

AEROSPACE RECOMMENDED PRACTICE

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Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

RATIONALE

The development of structural health monitoring (SHM) technologies to achieve vehicle health management objectives in aerospace applications is an activity that spans multiple engineering disciplines. It is also recognized that many stakeholders—i.e., regulatory agencies, airlines, original equipment manufacturers (OEM), academia and equipment suppliers—are crucial to the process of certifying viable SHM solutions. Thus, a common language (definitions), framework of SHM solution approaches, and recommended practices for reaching those solutions are needed to promote fruitful and efficient technology development. Revision A of this document provides updated guidance based on a Five-Year Review.

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<https://www.sae.org/standards/content/ARP6461A>

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1. SCOPE

This document is applicable to civil aerospace airframe structural applications where stakeholders are seeking guidance on the definition, development, and certification of structural health monitoring (SHM) technologies for aircraft health management applications.

Inputs to the structural health management are obtained from SHM equipment and/or from onboard sensors, delivering the detection and characterization of damage, load, or environmental parameters for operational and damage monitoring.

For the purpose of this document, SHM is defined as “the process of acquiring and analyzing data from on-board sensors to characterize the health of a structure.” The suite of on-board sensors could include any presently installed aircraft sensors, as well as new sensors to be defined in the future.

1.1 Purpose

The document has these major purposes:

- Provide guidance on the implementation of SHM in aircraft applications to assist developers in specifying the measurements, accuracy, reliability and other requirements of the system to be designed.
- Provide information on structural maintenance practices and provide guidance on how SHM can be incorporated within or as modifications to current maintenance and airworthiness documents.
- Standardize and harmonize worldwide understanding about SHM (including terminology).
- Provide basic requirements to guide SHM technology development.
- Recommend certification matters that are relevant to SHM.

1.2 Field of Application

This document may be applied by SHM stakeholders to assist with, among other things:

- Definition, development, maturation, design, and guidance on certification of SHM systems for application in civil fixed-wing aircraft. Note that guidance for military fixed-wing aircraft is found in AIR6245, while rotorcraft guidance is found in AIR6892.
- Modification of aircraft maintenance and aircraft structural health management to use and benefit from SHM systems.
- Improving maintenance practices by utilizing alternative tools to conventional NDI.
- Execution of scheduled and/or unscheduled maintenance tasks in a more time and cost-effective manner.

NOTE: Although guidance such as this may be crucial to successful implementation of an SHM system, use of this guidance alone cannot be assumed to constitute or ensure regulatory agency acceptance. Any regulatory accepted use to fulfill inspection requirements will require negotiation and agreement with the appropriate regulatory agency. This SAE document is not a regulatory document and neither the applicants nor the regulatory agency is compelled to follow them unless there is associated regulatory agency policy.

1.3 An Overview of This Document

1.3.1 General Approach

This document provides key definitions, guidelines, and examples that can assist civil stakeholders in the development, validation, verification, and certification of SHM systems. The approach adopted in developing the guidelines was to maintain harmony with existing applicable regulations, standards, and guidelines, and to augment them with specific interpretations or extensions pertaining to SHM, as necessary. Where existing definitions and processes were available from industry accepted publications, they have been adopted without modification; interpretations specific to SHM have been added for clarity. Additional definitions and processes have been collated or developed only where their equivalents did not clearly exist. In this way, consistency is maintained with existing regulations, standards, and industry-accepted practices. Applicable documents from which the SHM key guidelines and definitions were collated are listed in Section 2. This document does not replace any existing FARs, regulations, or certification requirements currently in existence.

1.3.2 Designing and Maintaining Airworthy Structures

Referring to FAA publications, Section 3 reviews the main airworthiness regulations for design and maintenance of structures. Equivalent EASA regulations can be extracted from the applicable documents presented in Section 2. As summarized in Figure 1, maintenance regulations and processes are introduced to overcome the threats to structural integrity, which can arise from the damaging effects of fatigue, environments, and accidents. Section 3 gives more details about these regulations and processes and briefly introduces SHM.

Having introduced SHM, Section 3 illustrates how SHM can assist in overcoming the threats to structural integrity using existing processes without violating relevant airworthiness regulations. Section 4 describes SHM as an improved means for maintaining structural integrity and classifies potential SHM-intended functions under two main headings: operational monitoring and damage detection. Operational monitoring functions maintain regular surveillance over the factors that can lead to or indicate fatigue damage (FD), environmental damage (ED), and/or accidental damage (AD). Damage detection functions directly detect FD, ED, and/or AD if they occur. Section 4 describes the outputs, potential benefits, and operational considerations of SHM. Section 4 also summarizes specifications for the use of SHM systems in aircraft maintenance that have been recommended and proposed by Airlines for America Maintenance Steering Group 3 (A4A MSG-3) in recent and pending document revisions (Revision 2009.1, Issue Paper 92, Issue Paper 105, Issue Paper 180), as well as regulatory guidance found in AC 43-218 and SHM IP.

Having described how SHM can assist in overcoming the threats to structural integrity and highlighted the A4A MSG-3 recommended specifications for SHM, the evolution phases of SHM are briefly discussed to identify the main processes that are recommended to approve/certify SHM systems.

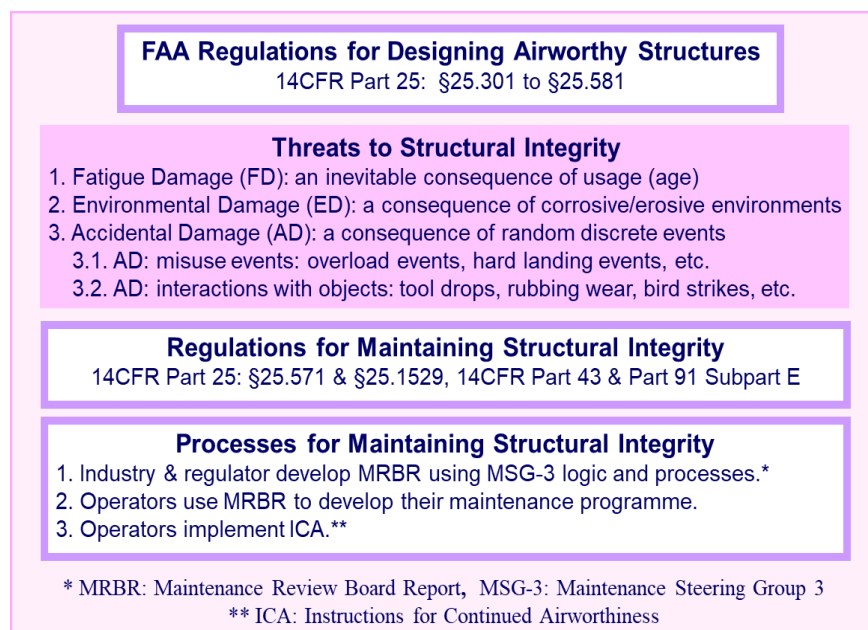


Figure 1 - Designing and maintaining airworthy structures



1.3.3 Evolution of Aircraft Products Including Structures and SHM Systems

[Figure 2](#) illustrates the evolution phases of any aircraft product, which span maturation, development, production, installation/integration, certification, utilization, and maintenance. The evolution phases start with identifying intended functions that address emerging demands. The SHM technology maturation efforts are motivated by demands for improving maintenance practices, underwriting new aircraft materials/designs, and improving aircraft operational practices. Once suitable SHM technologies are identified, a development process will be followed that addresses architecture, requirements, test and validation, aircraft integration, and instructions for continued operation. [Figure 2](#) identifies the sections of this document, by their numbers, that provide information about these activities.

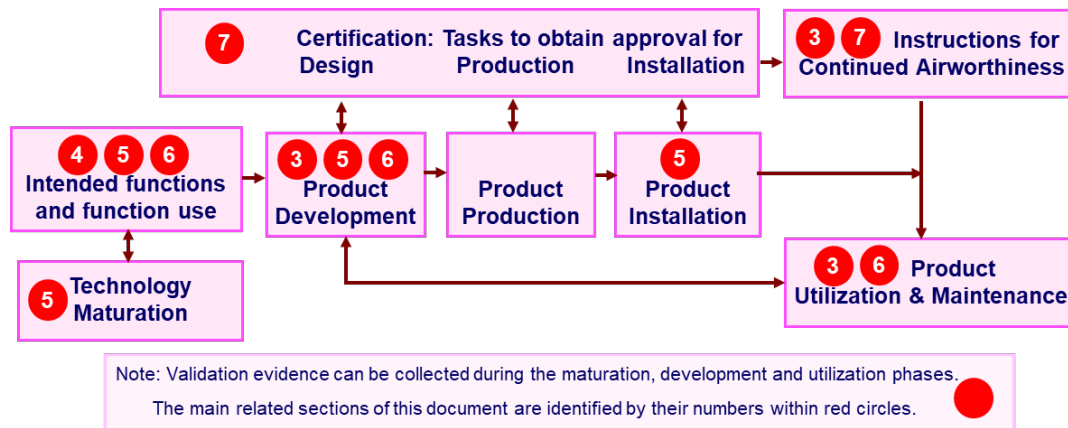


Figure 2 - Evolution of aircraft products including SHM systems

As indicated throughout this document, any SHM system uses data acquired by on-board sensors fitted in each individual aircraft to directly detect and/or monitor damage and to monitor the factors that can lead to or indicate damage. Other entities of an SHM system (for example, signal conditioning and information processing subsystems) can be located on-board the aircraft or within ground-based systems. Some or all of these entities may be designed specifically for SHM or can be shared entities from other pre-existing systems. Any given SHM-intended function may be realized by a variety of different system architectures.

1.3.4 Requirements, V&V, and Certification

Section [5](#) focuses on identifying SHM requirements. In this section, it is noted that the development of the system architecture and the allocation of requirements are tightly-coupled, iterative processes. The architectures of two SHM systems that provide the same intended function may have different design approaches, such as differences in: items shared with existing aircraft systems versus items designed specifically for SHM, ground-based items versus airborne items, similar airborne items installed into different aircraft location and, hence, exposed to different environmental conditions.

Section [6](#) presents typical methods used to validate and verify aircraft products and introduces interpretations and extensions specific to SHM systems. Section [6](#) recognizes that the rigor, and hence the assurance level, required for validation and verification depends on the chosen architecture and the consequence of the failure conditions of each SHM item on safe operations, if any. The more severe the consequence, the more rigor required. For SHM systems that have negligible effects on aircraft structures and systems, the validation and verification methods presented in Section [6](#) may not be required to support certification; such systems may be approved by a manufacturer qualified representative. However, SHM systems that have major effects can be approved only by the appropriate regulator after witnessing development, validation, and verification activities conducted with rigor proportionate to the consequence of SHM failure conditions.

For the purpose of this document, Section 7 considers certification as the processes required for obtaining approval from the appropriate Regulatory Authority (FAA, EASA, UK MOD, DOD, etc.) that the applicable airworthiness regulations, operating rules, and system requirements are met. Formal definition of certification taken from ARP4761 is presented in 2.3. The certification efforts involve the regulator, the product developer and the aircraft manufacturer along with any other stakeholders such as airlines and MROs. The certification efforts are initiated through an application made by the aircraft OEM, operator, or equipment vendor to the appropriate regulator, typically before the start of the product development phase; these efforts are performed in parallel to the other evolution phases and can overlap with the maturation phase. The outputs of successful certification phases include: design approval, production approval, installation approval, and Instructions for Continued Airworthiness (ICA). Section 7 presents more details about the certification phases, their outputs, and associated approval forms.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR6245	Perspectives on Integrating Structural Health Monitoring Systems into Fixed-Wing Military Aircraft
ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP5150	Safety Assessment of Transport Airplanes in Commercial Service
ARP5987	A Process for Utilizing Aerospace Propulsion Health Management Systems for Maintenance Credit
AIR6892	Structural Health Monitoring Considerations and Guidance Specific to Rotorcraft

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 21	Certification Procedures for Products and Parts
14 CFR Part 23	Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
14 CFR Part 25	Airworthiness Standards: Transport Category Airplanes
14 CFR Part 26	Continued Airworthiness and Safety Improvements for Transport Category Airplanes
14 CFR Part 27	Airworthiness Standards: Normal Category Rotorcraft
14 CFR Part 29	Airworthiness Standards: Transport Category Rotorcraft
14 CFR Part 33	Airworthiness Standards: Aircraft Engines

14 CFR Part 35	Airworthiness Standards: Propellers
14 CFR Part 121	Operating Requirements: Domestic, Flag, and Supplemental Operations
14 CFR Part 135	Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons On Board Such Aircraft
AC 20-115	Radio Technical Commission for Aeronautic, Inc. Document RTCA DO-178
AC 20-107	Composite Aircraft Structure
AC 20-152	RTCA, Inc., Document RTCA DO-254, Design Assurance Guidance for Airborne Electronic Hardware
AC 20-156	Aviation Data Bus Assurance
AC 25-571-1	Damage Tolerance and Fatigue Evaluation of Structure
AC 25-19A	Certification Maintenance Requirements
AC 29-2C MG 15	Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems
AC 43-218	Operational Authorization of Integrated Aircraft Health Management Systems
AC 121-22	Maintenance Review Board Report, Maintenance Type Board, and OEM/TCH Inspection EASA Publications
FAA CPI Guide	The FAA and Industry Guide to Product Certification
FAA Issue Paper	Comparative Vacuum Monitoring (CVM) for Damage Detection in Structure of Antenna Installations, Project Number: ODA-2499-01
Order 8110.37E	Designated Engineering Representative (DER) Guidance Handbook
Order 8100.8D	Designee Management Handbook

2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

CS-23	Certification Specifications for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes
CS-25	Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes
EC 748/2012	Annex Part 21: Certification of Aircraft and Related Products, Parts and Appliances, and of Design and Production Organizations

2.1.4 Transport Canada Publications

Transport Canada documents are available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

CARs 2012-1	Part I - General Provisions, Subpart 1 - Interpretation (CARs 101.01)
CARs 2012-1	Part V - Airworthiness, Regulations, Subpart 21 - Approval of the Type Design or a Change to the Type Design of an Aeronautical Product (CARs 521.01 to 521.456), Division IV - Changes to a Type Design (CARs 521.151 to 521.161)
AC 521-004	Changes to the Type Design of an Aeronautical Product

2.1.5 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
DO-178	Software Considerations in Airborne Systems and Equipment Certification
DO-200	Standards for Processing Aeronautical Data
DO-201	Industry Requirements for Aeronautical Information
DO-254	Design Assurance Guidance for Airborne Electronic Hardware
DO-278	Guidelines for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) System Software Integrity Assurance

2.1.6 Airlines for America (A4A) Publications

Available from Airlines for America (A4A), 1301 Pennsylvania Avenue, NW, Suite 1100, Washington, DC 20004, Tel: 202-626-4000, www.airlines.org.

A4A MSG-3	Operator/Manufacturer Scheduled Maintenance Development
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2.1.7 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

MIL-HDBK-1823	Nondestructive Evaluation System Reliability Assessment
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-810	Environmental Engineering Considerations and Laboratory Tests
MIL-STD-1472	Design Criteria Standard: Human Engineering
CMH-17	Composite Materials Handbook 17 (Vol. 3 Chapter 12 Damage Tolerance)

2.1.8 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ISO 5725	Accuracy (Trueness and Precision) of Measurement Methods and Results
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2.1.9 Other Publications

ENV13005 Guide to the Expression of Uncertainty in Measurement

JAA JAR145 Aviation Maintenance Human Factors

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4175 A Guide to the Development of a Ground Station for Engine Condition Monitoring

Azzam, H. and McFeat, J., "A Validation Methodology for Structural Health Monitoring," SAE Technical Paper 2011-01-2608, 2011, <https://doi.org/10.4271/2011-01-2608>.

2.2.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 39 Airworthiness Directives

14 CFR Part 43 Maintenance, Preventive Maintenance, Rebuilding and Alteration

14 CFR Part 91 General Operating and Flight Rules

AC 20-65 U.S. Airworthiness Certificates and Authorizations for Operation of Domestic and Foreign Aircraft

AC 20-77 Use of Manufacturers Maintenance Manuals

AC 20-107 Composite Aircraft Structure

AC 25.1309-1 System Design and Analysis

AC 25-1529-1 Instructions for Continued airworthiness of Structural Repairs on Transport Airplanes

AC 25.981-1 Fuel Tank Ignition Source Prevention Guideline

AC 500-002 Electromagnetic Compatibility Testing of Electrical and Electronic Equipment

AC 91-82 Fatigue Management Programs for In-Service Issues

Order 8110.54 Instructions for Continued Airworthiness Responsibilities, Requirements, and Contents

SFAR No. 88 Fuel Tank System Fault Tolerance Evaluation Requirements

Beard, S.J., Kumar, A., and Ikegami, R., "Smart Patch System (SPS) for Condition Based Maintenance of Rotorcraft Structures," U.S. Department of Transportation, Federal Aviation Administration report for contract # DTFAC-05-C-00022, 2013.

Spencer, F., Borgonovi, G., Roach, D., Schurman, D., and Smith, R., "Reliability Assessment at Airline Inspection Facilities, Volume I: A Generic Protocol for Inspection Reliability Experiments," Dept. of Transportation Report, DOT/FAA/CT-92/12-I, March 1993.

2.2.3 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ISO 13374	Condition Monitoring and Diagnostics of Machines - Data Processing, Communication and Presentation
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2.2.4 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

AMC 20-29	Composite Aircraft Structure
C.P006-01	Continuing Airworthiness of Type Design Procedure
CM-SWCEH-001	Development Assurance of Airborne Electronic Hardware
CM-SWCEH-002	Software Aspects of Certification
CS-27	Certification Specifications for Small Rotorcraft
CS-29	Certification Specifications for Large Rotor

2.2.5 NASA Publications

NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, 757-864-9658, Fax: 757-864-6500, <http://ntrs.nasa.gov/>.

NASA/CR-2000-210643	Analysis of Regulatory Guidance for Health Monitoring
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2.2.6 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

ADS-79-HDBK	Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for U.S. Army Aircraft
MIL-HDBK-217	Reliability Prediction of Electronic Equipment
MIL-HDBK-781	Reliability Testing for Engineering Development, Qualification and Production

2.2.7 Transport Canada Publications

Transport Canada documents are available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

CARs Part V	Airworthiness - Standards, Chapter 551 - Aircraft Equipment and Installation
CARs Part V	Airworthiness - Regulations, Subpart 21 - Approval of the Type Design or a Change to the Type Design of an Aeronautical Product
CARs Part VI	General Operating and Flight Rules

2.2.8 Other Publications

"Encyclopedia of Structural Health Monitoring," Boller, C., Chang, F.K., and Fujino, Y. (eds), John Wiley & Sons, Ltd., March 2009.

"Fault Tolerance Design and Redundancy Management Techniques," Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (France), Defense Technical Information Center, pp. 175, 1980.

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2.3 Definitions

AUTOMATED SHM (A-SHM): Automated SHM is any SHM technology which does not have a pre-determined interval at which maintenance action must take place, but instead relies on the system to inform maintenance personnel that action must take place. (MSG-3)

AIRWORTHINESS: The condition of an aircraft, aircraft system, or component in which it operates in a safe manner to accomplish its intended function. (ARP4754)

APPROVAL: The act of formal sanction of an implementation by a certification authority. (ARP4754)

ASSURANCE: The planned and systematic actions necessary to provide adequate confidence and evidence that a product or process satisfies given requirements. (RTCA DO-178)

CERTIFICATION: The legal recognition that a product, service, organization, or person complies with the applicable requirements. Such certification comprises the activity of technically checking the product, service, organization, or person, and the formal recognition of compliance with the applicable requirements by issue of a certificate, license, approval, or other document as required by national laws and procedures. (ARP4754).

CERTIFICATION AUTHORITY: Organization or person responsible for granting approval in accordance with applicable regulations. (ARP4754)

CONDITION-BASED MAINTENANCE: Performing maintenance based on need (i.e., based on the condition or health of a component or system rather than on a periodic or scheduled basis).

CONDITION MONITORING: The process of observing the state of an asset in order to provide data, which can be used to determine a maintenance need. The observations can be continuous or intermittent.

CRITICALITY: Indication of the hazard level associated with a function, hardware, software, etc., considering abnormal behavior (of this function, hardware, software, etc.) alone, in combination, or in combination with external events. (ARP4761)

DAMAGE MONITORING: Any direct measurement methods that allow the detection of damages in the structure.

DAMAGE TOLERANCE: The attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, or accidental or discrete source damage. (AC 25-571-1)

FAILURE CONDITION: A condition caused or contributed to by one or more failures or errors that have either a direct or consequential effect on the airplane, its occupants, and/or other persons. In identifying failure conditions, the flight phase, relevant adverse operational or environmental conditions, and external events should be considered. (AC 25-19A)

FUNCTIONAL HAZARD ASSESSMENT: A systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity. (ARP4754)

INDEPENDENCE: (1) A concept that minimizes the likelihood of common mode errors and cascade failures between aircraft/system functions or items. (2) Separation of responsibilities that assures the accomplishment of objective evaluation (e.g., validation activities not performed solely by the developer of the requirement of a system or item). (ARP4754)

INSTRUCTIONS FOR CONTINUED AIRWORTHINESS (ICA): Documentation that sets forth instructions and requirements for the maintenance that is essential to the continued airworthiness of an aircraft, engine, or propeller. (AC 25-571-1)

INTEGRITY: (1) Attribute of a system or an item indicating that it can be relied upon to work correctly on demand. (ARP4751)
(2) Structural integrity is a performance characteristic which is applied to a component, a single structure, or a structure consisting of different components. Structural integrity assures that the construction will perform its designed function, during reasonable use, for as long as the designed life of the structure. Items are constructed with structural integrity to ensure that catastrophic failure does not occur, which can result in injuries, severe damage, death, or monetary losses.

PRELIMINARY SYSTEM SAFETY ASSESSMENT: A systematic evaluation of a proposed system architecture and its implementation, based on the functional hazard assessment and failure condition classification, to determine safety requirements for systems and items. (ARP4754)

OPERATIONAL MONITORING: Any indirect measurement methods that can contribute to the evaluation of structure's condition or utility.

PRODUCT: (1) Hardware, software, item, or system generated in response to a defined set of requirements. (ARP4754)
(2) Aircraft, aircraft engines, propellers, as well as appliances and components or parts. (FAA CPI Guide)

QUALIFICATION: The processes of verifying that a product (system, hardware, and software) complies with a specified set of performance and airworthiness requirements.

SCHEDULED SHM (S-SHM): To use/run/read out a SHM device at an interval set at a fixed schedule. (MSG-3)

STRUCTURAL HEALTH MONITORING (SHM): The process of acquiring and analyzing data from on-board sensors to characterize the health of a structure.

SYSTEM SAFETY ASSESSMENT: A systematic, comprehensive evaluation of the implemented system to show that the relevant safety requirements are met. (ARP4754)

VALIDATION: The determination that the requirements for a product are correct and complete (e.g., "Are we building the right aircraft/system/function/item?"). (ARP4754)

VERIFICATION: The evaluation of an implementation of requirements to determine that they have been met (e.g., "Did we build the aircraft/system/function/item right?"). (ARP4754)

2.4 Acronyms

A4A Airlines for America, formerly known as Air Transport Association of America, Inc. (ATA)

AC Advisory Circular (FAA) or Airworthiness Certificate

ACO Aircraft Certification Office

AD Accidental Damage

AISC-SHM SAE Aerospace Industry Steering Committee for Structural Health Monitoring

AL Assurance Level

AMM Aircraft Maintenance Manual

ARP Aerospace Recommended Practice (SAE)

A-SHM Automated SHM

CAR Canadian Aviation Regulations

CCA Common Cause Analysis

CFR	Code of Federal Regulations
COTS	Commercial Off-the-Shelf
CVM	Comparative Vacuum Monitoring
DAL	Development Assurance Level
DAR	Designated Airworthiness Representative
DER	Designated Engineering Representative
DET	Detailed Inspection
DoD	Department of Defense
EASA	European Aviation Safety Authority
EC	European Commission
ED	Environmental Damage
EMI	Electromagnetic Interference
EWIS	Electrical Wiring Interconnection System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBG	Fiber Bragg Gratings
FD	Fatigue Damage
FHA	Functional Hazard Assessment
FMEA	Failure Modes and Effects Analysis
GAMA	General Aviation Manufacturer's Association
GVI	General Visual Inspection
HUMS	Health and Usage Monitoring System
ICA	Instructions for Continued Airworthiness
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IMRBPB	International Maintenance Review Board Policy Board
IP	Issue Paper
ISO	International Organization for Standardization
JAR	Joint Aviation Requirements
LOV	Limit of Validity
LRU	Line Replaceable Unit

MIL-HDBK	Military Handbook
MPIG	Maintenance Programs Industry Group (A4A)
MRB	Maintenance Review Board
MRBR	Maintenance Review Board Report
MRO	Maintenance, Repair, Overhaul (facility or company)
MSG-3	Maintenance Steering Group 3
MTBF	Mean Time Between Failures
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
OEM	Original Equipment Manufacturer
OM	Operational Monitoring
PMA	Parts Manufacturing Approval
POD	Probability of Detection
PSCP	Project Specific Certification Plan
PSP	Partnership for Safety Plan
PSSA	Preliminary System Safety Assessment
PZT	Lead Zirconate Titanate
RTCA	RTCA, Inc.
SDI	Special Detailed Inspection
SHM IP	Structural Health Monitoring Issue Paper
SHM	Structural Health Monitoring
SSA	System Safety Assessment
S-SHM	Scheduled SHM
STC	Supplemental Type Certificate
TC	Transport Canada, Type Certificate (context dependent)
TCH	Type Certificate Holder
TL	Technology Level
TRL	Technology Readiness Level
TSO	Technical Standard Order
TSOA	Technical Standard Order Authorization

UK MOD United Kingdom Ministry of Defense

USAF United States Air Force

XM Exceedance Monitoring

3. INTRODUCTION TO AIRCRAFT STRUCTURES DESIGN AND MAINTENANCE

This section introduces fundamental principles and references of aircraft structures design and maintenance. The understanding of these principles allows identifying opportunities, challenges, and benefits for structural health monitoring systems. The references will introduce key regulatory and recommended practices material associated with structures design and maintenance to consider when designing, developing, and certifying structural health monitoring systems.

3.1 Structures Design Principles

As a general principle, the aircraft structures are designed to carry all applicable loads and withstand all foreseeable conditions safely during its design service goal.

Certification requirements related to structural design for transport category airplanes is Part 25 - Airworthiness Standards within Title 14 of the Federal Aviation Administration in United States. The Electronic Code of Federal Regulations can be consulted for all details. Similar regulations are applicable for other aircraft categories and in other jurisdictions.

Subpart C (section § 25.301-§ 25.581) describes the different loads and conditions to consider in the design of structures. Maneuvers, gusts, pressurization, landing and lightning strike are few examples.

The section § 25.571 establishes the need for structural inspections to be included in the airworthiness limitations part of section § 25.1529 to be introduced later in this section.

Advisory Circular 25.571-1D provides guidance for compliance with the requirements for damage-tolerance and fatigue evaluation.

Damage tolerance is a property of a structure relating to its ability to withstand defects safely until detection and repair. The key steps of damage tolerance evaluation are introduced below along with additional notes relevant in the context of SHM.

- a. Identification of the principal structural elements (PSE) that are considered essential in maintaining the overall structural integrity of the airplane.

Examples are integrally stiffened plates, control surfaces, principal splices, and door frames. More than 200 PSEs are usually identified on a commercial aircraft.

- b. Assessment of the extent of damage in terms of: (1) detectability with the given inspection techniques, (2) estimation of damage extent (e.g., crack size), (3) residual-strength capabilities, and (4) likely damage-extension rate.

A SHM technology capable of reliably detecting damage of a specific nature and size over a specific line, area or volume is a candidate alternative to conventional non-destructive evaluation such as visual, eddy current, ultrasonic, and X-ray inspection methods.

- c. Identification and minimization of inaccessible areas for inspection.

The use of SHM technology for inspection of inaccessible areas may yield a range of structural benefits, including part count reduction, the potential for weight savings, and reduction of maintenance manpower to disassemble, inspect, and reassemble the inaccessible areas.

- d. Fatigue test.

The full-scale fatigue testing offers the opportunity to test the durability of the SHM installation subjected to representative loading conditions of the structure.

- e. Identification of locations for damage-tolerance evaluation by determining the general damage locations and the critical damage areas.

A good understanding of the damage scenario is critical in the development of an SHM solution that will eventually meet the inspection requirements. Nonetheless, in-service experience has demonstrated that this analysis cannot anticipate all damage. Currently, inspectors have the flexibility to adjust quickly to new inspection instructions. Currently, most SHM systems do not afford this type of flexibility and hence is a potential limitation.

- f. Damage-tolerance analysis supported by test evidences.

The ground testing campaign also offer the opportunity to demonstrate detection reliability of SHM technologies, particularly when artificial damage is introduced to initiate crack and characterize propagation rate.

- g. Inspections or other procedures, as necessary, to prevent catastrophic failure from accidental, environmental, or fatigue damage.

Every aircraft type has specific inspection manuals describing the inspection methods approved by the OEM (e.g., visual, eddy current, ultrasonic, X-ray). There is already a documented example of a SHM technology that has been introduced in an inspection manual as accepted method by an OEM. Nonetheless, to date no inspection procedures were reported to offer this method.

- h. Calculation of threshold for inspections.

Calculation of threshold for inspections is based on fatigue analysis and tests or slow-crack-growth analyses and tests. Generally, inspection thresholds are defined in terms of flight count, flight hour, or calendar days. SHM system for operational monitoring assesses parameters associated with the loads and conditions experienced in-service in order to further adjust inspection program rather than relying on past experience and projected utilization. This may yield in a lighter maintenance program for some operators. Additionally, the SHM system can influence the operation of the aircraft to reduce maintenance cost and optimize maintenance scheduling.

[Figure 3](#) illustrates how the structural strength is maintained by damage tolerance for structure having slow-crack growth and no growth case. Limit load is defined as the maximum loads to be expected in service and the ultimate loads as the limit loads multiplied by prescribed factors of safety.

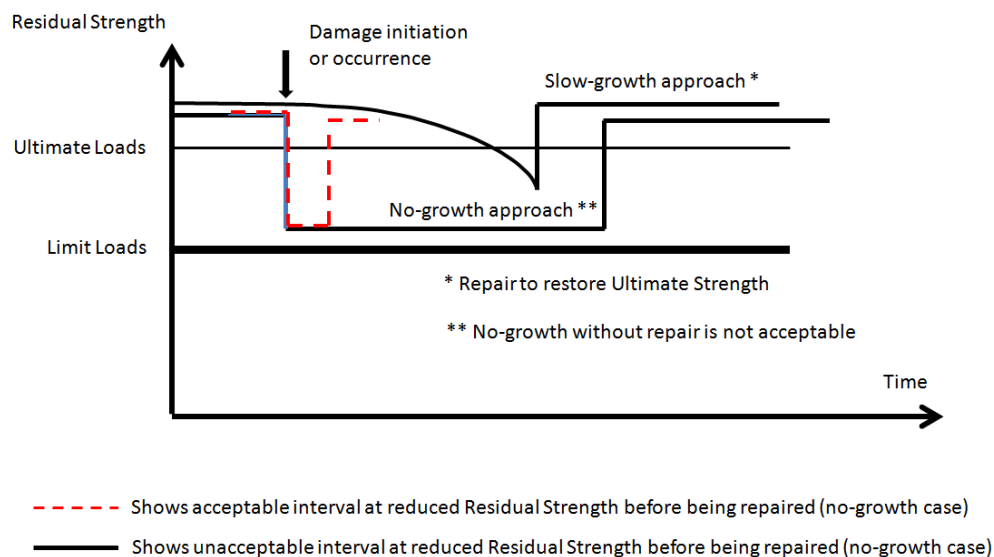


Figure 3 - Damage tolerant structural life

Damage tolerance evaluation § 25.571(b) is not required if it is considered impractical to apply to a specific structure. A classic example is the landing gear. In this case, the structure must comply to § 25.571(c). In this case, analyses supported by test evidence are required to demonstrate low probability of cracks for the service life of the structure, with the application of adequate safety factors (scatter factor). An SHM system for operational monitoring may be used to extend the service life of the structure in the case that the load spectrum experienced in-service is less severe than assumed in design.

More recently, section § 26.21 defines the requirement to establish a limit of validity (LOV) of the engineering data that supports the structural maintenance program. The LOV, in effect, is the operational life of the airplane consistent with evaluations accomplished and maintenance actions established to prevent widespread fatigue damages. The initial LOV defined during the certification process can be extended by additional analyses and/or tests. It is foreseen that SHM system for operational monitoring may also play a role in defining and extending the LOV.

3.2 Current Structures Maintenance Principles

3.2.1 A4A MSG-3 Document

The Airlines for America (A4A) MSG-3 Document is a result of combining more than 50 years of aircraft manufacturers, airlines, and regulatory authorities experience to create a minimum list of scheduled maintenance tasks for aircraft models under a given type certificate.

Through logical decision processes, A4A MSG-3 guides the development of scheduled maintenance programs with more effective tasks and intervals than the ones that would be generated directly from the engineering groups responsible for the aircraft design and certification.

The first version of this document was named Handbook MSG-1, "Maintenance Evaluation and Program Development," and concluded in July 1968. It was oriented only towards the Boeing 747 aircraft design and certification characteristics and therefore, it was necessary later to rewrite parts of its contents in order to turn it into a document that could be used by other aircraft types. The new version of the document was entitled MSG-2, "Airline/Manufacturer Maintenance Program Planning Document." It was used to develop scheduled maintenance programs for aircraft in the 1970s.

Around 10 years later, A4A airlines decided that a revision to existing MSG-2 procedures was necessary and with major participation of U.S. and European regulatory authorities and airlines as well as the U.S. Navy the MSG-3 document was developed. After the creation of the original A4A MSG-3, this document was revised several times (to be precise, nine times up to June 2012), in order to keep it up-to-date to the new regulations and maintenance processes as well as to clarify its contents. It was in the revision 2009.1 that the A4A MSG-3 document included for the first time SHM and scheduled SHM (S-SHM) concepts.

3.2.2 FAA AC 121-22, "Maintenance Review Board Procedures"

Understanding of the MSG-3 methodology is not sufficient for the approval of a maintenance program by a regulatory authority. An acceptable process is to coordinate the work of different groups with representatives from aircraft manufacturers, airlines and regulatory authorities. All these participants have distinct but complementary experiences on how to evaluate a given aircraft type, the model design documentation, and how to use their individual personal experience to reach agreements on what are the most applicable and effective maintenance tasks are and how to record them in an approved document.

Advisory circular (AC) 121-22 provides guidelines for what was mentioned above. Although it was developed by U.S. Federal Aviation Administration, it was adopted universally as a reference that may be used by industry during its development and revision of the initial minimum scheduled maintenance/inspection requirements for derivative or newly type-certificated transport category aircraft and power plants. These requirements constitute the Maintenance Review Board Report (MRBR) and after approval by the regulatory authorities, become a base or framework around which each airline develops its own individual maintenance program.

AC 121-22 provides a fairly detailed explanation about the process necessary to develop and approve an MRB Report, including roles and responsibilities of each group involved in this effort (Working Groups, Industry Steering Committee, etc.), and information about the MRBR format and contents.

As indicated in this AC, a maintenance review board report (MRBR) is generated as an expeditious means of complying in part with the maintenance instruction requirements of Appendix H to Title 14 of the Code of Federal Regulations (14 CFR) part 25. It is a means, in part, of developing instructions for continued airworthiness, as required by § 25.1529. Additional related regulations for this AC are: Title 14 of the Code of Federal Regulations parts 21, 23, 25, 27, 29, 33, 35, 121, 135; ss 21.50, 23.1529, 25.571, 25.1309, 27.1529, 29.1529, 33.4, 35.4, 121.25, 121.45, and 135.11.

3.2.3 Other Instructions for Continued Airworthiness

As mentioned before, the development and approval of a MRBR is necessary but not sufficient for an OEM to comply with requirements of Appendix H to 14 CFR part 25, "Instructions for Continued Airworthiness."

The complete set of instructions for continued airworthiness is listed below. ICAs, like MRBR, may be affected by the introduction of maintenance tasks based on SHM technologies:

- Airplane maintenance manual or section:
 - Includes an explanation of the airplane's features and data to the extent necessary for maintenance or preventive maintenance.
 - A description of the airplane and its systems and installations including its engines, propellers, and appliances.
 - Basic control and operation information describing how the airplane components and systems are controlled and how they operate, including any special procedures and limitations that apply.
 - Servicing information that covers details regarding servicing points, capacities of tanks, reservoirs, types of fluids to be used, pressures applicable to the various systems, location of access panels for inspection and servicing, locations of lubrication points, lubricants to be used, equipment required for servicing, tow instructions and limitations, mooring, jacking, and leveling information.
- Maintenance instructions:
 - Scheduling information for each part of the airplane and its engines, auxiliary power units, propellers, accessories, instruments, and equipment that provides the recommended periods at which they should be cleaned, inspected, adjusted, tested, and lubricated, and the degree of inspection, the applicable wear tolerances, and work recommended at these periods (normally covered by the MRBR).
 - Information describing the order and method of removing and replacing products and parts with any necessary precautions to be taken.
- Diagrams of structural access plates and information needed to gain access for inspections when access plates are not provided.
- Details for the application of special inspection techniques including radiographic and ultrasonic testing where such processes are specified.
- Information needed to apply protective treatments to the structure after inspection.
- All data relative to structural fasteners such as identification, discard recommendations, and torque values.
- A list of special tools needed.

- A section titled “Airworthiness Limitations.” This section must set forth:
 - The section must include a list of all mandatory maintenance tasks (e.g., any mandatory inspection/replacement/modification requirements) and should include all approved information, including limits, configurations, algorithms, and procedures that are required to perform the mandatory tasks by any designated maintainer independent of the OEM; for FAA regulations, refer to 14 CFR § 25.571 and 14 CFR § 25.981.
- Instructions for continued airworthiness applicable to EWIS as defined by 14 CFR § 25.1701.

3.3 Summary

Section 3 offers a brief summary of the regulatory requirements and recommended practices associated with the design and maintenance of aircraft structures. SHM is intended to impact maintenance and operations but does not replace the primary function of the structure. The essential aspects of structural health monitoring systems presented in the following sections are intended to be fully consistent with current regulation and the recommended practices for maintaining structural airworthiness.

4. ESSENTIAL ASPECTS OF STRUCTURAL HEALTH MONITORING

This section introduces the essential aspects of structural health monitoring that are generally recognized by the industry and the scientific community. These aspects cover the description of SHM, the motivations, architecture, and operational considerations. The material is presented for guidance purposes and should evolve as the technologies and the applications develop.

4.1 Description

SHM is the process of acquiring and analyzing data from on-board sensors to determine the health of a structure.

4.2 Motivations

The motivations for the use of SHM systems on aircraft structures are numerous. Presently the main motivations are for economic benefits through reduced downtime, labor, or repair cost. In the long term, SHM systems may also contribute to higher standards of safety and more efficient aircraft designs.

Before aiming for safety credits, the current demanding requirements for airworthiness need to be met. These requirements are introduced in the following section. A thorough understanding of the structure and its requirements can yield to identification of opportunities and benefits for SHM.

The main economic motivations for the use of SHM systems are to (a) reduce inspection time and cost, (b) improve repair planning, (c) increase, optimize, or customize inspection intervals, (d) extend the economic life of the structure, and (e) enable new design principles and maintenance concepts.

- a. Reducing inspection time and cost can be achieved by using more automated equipment and reducing indirect tasks such as gaining access, preparing surface, or reporting.
- b. Improving repair planning can be achieved by measuring conditions or parameters that are associated with potential structural defects prior to inspection. This information can be used to optimize maintenance planning and flight operation. An example is the detection of conditions that can lead to corrosion in a specific structural zone. This information can lead to conduct an inspection earlier than required by the maintenance manual. The benefit can be to perform a minor repair earlier (e.g., removing light damage and reapply coating) instead of a more significant repair later (e.g., replacing a part).
- c. Inspection interval can be increased, optimized, or customized in the instances that the aircraft is being operated in conditions less severe than the structure was designed for. An example is the pressure cabin which may not reach cruise condition in the instance of short flights.

- d. More common in military aviation, safe-life structures usage can be monitored to evaluate the remaining life more precisely than baseline parameters (i.e., flight count, flight hour, or calendar day). This improvement in precision can yield in the extension of the life of the structures when a structure is subjected to loads or conditions less severe than expected in design. The recent introduction of the limit of validity within the CFR Part 25 section § 26.21 may also offer opportunity for similar implementation within civil aviation.
- e. The design and the maintenance procedures of a structure are the result of an optimization of multiple parameters such as loads, material, geometry, weight, manufacturability, maintainability and all associated costs. SHM systems are not expected to have direct impact on each of them individually, but may yield in a better optimization of structures (e.g., weight, cost, etc.). This benefit is expected in longer term when reliability and durability of SHM technologies will be well established.

4.3 General Structural Health Monitoring Architecture

As presented in [Figure 4](#), structural health monitoring is generally recognized as an element of the structural health management, which is an element of the aircraft health management.

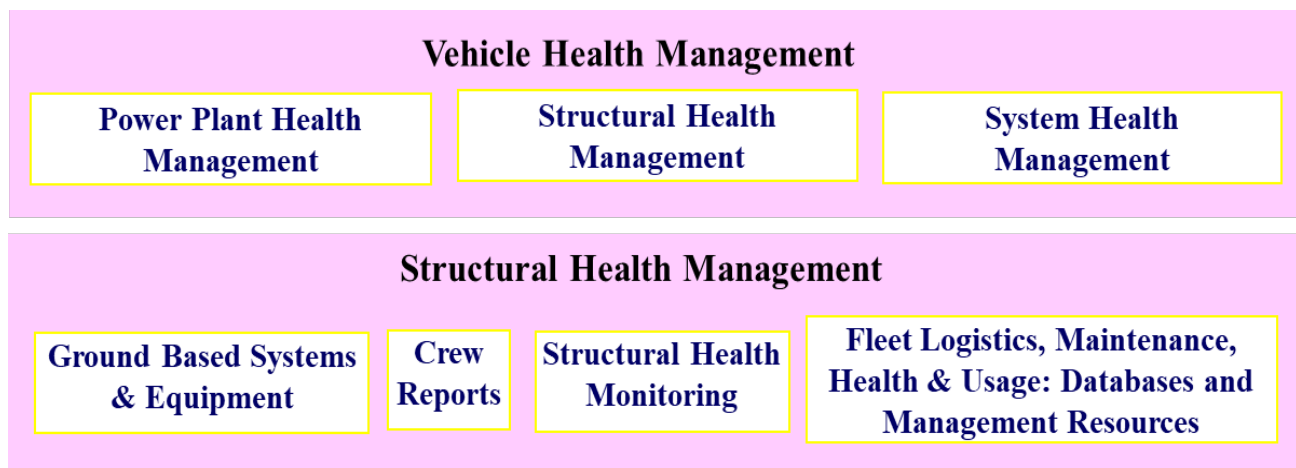


Figure 4 - Structural health monitoring as a part of aircraft health management

Structural health management intended functions use outputs from different sources as described in [Figure 4](#). The “outputs” are information processed from this data that provide a health assessment of the aircraft structure, which lead to the highlighted benefits.

This SAE Recommended Practice section outlines the means to deliver inputs such that benefits can be derived. [Figure 5](#) illustrates the main functional elements of structural health monitoring. Inputs to the structural health management are obtained from SHM equipment and/or from onboard sensors, delivering the detection, characterization of damage, load or environmental parameters for operational and damage monitoring.

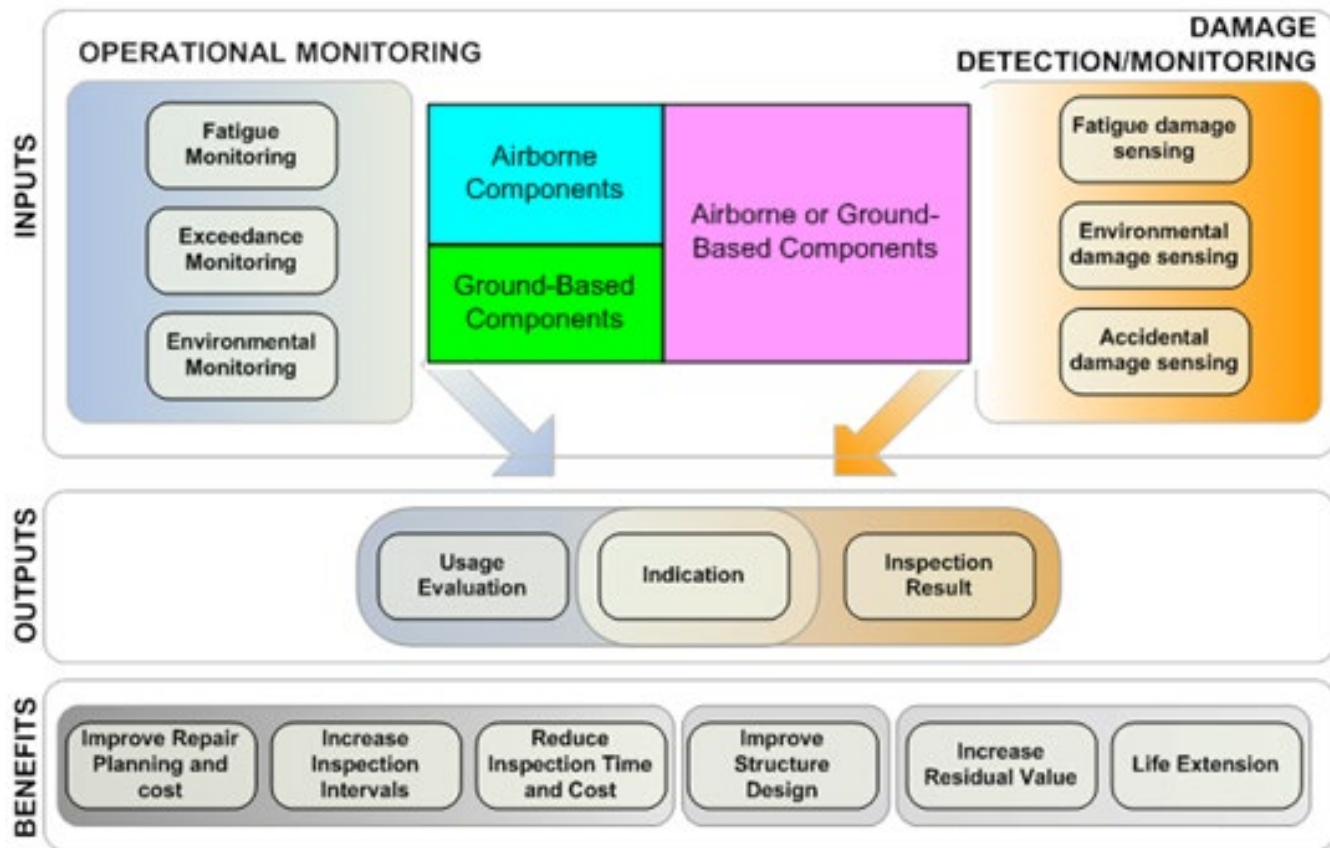


Figure 5 - SHM-intended functions and benefits

4.3.1 Inputs

Inputs can take many forms but all come from sensors installed onboard the aircraft. These sensors can be used specifically for SHM or be used primarily for other aircraft systems (e.g., accelerometers, altimeter, and flap position). The following describe the sub-function and benefit presented in [Figure 5](#).

4.3.1.1 Operational Monitoring

Operational monitoring (OM) groups all indirect measurement methods that can contribute to the evaluation of structures condition or utilization. OM parameters can be derived from the damage tolerance and fatigue evaluation of structure. The output of OM can be an advisory indication or the structure usage evaluation. The advisory indication can report abnormal operating conditions that are usually reported by the flight or ground crew. The usage evaluation can lead to modify inspection intervals as a function of aircraft use.

i. Fatigue monitoring:

Fatigue monitoring (FM) evaluates structural fatigue based on any fatigue related parameters (e.g., flight parameters or strain measurements). FM can be applied at part, assembly or aircraft level. Output from FM is the structure usage evaluation or the necessary data required to conduct this evaluation. FM can contribute to increasing the inspection interval when load spectra in-service are less severe than the design spectra.

ii. Exceedance monitoring:

Exceedance monitoring (XM) identifies instances when loads in-service exceed the design spectra. XM can contribute to identify abnormal loads to the structure (e.g., hard landing or severe gust) based on any load related parameters (e.g., flight parameters, strain measurements). This information can reduce the rate of false negative and false positive indications related to these instances. XM output are advisory indications that can trigger maintenance actions.