Nonlinear Crack Growth Monitoring

Donald E. Welch, Lee M. Hively, and Ray F. Holdaway, Engineering Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830.
Telephone: 865-576-0563, 865-574-7188, 865-576-2509
E-mail: wed@ornl.gov, hiv@ornl.gov, ray@ornl.gov
Mailing Address: Mail Stop 8066, Bldg. 9201-3
PO Box 2009
Oak Ridge, TN 37831-8066

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. Typical structures may be aircraft, ship= hulls, gun barrels, etc.

Oak Ridge National Laboratory has developed a new concept which will address the problem of aging structures to find cracks due to either hidden corrosion or stress-corrosion cracking, cracking in multi-layer structures, or cracks in fastener holes in multilayer structures.

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:

[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.

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, 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.

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