ABSTRACT

Assessment of Crack Path Prediction in Non-Proportional Mixed-Mode Fatigue

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Non-proportional mixed-mode loading is present in many systems and a growing crack can experience any manner of mixed-mode loading. Prediction of the resulting crack path is important when assessing potential failure modes or when performing a failure investigation. Current crack path selection criteria are presented along with data for Inconel 718 under non-proportional mixed-mode loading. Mixed-mode crack growth can transition between path deflection mechanisms with very different orientations. Non-proportional fatigue loadings lack a single parameter for input to current crack path criteria. Crack growth transitions were observed in proportional and non-proportional FCG tests. Different paths displayed distinct fracture surface morphologies. New crack path drivers & transition criteria must be developed.
Assessment of crack path prediction in non-proportional mixed-mode fatigue

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Outline

• Project motivation
  – Mixed-mode crack loading

• Background
  – Crack path selection criteria

• Problem
  – Criteria insufficient for non-proportional loading

• Testing & analysis

• Results & fractography

• Summary
Motivation:
Non-proportional loading

- Rotational & aerodynamic loads impose normal, bending & twisting loads
- Growing crack can experience any manner of mixed-mode loading
- **Objective**: Where will crack grow?
  - And how much mass/energy will it liberate?
Background - Mixed mode crack path

- Crack growth predominantly considered in terms of Mode I
- Microstructure, geometry, load transients can perturb crack angle or applied load
  - Addition of Mode II
- What is expected behavior of crack trajectory?
Background -
Mixed mode crack path models

- Erdogan & Sih (1963) - max hoop stress criterion (MHSC)
- Hussain et al (1974) - max strain energy release rate $G$ ("Griffith" theory)
- Sih (1974) - min strain energy density $S$
- He & Hutchinson (1989) - $K_{II}=0$
Background -
Mixed mode crack path models

- All generally predict same crack deflection as function of mixity

\[ \phi_M = \tan^{-1} \left( \frac{K_{II}}{K_I} \right) \]
Background - Fracture mode transition

- Hallback & Nilsson (1994) observe Mode I to Mode II-dominated transition (to max shear plane) around $\phi = 40^\circ$ in 7075-T6
  - Initial crack trajectory predicted by MHSC at lower mixities, by max shear stress criterion (MSSC) at higher mixities
- Amstutz et al (1995) also observe transition to shear crack growth in range of $68^\circ < \phi < 75^\circ$ in 2024-T3
Chao & Liu (1997) argue that crack propagation occurs along most critical mode.

Competition b/w MHSC and MSSC based on loading path (mixity):
- Transition based on ratio of $\tau_{\text{crit}}/\sigma_{\text{crit}}$
Background - Fracture mode transition

- Normal crack deflection dictated by max $\sigma_{\theta\theta}$
- As $K_{II}$ increases relative to $K_{I}$ the angle $\theta^*$ of max normal stress $\sigma_{\theta\theta}$ deflects downward
- Simultaneously the shear stress $\tau_{r\theta}$ is increasing on a positive deflected plane $\theta^{**}$
- At a material-dependent $K_{II}/K_{I}$ ratio, the critical shear stress is reached (at some characteristic distance) before critical normal stress and crack deflection shifts to shear
Background - Fracture mode transition

MHSC vs. MSSC

Mixity phase angle $\phi_m$ (deg)

Deflection $\theta$ (deg)

Orientation of max $\tau_{r\theta}$

Orientation of max $\sigma_{\theta\theta}$

$\phi_{crit}$
Problem - Non-proportional mixed mode loads

- Different points of waveform have different mixities
- Which parameters can be used to predict $\theta$?
- Can we do so using only LEFM / K?

![Graph showing MHSC vs. MSSC](image)

- Max tension of constant torque or OOP test
- Max torque of constant tension or OOP test
Testing - Tension-torsion tubular FCG

- Inconel 718
- 17 specimens tested at NASA Marshall
- Compression then tension pre-cracking
- Measure initial deflection angle from pre-crack upon mixed-mode loading
- Examine fracture surface morphology
Modeling - SIFs for tubular T-T specimen

- FRANC3D linear elastic boundary element model
- Local mesh refinement around precrack
- Each specimen precrack geometry modeled using fracture surface measurements
- Tension & torsion applied individually and together

Plan view of precrack
Testing -
Mixed mode test matrix

• Baseline in-phase tests over range of mixity
• Contant tension ($K_I$) / cyclic torsion ($K_{II}$)
• Contant torsion ($K_{II}$) / cyclic tension ($K_I$)
• $90^\circ$ out-of-phase
In-phase deflections follow Max Hoop Stress criterion as expected up to critical $\phi$ value, then see transition to Max Shear Stress.

- Torque limitations prevented further MSS testing.
In-phase fractography - 500x

- Tensile crack (MHS) deflection 
  \[ \theta = -27^\circ \]
- Shear crack (MSS) deflection 
  \[ \theta = 18^\circ \]

- Clear morphology difference reinforces transition in crack path deflection mechanism
In-phase fractography - 2000x

Tensile crack (MHS) deflection
\[ \theta = -55^\circ \]

Shear crack (MSS) deflection
\[ \theta = 18^\circ \]

- Fine microstructural features on shear crack flats suggest they are not the product of crack face contact
Results –
Constant Tension / Cyclic Torsion

- Two distinct groups of crack path deflection
- No clear indicator of transition criterion
Fractography -
Constant Tension / Cyclic Torsion 500x

Tensile crack (MHS) deflection
\[ \theta = -41^\circ \]

Shear crack (MSS) deflection
\[ \theta = +2^\circ \]

- Even more pronounced morphological difference but similar in nature to in-phase
Results - 90° Out of Phase

- Two distinct crack path deflections, but fractography not as clear
Fractography - Out of Phase 500x

Tensile crack (MHS) deflection
\[ \theta = -74^\circ \]

- Shear crack?
\[ \theta = 18^\circ \]

- Positive deflected crack looks more like a crushed tensile crack than like previous shear cracks
Fractography - Comparison to Tensile & Shear 500x

Constant tension/cyclic torsion

Tensile (MHS) crack
\[ \theta = -41^\circ \]

Constant tension/cyclic torsion

Shear (MSS) crack
\[ \theta = 2^\circ \]

Out-of-phase
\[ \theta = 18^\circ \]
Tensile crack (MHS) deflection
\[ \theta = -74^\circ \]

- \( \theta = 18^\circ \) crack shows MHS-like faceting at right; flat region appears crushed
- If both are tensile cracking, what is the driver?
Example: Kink SIF for Out-of-Phase crack deflections

- Crack tip SIFs $k_1$ & $k_2$ for putative kink
- Positive-kinked OOP test (mechanism unclear) tracks well to $\Delta k_1$
- Negative-kinked OOP test (likely tensile) does not
  - *Does* track toward max $k_1$ of cycle (at max torque)
  - But positive-kinked OOP test not as likely
Summary

- Mixed-mode crack growth can transition between path deflection mechanisms with very different orientations
- Non-proportional fatigue loadings lack a single parameter for input to current crack path criteria
- Crack growth transitions were observed in proportional & non-proportional FCG tests
- Different paths displayed distinct fracture surface morphologies
- New crack path drivers & transition criteria must be developed
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