SIMULATING THE MECHANICS OF FRETTING FATIGUE CRACK GROWTH

Tom Curtin, John Baynham, and Sharon Mellings
Computational Mechanics BEASY
OBJECTIVES

• Why is fretting fatigue important?
• Accuracy of predicted contact stress
  – Comparison of numerical and analytical solution
• Fretting fatigue crack growth simulation
  – Computer model
  – Predicted crack growth path
  – Stress intensity factor solution
• Impact of crack growth on edge of contact stress
• Extension of methodology to real parts
WHY DO WE NEED TO UNDERSTAND FRETTING FATIGUE

- Fretting causes wear and very high local stress near the edge of contact
- Results in crack nucleation and reduction in fatigue life of the part
- Fretting occurs in many types of contacting components subject to oscillating loads
- Recognized as one of the most costly forms of in-service damage particularly with regard to turbomachinery components
WHAT MAKES FRETTING FATIGUE DIFFICULT TO ANALYZE

- Very high stress gradient near edge of contact
- Non-proportional loading near contact interface even with proportional applied loads
- The R-ratio ($R = \frac{K_{\text{min}}}{K_{\text{max}}}$) is variable as cracks grow from contact zone.
- The impact of surface damage on fatigue life, at the micromechanical level, is still not clearly understood.
- Crack growth methodology must consider length of crack (*shorts crack behave differently*)
FRETting FATIGUE COMPUTER MODEL

Analytical Model

Rigid punch on incompressible semi-infinite half plane

P = 2000 N/mm
Q = 500 N/mm

E_{punch} = 200 \text{ GPa}
\gamma_{punch} = 0.3

E_{plate} = 50 \text{ GPa}
\gamma_{plate} = 0.499

slider interface boundary condition
contact interface
(400 elements with length = 0.05 mm)

σ (MPa)
COMPARISON OF NUMERICAL AND ANALYTICAL CONTACT STRESS SOLUTIONS
SHEAR TRACTION FOR FULL STICK CASE

FULL STICK CASE

\[ P = 2000 \text{ N/mm} \quad Q = 500 \text{ N/mm} \quad \sigma = 25 \text{ MPa} \quad \mu = 0.5 \]
SHEAR TRACTION FOR ONE SLIP REGION CASE

\[ P = 2000 \text{ N/mm} \quad Q = 500 \text{ N/mm} \quad \sigma = 75 \text{ MPa} \quad \mu = 0.5 \]
SHEAR TRACTION FOR TWO SLIP REGION CASE

TWO SLIP REGION CASE

P = 2000 N/mm  Q = 500 N/mm  σ = 140 MPa  μ = 0.5

Diagram showing X Traction - \( \frac{F}{Z_h} \) (MPa) vs. \( \frac{x}{a} \) with regions marked as slip and stick.
Fretting Load Cycle Simulation
INITIAL NORMAL LOAD

The diagram shows the initial normal load distribution with a load of 2000 N/mm applied at the center. The graph plots the XX stress (MPa) against the normalized coordinate x/a, demonstrating the stress distribution under the applied load.
FORWARD LOAD

stick-slip transition

\[XX\text{ Stress (MPa)}\]

\[x/a\]

-400 -300 -200 -100 0 100 200 300

\[x/a\]

\[P = 2000 \text{ N/mm} \quad Q = 500 \text{ N/mm} \quad \sigma = 125 \text{ MPa}\]
UNLOAD

stick-slip transition (note shift relative to previous case)

very steep tensile (pt. A) to compressive (pt. B) stress gradient near edge of contact

P = 2000 N/mm  Q = 500N/mm  sigma = 125 MPa  P = 2000 N/mm
REVERSE LOAD

The diagram illustrates the stress distribution under reverse load conditions. The graph shows the XX Stress (MPa) plotted against the distance x/a. The stress transitions from 'stick' to 'slip' at certain points, indicating a change in the mechanical behavior of the material.

Key Points:
- The graph includes lines for different loads: P = 2000 N/mm and Q = -600 N/mm.
- The stress values range from -400 to 0 MPa.
- The transition from 'stick' to 'slip' is marked by arrows indicating the direction of movement.
2nd UNLOAD

XX Stress returns to Initial Normal Load state

P = 2000 N/mm  Q = 600 N/mm  sigma = -.25 MPa  P = 2000 N/mm
CHANGE IN SLIP AMPLITUDE DURING FRETTING LOAD CYCLE

![Graph showing change in slip amplitude during fretting load cycle.](image)

- **Initial Load**
- **Normal Load**
- **Forward Load**
- **Reverse Load**
- **Unload**

The graph illustrates the change in slip amplitude with respect to the ratio x/a for different load conditions:

- **P = 2000 N/mm**
- **P = 2000 N/mm Q = 500 N/mm sigma = 125 MPa**
- **P = 2000 N/mm**
- **P = 2000 N/mm Q = 600 N/mm sigma = -25 MPa**

The graph shows the relationship between slip amplitude (in microns) and the ratio x/a for various load conditions, highlighting the effects of different normal and fretting loads on slip amplitude.
FRETTING FATIGUE CRACK GROWTH SIMULATION
CRACK GROWTH COMPUTER MODEL

FORWARD

\[ P = 2000 \text{ N/mm} \]

\[ Q = 500 \text{ N/mm} \]

\[ \sigma = 75 \text{ MPa} \]

REVERSE

\[ P = 2000 \text{ N/mm} \]

\[ Q = -500 \text{ N/mm} \]

\[ \sigma = -25 \text{ MPa} \]
GROWTH DIRECTION OF FRETTING FATIGUE CRACK

Crack Length (mm)

Crack Angle (deg)

0.25 mm
GROWTH DIRECTION OF FRETTING FATIGUE CRACK

Crack Angle (deg) vs. Crack Length (mm)

- Mechanically Short Cracks
- Microstructurally Short Cracks

Crack Length (mm): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0

Crack Angle (deg): 95.0, 90.0, 85.0, 80.0, 75.0, 70.0, 65.0, 60.0, 55.0, 50.0

0.1 mm
0.05 mm
1 mm

NAFEMS
THE INTERNATIONAL ASSOCIATION FOR THE ENGINEERING ANALYSIS COMMUNITY
GROWTH DIRECTION OF FRETTING FATIGUE CRACK

Long Cracks
A GENERAL COMPARISON OF CRACK PATH TO TEST DATA

θ_{initial} = 90^{\circ}

θ_{avg} = 55^{\circ}

θ_{avg} = 78^{\circ}

experimental crack path shown for opposite sense of loading \((Q, \sigma)\) and crack initiation location


\[ N = 7.31 \text{ N}, Q = 56.6 \text{ N} \text{ and } \sigma = 64 \text{ MPa} \]
MIXED MODE SIF VALUES FOR FRETTING FATIGUE SIMULATION

Forward Load Case

Stress Intensity Factor (MPa mm$^{0.5}$) vs. Crack Length (mm)

- K1
- K2
MAXIMUM PRINCIPAL STRESS
NEAR CRACK TIP
IMPACT OF CRACK GROWTH ON EDGE OF CONTACT STRESS
EFFECT OF CRACK LENGTH ON SLIP DISTANCE

Forward Load Case

$P = 2000 \text{ N/mm} \quad Q = 500 \text{ N/mm} \quad \sigma = 75 \text{ MPa}$
EFFECT OF CRACK LENGTH ON NORMAL STRESS AT EDGE OF CONTACT

---

EFFECT OF CRACK LENGTH ON NORMAL STRESS

- Normal Stress (MPa)
- x/a (mm)

Graph shows the effect of crack length on normal stress with values for 5.05 mm, 3.05 mm, 1.55 mm, and 0.52 mm crack lengths.

---

The International Association for the Engineering Analysis Community
EXTENSION OF METHODOLOGY TO REAL PARTS
Modified Mindlin Contact Solution

Fretting Fatigue Cracks are often found at the trailing edge of contact

Bulk stress has significant impact on stick-slip region and shear traction distribution
Modified Mindlin Contact Solution

Capture peak $\sigma_{xx}$ at edge of contact.
CRACK GROWTH ANALYSIS OF TURBINE BLADE AND DISK

Corner Crack Growing in Disk (viewed from inside of component)

BEASY Crack Growth Analysis of a Turbine Blade and Disk.
SUMMARY

- Fretting fatigue crack growth is a complex problem involving non-proportional, multiaxial loading and high stress gradients near the edge of contact.
- Boundary element contact solution provides accurate edge of contact stress.
- BEASY’s crack growth algorithm provides 2D/3D non-planar crack growth and coupled contact/crack growth solutions.
- Predicted crack path accounts for continuous change in stress field as the crack is advanced.
- Computer model offers some advantage over analytical solutions in that it accounts for deformation of the contact surface and the inherent geometric nonlinearity that may occur with a shifting stick/slip zone.