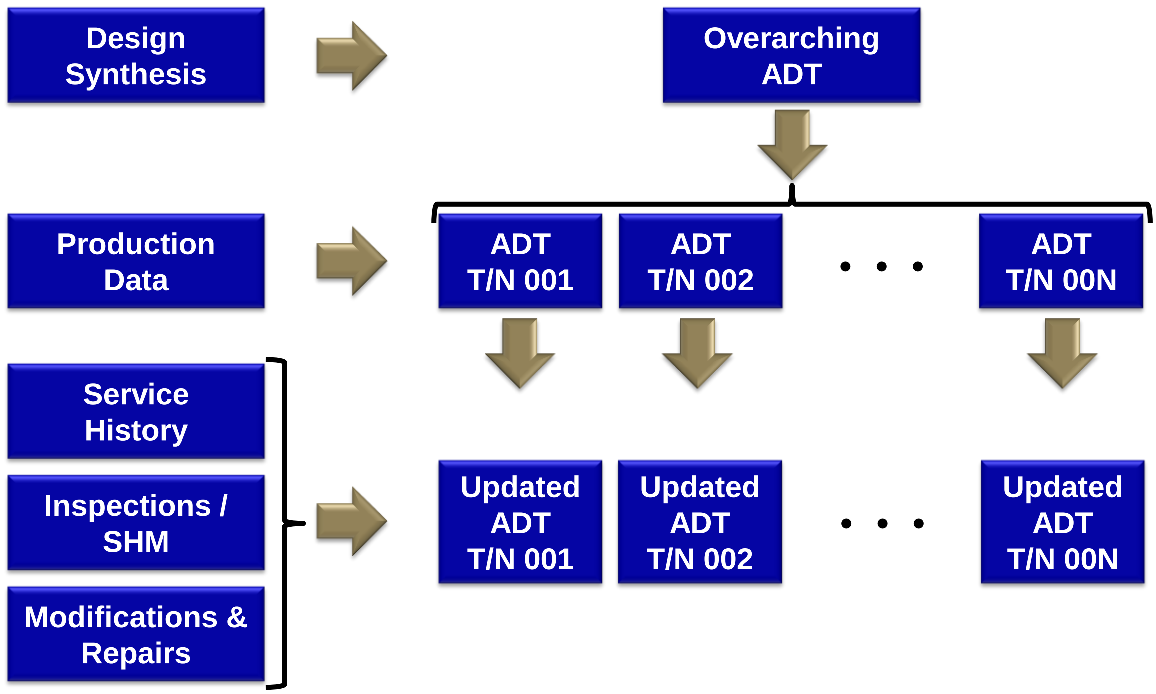


Figure 5. Hierarchy of Airframe Digital Twin Creation and Inputs at Each Level

There are numerous physics and engineering modeling challenges that need to be addressed for the Airframe Digital Twin to become a reality [4]. Those challenges can be grouped into the following broad categories:

1) Establishing the Initial Conditions for the ADT (e.g., the actual aircraft that is built may differ from the design due to manufacturing errors that will affect how the aircraft responds to loads)
2) Applying Correct Flight Loads to the ADT (e.g., the power of the ADT comes from simulating the continuous time history of a flight. A flight dynamics model can be coupled with an aeroelastic solver. Structural oscillations can be added to the rigid body motion measured by sensors on the aircraft)
3) Selecting and integrating the submodels for the ADT (e.g., several finite element models must be solved individually and the results shared between them: deformation of the structure, dynamic response of the airframe, and temperature fields. A hierarchical "search and simulate" strategy for forecasting when and where fatigue cracks will form is needed.)
4) Managing and Reducing Uncertainty in the ADT (e.g., the traditional approach towards bringing a model into agreement with reality is to "calibrate" the model to observed data. A better approach for "calibrating" a computer model such as the ADT is the Bayesian model calibration procedure [5].

Special attention needs to be drawn to managing and reducing uncertainty [3]. The uncertainty in most input variables and model parameters, expressed in terms of probability distributions, results in increasing uncertainty in results from the ADT the further in time we get from the current time. If the probability distributions for these variables and parameters are never revised, the ADT is never truly representative of the actual aircraft. One way to reduce the uncertainty in the input variables and parameters of the ADT is to perform experiments on the actual aircraft and use the results to refine the probability distributions. Each flight of the physical aircraft is essentially another "experiment" that reveals more information about the aircraft. This information could come from damage inspections - visual walk around, NDI, SHM damage sensing - usage monitoring, or other sources. Over time hundreds or thousands of "experiments" will be performed for a single aircraft. A formal, structured method that uses the results of these "experiments" to periodically update the ADT and the input distributions is Bayesian Model Calibration (Kennedy & O'Hagan, 2001). With Bayesian Model Calibration (BMC) we are able to quantify a model's predictive ability while also learning about and calibrating uncertain inputs. As shown in Figure 6, this approach accounts for the major sources of uncertainty in the modeling process; observation error and model bias or discrepancy. In addition to these uncertainties, the model results can be scaled proportionally by λ to reflect possible inadequacy of the model. Eventually, with continual BMC, the ADT becomes a "twin" to the airframe. In effect, the ADT becomes a virtual sensor for the health of the airframe.

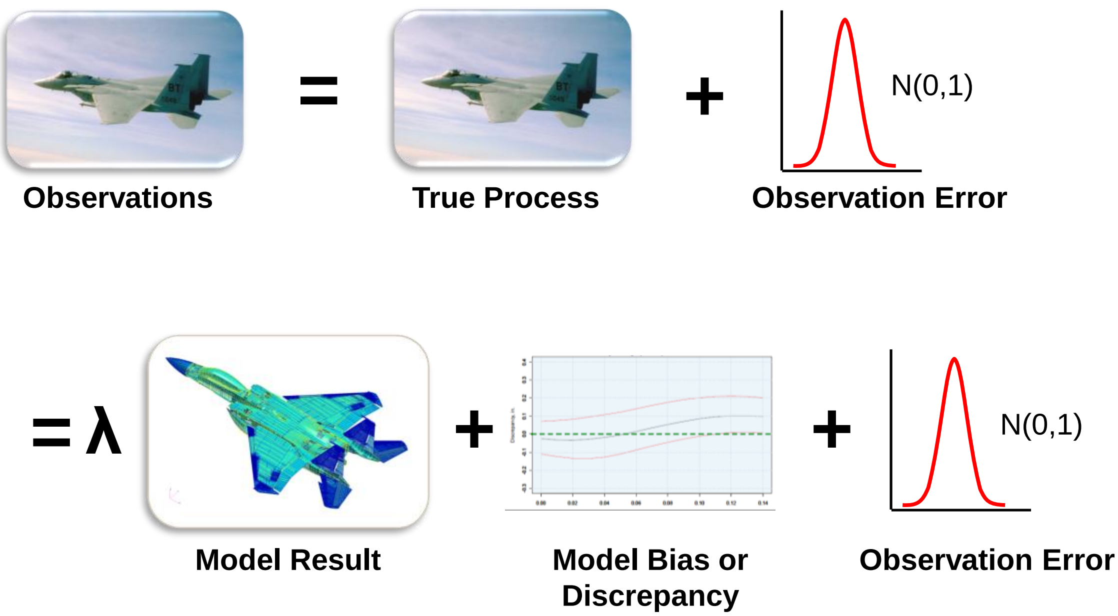


Figure 6. Bayesian Model Calibration Process

As previously stated, extensive knowledge is required of the four Emphasis Areas identified in the CMB+SI vision. There are challenges associated with each of these four Emphasis Areas that must be overcome before the ADT concept can be realized [3]. Some of those challenges are described below:

1) Damage State Awareness: Precursors to damage and to probabilistically model the likelihood of having these damage precursors at a given location needs to be identified. Both the initial state and repaired state of damage need to be quantified.

2) Usage: Knowledge of the fidelity of the loads/environment and of the individual aircraft flight loads is needed. Currently, the dynamic loads and the quasi-static maneuver loads are handled differently. With the introduction of digital technology, it is possible to faithfully reconstruct the load history of an entire flight including the dynamic loads by recording things like stick position, throttle setting, airspeed, control surface positions, etc., in flight data recorders.

3) Structural Analysis: The need exists for integrating models from multiple physics domains, determining the appropriate fidelity for the models in each of the physics domains, and putting the analysis on a high performance computer platform. Uncertainty in the inputs needs to be propagated through the analysis to enable the uncertainty in the results to be quantified. Advanced database techniques will be needed to store and access the results of these analyses as well as advanced computer visualization methods to graphically display them.

4) Structural Modifications: Knowledge of how structural modifications and repairs affect the response of the structure to loads is needed. Updates of these structural modifications and repairs need to be automated.

A spiral development approach is being taken in the development of the Airframe Digital Twin concept. A roadmap that describes three such spirals is presented in Figure 7. A more detailed roadmap that describes the Spiral 1 development is presented in Figure 8, which is described extensively in the next subsection.

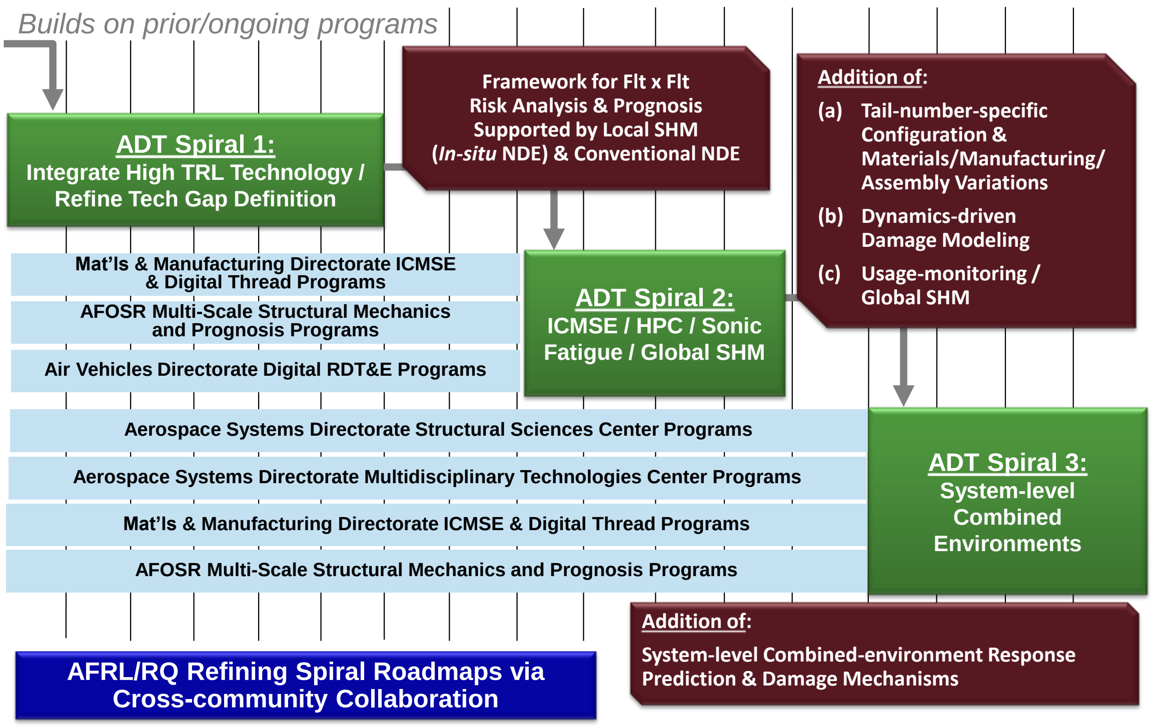


Figure 7. Spiral Development Approach

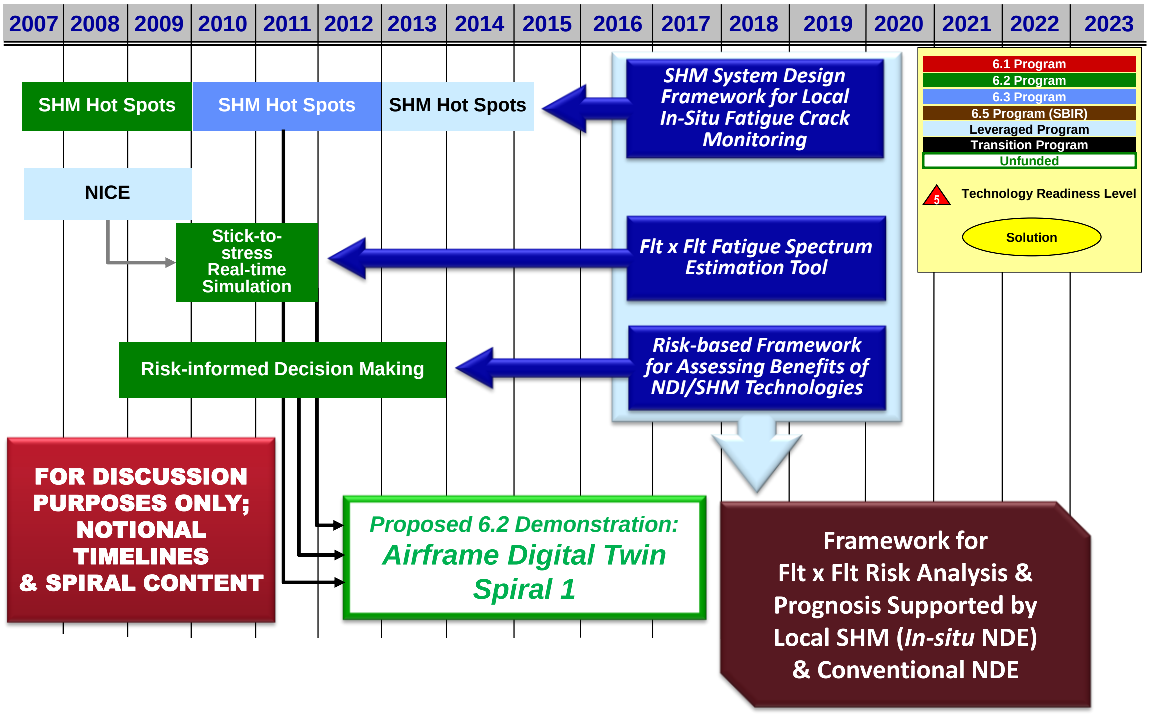


Figure 8. Spiral 1 Roadmap

Airframe Digital Twin (ADT) Spiral 1 Development

During the Operation and Support phase of the lifecycle of an aircraft, the Tail-number Specific ADTs (TADTs) would be used in the Individual Aircraft Tracking Program to track and anticipate the life limit of all structural parts to avoid catastrophic failures. Flight history data gathered for each aircraft as part of the Aircraft Structural Integrity Program can be used to "fly" each TADT virtually and simulate the internal loads and temperatures that the airframe experienced during each flight. The material state and damage evolution submodels in the TADT use the internal loads and temperatures to predict the condition of every component of the airframe. Findings from Nondestructive Inspections (NDI) or Structural Health Monitoring system queries are used to update the condition of airframe components which in turn reduces the uncertainty in the material state and damage evolution submodels in the TADT. Eventually, the uncertainty in predicting the damage state will become small enough that robust prognoses for each aircraft in the fleet can be developed by "flying" the TADT out ahead of the fleet. Structural issues that would arise as the aircraft continue in service can be anticipated, repairs designed, and individual aircraft scheduled for repair. An efficient and robust individualized Force Structural Maintenance Plan can be implemented. The above is illustrated in the ADT Spiral 1 development program described in the remaining paragraphs of this subsection.

The objective of the Airframe Digital Twin (ADT) Spiral 1 program is to develop and demonstrate a probabilistic, risk-based, flight-by-flight individual aircraft tracking (IAT) framework that will replace the baseline deterministic IAT framework currently used for legacy aircraft. Key uncertainty drivers and promising areas for future research will be identified. The feasibility of using the risk-based IAT framework for legacy aircraft will be assessed.

The approach of the ADT Spiral 1 program is to integrate the appropriate technologies involved into a modular probabilistic framework. This approach will enable the planning of aircraft maintenance by performing control-point-by-control-point, flight-by-flight risk analyses. The uncertainty of the input variables and model parameters will be quantified and periodically updated using the Bayesian Model Calibration process. The results of three research programs will be utilized in the ADT Spiral 1 program. Firstly, the results from the "Structural Health Monitoring (SHM) for Hot Spots" program will provide a SHM system design framework for local in-situ fatigue crack monitoring. Secondly, the results from the "Stick-to-Stress Real-Time Simulation" program will provide a flight-by-flight fatigue spectrum estimation tool. Thirdly, the results from the "Risk-informed Decision Making" program will provide a risk-based framework for assessing the benefits of NDI/SHM technologies. Sensitivity analyses will be performed to identify technology gaps and opportunities for reducing uncertainty. The feasibility and benefits of the risk-based approach will be demonstrated by comparing the results utilizing the approach to the results obtained utilizing the conventional deterministic approach. The comparisons will be made for two surrogate tail number aircraft as well as a complete legacy fleet.

For an Individual Aircraft Tracking (IAT) program, fatigue critical locations (FCLs) are selected for tracking purposes (Figure 9). Utilizing the conventional deterministic approach, analytical fatigue life predictions are made for these FCLs using a baseline usage spectrum (Figure 10). Baseline inspection intervals are established by dividing the analytical life prediction by a factor of two. The actual flight-by-flight usage of the individual aircraft is tracked and the analytical crack growth predictions are updated based on the actual usage. The actual usage is correlated to the baseline usage via a "Damage Index" and "Usage Severity Factor". The inspection intervals are adjusted accordingly.

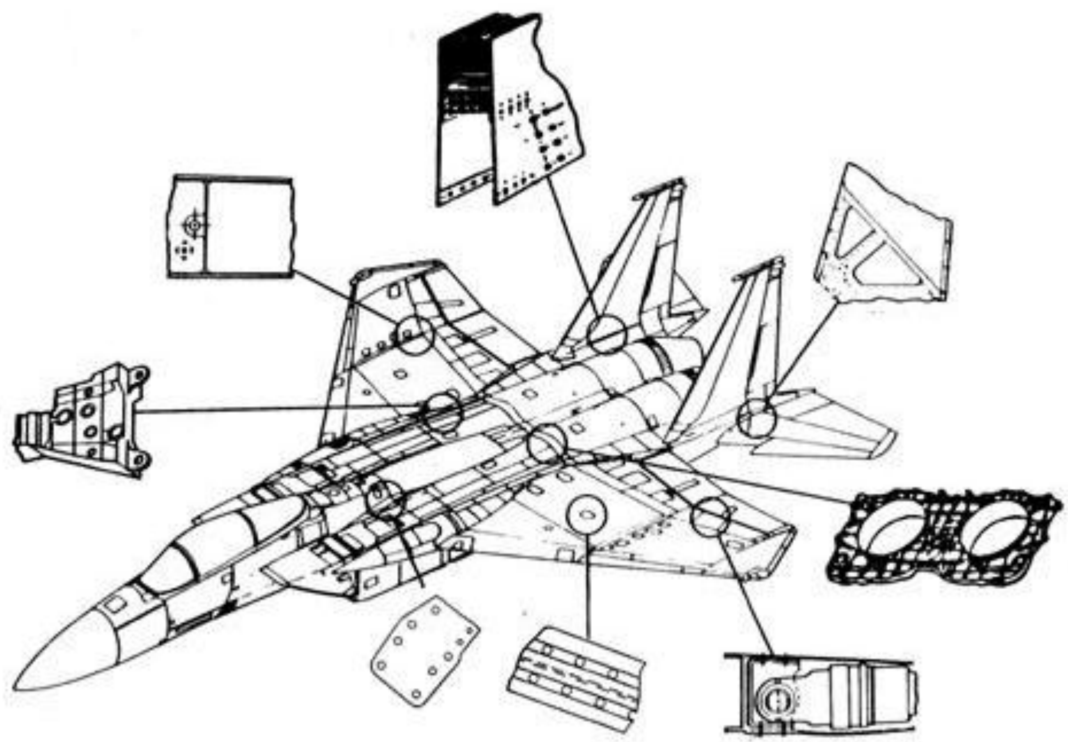


Figure 9. Directly Tracked Fatigue Critical Locations

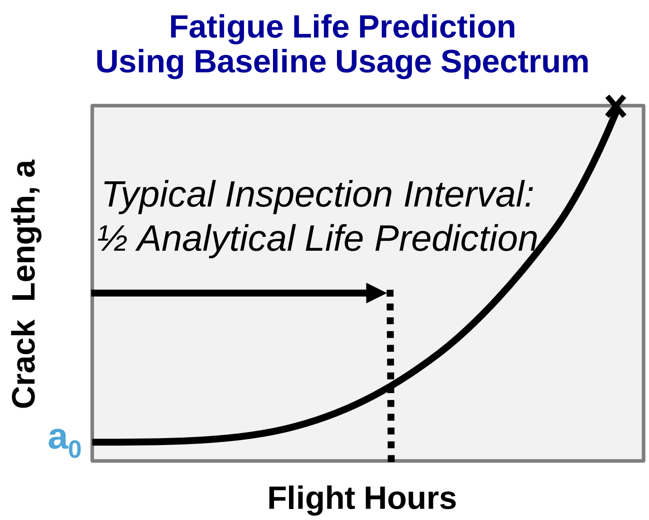


Figure 10. Fatigue Life Prediction Using Baseline Usage Spectrum

The inputs required to obtain the analytical fatigue life for each fatigue critical location (FCL) utilizing the conventional deterministic approach are identified in Figures 11 and 12. Those inputs are as follows: (a) Quality Assessment: an initial crack size which normally consists of assuming an initial rogue flaw size for damage tolerance analysis, a typical flaw size for durability analysis, and a probability-of-detection-based flaw size for post-NDI analysis, (b) Usage: stress history at each FCL, (c) Structural Property Data: stress intensity factor as a function of geometry, stress, crack shape and length, (d) Material Property Data: fatigue crack growth rates as a function of maximum stress intensity factor and stress ratio, (e) Damage Integrator: crack propagation model consisting of a cycle-by-cycle integration algorithm, and (f) Failure Criteria: fracture toughness used to determine the critical crack length.

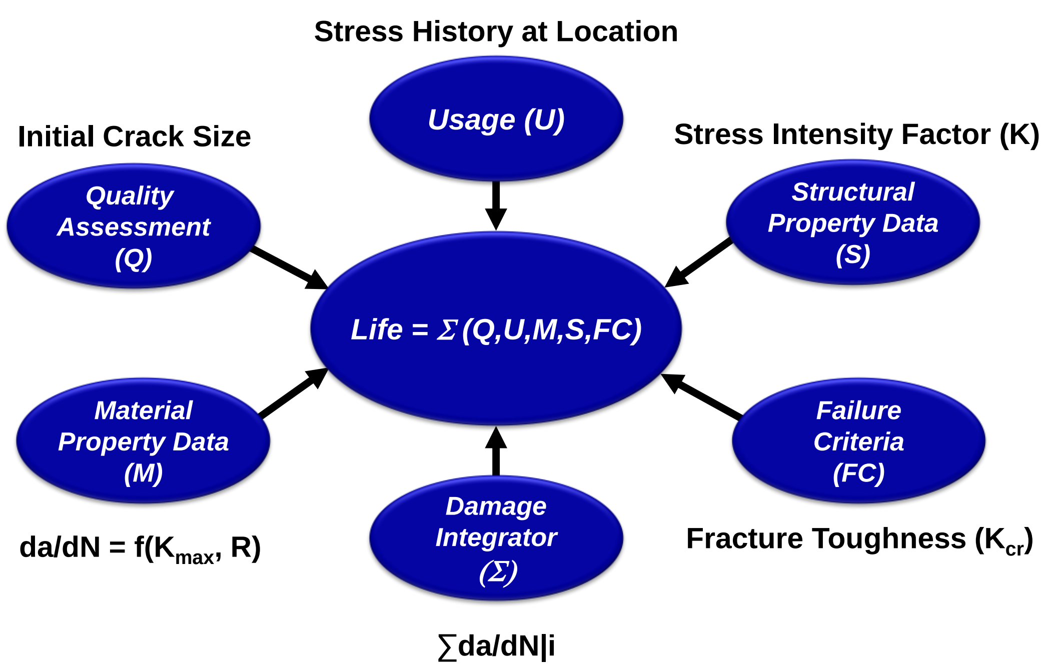


Figure 11. Generalized Inputs for Fatigue Life Prediction

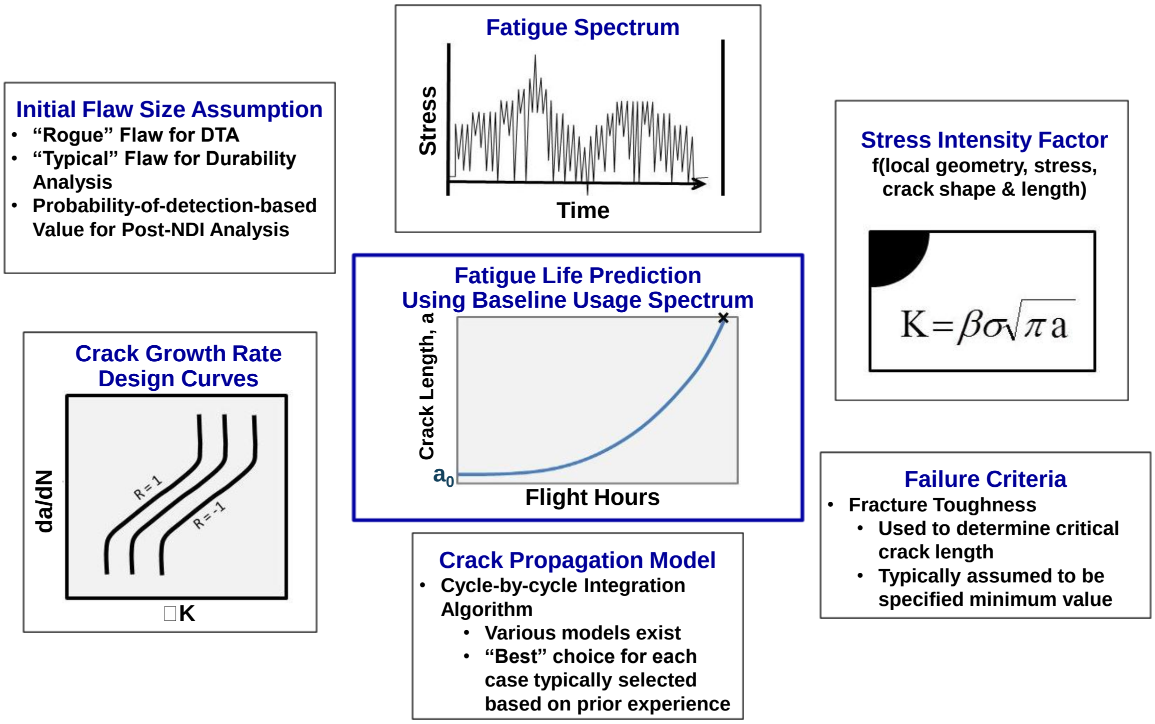


Figure 12. Specific Inputs for Fatigue Life Prediction

Updates to the analytical crack sizes obtained utilizing the conventional deterministic approach in the Individual Aircraft Tracking program are required after inspections for damage and actual aircraft usage is tracked. It is assumed there are no changes to four of the inputs to the fatigue life predictions (i.e., stress intensity factor, crack growth rate curves, crack propagation model, and failure criteria). When the inspection limit is reached, the following actions occur: (1) NDI is conducted per the Tech Order (TO), (2) the findings are recorded and reported, (3) any detected damage is repaired, (4) the analytical crack size is reset, and (5) the Individual Aircraft Tracking continues. Hence, the initial flaw size assumption after NDI is adjusted using a probability-of-detection-based value for the post-NDI analysis (Figure 13).

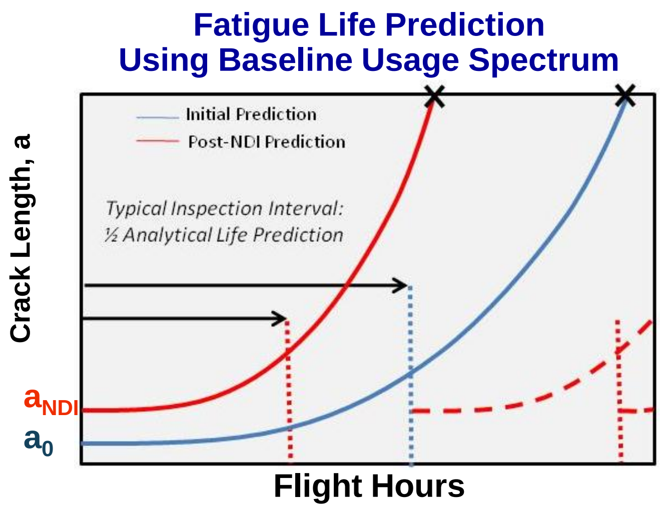


Figure 13. Updating Analytical Crack Sizes after NDI

Updates to the analytical crack sizes obtained utilizing the conventional deterministic approach in the IAT program are required after actual usage is tracked using one or more of the following methods: (1) crew chief "bubble sheet", (2) IAT system with counting accelerometers, (3) flight data recorder, and (4) L/ESS system with strain gages. Hence, the usage data must be converted into a fatigue spectrum for each IAT fatigue critical location.

A number of different assumptions, simplifications and conservatisms exist in several of the inputs used to predict the IAT fatigue lives utilizing the conventional deterministic approach, such as: (1) Initial Flaw Size Assumption: the rogue flaw assumption for damage tolerance analysis is usually highly conservative, (2) Fatigue Spectrum: the fidelity of the usage tracking data is questionable, (3) Crack Growth Rate Design Curves: average growth rates are typically used in the calculations. A scatter factor of two is normally assumed. Higher variability in the threshold and fast fracture regions can be problematic, and (4) Failure Criteria: the actual fracture toughness is often much higher than the specified minimum value.

Analytical fatigue life variability exists using the conventional deterministic approach. This is illustrated in Figure 14 which shows a fatigue life prediction using a baseline usage spectrum plus worst case and best case scenarios. The conventional deterministic approach cannot capture the variability as the actual "margins of safety" are essentially unknown. However, the probabilistic risk-based approach can account for variability/uncertainty (i.e., the "margins of safety" can be estimated over the life of the aircraft).

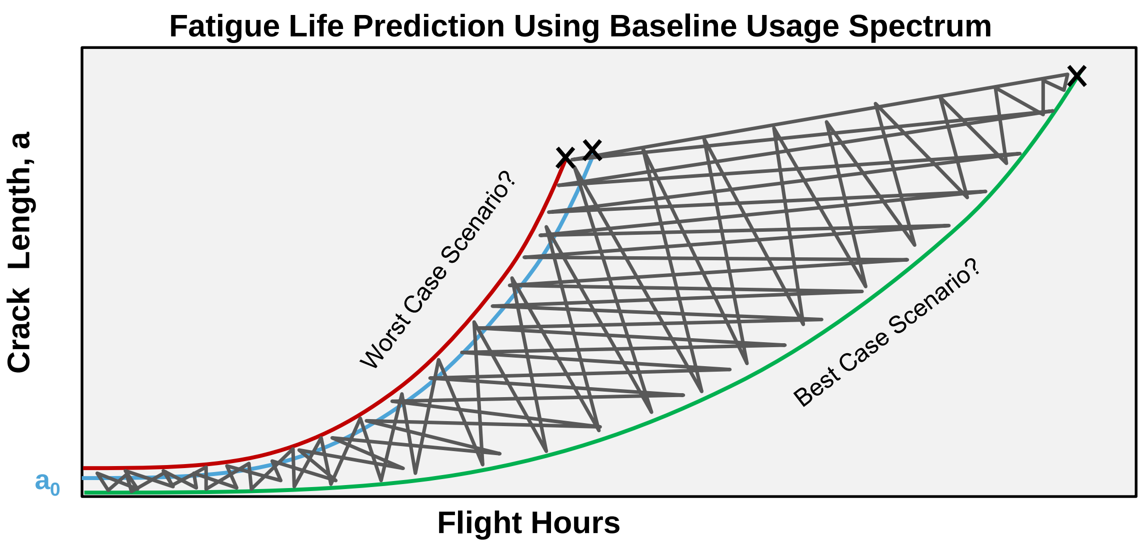


Figure 14. Analytical Fatigue Life Variability

The Probability of Fracture (PoF) utilizing the probabilistic risk-based approach is illustrated in Figure 15. Fracture occurs when the applied stress exceeds the residual strength or when the applied stress intensity factor exceeds the fracture toughness. For the stress/strength-based calculation, the left side of the equation is based on usage (e.g., configuration, mission types, and global static stresses) while the right side of the equation is based on condition (e.g., crack size, material properties, and local static and cyclic stresses).

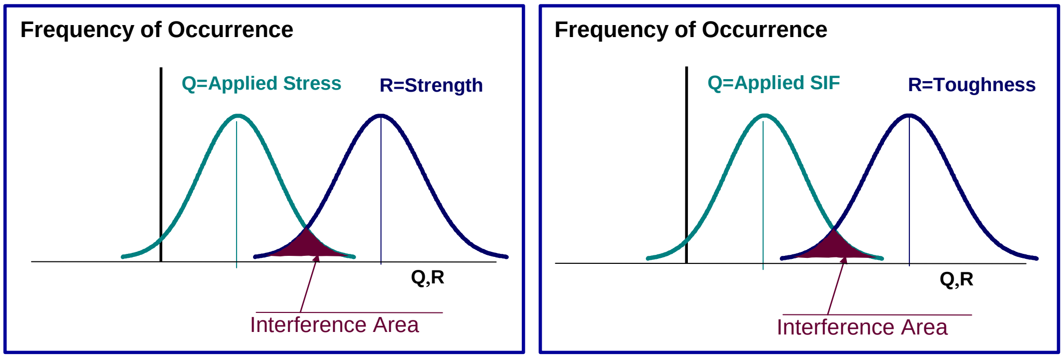


Figure 15. Probability of Fracture (PoF)

The probabilistic risk-based approach uses "risk" or "probability" instead of "analytical crack size" for Individual Aircraft Tracking (IAT). The objective is to maintain risk below allowable ASIP limits. The process for calculating the Probability of Fracture (PoF) is illustrated in Figure 16. Several inputs (i.e., initial quality and repair quality distributions, crack growth curve, crack geometry model SIF, loading, fracture toughness, detection capability, times between inspections, number of locations per aircraft, flight hours per flight, and number of aircraft) are fed into PROF (a probability of fracture computer code) to produce Single Flight Probability of Fracture (SFPoF) and Cumulative Probability of Fracture predictions.

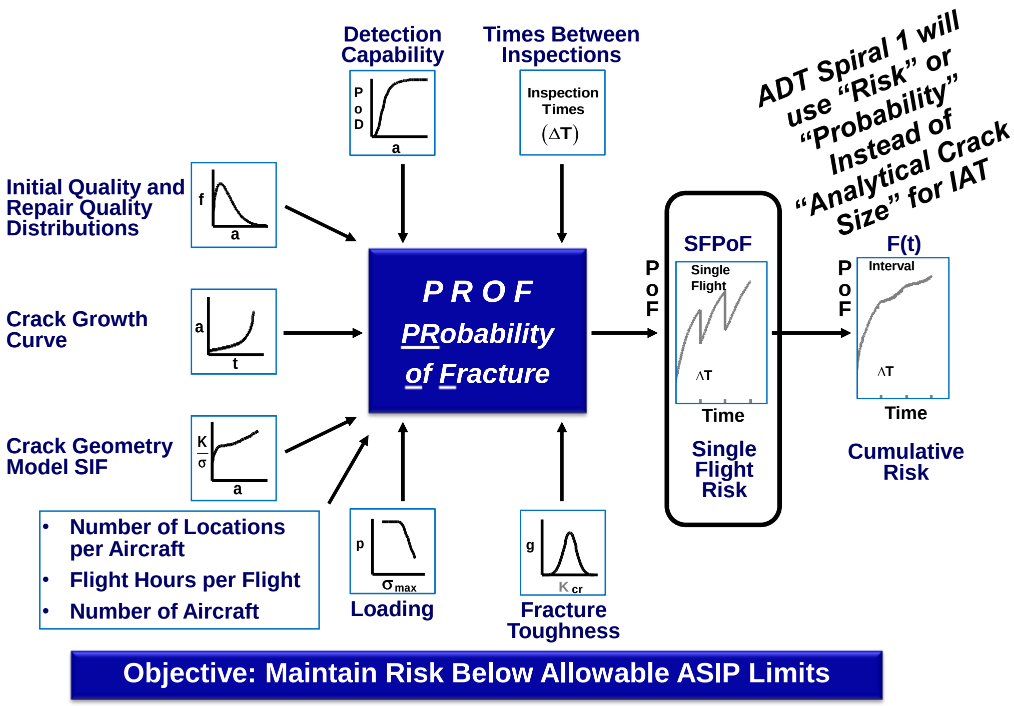
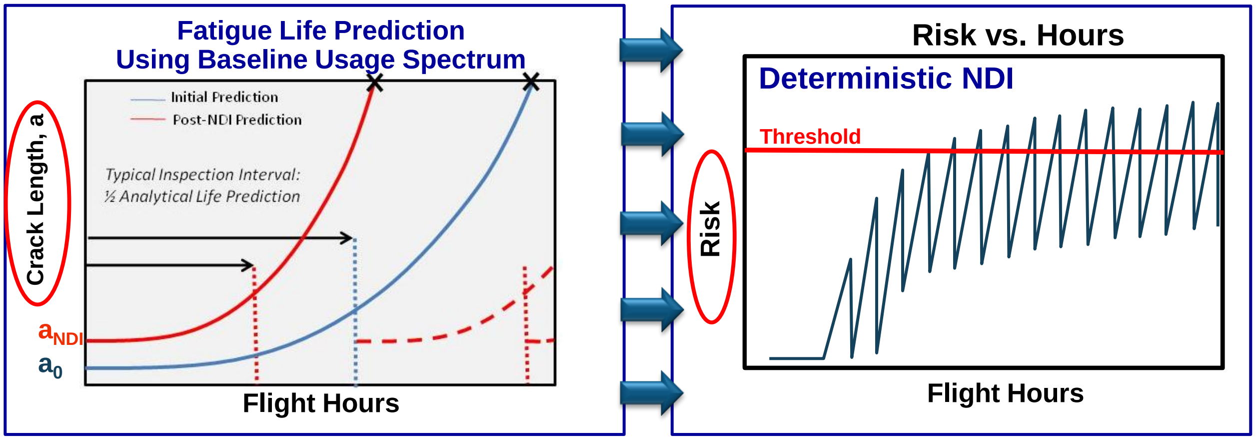


Figure 16. Calculating Probability of Failure

The establishment of inspection intervals for a selected fatigue critical location (FCL) utilizing the conventional deterministic approach was previously described (Figure 17a). The associated unacceptable risk (i.e., exceeds acceptable threshold) for this approach is illustrated in Figure 17b. This illustration indicates that we should be inspecting more frequently but won't know it. For another FCL, the conventional deterministic approach could result in unnecessary conservatism. This would indicate that we would be inspecting more frequently than necessary but won't know it.



a) Inspection Intervals b) Associated Risk

Figure 17. Conventional Deterministic Approach

The probabilistic risk-based approach uses "risk" or "probability" instead of "analytical crack size" for Individual Aircraft Tracking (IAT). Risk is maintained below an allowable threshold. Hence, inspections are performed once the allowable risk threshold is reached (Figure 18).

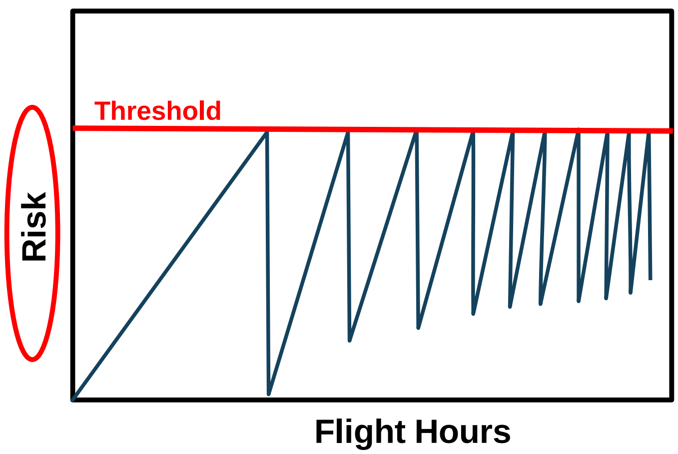


Figure 18. Probabilistic Risk-based Approach

Limitations of the current risk calculation method are as follows: (1) assumes calculation inputs (i.e., various probability distributions) are known and accurate, (2) assumes calculation inputs are the same for all the aircraft in the fleet, (3) is not formulated for updating inputs on tail number basis, (4) is not formulated for updating inputs with time, and (5) does not quantify uncertainty via confidence bound. Confidence in the risk calculation can be built through uncertainty quantification.

An initial prediction of risk vs. flight hours for the entire fleet with confidence bounds of $\pm 3\sigma$ is shown in Figure 19. The predicted distribution of flight hours when the risk threshold is reached is schematically shown. Methods are needed to quantify the uncertainty in the inputs and propagate that uncertainty through the risk calculation.

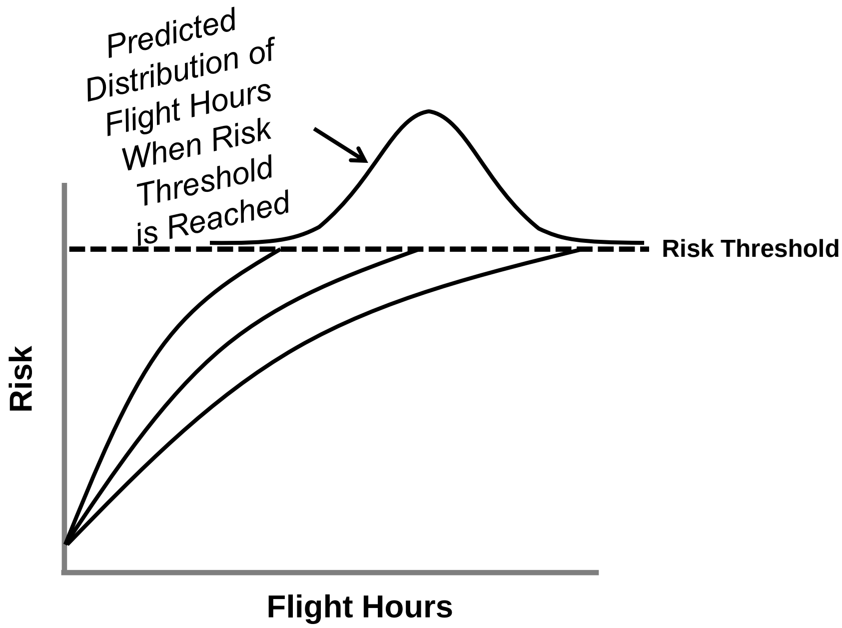


Figure 19. Initial Risk Prediction at 0 Flight Hours for Entire Fleet

Updated predictions of risk vs. flight hours for an individual tail number with confidence bounds of ± 3σ using the Bayesian Model Calibration process are shown in Figure 20. The predicted distributions of flight hours when the risk threshold is reached are schematically shown. Methods are needed to update risk predictions based on both fleet-wide and individual tail number experience.

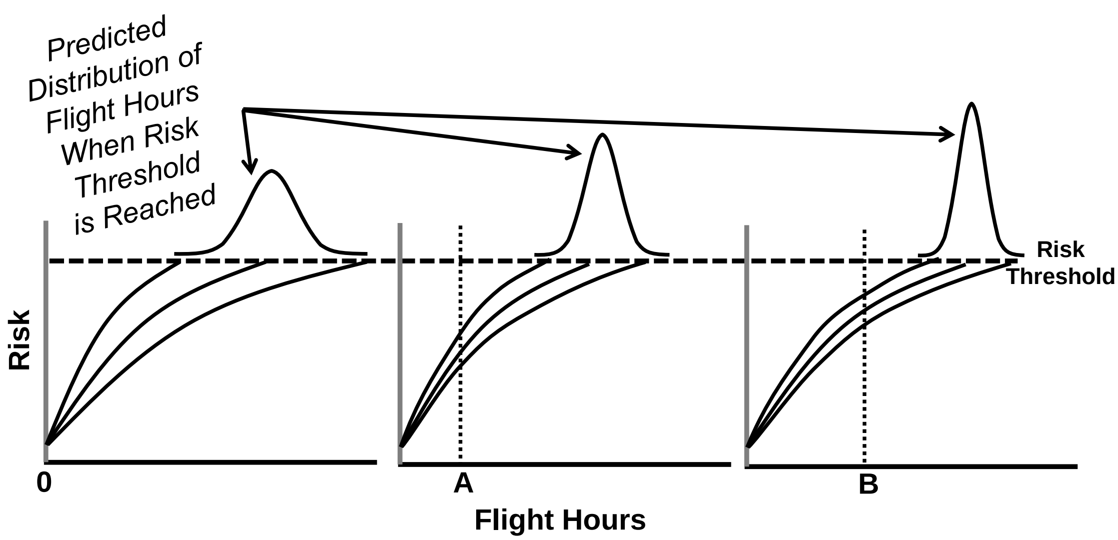


Figure 20. Updated Risk Predictions at 0, A, and B Flight Hours for a Single Tail Number

The demonstration goals for the Airframe Digital Twin (ADT) Spiral 1 program are as follows: (1) Demonstrate an integrated "CBM+SI" process as an alternative to the current ASIP Individual Aircraft Tracking (IAT) program process. Advanced usage estimation, "Hot Spots" SHM, and updated damage tolerance analysis and risk analysis will be included. Full-scale experiments of a real USAF aircraft structural module will be used in lieu of a flight test. The integrated "CBM+SI" and current ASIP IAT approaches will be compared. (2) Enhance the in-house expertise in CBM+SI Technology Focus Areas and the ASIP processes. (3) Create an analysis integration framework and test set-up procedures for the assessment of additional analysis and monitoring techniques. Provide a CBM+SI "test bed" capability and a first-generation Airframe Digital Twin (ADT).

A generalized framework for the Airframe Digital Twin (ADT) is presented in Figure 21. Inputs of Damage State Awareness and Usage provide an airframe's history and information that is fed into a Prognostic Model. Inputs of Structural Analysis are also fed into the Prognostic Model which produces numerous airframe outputs (e.g., state of health, remaining useful life, etc.). If the remaining useful life is sufficient, the airframe's history is updated as new damage state and usage information is gathered. If the remaining useful life is insufficient, Structural Modifications are made and the configuration is updated.

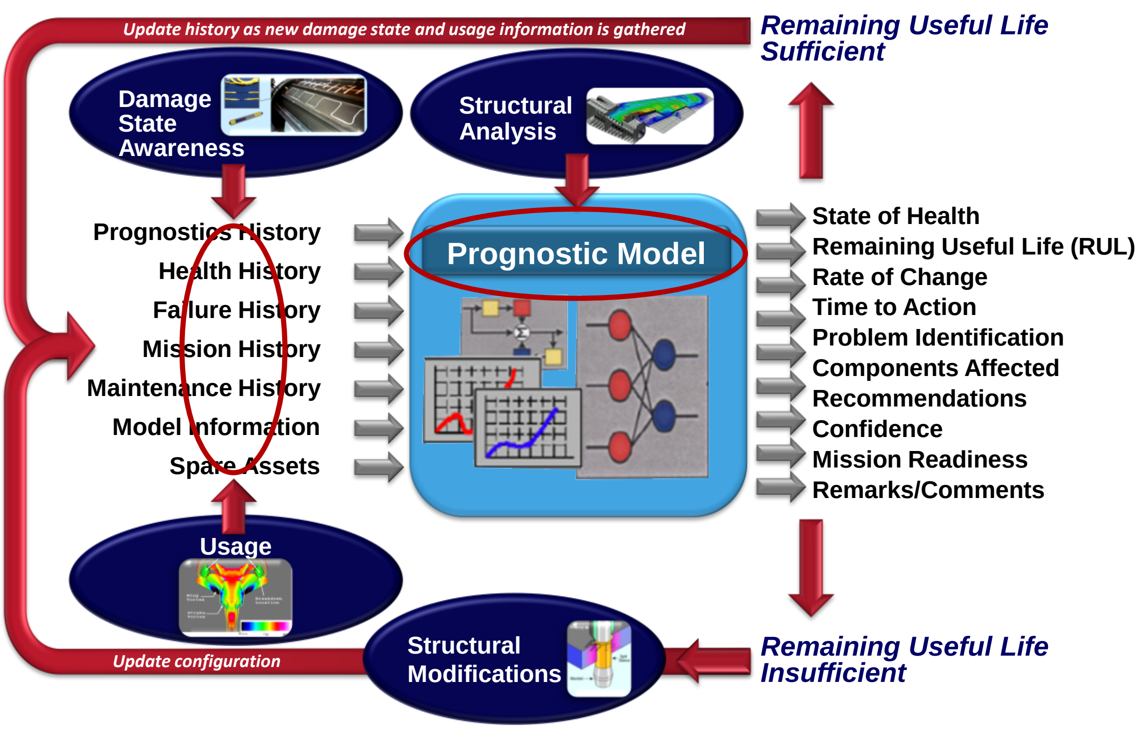


Figure 21. ADT Generalized Framework

The Spiral 1 framework for the Airframe Digital Twin (ADT) is presented in Figure 22. Damage State Awareness information is provided by NDI/local "Hot Spots" SHM. Usage information is provided by a stick-to-stress dynamic flight simulator. Structural Analysis information is provided by structural reliability analysis models. Structural Modifications information is provided by inspections/repairs. The output of the Prognostic Model is the probability vs. actual flight hours for each control point on each tail number.

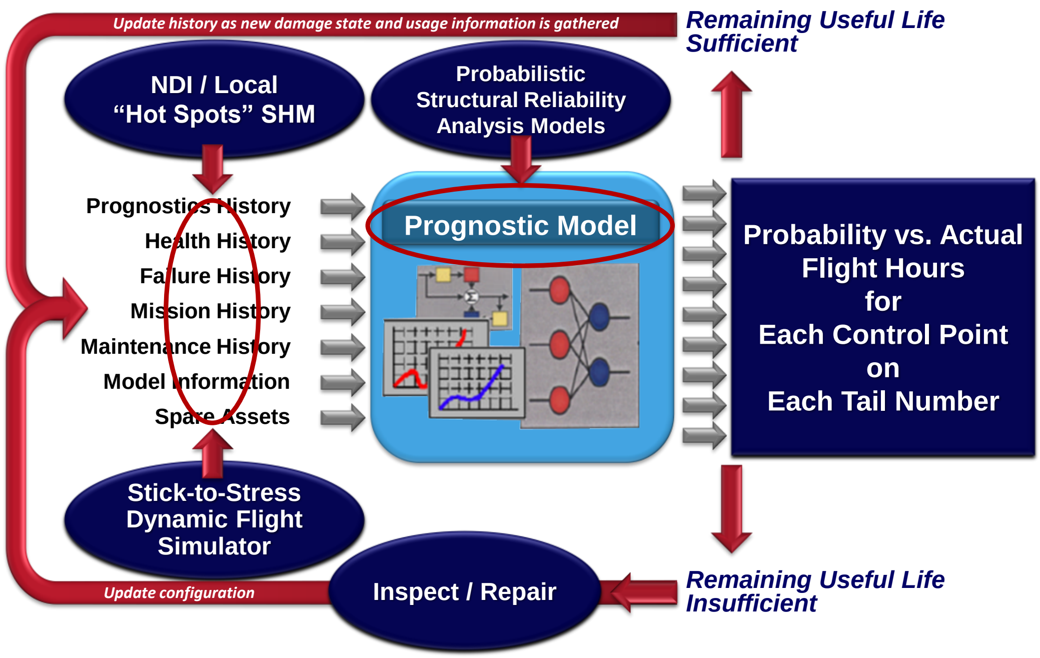


Figure 22. ADT Spiral 1 Framework

SHM for "Hot Spots"

Contributions to Damage State Awareness for the Airframe Digital Twin (ADT) Spiral 1 framework is provided by the results of the Structural Health Monitoring (SHM) for Hot Spots program [6]. Aircraft structural components may have know "hot spots" where a particular type of damage is anticipated to occur or has consistently been observed in the field. The SHM for Hot Spots program seeks to develop a systems-engineering approach to the design and implementation of SHM solutions for structural hot spots. A previous SHM program was conducted to ensure the integrity of bonded repairs. Together, these two SHM programs for bonded repairs and hot spots have utilized the building-block approach that covers the full spectrum of test specimens (i.e., coupons, cantilever beams, subcomponents, and full-scale specimens), as shown in Figure 23.

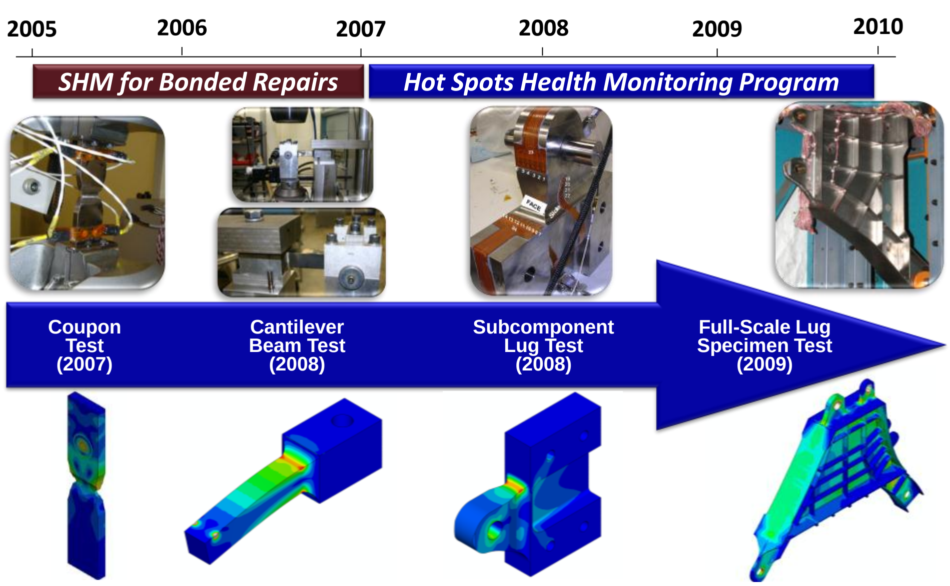


Figure 23. Building-Block Approach for SHM Test Specimens

The F-22 SPO was interested in increasing aircraft availability and decreasing maintenance downtime. Inspection methods were needed that did not result in LO intrusion. The current NDI methods used required the removal of a fuel door to gain access to hot spots on certain frames (Figure 24). A SHM system was needed to monitor fatigue critical locations on frames 2, 3 and 4 (Figure 25). A building-block approach was utilized that covers the following full spectrum of titanium test specimens: six coupon tests (Figure 26a), three cantilever beam tests (Figure 26b), 21 lug subcomponent tests (Figure 26c), and seven lug full-scale tests (Figure 26d).

Figure 24. NDI after Panel Removed

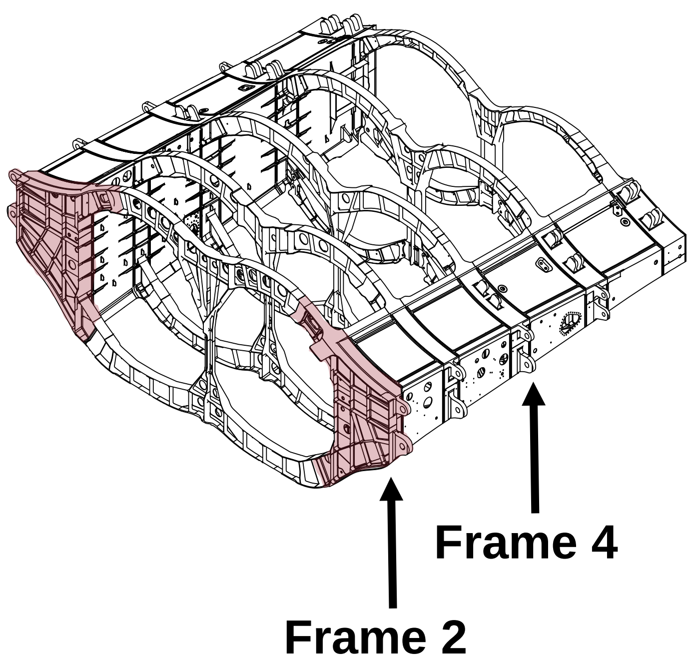
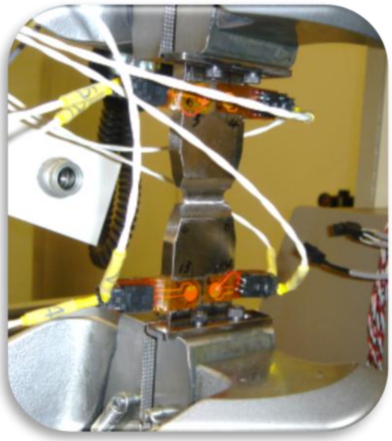


Figure 25. Fatigue Critical Locations



a) Coupon

b) Cantilever Beam

c) Lug Subcomponent

d) Lug Full-Scale

Figure 26. F-22 Test Specimens

The Structural Health Monitoring (SHM) modeling and simulation process for the six lug subcomponent tests (LE-41, 69, 78, 81, 82 and 103) is illustrated in Figure 27. The five-step process is described as follows: (1) Understand Problem: conduct "hot spot" analysis, (2) Stay Out Zone Analysis: conduct analysis for locations where sensors cannot be placed but must be placed in adjacent locations, (3) SHM Down-selection: identify type, size and number of sensors to be used, (4) Design Optimization: optimization of type, size and number of sensors to be used, and (5) Final Layout Design.

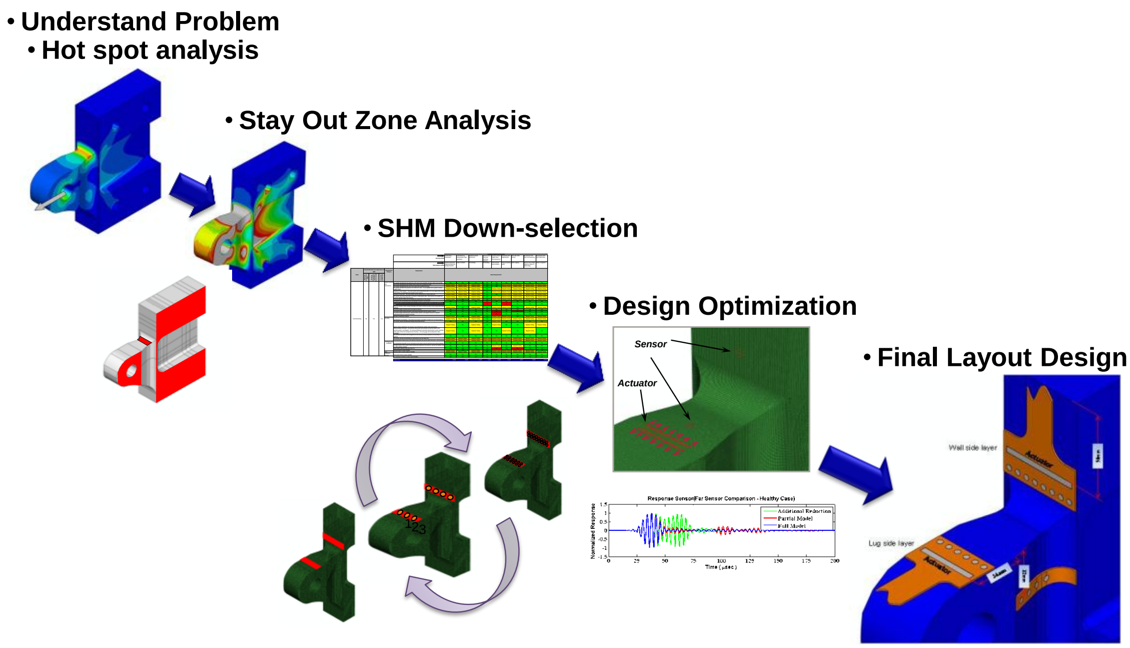


Figure 27. SHM Modeling and Simulation Process

The variability of operation environment and SHM durability were addressed for the six lug subcomponent tests that were conducted under representative environments. Variations considered included material properties (e.g., etching, surface treatment, and residual stress), peak stresses in the flight spectrum, and initial fatigue conditions at the time of SHM installation. Up to eight lifetimes of testing were performed to address SHM durability. Crack lengths were obtained using both microscope visual inspections and SHM sensors (Figure 28). The type of SHM sensors used included elastic (guided) waves (i.e., ultrasonic waves using piezoelectrics) that were applied at locations adjacent to the stay out zones. Correlations of the SHM and visual NDI results are presented in Figure 29. The results indicate that the SHM algorithm works well under significant test variability.

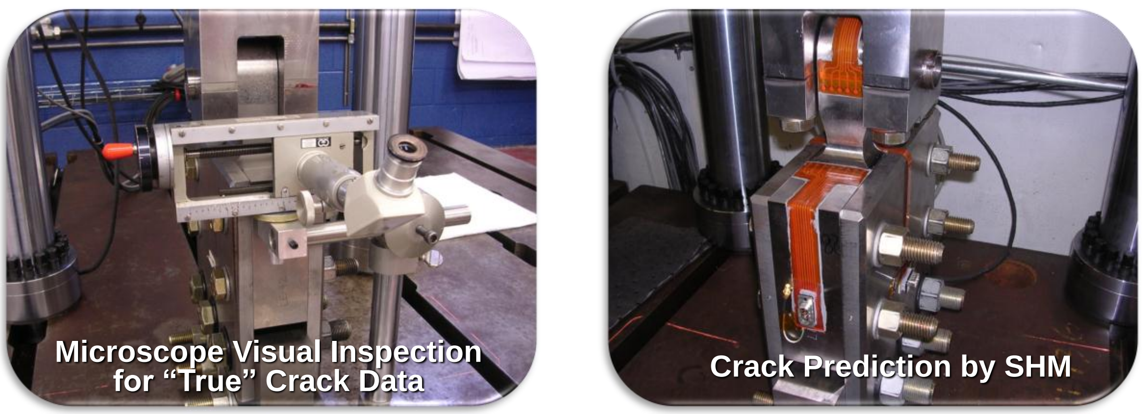


Figure 28. Methods for Determining Crack Length

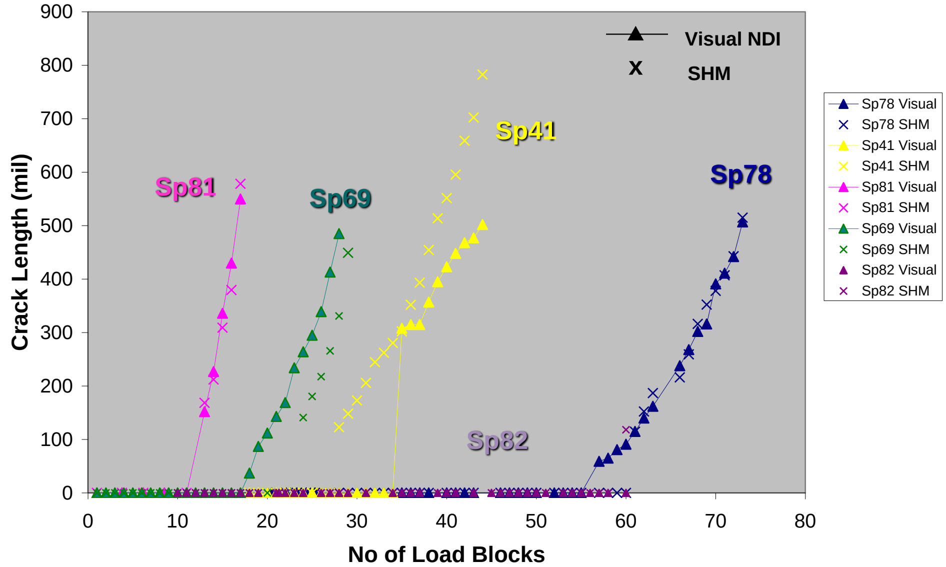


Figure 29. SHM vs. Visual NDI Correlations for Lug Subcomponent Specimens

Probability of Detection (PoD) formulations for the SHM sensors used in the lug subcomponent tests were obtained in a similar manner to that used to obtain PoD curves for NDI methods described in MIL-HDBK-1823A. The SHM method used represents a "Hit-Miss" in-situ NDE method in which the relationship between crack size (a) and signal response (â) is obtained (Figure 30). The data from Figure 30 are used to develop the PoD curves for a_{50}, a_{90} and $a_{90/95}$ (Figure 31). The PoD curves of Figure 31 are based on the data derived from the five test specimens previously identified in Figure 29. The data include 41 crack length data points and 49 noise data points. The $a_{90/95}$ crack size required by ASIP for target application is 0.1 inch. An additional 15 lug subcomponent specimens are currently being tested to provide additional data for the SHM system development and refinement. The PoD for on-board sensors may require evaluations to account for specific structures, applications and in-situ environments (e.g., temperature, load variations and sensor degradation). The statistical framework and Design of Experiments (DoE) for validating a SHM system needs to be developed. A model-assisted PoD approach is being investigated to minimize the number of experiments required.

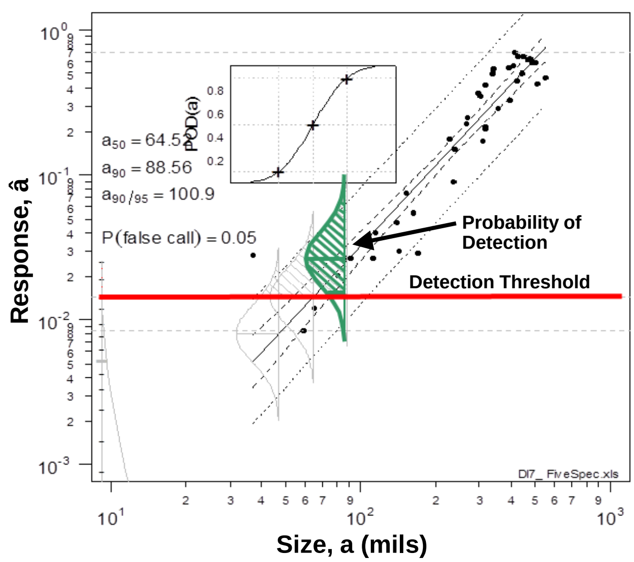


Figure 30. Response (â) vs. Crack Size (a)

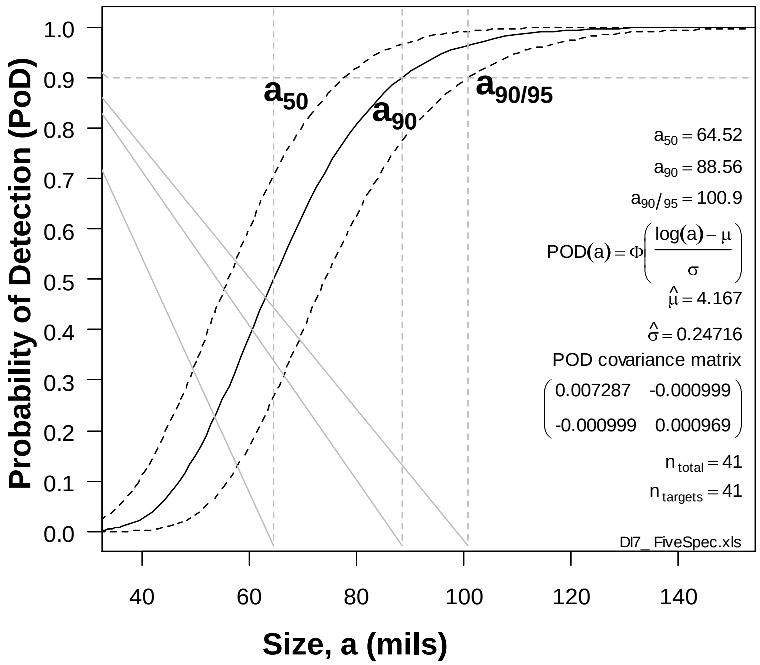


Figure 31. SHM PoD Curves

Correlations of the SHM and visual NDI results for one of the full-scale specimens (Figure 32) were also performed (Figure 33). The results indicated good correlation between the visual measurements and the SDM damage index for this more complex structure.

Figure 32. Full-Scale Specimen (Specimen 7A)

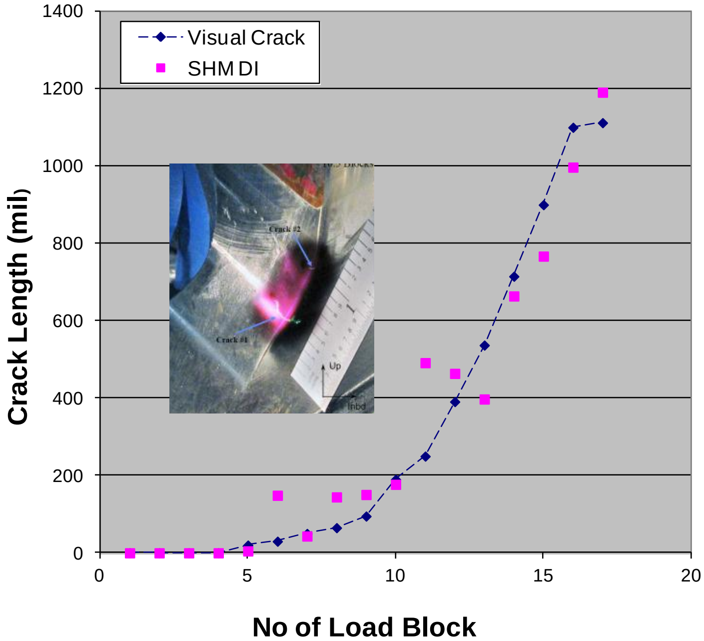


Figure 33. SHM vs. Visual NDI Correlations for Full-Scale Specimen

The SHM design framework developed for the F-22 aircraft is being used to develop SHM systems for F-15 hot spot applications. Validation and improvements will be accomplished on subcomponent and full-scale fatigue tests with the end goal being a flight demo on a F-15 aircraft (Figure 34).

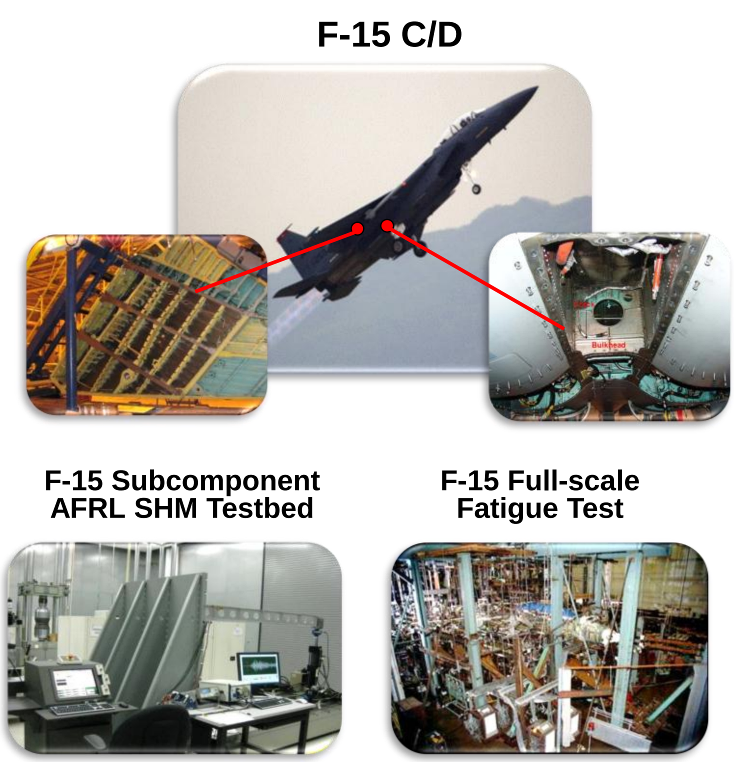


Figure 34. F-15 SHM System Development

Several Air Force Research Laboratory (AFRL) in-house SHM activities (Figure 35) are as follows: (1) SHM Test Bed Development: Performance of cyclic fatigue testing of representative or actual aerospace structures in a controlled laboratory environment. Development of experimental techniques to validate structural capability determination, (2) Multimodel Sensing: Fusing multiple sensing modalities (e.g., guided wave, acoustic emission, and electro-mechanical impedance) for improved crack length estimation, and (3) Lug Subcomponent Testing: Generating results to provide additional data for SHM system development and refinement.

Figure 35. AFRL In-House SHM Activities

Risk-informed Decision Making

The Risk-informed Decision Making program integrates the Structural Health Management framework (Figure 36) with probabilistic risk analysis (Figure 37) to provide a predictive prognostics (Level 4 CBM+) capability. The program addressed the F-15 FS 626 bulkhead cracking issue (Figure 38).

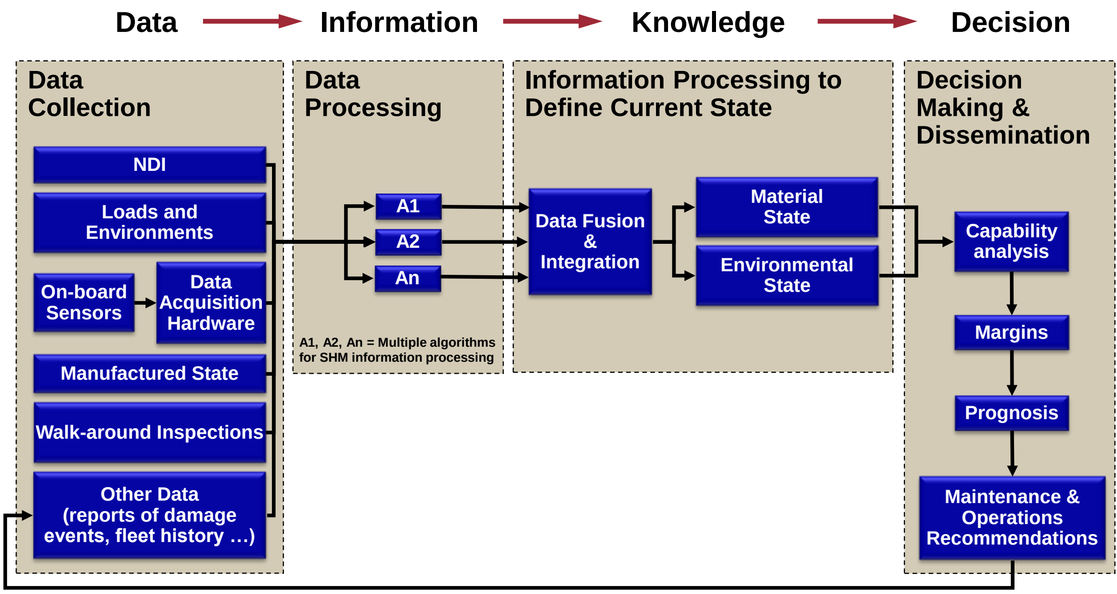


Figure 36. Structural Health Management Framework

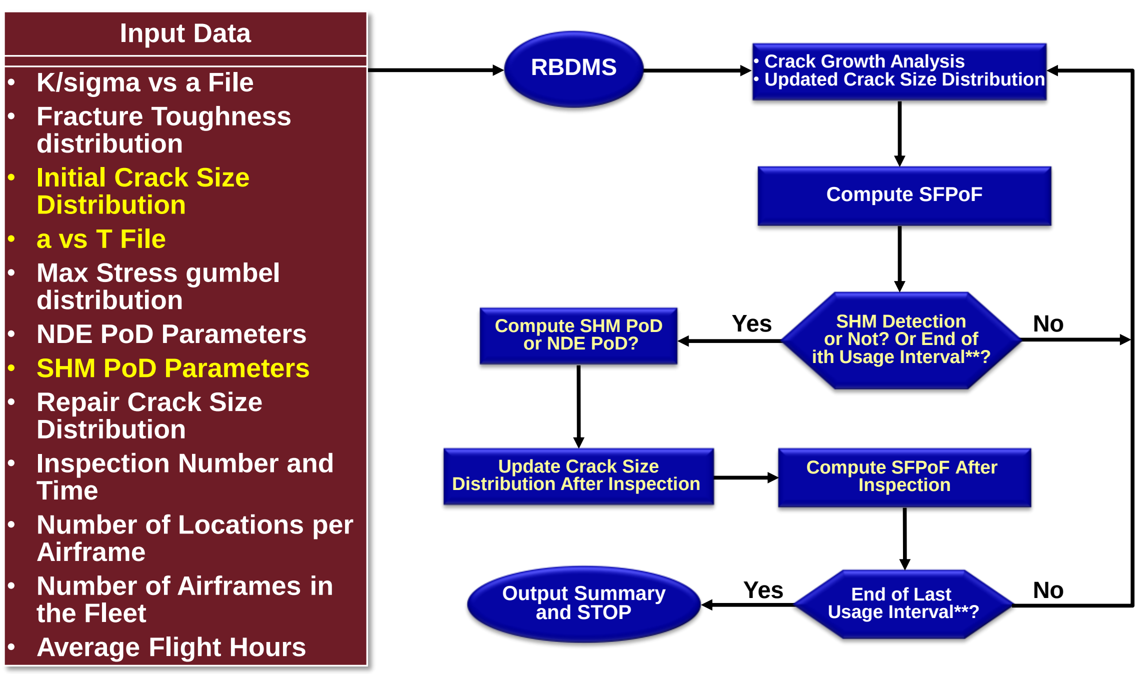


Figure 37. Probabilistic Risk Analysis

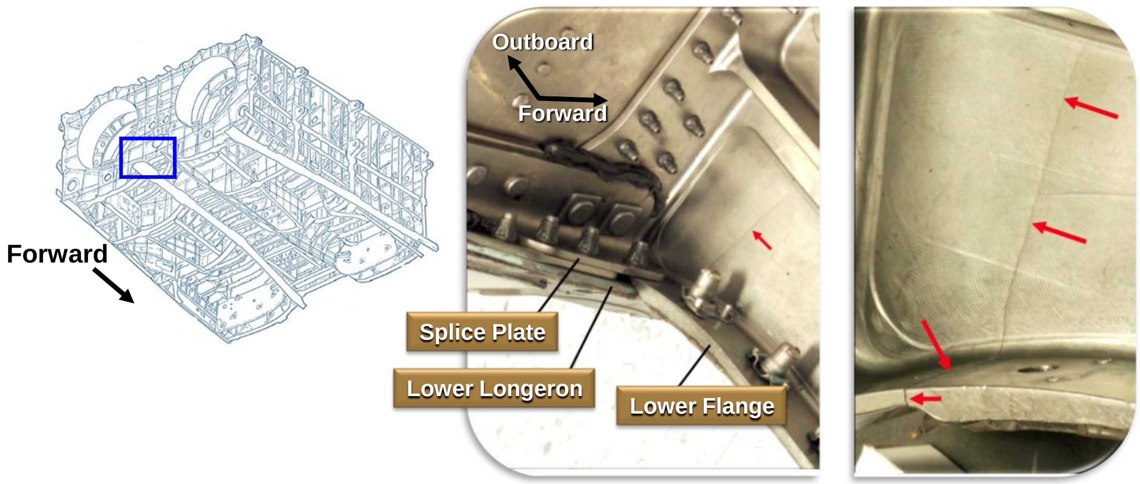


Figure 38. F-15 FS 626 Bulkhead Cracking

Maintenance schedules (i.e., inspection intervals) were established for the subject bulkhead using the baseline conventional deterministic ASIP approach and the following four probabilistic risk-based approaches: (1) Case 1: Risk-based Traditional NDE, (2) Risk Approach with "Hit-Miss" In-situ NDE, (3) Risk Approach with "Continuous Resolution" In-situ NDE, and (4) Case 1 with "Continuous Resolution" In-situ NDE.

The Baseline Conventional Deterministic Approach established 18 inspections, each with 650-hour intervals (Figure 39). The calculated risk (i.e., SFPoF) exceeded the risk requirement (i.e., threshold) at 4,550 hours.

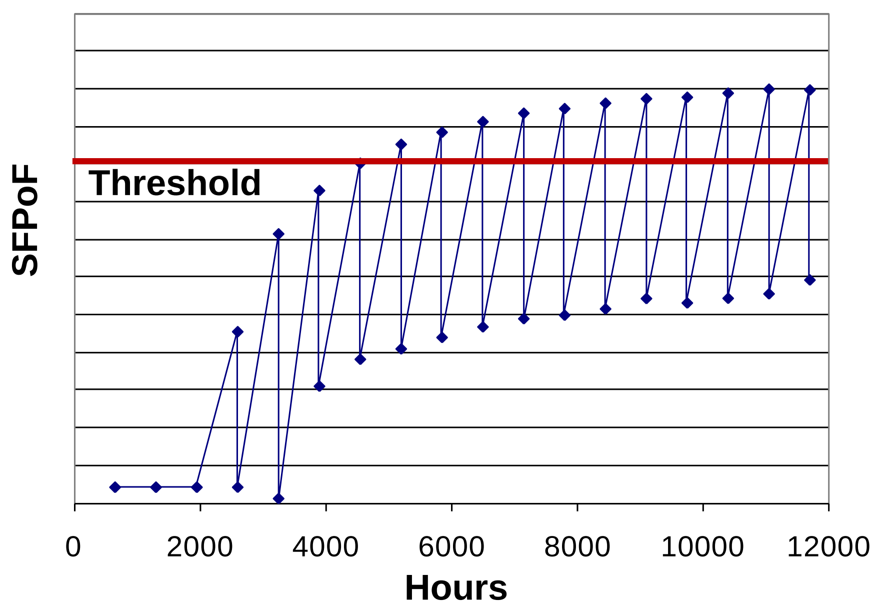


Figure 39. Baseline Conventional Deterministic Approach

The Case 1: Risk-based Traditional NDE Approach identified inspection intervals based on a prescribed risk requirement. The identified inspection intervals, which were not fixed, are as follows: 3,000, 720, 590, 580, 540, 520, 490, 480, 470, 465 and 460 hours (Figure 40). Note that after the second inspection, all subsequent inspection intervals are less than the 650-hour interval established by the Baseline Conventional Deterministic Approach.

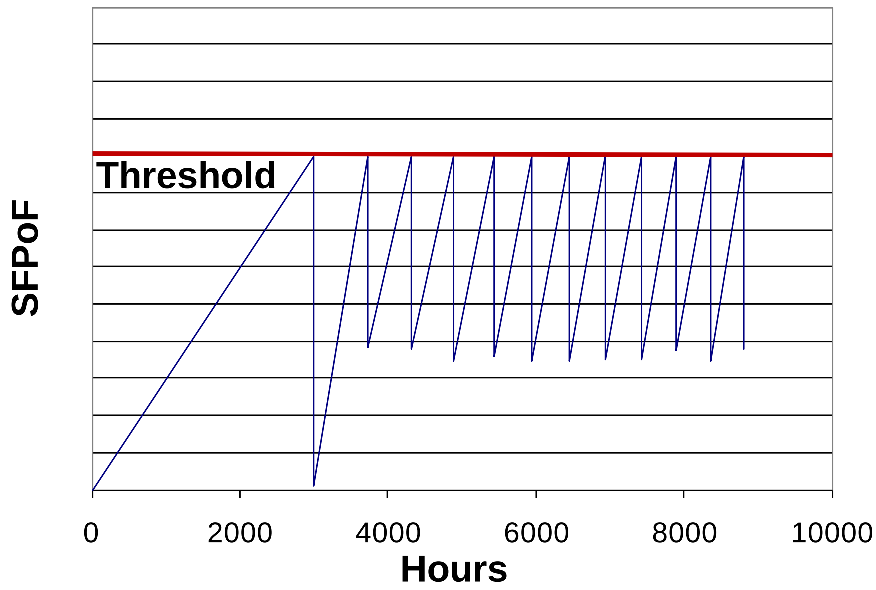


Figure 40. Case 1: Risk-Based Traditional NDE Approach

The Case 2: Risk Approach with "Hit-Miss" In-situ NDE assumed a 95% Probability of Detection (PoD) at the critical crack length. Fixed in-situ inspection intervals were preset at 200, 300 and 400 hours. A large number of inspections were required with the risk threshold exceeded in all cases up to 8,000 hours (Figure 41). A lower investment in a lower capability system can be overcome with increased timing of inspections. Non-recurring costs are moved to the recurring cost of increased inspections.

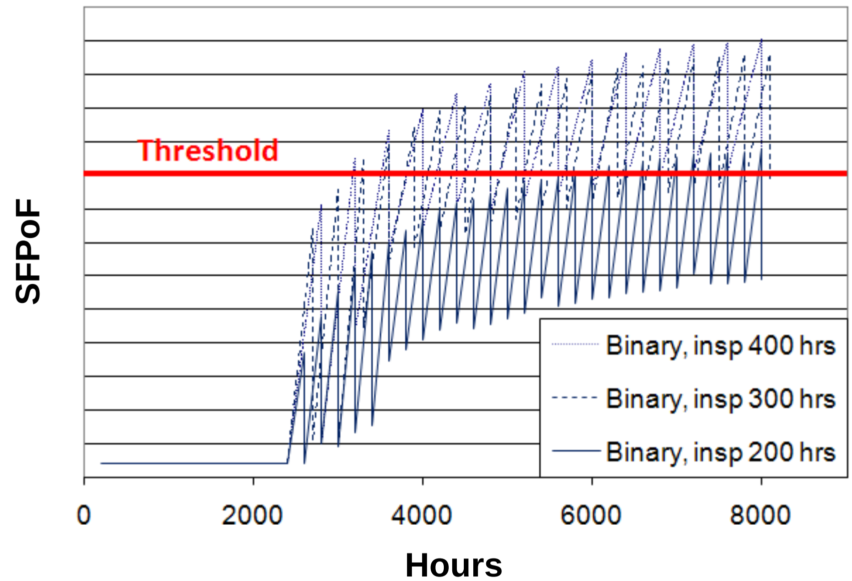


Figure 41. Case 2: Risk Approach with "Hit-Miss" In-situ NDE

The Case 3: Risk Approach with "Continuous Resolution" In-situ NDE assumed a "Continuous Resolution" Probability of Detection (PoD) equal to the NDE PoD. Fixed in-situ inspection intervals were preset at 400 hours. A large number of inspections were required (Figure 42). The risk remains below the threshold through 8,000 flight hours.

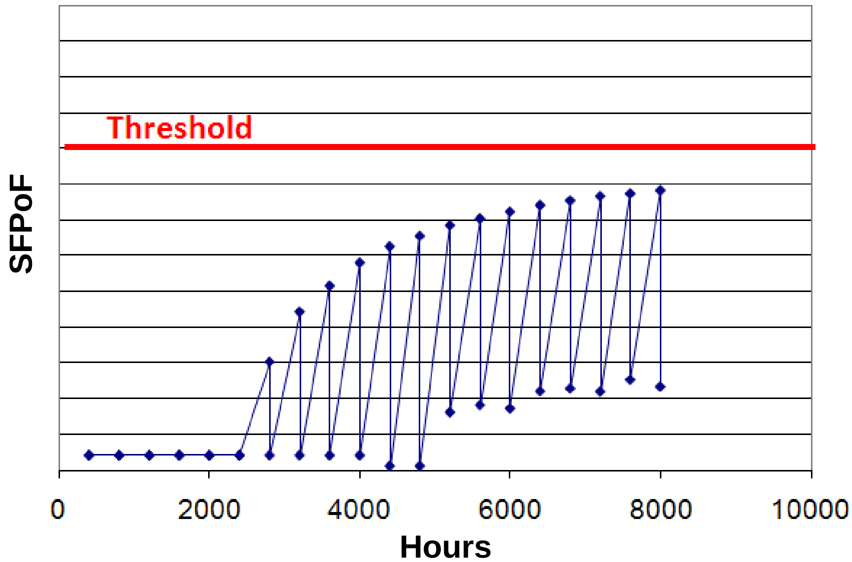


Figure 42. Case 3: Risk Approach with "Continuous Resolution" In-situ NDE

The Case 4: Case 1 with "Continuous Resolution" In-situ NDE assumed that the In-situ "Continuous Resolution" Probability of Detection (PoD) was equal to the NDE PoD. The first in-situ inspection was set at the risk threshold (i.e., 3,000 flight hours). Fixed in-situ inspection intervals were preset at 400 hours thereafter. Less inspections were required for Case 4 than were required for Case 3 (Figure 43). Both Case 3 and Case 4 had the same investment cost, but Case 4 had reduced recurring costs. The risk remains below the threshold through 8,000 flight hours.

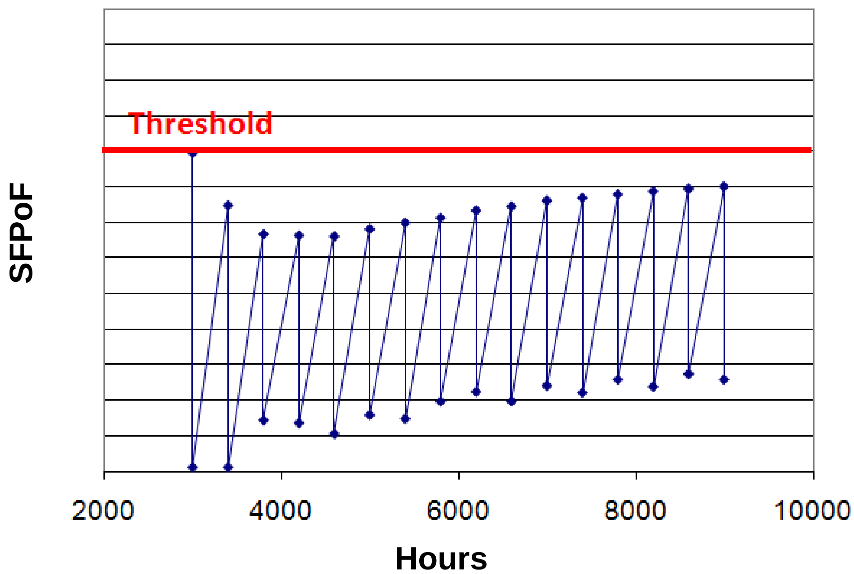


Figure 43. Case 4: Case 1 with "Continuous Resolution" In-situ NDE

A business case was developed to show the benefits of risk-informed decision making. The following technical performance measures (TPMs) were used to demonstrate the benefits of CBM+SI: (1) Fleet Availability or Aircraft Availability Rate: percentage describing the readiness of fleet available for missions and not in any maintenance, (2) Total Cost of Ownership: total cost to own and maintain platforms and weapon systems from cradle to grave, and (3) Maintenance Man Hours per Flight Hour: labor hours associated with maintenance (unscheduled and scheduled) per flight hour. The Technical Performance Measures (TPMs) of the baseline/current platform configuration were compared with the TPMs of the CBM+SI configured platforms.

Input data and assumptions used for the business case were as follows: (1) Number of F-15s in the fleet was 300, (2) Average flight hours per flight (based on the composite) was 1.3 hours, (3) Average flight hours/plane/year was 275 hours, (4) Timeframe was 25 years, and (5) Number of locations on the platform was 20 (18 bolt holes and 2 clamped sections).

The operational and cost benefit results are shown in Table I. The normalized values shown in the table are measured against the baseline. It should be noted that smaller values are better.

Table I. Operational and Cost Benefit Results

	NDE Risk-Based Approach (Case 1)	SHM From Time Zero (400FH Intervals) (Case 3)	NDE Risk-Based @ 3,000FH + SHM (400FH Intervals) (Case 4)
Operational Metrics			
Maintenance Man Hours per Flight Hour	0.71	0.50	0.37
Mission Capability	1.00	1.00	1.00
Cost/Benefit			
NPV Lifecycle Cost	0.32	0.05	0.18

SUMMARY

This technical effort addressed the sustainment strategic goal to eliminate programmed repair cycles. To achieve this goal, a Condition-based Maintenance Plus (CBM+) initiative was established which identified four levels of complexity and cost. The current Aircraft Structural Integrity Program (ASIP) addresses the first three levels of complexity and cost but does not address Level 4: Predictive Prognostics. A CBM+SI vision was established to provide a predictive prognostics capability. Specifically, the CBM+SI vision is being realized through the following Airframe Digital Twin Concept: "Real-time, high fidelity operational decisions for individual aircraft enabled by tail number health awareness." Successful completion of the Airframe Digital Twin (ADT) Spiral 1 program will provide a CBM+SI "test bed" capability and a first generation ADT.

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