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ADAPTIVE DAMAGE TOLERANCE FOR STRUCTURAL AND ENGINE COMPONENTS

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ABSTRACT

For many years the nondestructive evaluation (NDE) and health monitoring communities have been working in parallel to provide enhanced safety with reduced ownership costs. The new focus on actual damage (material condition) monitoring, as opposed to monitoring of usage only, has emphasized the importance of integrating NDE and health monitoring data. This can be realized in two different forms. One is on-board implementation of conventional NDE technologies, such as eddy current and ultrasonic techniques so that the data formats from on-board and traditional NDE methods are similar to enable self-consistent comparisons between NDE and health monitoring data. The second is integration of on-board actual damage sensing with usage information to alter the conventional NDE inspection schedule.

This paper describes a novel Adaptive Damage Tolerance framework that merges NDE data with on-board health monitoring data for aircraft life management. Recent advances in on-board eddy current sensor technologies and related developments in dielectrometry are also discussed. Specific examples will be addressed for both structures and engines, including multi-site damage detection for structures and early detection and repair, i.e., health control actions, for engine components.

KEY WORDS: Nondestructive Evaluation, Damage Tolerance, Health Monitoring, MWM

1. INTRODUCTION

Life extension, reduction of sustainment costs and reduction of fixed resources (e.g., depot/field facilities and personnel necessary for sustainment) are urgent needs for new and legacy platforms. Adaptive Damage Tolerance (ADT) provides a self-consistent framework to address these cost-driven issues and to increase readiness while reducing or at least containing risks by maintaining safety margins at current levels. ADT integrates new Nondestructive Evaluation (NDE) capabilities, Condition Based Maintenance (CBM), and Prognostics and Health Management (PHM). In the simplest sense, ADT is a damage tolerance (DT) methodology that adds a model-based adaptation of inspection intervals based on observable precursor and damage states [1].

Currently, Damage Tolerance (DT) methods use predictive tools for crack growth to set NDE inspection intervals. While DT practices assume fixed preexisting crack sizes, ADT methods utilize actual precursor and damage states for decision support. Due to enhanced observability afforded by emerging NDE methods, damage states are monitored throughout the component life from the as-manufactured condition, through in-service degradation, to failure.

Figure 1 provides a flow diagram of a typical damage tolerance (DT) methodology [2-7], including the initial iterative design process for a component. Figure 2 provides a flow diagram of a possible adaptive damage tolerance (ADT) methodology, introducing several new concepts, as described below.

(1) Observability[1] of relevant precursor states[2] is required.

(2) Unobservable damage state[3] assumptions are adjusted to produce model derived failure statistics representative of observed failures in the fleet or component tests; in current DT practices, the assumption about the initial unobserved crack size is not adjusted.

(3) Data from field and depot NDE inspections are combined with data from on-board sensors for monitoring of both usage and damage state progression.

(4) Traditional inspection intervals and onboard sensor data analysis intervals are adjusted based on progression of damage states and usage i.e., data from on-board sensors might only be downloaded and analyzed at specified, adjustable intervals by selected authorities, as opposed to on-site – to limit the effects of false positive indications on readiness.

(5) Possible upset events[4] are detected and counted.

(6) Adaptive recapitalization[5] is achieved through maintenance/rework/repair and replacement actions as a method of introducing health control[6], i.e., going a step beyond health management.

(7) Neural plasticity is proposed as a means for reallocating and dedicating limited on-board health and usage monitoring resources in a sensor network [7].

“Health control” actions, such as rework or repair events, which are a part of the ADT framework, initiate supplementary condition characterization operations. In this way, real-time materials monitoring combined with onboard diagnostics, provide new opportunities to reduce maintenance costs and bolster mission readiness.

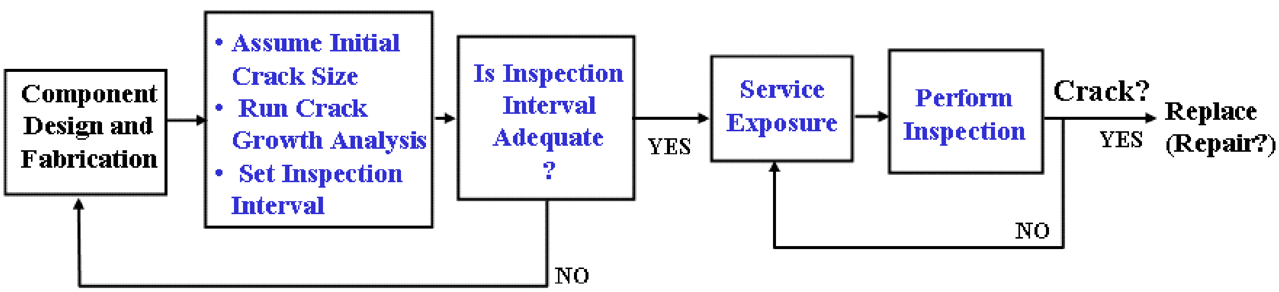

Figure 1. Established approach for Damage Tolerance (DT) for fatigue cracks.

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1 Observability – is a control theory term, represented for linear multivariate systems by the observability matrix. In this context, observability implies not only the capability to measure specific damage states and their rates of change, but also to measure them independently and reliably.

2 Precursor States – are defined here as states that affect the early behavior of a specific damage mode. Examples of precursor states are inadequate residual stresses, either as manufactured or as modified in service, undesirable surface conditions (e.g., from manufacturing or fretting), geometric features, microstructure variations (e.g., from aggressive machining in titanium engine disks, or from grind burns in low alloy steel components).

3 Unobservable Damage States – are states that cannot yet be monitored nondestructively, but can be included in prognostics models of failure mode progression. Note, however, that the sequential nature of damage behavior may permit the bounding of unobservable conditions through observations that the next stage of behavior has not yet started, e.g., no failures in the fleet might imply that cold working was accomplished correctly for a component population or population subset and that the unobservable damage states are still benign.

4 Upset Event – a discrete event that shifts relevant damage or precursor states either in a positive or negative direction.

5 Adaptive Recapitalization – recapitalization is defined as a means of resetting or at least recovering a substantial portion of the component life through health control actions, such as grinding/blending areas affected by cracks or pits and re-shotpeening, or stripping and recoating, expanding a fastener hole, or adding a doubler. Adaptive recapitalization includes adaptation of recapitalization methods based on models of damage progression for specific failure modes of concern, and within mission constraints.

6 Health Control- beyond health management, control implies the capability to alter the precursor and damage states using a measured action with a predictable response.

7 Neural plasticity – a concept born in the life sciences, used here to mean reallocation of data acquisition and processing resources for a sensor network to enhance performance based on lessons learned and other knowledge.

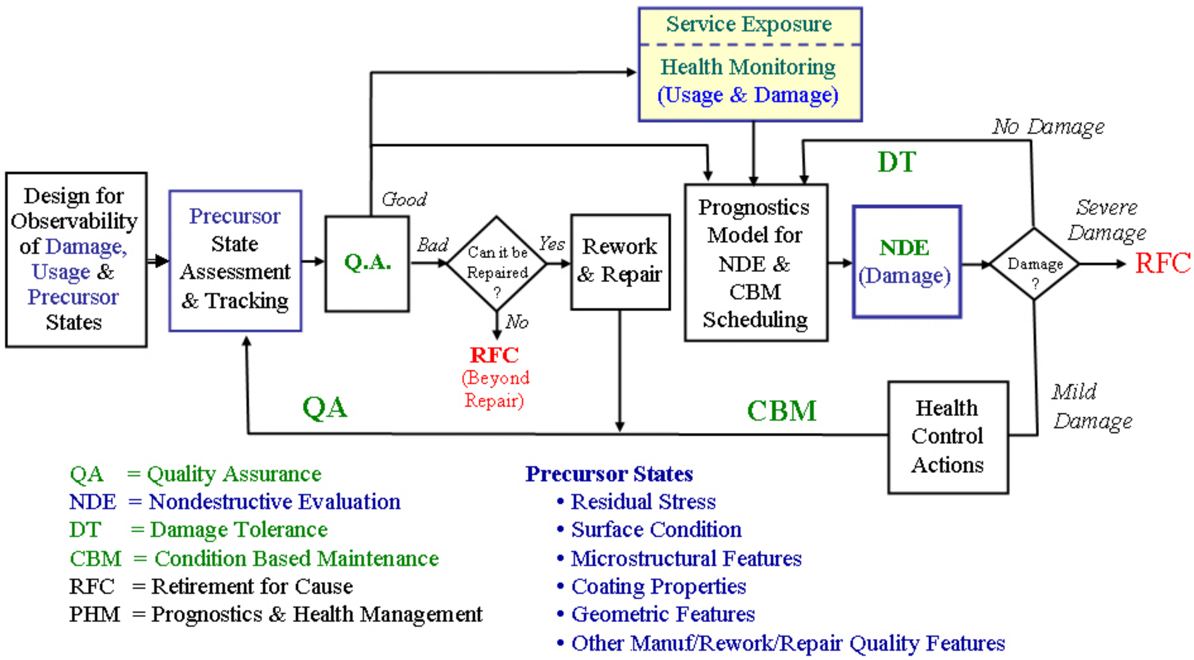


Figure 2: General Adaptive Damage Tolerance (ADT) flowchart.

2. STRUCTURES AND ENGINE COMPONENTS APPLICATIONS

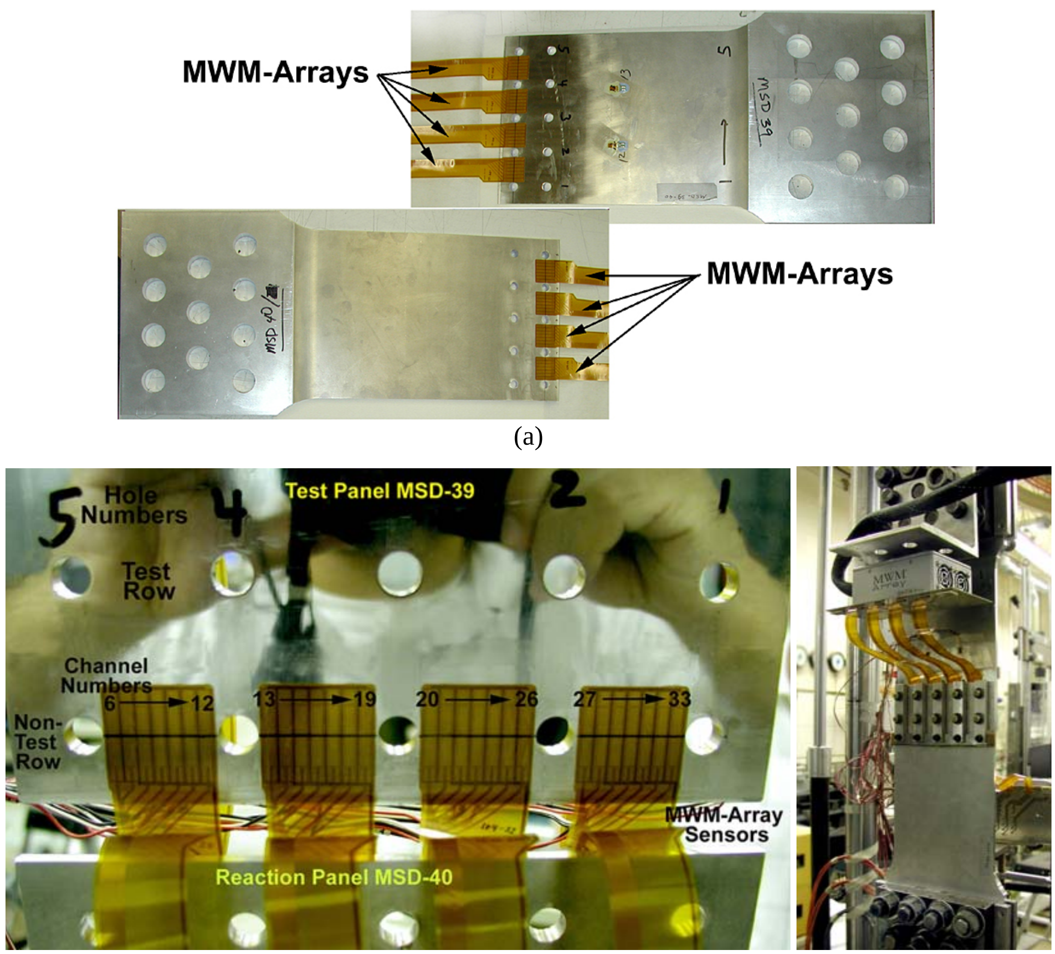
Adaptive Damage Tolerance is enabled by new nondestructive evaluation (NDE) capabilities. While potential NDE techniques may include inductive, capacitive, ultrasonic, thermal, and optical characterization methods, this paper focuses specifically on integration of recent developments in inductive (magnetoquasistatic) and capacitive (electroquasistatic) sensing. The ability to quantify both as-manufactured precursor states and damage states incurred in service from use, these advances in real-time, nondestructive materials characterization provide the means for implementation of ADT.

Networks of magnetoquasistatic MWM-Arrays (Meandering Winding Magnetometer, or MWM® sensor arrays) have been used to monitor damage initiation and propagation in metallic structures. As shown in Figure 3, these flexible, inductive sensor arrays can be utilized not only in a simple contact/scanning mode, but also with stationary sensors mounted inside holes, or on other curved surfaces, as well as embedded within joints and composites.

Figure 4 illustrates a ten-hole specimen with embedded MWM-Arrays. The MWM-Arrays were mounted between the holes in the lower and upper rows, see Figures 4(a) and (b). The equipment set-up with the specimen in the load frame and the JENTEK 37-channel probes are shown in Figure 4(c). A variety of precrack configurations were tested with larger ("primary") and smaller ("secondary") precracks. The crack tip progression data are shown in Figure 5. The lines indicate progression of crack tips from one hole towards another as a function of number of cycles. The MWM-Arrays successfully monitored crack growth throughout the test with the sensors embedded at the buried interface between the metal plates. The sensors survived, even though the test was run to failure; thus, these sensors can be used for multiple fatigue tests. In fact, once procedures were finalized, no sensors failed in subsequent tests, and the same sensors were reused in multiple tests – lasting several coupon lifetimes.

(a) In Hole: **(b) Curved Surface:** **(c) Embedded:**

Figure 3: Mounted and embedded MWM-Arrays.



(b) (c)

Figure 4: (a) MWM-Arrays mounted along both rows of fastener holes. (b) The ten-hole specimen with embedded MWM-Arrays shown prior to bolting up. (c) The ten-hole specimen mounted in the load frame.

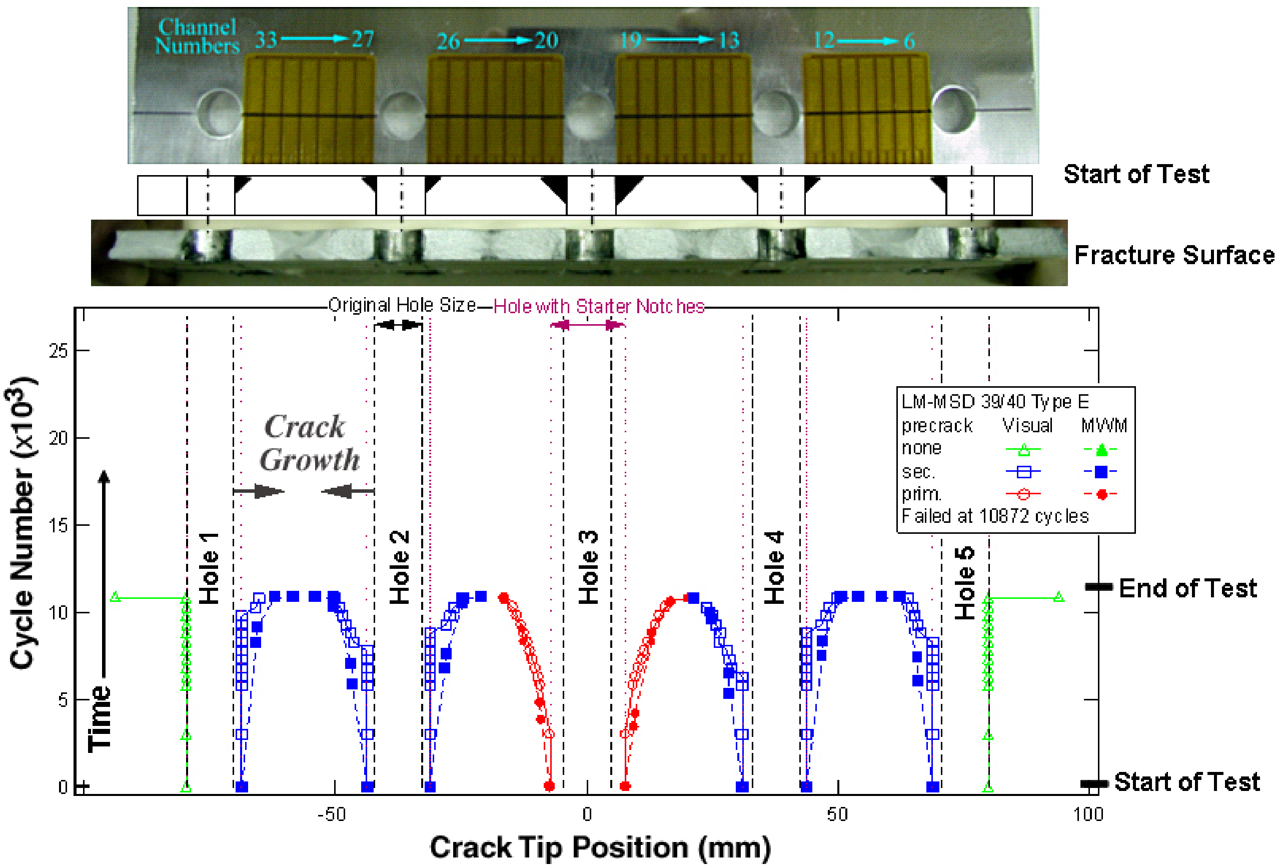


Figure 5: Representative multiple crack growth monitoring data. The specimen had primary (prim.) precracks at Hole 3 and secondary (sec.) precracks at the other holes.

In addition to metal structures, graphite fiber composite parts and metal-composite joints can be monitored using MWM-Arrays. Figure 6 shows absolute electrical conductivity measurements from an MWM-monitored graphite fiber composite load test. In this test, damage to the composite joint was detected in real time through changes in absolute materials properties. MWM-Arrays demonstrated capability to detect disbonds/delaminations through a relatively thick composite at a buried interface. While breakdown of graphite fibers can be detected in this composite structure, the same technology can also image damage that might occur within a composite-metal joint. In Figure 7, scans of a Reinforced Carbon-Carbon (RCC) composite are shown with simulated corrosion loss defects. Here, the MWM-Array provides not only defect imaging but also provides an absolute conductivity map. For RCC and other advanced composites, oxidation/thermal damage will cause gradual degradation, which appears in the absolute conductivity image data.

The output of a permanently mounted MWM-Array sensor revealing hidden metal loss in a mock-up demonstration test is illustrated in Figure 8. This demonstration exemplifies how a permanently-mounted sensor network could be used to monitor hidden metal loss from corrosion.

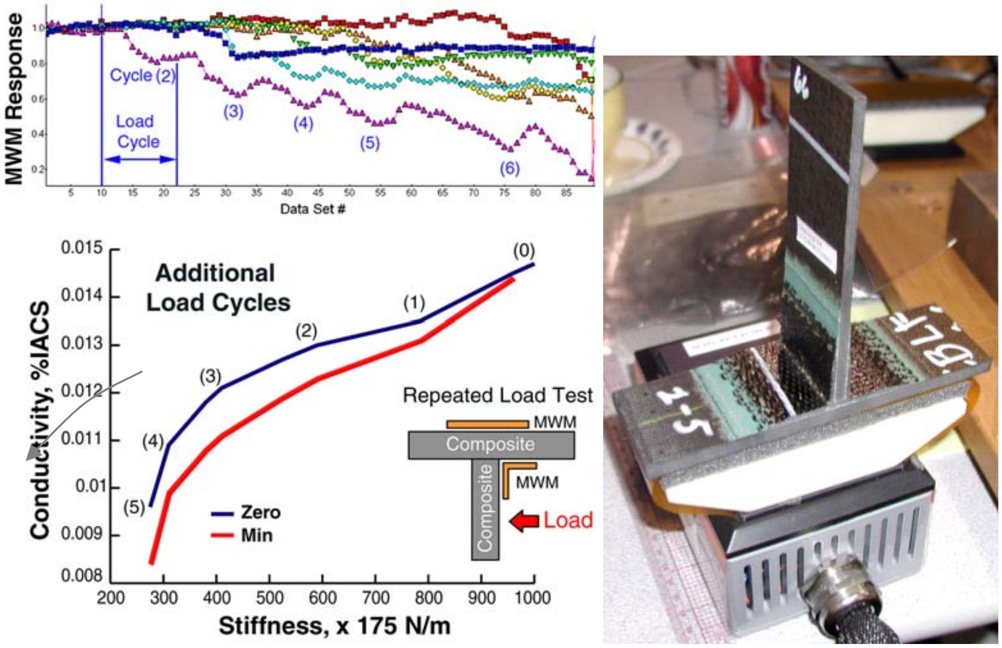


Figure 6: Graphite fiber composite joint test monitored with MWM-Arrays.

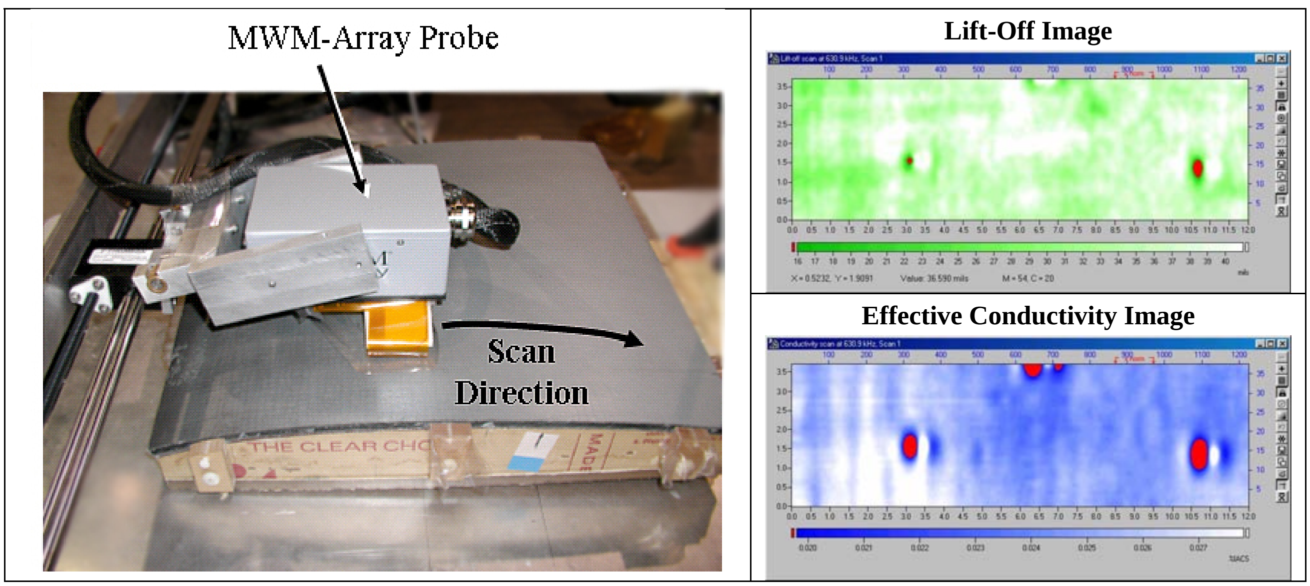


Figure 7: Blind test RCC sample provided by NASA Langley Research Center.

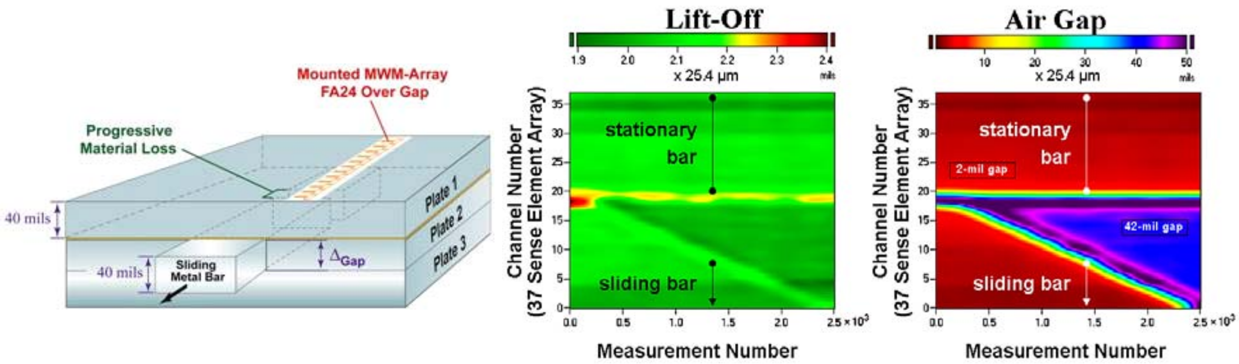


Figure 8: Continuous MWM-Array monitoring of metal loss due to hidden corrosion.

While the inductive sensing modality is effective in characterizing conducting media, such as metals or graphite fiber composites, capacitive sensing, i.e., dielectrometry has been used to assess the materials properties of electrically insulating layers and components. Example dielectric sensor (IDED) measurements showing structural dielectric property changes in a glass fiber composite specimen are presented in Figure 9. The data show the effect of tensile loading on the relative permittivity of the composite material. The measurements were made at a single temporal frequency and the decrease in permittivity is consistent with a reduction in the local density of the material, expansion of voids, or degradation (microcracking) of the fiber or matrix.

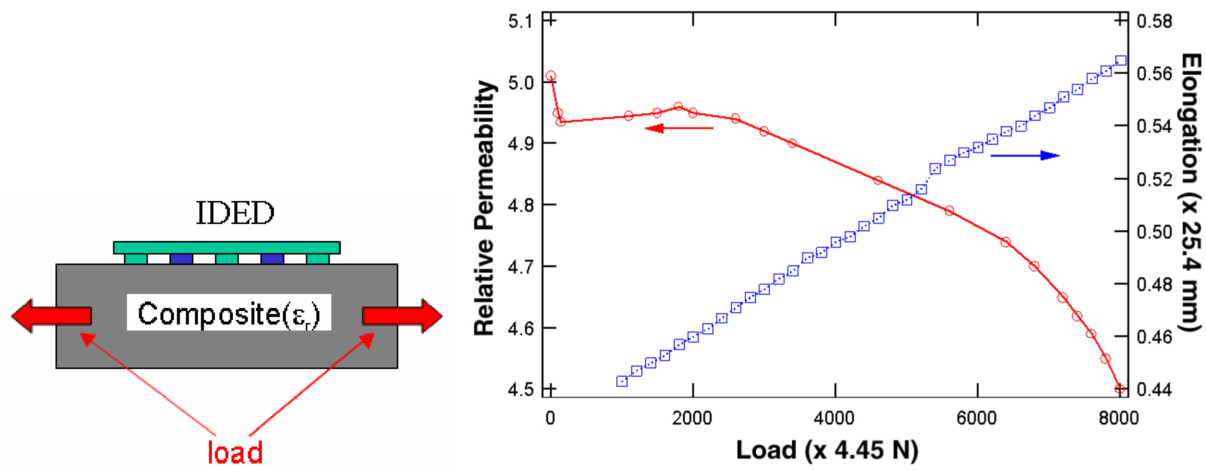
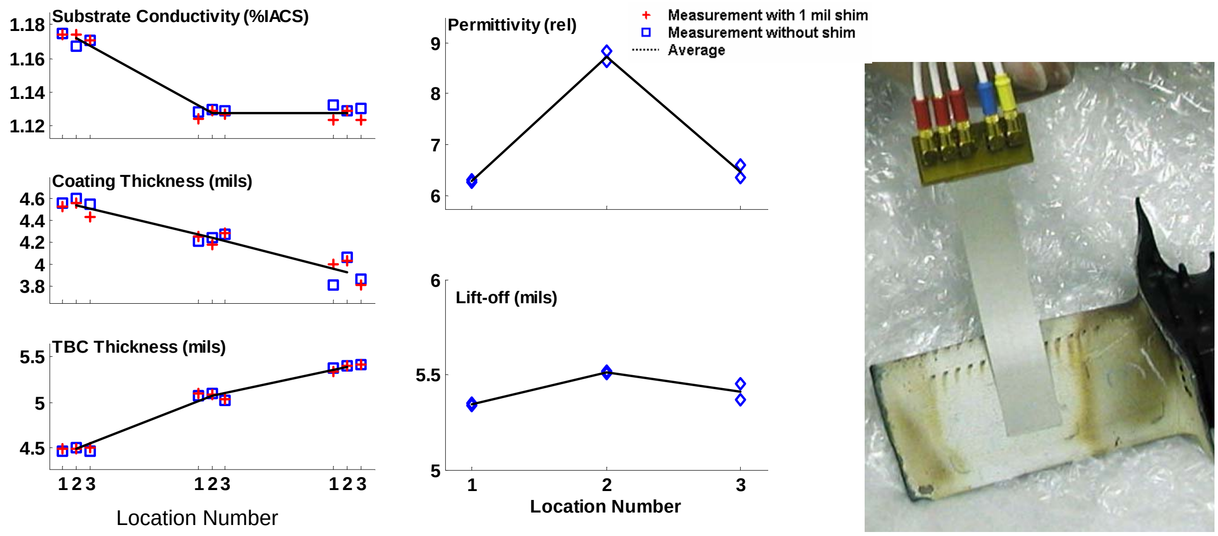


Figure 9: Stress and damage monitoring for glass fiber composites.

Figure 10 shows a flexible IDED sensor placed on a turbine blade with a thermal barrier coating (TBC), and the combined MWM - IDED dataset used to characterize the condition of the layered media. In the case of thermal barrier coatings, improved condition assessment capability within an ADT framework offers potential to lower maintenance costs and improve safety margins.

The use of composite materials and nonconductive coatings in aircraft structures and engines presents a variety of potential applications for capacitive sensing. For example, IDED sensors have been used to assess porosity in ceramic parts, to detect disbonds or cracks in composite materials, and to monitor moisture ingress below corrosion protective coatings (patents issued and pending).



(a) (b) (c)

Figure 10: Results of the combined measurement with the FS35 magnetometer and DS04 dielectrometer on a 1st stage high-pressure turbine blade with TBC: (a) three-unknown magnetometer results, (b) two-unknown dielectrometer results; (c) photograph of the JENTEK patented flexible IDED sensor on the turbine blade.

3. MANUFACTURING PROCESS EFFECTS ON LIFE MANAGEMENT

The principal distinction between precursor states and damage states is that precursor states result from manufacturing processes and rework/repair events. Characterization of these states may introduce requirements for quality assessment beyond typical practices. Some precursor states, e.g., inadequate residual stress, may be further modified by subsequent in-service damage. For example, a shot peened or otherwise cold worked structural component might have been cold worked to extend high cycle fatigue life, but in practice substantial low cycle fatigue contribution may result in stress relaxation, making the component more susceptible to fatigue crack initiation and propagation.

In some applications, gradual or sudden changes of such precursor states may provide the only sufficiently early warning of subsequent failure, when for example, time between crack initiation and failure is too short for practical NDE flaw detection. This might be the case in a landing gear where a previous overload event, e.g., hard landing, changed the precursor states, e.g., residual stresses, without producing a detectable crack. For this example, the next overload event may result in a failure of the component. In this case, the focus should be on materials characterization to observe changes in the precursor states, and, when possible, on in-situ monitoring of critical locations using permanently mounted sensors.

One example of a currently used method for monitoring precursor states is the use of the Barkhausen noise method [8] for inspection of landing gear. Results of this inspection are used to make a decision to remove landing gear components from service if they exhibit unacceptable residual stresses. Unfortunately, this method requires costly stripping of paint and produces a substantial number of false positive indications. MWM-Arrays are an alternative method that does not require paint removal and should provide substantial improvements in reliability with reduced false indications. For example, the high-resolution imaging capability of the MWM-Array combined with the capability to perform bidirectional measurements provides the new potential to differentiate between residual stress patterns and microstructural conditions, for example, grinding burns.

4. SUMMARY

Networks of electroquasistatic or magnetoquasistatic sensors and sensor arrays can provide information about structural material conditions and fitness for service. This information can be used to assess precursor, damage, and usage states for the structure and can be incorporated into an adaptive framework for damage tolerance that would influence repair and maintenance decisions and permit efficient operation and management of the structure. The ADT framework described here, combined with compatible NDE and health monitoring sensing methods, should enable substantial reductions in total ownership costs for high value assets such as aircraft and ships.

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