

Demonstration, Qualification, and Airworthiness Certification of Structural Damage Sensing (SDS) Systems for Air Force Applications

John Brausch, Gary Steffes

Materials & Manufacturing Directorate, Air Force Research Laboratory,
Wright-Patterson AFB, OH 45433-7101

ABSTRACT

Structural Health Monitoring (SHM) sensor systems have gained much interest in the aerospace community as potentially enabling technologies for reducing maintenance costs while maintaining flight safety of aging structures. Many candidate SHM technologies are essentially damage detection systems i.e. variations of well established NDI methods such as ultrasonics, electro-magnetic (eddy current), and acoustic emission. Still others employ displacement detection such as strain-sensing and dynamic vibration sensing. Depending on the SHM system's capability and configuration, it can be tailored for both global or local detection. Unfortunately, the path for transition onto United States Air Force (USAF) weapon systems, including requirements for demonstration and qualification, are not well defined. Before SHM technologies can be qualified for aircraft flight demonstrations and fleet-wide usage, these systems must demonstrate their capability to meet performance requirements in terms of detection capability, reliability, and safety while and providing an economic benefit. Ultimately the qualification program must be sufficiently robust to support an airworthiness certification decision.

The goal of this paper is to provide guidance for the demonstration and qualification of permanently mounted damage detection systems intended for use on USAF aircraft. A detailed description of current Air Force policy concerning airworthiness certification is beyond the scope of this paper. More specifically, this paper will a) focus on applications where damage tolerance principles are used to manage structural integrity, b) propose a task-based approach for system qualification, and c) identify existing Air Force policies that define the path for modification management and obtaining airworthiness certification approval.

INTRODUCTION

The United States Air Force (USAF) is facing challenges in maintaining an increasingly aging fleet. Increasing maintenance and inspection requirements result in extended maintenance downtime and lower mission capable rates. To address these issues, the USAF is exploring approaches to reduce the disassembly and downtime required to execute invasive structural inspections that are critical to maintaining structural integrity and to anticipate maintenance needs⁽¹⁾. One potential solution is the use of structural health monitoring (SHM) to provide state awareness of structural health and usage.

However, before these technologies can be embedded in aircraft, their performance, reliability, impact on aircraft safety, and economic benefit must be successfully demonstrated.

This paper focuses exclusively on defining a framework for qualifying on-board damage detection systems, from this point forward defined as *Structural Damage Sensing (SDS)* systems. SDS systems exist as pieces of the overall SHM concept (Figure 1) ⁽¹⁾. The entire SHM concept is not limited to SDS systems but is more broadly defined as a system utilizing multiple sensor data streams such as loads and environment (vibration, temperature, corrosive environments, etc.) in conjunction with the SDS data and pre-existing structural models to predict structural health through a processing reasoner.

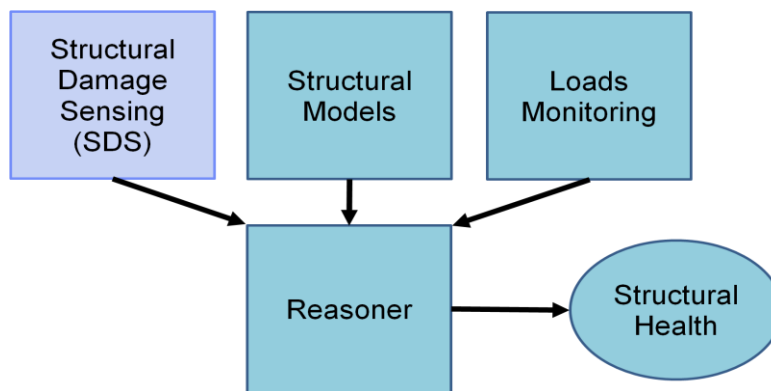


Figure 1: The several components of a Structural Health Monitoring concept including the Structural Damage Sensing (SDS) component.

The concept of structural health management differs from structural health monitoring as it includes data collected from multiple sources including findings from previous inspections, manufacturing & repair data, other engineering data, etc. Structural health management includes greater prognostic and decision making capabilities to aid in structural life prediction. The flowchart in Figure 2 illustrates the various elements that make up a possible version of an overall structural health management model. The SDS piece is included in the Sensors box within the Data Collection element. Therefore, SDS and SHM are entirely contained within and exist as sub-functions of an overall structural health management concept.

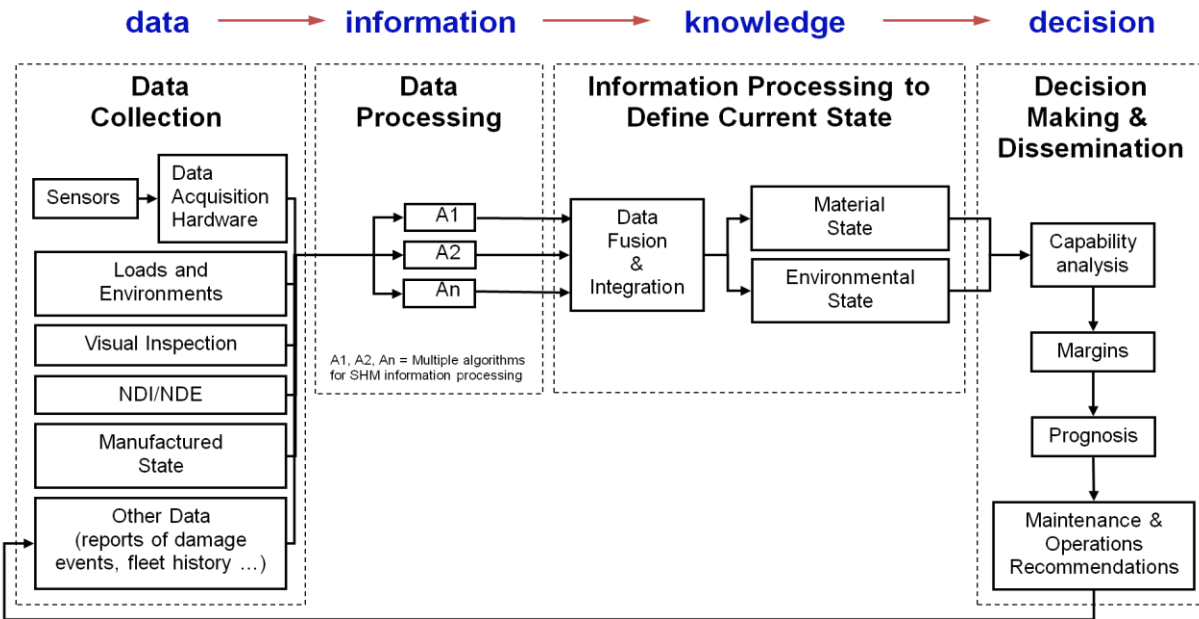


Figure 2: Elements and process for Structural Health Management. The SDS component is contained within the Sensors box under the Data Collection element. Diagram courtesy of The Boeing Corporation and AFRL/RBSI

How SDS systems are qualified and implemented within this structural management methodology greatly depends on the operational principles of the SDS system. Two basic scenarios are envisioned:

Category I Systems – Active Systems: Active SDS systems use on-board continuous monitoring where the inspection result is monitored and interpreted real-time or at relatively short intervals. In this scenario correlation of the sensor output to damage severity is required to establish a decision threshold. Moreover, since the sensor is constantly monitored, the probability of a miss may potentially be reduced but with a corresponding increase in false positive rates. Of course this advantage is only realized if the system is installed correctly and is monitoring the region where a flaw occurs. High false-positive rates could negatively impact aircraft availability by requiring the aircraft to be down for SDS system troubleshooting and/or for “chasing” imaginary damage. On-board installation of the interrogating instrumentation as well as an on-board power is assumed to be required; as a result, flight-safety certification for this category becomes significantly more complex.

Category II Systems – Passive Systems: Passive SDS systems use a “plug-and-play” approach where the damage sensor interrogates structural only at a prescribed interval similar to the tradition NDI methodologies. Characterization of the detection capability is critical and false positive rates are expected be lower since the sensor is not constantly monitored. For this scenario, it is assumed that onboard installation of only the sensor and cabling is required. The system is not activated in-flight and no on-board power is

required. Because of the limited hardware installation, this category reduces the complexity for airworthiness certification.

DEFINING SDS REQUIREMENTS

Establishing a program to implement SDS systems requires a clear definition of the application. There are several considerations that must be addressed when formulating this definition. These considerations include, but are not limited to, structural configuration, structural variation, usage environment, system durability requirements, configuration management, and system maintenance. As such, a Master Requirements Document (MRD) must be generated to capture the application specific requirements and drive the plan formulation. The MRD should be approved by the weapon system ASIP Manager and Chief Systems Engineer and must be releasable to potential vendors wishing to propose an SDS system or technology.

As a minimum the MRD must define the following ⁽⁷⁾:

1. Part Geometry – Often conveyed through production/engineering drawings and usually developed and supplied by the Original Equipment Manufacturer (OEM). While these drawings typically define specific dimensional information regarding the part or assembly, they sometimes lack information necessary to fully define the local structural interfaces, geometric interference, manufacturing variability and access. It is often necessary to “lay-hands” on the structural details to guide SDS system development decisions.
2. Part Material – The material description must include, in the case of metallic structure, the alloy type and heat treatment or temper condition, and may require a description of any surface treatments including coatings or plating and thicknesses. In addition, material details may be required for other structure located adjacent to the region of interest, and, if fasteners are located within the region, the fastener type and material composition must also be provided.
3. Flaw Location and Orientation – A clear definition of both the expected flaw location and orientation is required. This information may be available in the form of damage tolerance analysis, and fatigue test results (subcomponent, component, or full scale). The reliability of this information is greatly dependent on the fidelity of the test program and analysis and will often evolve as the aircraft system matures. These details will focus the development and testing of SDS systems, providing the optimum opportunity to maximize the detection capability.
4. Effectivity/Configuration Changes – A list of affected aircraft or systems by tail or serial number is also required. This information should include a description of any deviations or configuration changes in component design, including variances in any of the items described above. Such an accounting provides a level of assurance that all affected systems are inspected and that SDS processes are appropriately adjusted to compensate for known variances.
5. Assembly – In many cases, the structural assembly is also conveyed through production/engineering drawings. This description must define the geometry and

composition of mating components and how these mating components are joined to the component under interrogation. This assembly defines the boundary conditions under which the SDS system must reliably function. The assembly configuration can affect the sensor design and placement. Adjacent components or local part geometry could result in a confounding SDS response that could be misinterpreted as a defect or even mask a defect.

6. Structural Variability – Potential structural variability that could affect the reliability or repeatability of an SDS system should be defined. Sources of variability include but are not limited to variations in structural faying surface interfaces, coating systems, or part configuration often due in large part to production changes, repairs or deterioration of materials over time that are not otherwise captured by the aircraft configuration control process. Records of these deviations may include any documented nonconformance as accepted by Materials Review Boards. In addition, standard repair processes that have been applied to fielded components that will be encountered during inspection should also be documented. The development of an SDS demonstration program should account for structural variability within the test matrix.
7. Access for Installation/Stay-Out Zones – Points of access for installation and repair of the SDS system must be identified. This description should include: a) panels or doors that can be removed which may provide access and facilitate system installation, b) description of local structure or subsystems that may hinder access (particularly on low observable platforms), c) areas that can be used for cable routing or other system subcomponents, d) aircraft systems that may be affected by SDS hardware, e) regions that cannot be used to mount SDS system subcomponents (stay-out zones).
8. Capability (a_{NDI}) –It is good practice to provide both a goal and threshold a_{NDI} value. Historically the value of a_{NDI} has been established as the $a_{90/95}$ value ideally determined statistically using the empirical methods defined in MIL-HDBK-1823A ⁽⁵⁾. The $a_{90/95}$ is an estimate of the crack size that will be detected 90% of the time with a statistical confidence of 95%. The goal value is the detection capability that may be very challenging to meet but would result in inspection intervals that provide an economic or maintenance benefit to the program. The threshold value is the detection capability that cannot be exceeded and if exceeded would pose an unacceptable economic or availability burden to the program. For example, the inability to achieve the threshold size would require aircraft groundings or drive structural replacement or modification actions. The goal and threshold values should be used to develop the SDS demonstration experiment. In addition, these values should be used to develop SDS interrogation intervals. Detection capability estimates for standard inspection processes are summarized in Structures Bulletin EN SB-008-012, *Nondestructive Inspection Capability Guidelines for United States Air Force Aircraft Structures*.
9. False Positive Rates – False positives (also known as false alarms) can present a significant economic and availability burden if not appropriately controlled as they can drive costly and intrusive structural disassembly. Therefore the maximum rate of false positives must also be defined. It is recommended that

false positive rate should not exceed 1×10^{-4} per inspection cycle for SDS systems.

10. Durability: System durability requirements, in terms of minimum mean-time-between failure rates, should be defined. Failure rates must be sufficiently low to support the maintenance concept and provide long term monitoring without the need for invasive maintenance or repair of the monitoring system. Durability will be discussed in more detail later in this paper.
11. Usage Environment: The usage environment includes but is not limited to temperature profiles, humidity, fuel, hydraulic fluid or chemical exposure, strain and vibration. A definition of this environment will drive the design of environmental and durability testing and the qualification/airworthiness requirements.
12. Other Requirements: The MRD should clearly define other aircraft specific requirements. These may include maximum system weight and size, power requirements, etc. Development of the MRD should be closely coordinated with the appropriate system engineering authority and safety.

Vendors submitting proposals must define the candidate technology's maturity level (i.e. technology readiness level) and ability to meet each of the detailed requirements defined by the MRD. These proposals should be accompanied by technical data (e.g. test results, drawings, documentation of previous applications) to support the performance claims. Sufficient evidence must be provided to the Program Manager that a proposed technology is applicable and is sufficiently mature to justify a qualification test program.

IMPLEMENTING SDS FOR DAMAGE TOLERANCE APPLICATIONS

Implementation of SDS systems into USAF aircraft requires an understanding of processes used by the USAF to manage structural integrity over the aircraft's lifetime. The Aircraft Structural Integrity Program (ASIP), required by MIL-STD-1530C ⁽²⁾ employs damage tolerance (DT) as the methodology for managing the safety, repair, modification and inspection of safety-of-flight aircraft structures. Damage tolerance (DT) is defined as the ability of a structure to retain its required strength for a period of unrepaired usage after the structure has sustained specific levels of fatigue cracking, corrosion or discrete damage. In simple terms, maintenance and inspection actions are scheduled such that the damage is detected and repaired before it reaches a size that presents an unacceptable risk to structural safety or that cannot be economically repaired.

When DT is implemented for slow crack growth metallic structures, initial inspections are typically based on "rogue" initial flaw size assumptions and slow crack growth. When inspections are prescribed, it has been USAF policy to require the initial inspection to occur at a point in time (T_1) which corresponds to half the crack growth life associated with growing the crack from its initial rogue flaw size (a_0) to the critical crack size, (a_{cr}) (Figure 3)⁽³⁾⁽⁴⁾. The critical flaw size is the size at which immediate and catastrophic failure of the structure can occur if the structure experiences limit load.

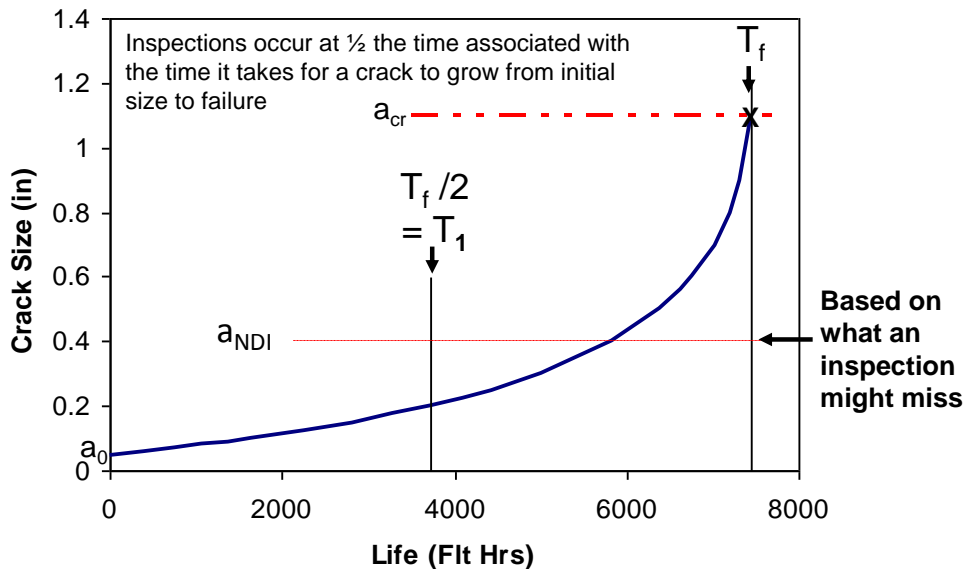


Figure 3. Slow crack growth curve from initial rogue flaw (a_0) at time zero to critical crack size (a_{cr}) at the time for catastrophic failure (T_f). Per USAF ASIP policy, the initial inspection is required at a time (T_1) occurring at half the crack growth life. The capability of an inspection system may be defined by the length of crack that such a system might miss (a_{NDI})

Recurring inspection intervals are established at half the time required for a crack to grow from the largest crack length that may be assumed to be missed (i.e., the NDI capability) during an inspection, a_{NDI} , to the critical size a_{cr} (Figure 4). If no crack is detected during an inspection, the crack size is analytically “reset” to a_{NDI} (i.e., the structure is assumed to have a crack of length a_{NDI} present) and the next inspection interval is calculated as before. Recall that a_{NDI} signifies an estimate of the detection capability an inspection system typically established at the $a_{90/95}$ crack size. Again, the $a_{90/95}$ is a statistical estimate of the crack size that will be detected 90% of the time with a statistical confidence of 95%.

The ability to define the damage detection capability of potential SDS solutions is critical for successful implementation. Therefore it is critical that SDS systems demonstrate the capability to reliably detect damage such that the probability-of-miss (POM) is very low (i.e. the probability that a missed crack of significant size, $a_{cr-miss}$ will not grow to failure before the next inspection interval). Estimating detection capability is not a trivial task and requires considerable expertise in statistics and design of experiments to successfully accomplish. The statistical methods defined in MIL-HDBK-1823A ⁽⁵⁾ should always be used.

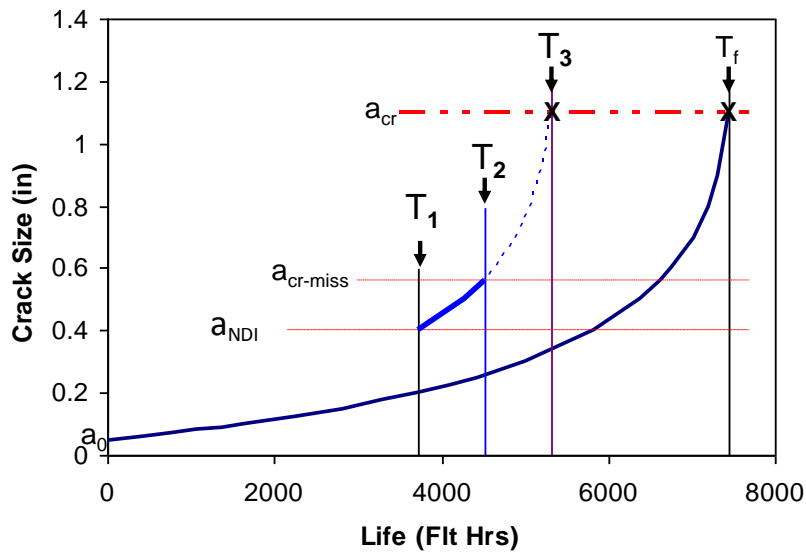


Figure 4. The slow crack growth curve from a post-inspection based “reset” crack size (a_{NDI}) growing from time (T_1) to the critical crack size (a_{cr}) at time (T_3) defines the time for the next inspection (at time T_2). Also shown in the figure is the critical-miss crack size ($a_{cr-miss}$) associated with a crack that will grow to failure before the following inspection at time T_3 if missed during the next inspection at time T_2 .

The DT methodology, first established in the 1970s⁽³⁾, has evolved over the years but remains focused on establishing structural configurations and stress allowables to control and mitigate the potential for structural failures, throughout the design lifetime, as a result of crack-like damage. It is important to note that USAF ASIP policy strives to address manufacturing and design issues early in a program’s life-cycle to preclude costly structural retrofits or recurring inspections required to maintain structural safety. The current version of the Department of Defense Joint Service Guide Specification, JSSG 2006⁽⁶⁾ clearly states in §3.2.14.5 “By design, the airframe structure shall not require inspection during the service life specified in §3.2.14”. However, if it is determined that cracks will likely occur in service and may propagate to failure before two design lifetimes, then the program must consider the business case justification for one or more of the following solution options:

- Option 1: Redesign the part and change the configuration during production
- Option 2: Redesign the part and retrofit during sustainment
- Option 3: Develop an inspection and repair program to ensure that cracks do not grow to failure or beyond an economically repairable size during the expected service life of the airframe.

Historically, design shortfalls are often discovered during full-scale fatigue testing very late in the design and development phase. This challenge is often compounded by some level of concurrency between production and the test program. As a result, the ability to implement an Option 1 solution for early production airframes is extremely

limited and Option 2 and 3 solutions are often employed. Consequently, the ability to embed an SDS solution early in production is severely limited or is not borne out by the typical business case which often leads to structural retrofit. SDS systems may, however, provide a technically viable and cost effective alternative as an Option 3 solution.

Structural inspection requirements are defined through a combination of analysis, full-scale fatigue testing, and field findings and are often refined and focused to specific structural locations and details. It is rare for individual inspection requirements to encompass large areas. These individual “control points” are typically defined by an airframe’s Force Structural Maintenance Plan (FSMP) that clearly describes each point’s structural location, required inspection capability and required inspection interval. These requirements are, for the most part, well defined and provide a foundation for SDS system performance testing.

SDS TRANSITION PATH

A successful SDS solution must provide a robust and reliable capability to protect structural safety while providing cost savings over traditional inspection processes. The decision to implement must be supported by a rigorous transition program that includes the following tasks:

- Task 1: Demonstration
- Task 2: Structural Risk Assessment
- Task 3: Cost Benefit Analysis
- Task 4: Airworthiness Certification
- Task 5: Implementation and Tracking

Task 1: Demonstration

The basis of a demonstration program is the development of an SDS demonstration test plan that addresses the following four critical factors:

- Capability
- Durability
- Installation/Supportability
- Safety

A robust demonstration program should use a multi-phased, building-block approach with clearly defined exit criteria for each phase documented in a SDS Demonstration Test Plan. Typically such a demonstration program will begin with basic laboratory testing that will eventually lead to on-aircraft flight test (Figure 5). Each phase must address various aspects of the four critical factors (detection capability, durability, installation/supportability, safety) with a successful outcome supporting a decision milestone to move to the next phase. It is intended that this approach should be tailored based on the criticality of the application and the maturity of the proposed SDS system.

Both the increase in the criticality of the intended application and the lack of demonstrated maturity of a proposed SDS system will drive more extensive development and testing.

To address this scale-up approach a demonstration program should include the following phases:

- Phase I: Laboratory Testing
- Phase II: Simulated Relevant Environment
- Phase III: Systems Level Test
- Phase IV: Installation Validation
- Phase V: Flight Test

Figure 5 illustrates this building-block approach with decision gates at the conclusion of each phase. The primary objective of the demonstration test program is to generate sufficient evidence that the proposed SDS system meets the MRD requirements prior to transitioning to Task 2. Each demonstration phase must be structured to address specific objectives described as follows:

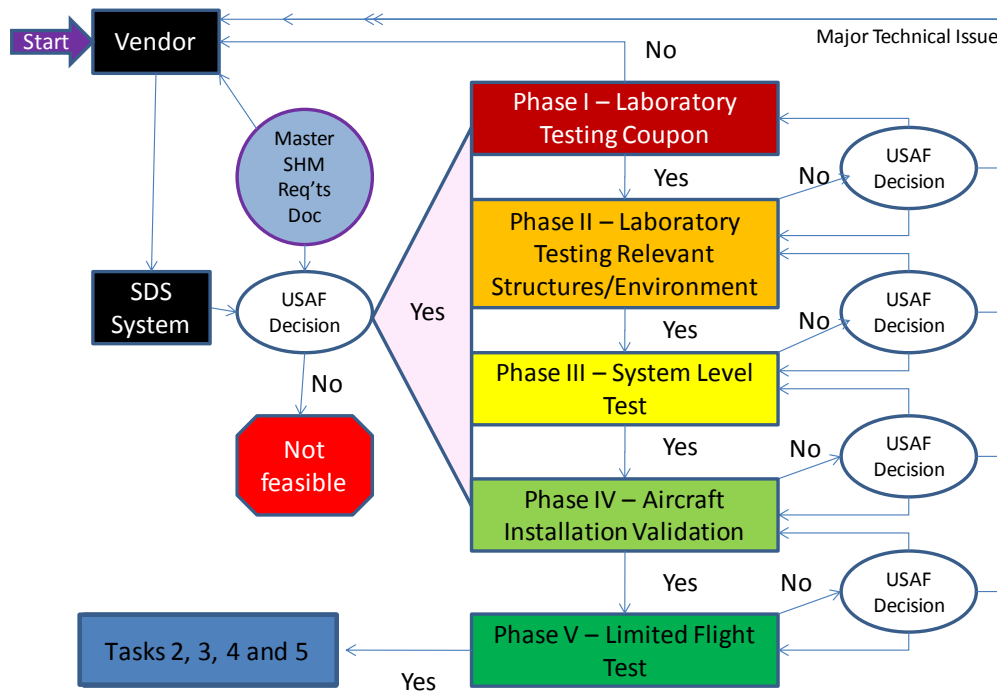


Figure 5: Task 1 - Notional Demonstration Test Program for SDS Systems

Demonstration: Phase I - Initial Laboratory Testing:

Initial laboratory testing provides the initial proof-of-concept or feasibility with a primary focus on demonstrating compatibility to the intended application and capability of the system to detect type and size of damage within representative test samples. For an SDS system to successfully meet the requirements for Phase I testing, the following objectives must be met:

- Demonstration of compatibility with the intended application. This includes, but is not limited to, compatibility with the simulated structural configuration, geometry and materials. The simulated structure should be manufactured using the same processes defined by the design.
- Demonstration of capability to detect damage as required by the MRD within the defined environment on specimens representing the material and configuration of the component of interest.
- Demonstration of the SDS system calibration approach and procedures.
- The hardware and interface used for monitoring the SDS system response must demonstrate the ability to provide a clear and unambiguous indication of damage. The damage response should continuously increase with increasing levels of damage until a saturated response is encountered. The signal response should be directly correlated to damage severity.
- The ability to threshold the SDS signal response to indicate a discrete level of damage must also be demonstrated. The threshold level must be selected to detect the type and size of interest as defined by the MRD without false-positives.

Basic feasibility testing can consist of mounting SDS sensors to representative specimens and cyclically loading the specimens to generate and grow fatigue damage. Preliminary testing may involve the use of simulated defects (e.g. electro-discharge machined (EDM) notches, simulated disbonds/delaminations) to represent damage but should progress to use of cyclically loaded fatigue damaged specimens. The loading spectrum used for fatigue propagation should be based on the anticipated on-aircraft load environment; however, higher load rates may be required for economy. Test specimens must be manufactured from the same material, alloy, heat treat and possess a similar microstructure as the intended application. The sample design sufficiently complex (contain stiffeners, fastener holes, tapers, curves, etc. as appropriate) to represent the intended application but may not require the detailed replication of aircraft structure geometry or assembly.

Demonstration: Phase II - Simulated Relevant Environment:

Building upon the Phase I milestones, the goal for this phase is to demonstrate the system detection capability to sense and reliably identify relevant damage on structures in a relevant environment. A relevant environment is defined as test conditions that

closely simulate the load spectrum when the test coupons are exposed to an environment similar to the intended application. Conditions that may have to be simulated include vibration, temperature, pressure, and exposure to moisture or aircraft fluids (hydraulic fluids, fuel, greases). The test samples should represent the intended application in terms of geometry, material, and assembly, including boundary conditions. In addition, the simulated environmental testing should mirror actual in-service conditions to the greatest extent possible. The test duration should be at least twice the intended monitoring period of the SDS system. For example, if the structure will be monitored by the SDS system between depot maintenance cycles and conventional NDI will take place during the depot maintenance then the test duration should replicate at least two depot cycles.

The objectives of this phase include:

- Demonstration of the capability of the SDS system to provide accurate detection information without performance drift in a simulated relevant environment. An initial estimate of system durability in terms of equivalent flight hours should result.
- Demonstration of the long-term integrity of sensor, wiring and hardware mounting and/or bonding to the structure.
- Demonstration of the sensing modality and full characterization of sensor response to damage severity within the relevant environment.
- Demonstration of the capability to reject relevant damage well above the system or environment induced noise. Any anomalies in the results must be explained with physical concepts.
- Validation of the capability to reliably detect damage in terms of probability of detection as defined by the MRD in a relevant environment.

The SDS sensors and systems must survive in a relevant environment for at least twice the maximum intended monitoring period of the SDS system appropriate for the particular application(s). An initial assessment of the possible sensor failure modes, mean-time-between failure (MTBF) rates and incorporation of design improvements or mitigation strategies should result.

Table 1: Conditions that should be considered during simulated relevant environmental testing ⁽⁸⁾.

Environmental Conditions
High/Low Temperature (warm climate, altitude temperature)
Thermal Shock (engine exhaust blast)
Humidity
Fluid Susceptibility (jet fuel, hydraulic fluid)

Altitude/Low Pressure
Static loading and strain (fuel/weapons/cargo weight)
Fatigue cycle loading (compressive and tensile)
High and low velocity impact loading/unloading (bird strikes, fuel, missile firings)
Vibration (engine, aero or acoustic vibration)
Exposure to slipstream (for sensors placed on outer mold line)
Electromagnetic interference (communications, avionics, flight systems)

Demonstration: Phase III - System Level Test: Once the demonstration test program progresses to Phase III, testing shifts to evaluations on complex structure that mirrors the structural geometry, materials, scale and boundary conditions of the target structure. The loads and environment must replicate the target mission profiles. Demonstration on full scale fatigue test articles is ideal. This may also include a subset of the simulated environments listed in Phase II. As with Phase II, the test duration should be at least twice the maximum intended monitoring period of the SDS system.

The objectives of this phase include:

- Demonstration of the capability to reliably detect damage on structure representing the target structure including the geometry, scale, materials and assembly interfaces.
- Demonstration of the SDS system monitoring scheme.
- Demonstration and verification of the in-situ calibration procedures.
- Demonstration and verification of SDS system fault sensing capability.
- Identify any failure modes and mitigation strategies not previously encountered in Phase II and establish statistical basis for mean-time-between-failure (MTBF) estimates

In the previous testing phases, the feasibility of the SDS installation, capability and durability was explored. Phase III builds on previous testing by incorporating the lessons learned from previous phases through improvements in SDS hardware, monitoring schemes, data collection, calibration and installation processes. Preparation for Phase III requires careful engineering to ensure that all potential failure modes are considered and addressed.

The experimental design for Phase III must ensure that the number of sensors, control points and test duration are sufficient to provide a statistically relevant estimate of SDS system MTBF. The extended test duration also provides an opportunity to address SDS system variability and calibration over time.

At the conclusion of this testing phase, the SDS system calibration and monitoring procedures should be sufficiently mature, potential SDS system failure modes should be well understood and addressed, mounting/bonding processes⁽⁹⁾ should be established and all potential impacts of installation to aircraft system safety addressed. At this stage the SDS must also have demonstrated validated detection capability as required by the MRD with the sources of potential of false-positives understood and controlled.

Demonstration: Phase IV - System Installation and Validation:

The purpose of the System Installation and Validation phase is to exercise the documented installation processes and identify barriers that may prevent the successful installation of an SDS system.

The objectives of this phase include:

- Demonstration and validation of the installation procedures, mounting and/or bonding processes, wire and cable runs and monitoring/access points.
- Develop and validation of initial installation, monitoring and maintenance procedures to be used by maintainers.
- Top-to-bottom evaluation of the SDS system safety for potential hazards (e.g. EMI interference, foreign object debris potential, intrinsic safety in fuel vapor environment, electrostatic discharge, etc.)

This phase differs from the previous phases in that it involves the installation of the final SDS system configuration onto a representative airframe. The preference is to demonstrate the installation on a non-flight worthy airframe, such as a maintenance trainer, to ensure maximum flexibility in resolving installation challenges.

Potential impacts to aircraft safety and potential system interactions must be evaluated using the guidance of DoD MIL-HDBK-516B *Airworthiness Certification Criteria*,⁽¹⁰⁾. Effects on the basic aircraft functions and potential interaction with subsystems must be addressed. Potential interactions include electromagnetic interference (EMI)⁽¹¹⁾, effects on avionics and communications, power-supply distribution and interactions. To that end, ground based testing of the SDS system prior to installation on an airworthy aircraft is desirable.

At the end of this stage all installation requirements and processes should be demonstrated and validated, and all potential system interactions and safety considerations must be evaluated, addressed and verified.

Demonstration: Phase V - Flight Test: The flight test phase marks the installation and demonstration of the mature SDS system on a flight worthy aircraft. Approval for flight test is gained using the temporary modification process (type T2 modification) defined by AFI 63-131, *Modification Program Management*⁽¹²⁾, with the technical justification for

this modification provided by the results of the previous demonstration phases. This phase will typically involve a limited number of aircraft; therefore, in order to gain maximum information about system reliability, mounting and monitoring it is recommended that multiple sensors and sensor systems be used. **To maintain flight safety during the demonstration program the current inspection requirements must be performed in parallel to SDS monitoring.**

The objectives of the flight test demonstration phase include:

- Validation of field or depot installation processes and procedures
- Validation of the data capture, monitoring and analysis processes
- Validation of SDS system reliability in intended environment.
- Verification of the reliability of the SDS system in terms of failure rates and false-positive rates.
- Identification of training requirements for SDS system installation, maintenance and monitoring.
- Assessment of any unforeseen system interactions.

Task 2 – Risk Assessment

A successful Task 1 demonstration program should have addressed the following:

- What damage type, size and location will be reliably detected?
- What is the system capability in terms of probability of detection and probability of miss?
- What is the expected rate of false positive indications?
- What mean-time-between failure rate? (i.e. What is the expected service life of the sensor System?)

The first two questions addresses the risk to structural safety while the third and fourth questions drive economic risk in terms of unanticipated maintenance costs and impacts to aircraft availability. If these questions have been satisfactorily answered, then a risk-based decision must be made.

An SDS system that is used to monitor fatigue crack growth on fracture-critical components must demonstrate the capability to reduce risk of catastrophic structural failure while providing an economic benefit over convention NDI methodologies. For safety of flight (SoF) structural locations a risk assessment must be performed to establish that the candidate SDS system will maintain a probability of loss of an aircraft

(PLOA) below 1×10^{-7} per flight. **If the SDS system cannot maintain a PLOA below this level, then the system cannot replace the current inspection program.**

This risk assessment must be based on a credible demonstration of the SDS system's detection capability and the systems reliability in addition to the information obtained in Task 1. The responsibility for conducting this risk assessment falls to the responsible engineering authority. **In addition to a risk assessment, the risk must be accepted by the appropriate authority as called out in Airworthiness Bulletin AWB-013A.**

If the risk is unacceptably high, and not accepted at the appropriate level, then various risk mitigation options are available such as use of the SDS system in combination with limited NDI (i.e. – every other inspection interval) or use of an SDS system to provide expanded coverage at specified control points in addition to the focused NDI program or to monitor fail-safe structures for impending failure.

Task 3 - Cost Benefit Analysis

The decision to implement an SDS system will ultimately hinge on the economic benefits the solution provides both in terms of cost avoidance and system availability. The Program Manager must develop formal cost estimates to implement the proposed modification. Approaches for developing these cost estimates are defined in AFPD 65-5, *Cost and Economics*⁽¹³⁾. AFPD 65-5 requires estimate include all life cycle costs including recurring cost (e.g. operation, maintenance and monitoring) and non-recurring costs. Non-recurring costs include development (laboratory and flight test), production, and engineering efforts to establish airworthiness certification in accordance with Air Force Policy Directive (AFPD) 62-6, *USAF Airworthiness*,⁽¹⁴⁾ and the identification and assessment of all applicable criteria in accordance with MIL-HDBK-516B. Cost estimates for temporary modifications to support activities such as flight test must also include host system de-modification. If the program is determined to be a low cost modification (i.e. less than \$2 million) then preparation of a formal, detailed cost estimates may not be required. Additional cost estimating requirements are prescribed in AFI 63-101, *Acquisition and Sustainment Life Cycle Management*⁽¹⁵⁾.

False positives and SDS sensor failures will drive additional maintenance actions including gaining access to the target structure, performing conventional NDI, repairing the SDS sensor system, and restoring the aircraft to flying status. The potential economic risk presented by the projected false positive rates must be included within the formal Cost Benefit Analysis conducted in this task.

Task 4 – Airworthiness Certification

The responsibility falls on the Program Manager (PM) to establish a certification basis for all aircraft modifications. This requires that the PM obtain and maintain airworthiness certification for aircraft under their direct management. Airworthiness certification for a given USAF aircraft system is managed by AFPD 62-6 which “establishes the policies for formal airworthiness assessments to ensure that AF

organizationally operated aircraft are airworthy over the entire life cycle and maintain high levels of safety". This policy establishes a Technical Airworthiness Authority (TAA), designated by the Commander of the Air Force Material Command, to provide independent airworthiness determinations. The TAA is supported by an Air Worthiness Board comprised of Major Command (MAJCOM) representatives and subject matter experts.

The criteria for establishing an airworthiness decision is contained in MIL-HDBK-516B. Airworthiness determination is based on an assessment of system level effects and risks posed by potential modifications. It is critical that specific attention be given to system level installation effects and potential interactions particularly if Active (Type II) SDS systems are proposed. Justification for airworthiness approval requires verification that all applicable airworthiness criteria are addressed; therefore, the veracity and documentation of activities conducted in Tasks 1 and 2 are vital. Failure to establish technical justification (Task 1) or demonstrate an acceptable risk (Task 2) for a proposed SDS solution will ultimately fail to meet with TAA approval.

Task 5 – Implementation

As previously stated, USAF aircraft modifications are managed by the Modification Management process defined by Air Force Instruction (AFI) 63-131 and the associated MAJCOM supplements. Although a detailed analysis of the required processes defined by this AFI is beyond the scope of this paper, the tasks described above directly support the implementation strategy.

The PM will be required to develop an implementation strategy that clearly defines how the modification program will be funded, developed, tested, produced, fielded and supported. Careful consideration must be given to system spares, maintenance technical data and training of field maintainers. A schedule for implementation must be established. All permanent (P) modifications will require approval through a Change Review Board (CRB). Justification for approval will be based on the documented results of Tasks 2 through 4. The approval process will vary depending on the using command; therefore, definition of a comprehensive implementation plan very early in the program as well as close communication with the PM is key to successful execution. Ultimately, CRB approval for permanent SDS installation will require careful execution of all Tasks. SDS modification programs should only be presented to a CRB when a sound technical justification is established, there is a clear and compelling cost benefit, the solution provides acceptable risk, and airworthiness certification is obtained from the TAA.

CLOSING REMARKS

SHM and more specifically SDS systems for monitoring the structural integrity of USAF aircraft may provide viable alternatives to invasive inspections. The success of and the decision to implement SDS solutions ultimately hinges on the capability of the system to

reduce the risk of structural failure while providing economic benefit in terms of maintenance cost savings and aircraft availability.

The proposed task-based approach described above defines a logical path for SDS system qualification. It is comprehensive in nature and is guided by existing USAF policy, namely Air Force Instruction (AFI) 63-131 and MIL-HDBK-516B, and is tailorable to the application.

It is anticipated that formal guidance in the form of Air Force Instructions or standards will be required to direct the transition and qualification of activities in the future. As SHM and SDS systems develop and mature so, too, will the methodologies for characterizing their performance. Therefore, any future guidance should reflect the knowledge base as it evolves.

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