Nonlinear Crack Growth Monitoring for Structural Assessment of Military Hardware

This concept will address the structural problem of failure due to cracks which are either hidden, in the presence of corrosion, due to stress-corrosion cracking, cracking in multi-layer structures, or cracks in fastener holes in multilayer structures. It will also provide useful information with regard to Usage monitoring/data recording.

The techniques require measurement of global loadings and local deflections/strains at critical structural locations to indicate the rapidly increasing growth of hidden cracks with sufficient warning time prior to structural failure to take preventative action to correct the problem or retire the structure before failure. The techniques, as described in the referenced report and patent application (US government rights reserved)[1], have been proven on a laboratory scale to successfully detect the onset of structural failure due to fatigue cracking (including simulated widespread fatigue cracking and cracking in the presence of corrosion), stress corrosion cracking, and low temperature creep crack growth, with a reasonable degree of forewarning before failure. It is also believed that these techniques will be successful for corrosion fatigue and high temperature creep crack growth.

The techniques are Griffith Energy absorption measurements for structures under load and subject to cracking, based on the concept of G_{Ic} or J_{ic} as critical strain energy release rates. The Griffith critical strain energy release rate criterion for structural failure by cracking states that a crack will begin to extend when the strain energy released from the structure by relaxation during crack extension exactly equals the consumption of energy demanded by the formation of new surface area. This criterion has been established to be a material property, and is stated as:

$$G_{Ic} = \frac{-dU}{da}$$

Where
U= the strain energy within the structure at the point of the beginning of crack extension
a = crack length
dU/da = decrease in internal strain energy during crack extension da for fixed end displacement, or increase in internal strain energy during crack extension da for constant end load.

Using this technique for fatigue loading, the energy input into the structure during each cycle is measured by integrating the global load and the local critical deflection. Then,

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[1] Welch, D. E., Hively, L. M., and Ruggles, M. B., *Nonlinear Crack Growth Monitoring*, ORNL-TM-1999/117, Oak Ridge National Laboratory, Oak Ridge, TN, October, 1999.

during the unloading portion of the cycle, the global load and the local critical deflection are again integrated, and by subtracting the two, we obtain a net residual energy input into the local structure area during each fatigue cycle. For structures which are loaded principally in the elastic regime (as most structures are), this energy will consist principally of two components. These are the thermoelastic damping component, representing the cumulative effect of adiabatic tension followed by thermal expansion, then adiabatic compression followed by thermal contraction. The second component is the incremental consumption of new surface energy by the slowly increasing crack size.

Our experiments have shown that the initial crack size, and hence the initial crack growth energy component, is small compared to the damping energy component for new undamaged structures. By plotting the hysteresis strain energy (energy consumed per fatigue cycle) vs. number of cycles, we initially see a relatively constant level of energy consumption (due to damping alone). However, as the internal critical crack grows larger and larger, the crack growth energy consumption component grows larger and larger compared to the constant damping energy component, so that the curve of overall energy consumption begins to rise noticeably near the end of life. It is this **increase** in strain energy consumption, rather than the level of strain energy consumption itself, which is used as the indicator of the approach of structural failure. Therefore, it may be applied to any structure, and at almost any point in a structure's lifetime. We have tested the technique in Mode I and Mode III cracking, and for tensile, compressive, flexural, and torsional loadings.

We have established a reliable statistical indicator, which indicates the point at which the end of structural fatigue life is near. This indicator provides an indication of approaching failure at between 1% and 20% of fatigue lifetime before structural failure. In 50-60 experiments with steel, aluminum, and fiberglass materials, no false positive indications (indications without being closely followed by structural failure) or false negatives (failure to indicate before fatigue failure) were noted.

Oak Ridge National Laboratory has performed limited laboratory scale experimentation of the use of Nonlinear Crack Growth Monitoring (NCGM) for monitoring to detect signs of impending fatigue failure in uncorroded aircraft aluminum and bridge steel, simulated corroded aircraft aluminum and bridge steel, samples of both materials unnotched, with internal holes simulating multiple site damage, and with internal notches or cracks. We also have plans to perform limited tests with varying stress amplitudes on the same samples.

A series of experiments to simulate multiple site damage in aircraft was conducted on eight unclad 2024-T3 aluminum coupons, each containing a central drilled hole. The samples were subjected to tension-tension fatigue at R=0.1 on a servohydraulic load frame in load control until failure to support the load.

The coupon material is an unclad 2024-T3 aluminum alloy sheet 0.090 inches thick, a material commonly used in airframes. The coupons were machined to an ASTM E466 standard fatigue specimen with a nominal cross-sectional shape of 0.5-inches wide by

1.22 inches long. The coupons contained a No. 55 drilled hole (0.052") in the center of the gage length.

The nominal specimen cross-sectional area was 0.045 in^2 and the fatigue maximum and minimum loads were 2340 lbs and 234 lbs respectively for sample TM2-MSD-1, 2000 lbs and 200 lbs for samples TM2-MSD-2 through TM2-MSD-5, and 1500 lbs and 150 lbs for samples TM2-MSD-6 through MSD-8.

Table 2. Fatigue test results

	Specimen							
	MSD-1	**MSD-2**	**MSD-3**	**MSD-4**	**MSD-5**	**MSD-6**	**MSD-7**	**MSD-8**
Cross-sectional area, $in.^2$	.045	.045	.045	.045	.045	.045	.045	.045
Nominal peak tensile load, lb	2,340	2,000	2,000	2,000	2,000	1,500	1,500	1,500
Nominal peak tensile stress, psi	52,000	44,444	44,444	44,444	44,444	33,333	33,333	33,333
Nominal minimum tensile load, lb	234	200	200	200	200	150	150	150
Nominal minimum tensile stress, psi	5,200	4,444	4,444	4,444	4,444	3,333	3,333	3,333
Cycles to failure	2,550	6,888	5,829	7,923	7,891	27,008	24,180	31,795
Cycles of fatigue life remaining after indication	205	649	833	817	1,138	3,307	2,441	3,769
Fatigue life remaining after indication, %	8.04%	9.42%	14.29%	10.31%	14.42%	12.24%	10.10%	11.85%

The purpose of this research and development effort is to develop and demonstrate methods for using Nonlinear Fatigue Monitoring methods to sense precursor signs of imminent structural fatigue failure in aircraft aluminum laboratory samples under conditions of varying stress amplitude, loading frequency, temperature, and varying materials. The objective is to develop the NCGM method to the point that a real time comparison between NCGM methods and conventional damage tolerance and fracture mechanics methods on a laboratory scale under a number of environmental and loading conditions is possible.

The technique described may be implemented either as a continuous online monitoring system adapted to the military structure itself, or as a series of periodic loading tests applied during routine maintenance to measure the response of the structure to standard loadings.

0.1 Implementation Cost/Strategy

The strategy for beginning implementation of this technology for assurance of structural safety of US Air Force military structures while extending their useful life will be based on a three-step implementation program, utilizing the resources provided by the previously established partnership between ORNL and the 134th Air Refueling Wing of the Tennessee Air National Guard based at McGhee-Tyson Air Base in Maryville, TN.

The first implementation step will require laboratory testing of a selected structural life-limiting element from actual Air Force flight hardware, under simulated operational loading and environmental conditions. Suitable structural elements could be air frame longeron stringer ties, wing spars, or fuselage pressure bulkheads.

The second implementation step will require prototype monitoring of this selected structural element in a test bed of actual Air Force flight hardware, as a supplement to conventional fracture mechanics based safety assurance practices. In this phase, the results of this new technique can be validated by comparison to existing fracture mechanics safety assurance techniques.

The third implementation step will require migration of the proven implemented technology to routine maintenance implementation for the chosen military hardware at large. This step would be coordinated with the AFRL and the Air Force hardware Program director.

This program is envisioned to require three years and a cost of $1.5M.

0.2 Payoff

The prediction of the future failure of structures subject to fatigue is very difficult. This is primarily due to the fact that the vast majority of structures' fatigue lifetimes (90-95%) are spent in nucleation of very tiny flaws into measurable crack sizes. Due to the large variation in nucleating flaw sizes and the mathematics of flaw growth, the fatigue lifetimes, even of high quality structures, can vary by a factor of as much as 10 to 20 in a small fleet. This large variation in fatigue lifetimes leads to conservative statistics, which often prompts the premature retirement or overhaul of vehicles or other structures, since they focus on the weakest members of the fleet, while the remainder of the fleet is sound.

In the case of military hardware, structural components are considered primarily in two groups: those where undergoing NDE/NDI with service life management by current fracture mechanics techniques is feasible, within the limitations of current technical complexities and future service condition predictions, and those where it is not feasible or economical to undergo NDE/NDI, and must be managed by conservative statistical techniques. This results in the replacement of many structures at lifetimes that are far short of their inherent lifetime, thus limiting the possibility of fatigue failure in the weakest member in the group.

Currently, many elements of military hardware are reaching the limits of their intended calendar service life. Civilian structures, with their greater duty cycle of use, tend to approach their design fatigue use limits, while military structures, with their lower duty cycle of use, tend to face retirement due to aging phenomena such as corrosion, multiple site damage, and widespread fatigue damage, leading to uncertainty in their remaining safe service life. Consequently, owners of these structures are facing the economic penalties of shutting down many healthy structures, or of assuming the increasing risk of continued operation under current practices. The legal liabilities of continued uncertain operation tend to force the owners to accept the economic penalties of premature retirement or to look for additional alternatives. Until now, no reliable method for real time condition assessment has been devised on which to base continued use of structures subject to fatigue or other crack-dominated phenomena.

The techniques described here for directly sensing conditions that indicate impending fatigue failure have been proven to be reliable on other physical and biological systems, and have been demonstrated in laboratory scale experiments to be able to sense precursors of fatigue, stress corrosion, and low temperature creep failure in fiberglass, aluminum, and steel under pristine conditions and under conditions of simulated corrosion and multiple site damage. The failure indications were from 1 to 20% of fatigue life in advance of actual failure under constant load.

The best estimate of cost avoidance or savings is that a 50% improvement in overall group-average structure lifetime limited by fatigue cracking, with no reduction in structural safety, can be achieved within 10 years. It is also estimated that, as confidence is gained in the ability to detect significant hidden crack growth, the frequency, and hence cost, of nondestructive inspections can be reduced.

0.3 Background Research

The principal nondestructive techniques available at present to indicate hidden cracks, cracks due to widespread fatigue damage, or cracks which are exacerbated by corrosion, are ultrasonic examination, eddy current examination, X-ray examination, dye penetrant examination, and acoustic emission measurements. These techniques are used in a Griffith fracture-mechanics based system to assure structural safety by modeling crack growth in the structure, based on projected loading patterns and environmental conditions, and determining a maximum acceptable flaw size allowable in the structure, assuming crack growth under the assumed conditions until the next nondestructive inspection period. The nondestructive inspection technique is then used to locate and quantify the size of flaws within the structure, and ensure that flaws larger than the maximum allowable size are not permitted to remain.

The ultrasonic examination, eddy current examination, X-ray examination, and dye penetrant examination techniques are all used to ensure that cracks no larger than the allowable size are allowed to remain in the structure during the nondestructive inspection service interval.

The uncertainties, which remain in this system, are based on the fact that the crack growth rate projections are only as accurate as the projections of future loading frequency and service patterns and future environmental exposure conditions. Also, significant analytical uncertainties exist with regard to how to treat cracks in the presence of general corrosion and widespread fatigue cracking. Of necessity, to account for these uncertainties, additional conservatism must be incorporated into the allowable structure flaw size, leading to more frequent and costly nondestructive inspection intervals.

The acoustic emission system more closely resembles the technique presented here, in that it attempts to detect imminent structural failure by using indications of the structure itself, in this case acoustic noise emitted as energy during the cracking process. However, this technique is heuristic at best, and has failed to produce a reliable precursor to structural failure in all environments, and can be affected by numerous other variables.

0.4 Deliverables and Targeted User

The deliverable for the initial implementation program would be a specification and prototype system for implementation on a chosen military structural element. It would also include assistance in incorporation into the structural safety assessment system of this hardware. The targeted user would be the depot maintenance center.

0.5 Applicability to multiple weapons systems

he techniques described in this paper will be applicable to assisting the fracture-mechanics based structural safety monitoring of all military structural components which are subject to failure by cracking.