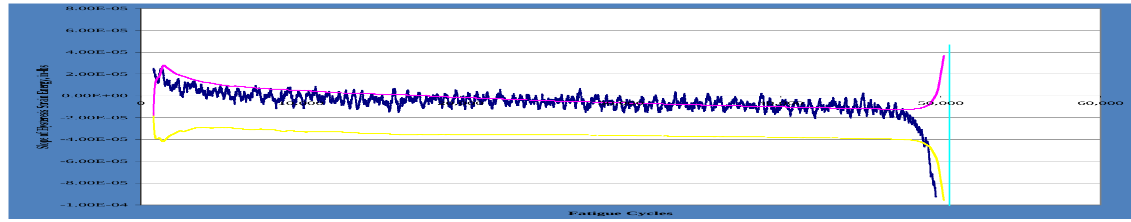
Complex Failure Forewarning System



Robert K. Abercrombie

DHS Science Conference Catastrophes & Complex Systems: Panelist

March 31, 2011

Lee H. Hively
Stacy J. Prowell
Bob G. Schlicher
Frederick T. Sheldon

Failure Forewarning in Complex Systems

Oak Ridge National Laboratory

Agenda

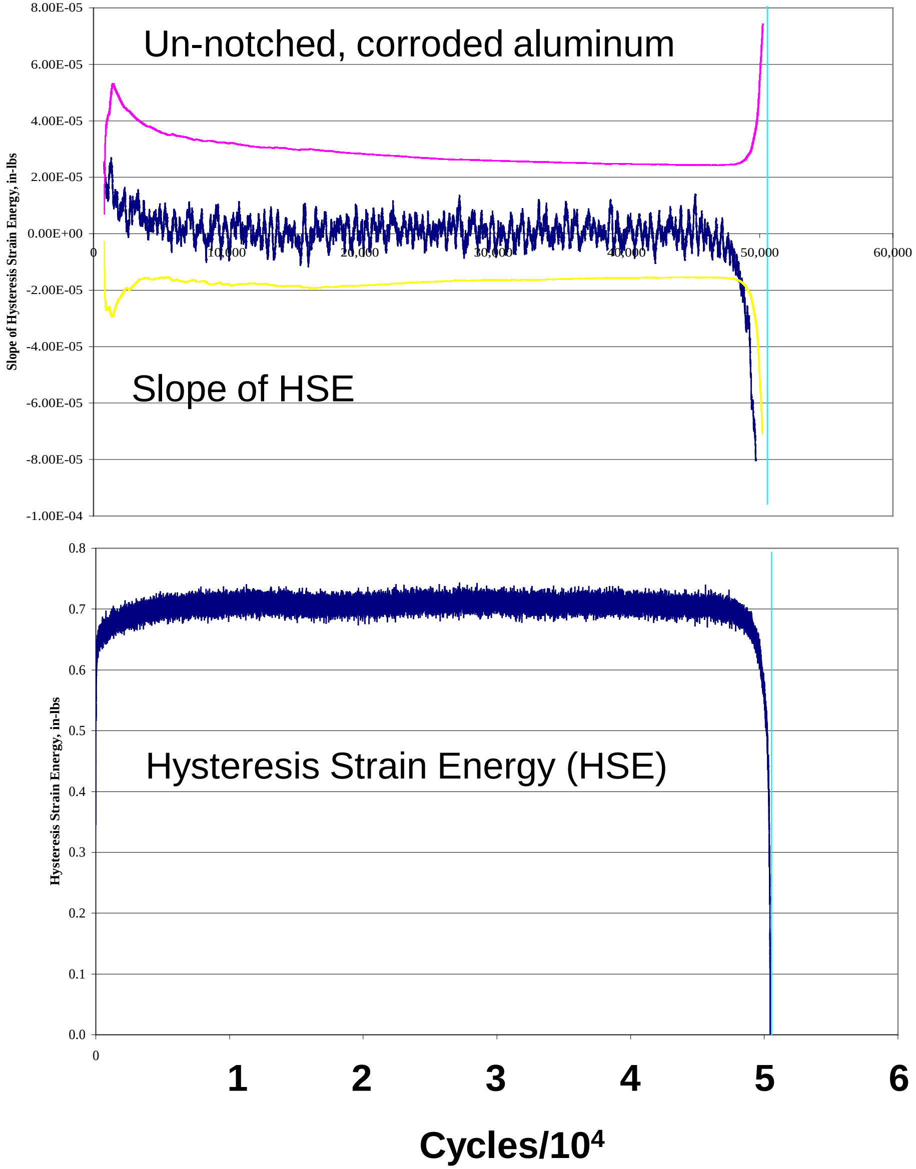
Failure Forewarning in Complex Systems

- **Purpose – Problem Statement**
- **Failure Prediction in Real Systems**
- **Examples/Listing of 21 Case Studies**
- **Plan for Beneficial Using ORNL Intellectual Property**

Purpose – Problem Statement

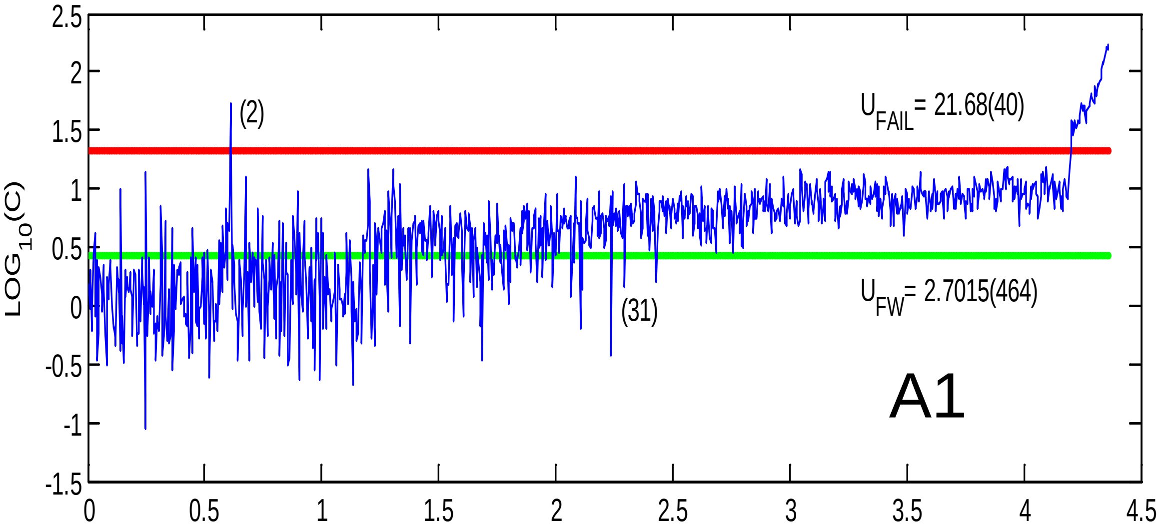
- **As the critical infrastructures of the United States have become more and more dependent on public and private networks, the potential for widespread national impact resulting from disruption or failure of these networks has also increased.**
  - **Securing the nation's critical infrastructures requires protecting not only their physical systems**
  - **but, just as important, the cyber portions of the systems on which they rely.**
- **A failure is inclusive of random events, design flaws, and instabilities caused by cyber (and/or physical) attack.**
  - **One such domain, aging bridges, is used to explain the Complex Structure Failure Forewarning System.**
  - **We discuss the workings of such a system in the context of the necessary sensors, command and control and data collection as well as the cyber security efforts that would support this system.**
  - **Their application and the implications of this computing architecture are also discussed, with respect to our nation's aging infrastructure.**

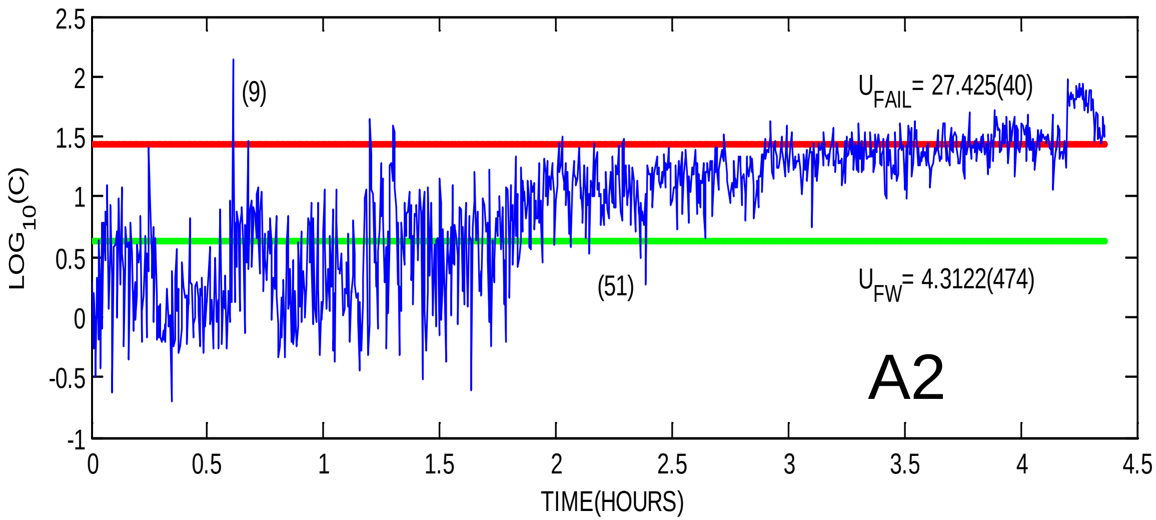
Structural Failure

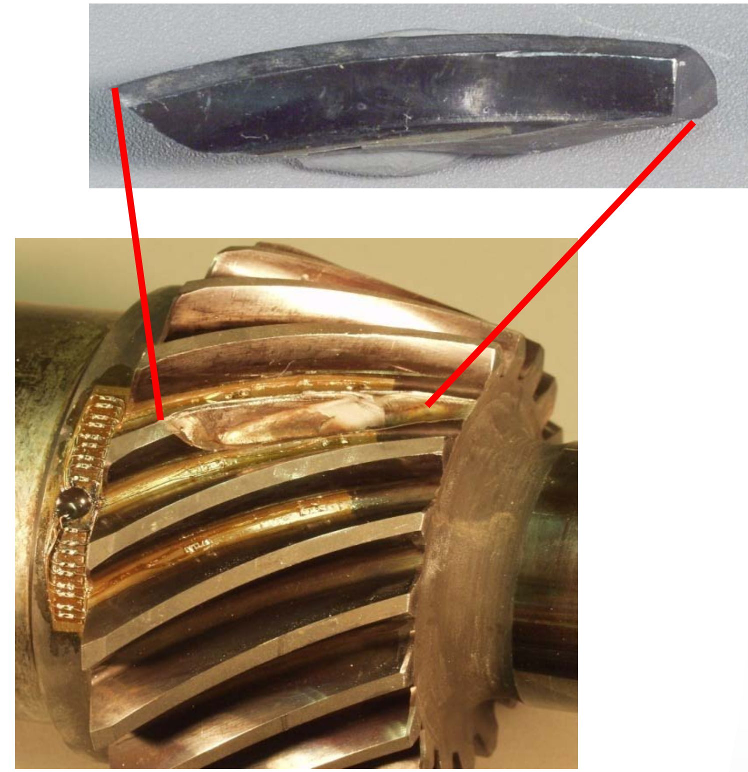


- **Measure load, *P*, and deflection, δ**
- **$dU/dN = \int P\, d\delta$ over load cycle**
  $= (dU/da) \times (da/dN)$
  N = cycle number
  a = crack length
  $dU/da \geq G_C$ (material property)
- **Demonstration for …**
  - composites, aluminum, steel
  - (un)corroded materials
  - single/multiple site damage
  - widespread fatigue damage
  - periodic overloads
  - Crack Modes I, II, III
- **Change in crack growth for forewarning: slope of hysteresis strain energy HSE beyond ± 4σ**

Helicopter (OH58C) Spiral Pinion







1.5 x (max torque)
4.4h to failure
Tri-axial acceleration
150 kHz x 1.5 sec

Failure Forewarning in Complex Systems

Machine Applications: Forewarning Tests

Data Provider	Equipment and Type of Failure	Diagnostic Data
1) EPRI (S)	800-HP electric motor: air-gap offset	motor power
2) EPRI (S)	800-HP electric motor: broken rotor	motor power
3) EPRI (S)	500-HP electric motor: turn-to-turn short	motor power
4) Otero (S)	¼-HP electric motor: imbalance	acceleration
5) PSU/ARL (A)	30-HP motor: overloaded gearbox	load torque
6) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
7) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
8) PSU/ARL (S)	crack in rotating blade	motor power
9) PSU/ARL (A)	motor-driven bearing	vibration power
10) EPRI (S)	800-HP electric motor: air-gap offset	vibration power
11) EPRI (S)	800-HP electric motor: broken rotor	vibration power
12) EPRI (S)	500-HP electric motor: turn-to-turn short	vibration power
13) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
14) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
15) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
16) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
17) PSU/ARL (S)	crack in rotating blade	vibration power
18) ORNL (A)	failure of laboratory structural samples	stress & strain
19) ORNL	machine tool chatter	acceleration
20) ARL (AS)	gear for overhead rotor of helicopter	acceleration
21) Y12	bellows coupling in machining center	motor current

Failure Forewarning in Complex Systems

Aging Bridge System in context of Failure Forewarning in Complex Systems

- **Beneficial Use will Require Phased Tests of Failure Forewarning Techniques:**
  - **necessary sensors, command and control and data collection, as well as the cyber security efforts to support this system.**
- **Progressing from:**
  - **scale models to**
  - **simple slab structural spans to**
  - **full size tests of failing structure ready for destruction.**
- **Use Same Logic for Other Complex Structures**

Intellectual Property

- R.K. Abercrombie and L.M. Hively, "Method of forewarning of critical condition changes in monitoring civil structures," U.S. Patent pending (2010)
- L.M. Hively, "Methods for improved forewarning of condition changes in monitoring of physical processes," U.S. Patent pending (2010)
- #7,209,861, "…improved forewarning of critical events…," 24 April 2007
- #7,139,677, "… consistent forewarning …," 21 November 2006
- #6,484,132, "Condition assessment of nonlinear processes," 19 Nov 2002
- #6,460,012, "Nonlinear structural crack growth monitoring," 1 Oct 2002
- #5,857,978, "… Prediction by Nonlinear Methods," 12 Jan 1999
- #5,815,413, "Integrated … Chaotic Time Series Analysis," 29 Sep 1998
- #5,743,860, "… Detection using Nonlinear Techniques," 28 Apr 1998
- #5,626,145, "… Extraction of Low-Frequency Artifacts …," 6 May 1997

Robert K. Abercrombie, Ph.D.

Email: abercrombier@ornl.gov

Phone: (865) 241-6537

http://www.csiir.ornl.gov/abercrombie

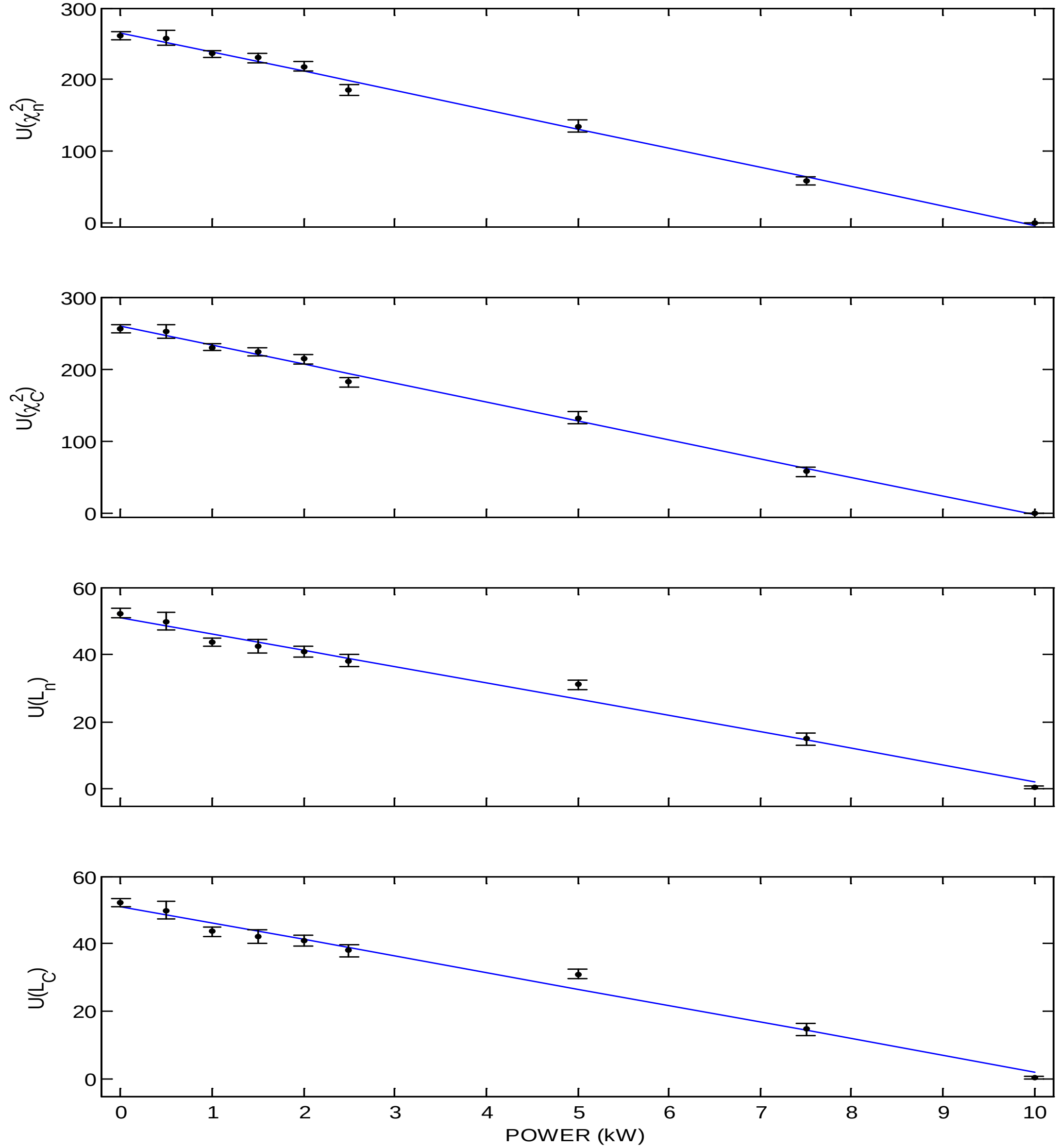
http://www.ornl.gov/~abe

Failure Forewarning in Complex Systems

- **BACKUP Slides**

- **Additional Examples of Systems**

Tactical Quiet Generator



Testing: 10-0 kW
(Low to high stress)
Tri-axial acceleration
100 kHz x 10 sec

Failure Forewarning in Complex Systems

Broken Coupling

Real Failure: CMI Magnum

- B9707 at Y12
- Machining center
- Coupling failed: W-axis
- Motor current
- Baseline: 17 Mar 1997
- Forewarn: 07 July 1997
- Failure: 17 July 1997
- Repair: 04 Aug 1997

*** 10-day forewarning**