Variable Amplitude Fatigue of FMLs
On Developing a Mechanistic Understanding

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Outline

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• Background
• From constant to variable amplitude loading
  • Delamination growth
  • Delamination shape
  • Crack tip plasticity
  • Crack Growth
• Conclusions
Introduction

Fatigue of FMLs

- Superior fatigue crack growth performance
  - Thin metallic layers (plane stress)
  - Fiber bridging mechanism
Introduction

Fatigue of FMLs

- Full utilization of FML potential requires a fundamental understanding of fatigue phenomenon
- This is not possible through standard open hole initiation and center cracked tension specimens
  - Infinite combination of metals and fibers → infinite tests
  - Testing is expensive!
  - Data for past configurations will limit exploration of new configurations
- Analogous to composite world
  - Continued use of quasi-isotropic layups despite promises for full customization
Introduction

Fatigue of FMLs

- Development and certification can be done the hard way
  - Demonstrated for the A380
- Airbus recognized the value of developing generic models
  - Research collaboration resulted in generic crack initiation and growth models for constant amplitude loading
  - Continued research on variable amplitude fatigue and residual strength
- Efforts will allow design and virtual testing of arbitrary FMLs for arbitrary loading scenarios!
Background

Constant Amplitude Fatigue Model for FMLs
Background

Constant Amplitude Fatigue Model for FMLs

- Superposition of bridging load

\[ G = f(S_{metal}, S_{fibre}, S_{br}) \]
Background

Determining the Bridging Load
Background

Determining the Bridging Load

- Cracked adherent
  \[ \nu = \nu_\infty - \nu_{br} \]

- Undamaged adherent
  \[ \delta = \delta_\infty + \delta_{br} + \delta_{ad} \]

Over delamination length, \( b \)
\[ \nu = \delta \rightarrow S_{br} \]
Background

Implementation for Constant Amplitude Fatigue

Crack Length

Delamination Shape/Size

Applied Loads

Lamina stress

Determine bridging stress for current geometry

\[ K = K_{\infty} - K_{br} \]

\[ G = f(S_{metal}, S_{fibre}, S_{br}) \]
From CA to VA Fatigue
Developing a Fundamental Understanding

- How does variable amplitude loading affect each mechanism?
  - Delamination behavior
  - Crack growth behavior
- What mechanisms are present?
  - Load history effects
  - Plasticity and retardation effects
- Can we develop a generic understanding?
Delamination Behavior

Variable Amplitude Growth

- Useful to study delamination growth behavior independent of crack growth
- Use of ply interrupt specimen (Mode II growth)
- Configuration provides precise control over delamination growth driving force

\[ G \neq f(b) \]
### Delamination Behavior

#### Variable Amplitude Growth

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Delamination Behavior

Variable Amplitude Growth

- No apparent retardation effects
- No history effects observed for block loading
- Results correspond to CA delamination growth rates

\[ \frac{db}{dN} \propto \sqrt{G_{\text{max}}} - \sqrt{G_{\text{min}}} \]

Suggests suitability of LDA
Delamination Behavior

Variable Amplitude Growth

- LDA under predicts delamination growth (changing mean stress)
- Small shear deformations do not contribute to growth

Overcome with rain flow counting
Delamination Behavior

Shape Behavior After Over Load

- What happens when there is a crack?
Delamination Behavior

Shape Behavior After Over Load

- Kinked shape not predicted by linear damage accumulation
- Plastic zone due to overload causes local stress redistribution
  - Analogous to post stretching
  - Reversal of residual stress state
  - Modified bridging load

\[ \text{stress} \]

\[ \sigma_{\text{aluminium}} \]

\[ \sigma_{\text{fiber layer}} \]

\[ \text{strain} \]

residual stress in ‘as cured’ laminate

residual stress in ‘stretched’ laminate
Delamination Behavior

Shape Behavior After Over Load

- Reduction of metal layer and bridging stress in overload plastic zone
- Reduced bridging stress => reduced delamination growth
- No effect on crack growth \( (K_{\text{tip}} = K_{\text{ff}} - K_{\text{br}}) \)

\[
S_{\text{al}} + S_{\text{br}} = S_{\text{applied}}
\]

Section A-A: ‘as-cured’

Section B-B: ‘post-stretched’
Crack Tip Plasticity

Stiffness Miss-Match Considerations

- Plasticity known to influence metal VA fatigue
- Considering combination of aluminum with glass/epoxy
  - Stiffness of metal higher than fibers
  - Stress in metal layers higher than applied stress
  - Exacerbated by curing stress
- Situation can be different
  - Relative stiffness of constituents
  - Thermal expansion coefficients of constituents

![Stress Diagram](image)
Crack Tip Plasticity

Fiber Bridging

- Fiber bridging reduces crack tip stress
- Relative to monolithic Al under same load
  - Smaller plastic zone
  - Less crack growth retardation due to overload

GLARE3 – 5/4 – 0.4

Note the higher far field strain in FML
Crack Tip Plasticity

Metal Layer Thickness

- FML layer thickness < 0.5mm
- Transition from Mode I to slanted crack almost instantaneous
- Implications for application of da/dN data from thicker sheets
Crack Tip Plasticity

Fiber Bridging

- Isn’t less crack retardation bad? **No!**
  - Crack bridging present regardless of overload
  - Less crack length dependency on number of delay cycles
  - Overall crack growth performance superior

Less retardation makes it easier to predict VA fatigue behaviour
Variable Amplitude Fatigue of FMLs

Crack Growth

- No history effect for delamination growth
  - Linear damage accumulation possible (delamination growth only)
  - Application of rain flow counting to eliminate small load cycles
- Local stress redistributions affect delamination shape
  - Analogous to post stretching
  - Difference in bridging balanced by stress redistribution (can be neglected in predictions)
- Plastic zone size much smaller in FMLs
  - Complicated retardation models not necessary
Variable Amplitude Predictions

A Simple Example

Crack Length

Delamination Shape/Size

Applied Loads

Lamina stress

Determine bridging stress for current geometry

Wheeler Yield Zone Model

\[ K = K_\infty - K_{br} \]

Linear Damage Accumulation

\[ G = f(S_{metal}, S_{fibre}, S_{br}) \]
Variable Amplitude Predictions
Block Loading
Variable Amplitude Predictions

Overloads
Variable Amplitude Predictions

Spectra

Significant overloads require crack closure model
Summary

Variable Amplitude Fatigue of FMLs

- It is possible to approach fatigue in FMLs by developing a fundamental understanding of the failure mechanisms
- Such an approach has considerable advantages
  - Generic design tools
  - Optimization potential
  - Reduced testing
  - Improved understanding
- This understanding does exist for FMLs!
Acknowledgements

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It is clear that development of fundamental understanding and related predictive capability relevant for actual structural applications is only possible with close and direct collaboration between academia and industry.