Quantifying Fretting Damage Using a Contact-Evolution Based Modelling Approach

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Study of Spline Couplings

- Experimentally characterise the fretting behaviour of splines using scaled-down spline and/or representative specimens
- Develop lifing methodologies for spline against fretting
Contact-evolution based lifing methodology

- An approach that considers transient interaction between wear and fatigue under fretting, especially the effect of wear on fatigue life.

- Contact-evolution based lifing approach comprises:
  - A finite element wear simulation tool to determine the evolution of contact geometry.
  - Damage Accumulation approach for crack nucleation.

- Ongoing EPSEC project in collaboration with Oxford (total grant ~0.6 Millions)
The approach integrates a number of 'tools'.

- Fretting wear tool is central, which predicts the extent of wear damage and the concomitant change of contact geometry.

**Archard’s Wear equation:**

\[ dh_i(x,t) = k_i \times p(x,t) \times ds(x,t) \]

- For each wear step \( n \), accumulated fatigue damage is calculated by fatigue parameter Smith-Woston-Topper; thus, total accumulated damage is given by

\[ \iota = \sum_{n=1}^{N_T} \frac{1}{\Delta N_{i,n}} \]

Initial parameters

- Contact geometry
- Applied loads
- Wear coefficient & friction coefficient

FE analysis of fretting contact

Calculate wear depth increment by modified Archard’s equation

Calculate cumulative fatigue damage of the load step

All cycles completed?

Update contact geometry

Output results
Fretting Wear Modelling

Normal load -120 N/mm
Stoke - 20 μm

Contact width increase markedly from Hertz prediction

Gross slip case

Worn surface profile (after 5000 cycles)
Original surface profile

Normal load -120 N/mm
Stoke - 5 μm

Little change of contact size, wear occurring at slip zone

Partial slip case

(Ding et al, *Int J of Fatigue, 2004*)
Fretting Wear Modelling

Evolution of contact pressure

Gross slip case

Partial slip case

Normal load -120 N/mm
Stoke - 20 μm

Normal load -120 N/mm
Stoke - 5 μm

The University of Nottingham

2nd Workshop on Joints Modelling, Dartington Hall, Totnes, Devon, UK 26-29 April 2009
Contact-evolution based prediction of crack nucleation (I) gross sliding

- Electromagnetic vibrator and force transducer
- Dead weight

**Sample SWT evolutions**

- SWT (MPa)
- Number of fretting cycles
- Ti-6Al-4V

**SWT snapshots**

- Horizontal position (μm)
- Surface height (μm)

- Predicted profile
- Measured profile

**Sample SWT evolutions**

- SWT (MPa)
- Number of fretting cycles
- x/a=0.90
- x/a=1.24
- x/a=1.75

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Contact-evolution based prediction of crack nucleation (II) partial slip

Wear scar evolution

Wear depth (mm)

Sample SWT evolutions

SWT (MPa)

Number of cycles

Sample SWT evolutions

SWT (MPa)

Number of cycles

Wear scar evolution

Wear depth (mm)

Sample SWT evolutions

SWT (MPa)

Number of cycles
Contact-evolution based prediction of crack nucleation
(II) partial slip

- Complex pressure evolution predicted due to plasticity effects
- Multiple cracking locations
  - $x \approx \pm 0.11$ mm (light blue)
  - $x \approx \pm 0.04$ mm (red)
  - $x \approx \pm 0.13$ mm (yellow)
- $x \approx \pm 0.13$ mm
  - Initial Hertzian contact edge
  - early cycles, low COF: gross sliding ($N < 3k$)
- $x \approx \pm 0.04$ mm
  - initial stick-slip boundaries
  - late cycles ($N \approx 150k-300k$)
- $x \approx \pm 0.11$ mm
  - intermediate cycles ($3k < N < 150k$)
  - due to flat indenter type pressure peaks
Effect of slip amplitude on fretting fatigue is captured by taking into account how wear affects fatigue damage parameter.

Prediction vs. tests (Madge et al, 2007)
Cyclic Plasticity in Fretting

- Prager linear kinematic hardening
- Material: Ti-6Al-4V ($\alpha + \beta$)
- Coefficient of friction – 0.9

Plastic shakedown
steady reversed cyclic plastic strains

Ratchetting
plastic strain magnitude increases continually with load cycling
Cyclic Plasticity in Partial Slip

- Nominal Hertzian geometry ➔ elastic
- Wear simulation with plasticity ➔ ratchetting phenomenon
- Possibility of damage/cracking due to ductility exhaustion

Predicted wear-induced evolution of plastic strains at final stick-slip interface
Cyclic Plasticity in Gross Sliding

- Gross sliding: shear-dominant plasticity
- g.s. plasticity take a W-shape
- Wearing away of plasticity $\Rightarrow$ reduction in equivalent plastic strain
Conclusions and Future Challenges

• Contact-evolution based fretting lifing methodology provides
  o an integrated solution for fretting wear and fatigue prediction.
  o a convincing explanation about the effects of slip amplitude on fretting fatigue

• Future challenges:
  o Incorporate near-surface effects into fretting fatigue prediction, such as asperity, oxidation, plasticity and debris accumulation. How important are they for fretting crack nucleation?
  o Fretting contact mechanics under micro or nano scales.
Contact-evolution based prediction of crack nucleation (I) gross sliding

Crack nucleation defined to occur at material point \( i \) when accumulated damage \( \omega \) reaches value of 1, where \( \omega \) is defined as:

\[
\omega = \sum_{n=1}^{N_T} \frac{\Delta N}{N_{i,n}}
\]

Each \( N_{i,n} \) is calculated based on a critical-plane fatigue damage parameter Smith-Watson-Topper (SWT).

\[
(\sigma_{\text{max}}\Delta e_a)_{i,n} = \frac{(\sigma_f')^2}{E} (2N_{i,n})^{2b} + \sigma_f'\varepsilon_f'(2N_{i,n})^{b+c}
\]

Sample SWT evolutions

SWT snapshots