Fretting Fatigue Considerations in Holistic Structural Integrity Based Design Processes (HOLSIP)- a continuing evolution

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HOLSIP-holistic structural integrity processes
ITS ALL ABOUT LIFE AND RELATED ISSUES. WHOLENESS (OROBOROS) IS ONE OF THE GOALS.


See D. Bohm, Wholeness and the Implicate Order, Ark Paperbacks, 1980
Acknowledgement

• I am indebted to Mr. Robert Jeal, formerly Director of Mechanical Technology and materials Engineering, RR-Derby, England and later Technical Director-Hawker DeHavilland, Sydney, Australia; now retired in Australia. Bob has constantly encouraged all my work in HOLISTIC approaches to structural integrity over 38 years. Also I want to thank RR-Aeroengine Co. of Derby, England for 26 years of funding my research at four different locations. As well, funding of Pratt and Whitney Canada, Office of Naval Research in the USA, and the Connaught Foundation of Toronto are greatly appreciated and made a great deal of research possible on fretting fatigue and other areas. I wish to thank Dr. Zhou and his colleagues for putting this 6th symposium together and inviting me to present this opening talk/paper.

Holistic Design Methodology – Phases
Indicating Effects of Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Methodology</th>
<th>Effects</th>
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Presented at ISFF6-Chengdu, China, April 19-22, 2010 © David W. Hoeppner, P.E., Ph.D.

- “Wholeness, Smuts said, is a fundamental characteristic of the universe—the product of nature’s drive to synthesize. **Holism** is self-creative, and its final structures are more holistic than its initial structures. These wholes - in effect, these unions-are dynamic, evolutionary, creative. They thrust toward ever higher orders of complexity and integration. “Evolution,” Smuts said, “has an ever deepening, inward spiritual character.”

- As we’ll see shortly, modern science has verified the quality of whole-making, the characteristic of nature to put things together in an ever-more synergistic, meaningful pattern. This includes work on fatigue, corrosion, corrosion fatigue, fretting, fretting fatigue!

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**EVEN STRUCTURAL INTEGRITY HAS BEEN FRAGMENTED IN OUR APPROACH AS SOME WANT IT.**

- Bohm, D., p16-”So fragmentation is in essence a confusion around the question of difference and sameness (or one-ness), but the clear perception of these categories is necessary in every phase of life”. “To be confused about what is different and what is not, is to be confused about everything”.

- Bohm goes on to say (p17) “that our theories, even “holistic” will have distinctions that could be treated as divisions implying separate existence”.
FRETTING
FATIGUE

Where?
How?
When?

Anticipation
Prediction
Prevention
Control
Repair

WHERE DOES IT OCCUR

Fretting problems are generally found in nearly all mechanical components used in any of the following equipment:

- Helicopters
- Fixed-wing aircraft
- Trains
- Ships
- Automobiles, trucks, buses
- Farm machinery
- Engines
- Construction equipment
- Orthopedic implants
- Artificial hearts
- Implants of various types
- Rocket motor cases
- Wire rope
- Cables
- And many others
Safe Life Design Approach

- In the “safe life” design paradigm, cracks are not considered as an intrinsic part of the component design and are defined as a true defect. Often corrosion degradation of various types, fretting, and other extraneous effects are NOT considered.

- This has led to the find and fix paradigm. If you find fretting damage including cracks you must fix it or the component is defective.

- This has led to loss of availability of products, excessive inspection costs, excessive maintenance costs (often unplanned), failure of components prematurely that leads to other failures, high warranty costs, loss of market share, deaths, and liability costs that are excessive.

- The safe life paradigm does not have a directed inspection tied to it until problems occur and then the inspections often are not quantified. Engineers around the world are not educated on NDI for the most part.
**BASIC FATIGUE CONSIDERATIONS**

- Basic Material
- Mechanical Deformation
- Response to environment, combined contact and cyclic mechanical deformation
- Cyclic Loading
- Stress State
  - Stress range
  - Stress amplitude
  - Frequency
  - Sequence of loading (spectrum)
  - Time/Waveform effects
- Product form, thickness, geometry, inspectability
- LIFE

**FATIGUE RESPONSE DIAGRAM**

- Total strain range*
- Fatigue life at $\Delta \sigma$ or $\Delta \varepsilon$
- Cycles or reversals to failure*, $N_f$
- Fatigue strength at n cycles.
- Scatter

Legend: CA or VA, temperature, type of loading, type of control, frequency, waveform, unnotched or notched, chemical environment, tmf, manufacturing process, basic material spec., microstructure.

*Note-usually log scales. Specify failure criterion.
**Environmental Fatigue, (Corrosion) Fatigue Considerations**

- Environment Chemistry / temperature
- Basic Material
- Mechanical Deformation
- Response to environment, combined contact and cyclic mechanical deformation
- Cyclic Loading
  - Stress State
  - Stress range
  - Stress amplitude
  - Frequency
  - Sequence of loading (spectrum)
  - Time/Waveform effects
- Chemical or electrochemical factors
  - Potential
  - Current density
  - Oxide
  - Time
  - Pitting
  - Dissolution
  - Embrittlement
  - Film formation
- Corrosion Fatigue
  - Product form, thickness, geometry, inspectability

**Δσ**

Baseline “lab air”.

SCATTER: CORROSION FATIGUE USUALLY REDUCES SCATTER

Environmental Effect-potential

Cycles to failure (defined) N-log scale
Basic Material Mechanical Deformation

Response to environment, combined contact and cyclic mechanical deformation

Contact surfaces

Environment

Chemistry / temperature

Basic Material

Mechanical Deformation

Normal load

Chemical or electrochemical factors

Cyclic Loading

Stress State

Stress range

Stress amplitude

Frequency

Sequence of loading (spectrum)

Time/Waveform effects

Product form, thickness, geometry, inspectability

Fretting-Fatigue

FRICTION

Magnitude amplitude of relative displacement

Surface stress

Frequency

T, environment

Material compatibility

Potential

Current density

Passivity

Oxide

Time

Pitting

Dissolution

Embrittlement

Film formation

Normal load

Magnitude amplitude of relative displacement

Surface stress

Frequency

T, environment

Material compatibility

Friction

Fretting-Fatigue

LIFE, N (LOG SCALE)

MAXIMUM STRESS \( \sigma_{\text{max}} \)

BASE LINE FATIGUE

LIFE REDUCTION DUE TO FRETTING

FRETTING FATIGUE
EFFECTS OF FRETTING DEGRADATION

1. Surface(s) become dysfunctional
2. Degradation leads to other corrosion mechanisms, mechanism overlap
3. Debris may contaminate lubricant and decrease its effectiveness
4. Cracks may **Form/Nucleate** where never expected and propagate by fatigue impacted by fretting and eventually propagate by fatigue or environmentally assisted fatigue
5. Host body is infected from debris as in implants

Definitions of discontinuity states-

- 
- 
- 
- IDS is modified by single or multiple mechanisms occurring to produce an evolving discontinuity state (EDS).
- Fretting produces an evolving discontinuity state!
- And if you stop it at any time, t, to evaluate it you produce an 
- MDS-modified discontinuity state
FRETTING IN HOLE AND ON FAYING SURFACE-SAFE LIFE DESIGN, NO CRACKS WERE EXPECTED. CRACK WAS 8 INCHES LONG WHEN CRITICAL FRACTURE OCCURRED.

Moving to fracture mechanics based lifing for fretting fatigue design

- After many years it was clear that the safe life approach was not adequate in and of itself when applied in a manner most use it. The discovery of the fretting damage boundary in the late 1960 period by Waterhouse et al. and Myself (independently) showed clearly that a fracture mechanics based method of design also must be employed to deal with fretting fatigue. This was discussed extensively at the First International Symposium on Corrosion Fatigue held in 1971 at U of Connecticut. See NACE 2, 1972.
SUBCRITICAL CRACK GROWTH CONCEPTUAL VIEW

Fatigue Instability at a for given material toughness

SUBCRITICAL CRACK GROWTH DURING SERVICE BY:

- Overload-single cycle
- Cyclic Loading (fatigue)
- Sustained Loading (stress corrosion cracking, hydrogen embrittlement creep)

Inherent or service or maintenance-induced discontinuity

Fretting Degradation often starts out well below NDI detection thresholds, but few studies have been done on this issue to date.

Damage Tolerance (ex. MIL-STD-1530)

- Damage Tolerance assumes that all fatigue “critical” components contain growing cracks and failure can occur when actual conditions are different to those modeled.
- Safe inspection interval determined based on crack growth to critical size (50% of life to critical crack).
- This paradigm means that undamaged components are not retired and factors of safety can be reduced resulting in cost savings.

Accident: Aloha B737 (1988) due to MSD, fretting, and corrosion

- Schematic of inspection interval by DT.
- Does not take into account environmental or age degradation effects.
CORRELATIVE RELATIONSHIPS

\[
\frac{da}{dN} = C_1 (\Delta K)^n \quad \text{Paris, Gomez, Anderson (straight line)}
\]

\[
\frac{da}{dN} = \frac{C_2 (\Delta K)^n}{(1 - R) \cdot K_c - \Delta K} \quad \text{Forman: Shape, Location, and Upper Instability, Parameter } K_c \introduced
\]

\[
\frac{da}{dn} = f(\Delta K, \omega, \text{spectrum, environment, microstructure})
\]

\[t = \text{time and, } \omega = \text{frequency}\]

Correlation and prediction within bounds of known applicability, extrapolation to conditions outside bounds involves unknown risk. (Hoeppner, 1965; Hoeppner, Krupp, 1973)

Role of Non Destructive Inspection in Damage Tolerant Design

FRAMEWORK

• What to look for! Damage specific.
• Where to look.
• How to look.
• When to look.
• How often to look.
• Probability of detection.
• Detection threshold.

Because fretting is often "hidden" degradations in joints it is often necessary to disassemble joints to see fretting so inspections are challenging at best.
Holistic Design Methodology – Identification of Component Life into Phases

- **Phase L1**: Nucleation or formation of damage by a specific, physical or Fretting damage process interacting with the fatigue process if appropriate. Corrosion and other processes (fretting) may act alone to create the damage. A transition from the nucleation stage to the next phase must occur.

- **Phase L2**: Microstructurally dominated crack linkup and propagation (“short” or “small” crack regime).

- **Phase L3**: Crack propagation in the regime where LEPM, EPFM, or FPFM may be applied both for analysis and material characterization (the “long” crack regime).

- **Phase L4**: Final instability.

  “A”: Length of the “first” detectable crack by field NDI techniques. “A” varies for given NDI techniques and field conditions.

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### Holistic Design Methodology – Phases Indicating Effects of Parameters

#### METHODS FOR EACH LIFE PHASE

<table>
<thead>
<tr>
<th>Formation/Nucleation Of cracks</th>
<th>“SMALL CRACK” Growth</th>
<th>Stress Dominated Crack Growth</th>
<th>Failure (Fracture)</th>
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<td>Nucleated discontinuity (not inherent) type, size, location</td>
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<td><em>boundary condition</em></td>
<td></td>
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<td>Data base **</td>
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*IDS-initial discontinuity state
Holistic Design Methodology – Phases

Indicating Effects of Parameters

METHODS FOR EACH LIFE PHASE

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FATIGUE LIFE ESTIMATION FOR FRETTING FATIGUE

- Cyclic stress/strain
- Material
- Environment
- Thermal Contact Stress

Fretting Damage Growth

- Mode 1 or N11
- Cycles to Crack Formation
- Crack Formation Stress K1 (th)

Failure by Fracture (Unstable or Stable)

- Cycles of Fretting Fatigue Life

Modeling-DWH-1969-current

**Equation:**

\[
\frac{dN}{d\Delta\sigma} = C(\Delta\sigma^m)
\]

- \(N_f\) or \(N_{ff}\)
- Cycles to initiation of fretting

- Time (cycles)

- Mode 1

- \(K_{th}\) or \(K_{ib}\)
Challenges ahead

- Nucleation/formation of cracks from fretting areas of degradation
- Use of maps
- French work and evolution of degradation has been very helpful
- Transition from fretting to cracks and the stages of cracking

Some fretting corrosion/wear giants

- Professor Robert Waterhouse
- Professor Hirakawa
- Dr. Nishioka
- Professor Vincent
- Dr. Philippe Kapsa
- Dr. Hattori
- Professor Mutoh
- Dr. Endo
- W. G. Baroils
- Dr. Helmi Attia
- Mr. Trevor Lindley,
- Dr. Robin Cooke
- Many students who paid me the honor of studying with me in fretting fatigue-
  - Dr. Cheung Poon, Dr. Gary Salivar, Dr. Roger Reeves,
  - Mr. Doug Mann, Dr. Sachin Shinde, Dr. Paul Clark, Dr.
  - Steve Kinyon, Dr. Mark Moesser, Dr. Saed
  - Abidnazzari, Dr. Charles Elliott, Mr. Conrad Yeung, Dr.
  - Paul Clark, Mr. Conrad Yeung
  - Dr. Chandrasekaran Venkatusen,
Some fatigue and fracture mechanics giants

Fatigue

• Professor Francis Shanley
• Dr. Franz Vitovec
• Dr. August Wöhler
• Professor George Sines
• Dr. Horace Grover
• Dr. Waloddi Weibull
• Professor A. Freudenthal
• Dr. Ralph Stephens
• Dr. Walter Schütz
• Mr. Walter J. Chrichlow
• Professor Henry Fuchs
• Peter Forsyth

Fracture Mechanics

• Professor A. H. Love
• Professor C. E. Inglis
• Dr. Alan Arnold Griffith
• Professor Max Williams
• Dr. Egan Orowan
• Professor George Irwin
• Dr. Westagaard
• W. G. Barenblatt
• Dr. Mirakami

IMPORTANT REFERENCES

(1) Waterhouse, R.B. (1972), Frettin Corrosion, Pergamon Press, USA.
(2) Specialist Meeting on Fretting in Aircraft Systems (1974), NATO-AGARD Conference Proceedings No. 161, AGARD.
(3) Control of Fretting Fatigue (1977), Report of the Committee on Control of Fretting-Initiated Fatigue, NMAB, NRC, Publication NMAB-33, National Academy of Sciences, Washington, D.C.
(5) Attia/Waterhouse [Editors], Standardization of Fretting Fatigue Test Methods and Equipment, ASTM STP 1159, 1992, ASTM, Philadelphia, PA.
Recent International Symposium on Fretting Fatigue

- Held in Montreal, Quebec, Canada, April 21-23, - 2007, Published on line-Elsevier Publishing.

- ASTM Standard Guide for Fretting Fatigue Testing- , IN VOTING FOR APPROVAL NOW. Scope

  - This guide defines terminology and covers general requirements for conducting fretting fatigue tests and reporting the results. It describes the general types of fretting fatigue tests and provides some suggestions on developing and conducting fretting fatigue test programs.

Thank you.

Any questions?