Virtual Testing of Composites for Damage Tolerant Designs

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Motivation and Scope

Virtual testing can:

- **Identify the key test data** required for minimal model uncertainty
- **Guide the physical testing** for a leaner and more efficient programme
- **Augment** the data with further combinations of test cases
- **Replace physical tests** at intermediate levels
Example: Defects in Tapered Laminates

- Automatic mesh generation, job submission & post-processing
- Large numbers of analyses with minimal human intervention

Kawashita LF, Jones MI, Giannis S, Hallett SR, Wisnom MR; 18th ICCM, Korea (2011)
Example: Defects in Tapered Laminates

- ‘Worst case’ defect location identified in a few hours using a HPC cluster:

Kawashita LF, Jones MI, Giannis S, Hallett SR, Wisnom MR; 18th ICCM, Korea (2011)
Contents

- Automatic meshing algorithms for Automated Tape Laying (ATL)
- **Fatigue** models of delamination and matrix cracking
- **XFEM** models for quasi-static and dynamic crack growth
- Additive Layer Manufactured hybrid joints

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Automated Meshing for AFP

- Example: tapered laminates with ply terminations and embedded defects

Meshing algorithms use debulking and consolidation ‘rules’ to ensure that the geometries of internal features are realistic – important for mechanical analyses.
Automated Meshing for AFP

- Example: analysis of gap/overlap manufacturing defects

- Large numbers of variants can be investigated numerically → reliable knockdown factors

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Dynamic open-hole test

Impact damage on a cross-ply laminate

Interaction between damage modes in angle-ply DCB specimens

Kawashita LF, Bedos A., Hallett SR; CMC, v. 32(2) (2012)

Kawashita LF, Hallett SR; 10th WCCM (2012)

Kawashita LF, Pernice MF, Hallett SR; 4th ECCOMAS Composites (2013)
Supratik Mukhopadhyay has further developed the XFEM capability and applied it in the analysis of manufacturing defects:

Experimental CT scan of specimens with wrinkle defects

Numerical mesh-independent matrix cracking

Numerical delamination planes

Mukhopadhyay S, Kawashita LF, Hallett SR; 5th ECCOMAS Composites (2015)
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Fatigue Crack Growth

- Models of delamination growth and matrix cracking using **cohesive elements** and **Paris laws**
Fatigue Crack Growth

- Example: Fatigue delamination in tapered laminates:

\[
\sigma_{\text{max}}(t) \quad G_{\text{max}}(t) \quad G_{\text{fail}} \quad F \quad \delta
\]

\[
\sigma_{\text{max}} \quad t \quad t - \Delta t \quad F_{\text{max}} \quad F_{\text{min}} \quad \Delta F \quad \delta
\]

\[
\sigma_{\text{max}} \quad t \quad t - \Delta t \quad F_{\text{max}} \quad F_{\text{min}} \quad \Delta F \quad \delta
\]

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Fatigue Crack Growth

- Example: Fatigue delamination in tapered laminates:

![Fatigue Crack Growth Diagram](image-url)

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Fatigue Crack Growth

- Example: Fatigue delamination in tapered laminates:
Fatigue Crack Growth

- Example: Fatigue delamination in tapered laminates:

\[ F_{\text{min}} \rightarrow F_{\text{max}} \rightarrow \Delta F \]

\[ \sigma \rightarrow \sigma_{\text{max}} \rightarrow \delta \rightarrow \delta_f \]

\[ G_{\text{init}}(t) \]

\[ G_{\text{fail}} \]

\[ \Delta t \]

\[ t \]

\[ t_0 \]

\[ \delta \]

\[ \sigma_{\text{max}} \]

\[ \sigma \]

\[ \delta_f \]

\[ \delta \]

\[ F \]

\[ \Delta F \]

\[ initialisation \rightarrow fatigue \text{ degradation} \]

\[ pseudo-time \]

\[ elastic \]

\[ damaged \]

\[ fatigue \]

\[ failed \]
Fatigue Crack Growth

- Example: Fatigue delamination in tapered laminates:

\[ G_{\text{max}}(t) \]

\[ G_{\text{fail}} \]

\[ F_{\text{max}} \]

\[ F_{\text{min}} \]

\[ \sigma_{\text{max}} \]

\[ \sigma_{\text{max}} \]

\[ \delta_f \]

\[ \delta_f \]

\[ \Delta \delta \]

\[ \Delta \delta \]

\[ \sigma_{\text{max}} \]

\[ \sigma_{\text{max}} \]

\[ \sigma_{\text{0}} \]

\[ \sigma_{\text{0}} \]

\[ \delta_{\text{fail}} \]

\[ \delta_{\text{fail}} \]

\[ \Delta F \]

\[ \text{initialisation} \]

\[ \text{fatigue degradation} \]

\[ \text{pseudo-time} \]

\[ \text{elastic} \]

\[ \text{damaged} \]

\[ \text{fatigue} \]

\[ \text{failed} \]
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Additive-Layer Manufac’d Hybrid Joints

- Current metal-composite structures require secondary adhesive bonding:
- Hybrid joints combine adhesion and mechanical interlocking
- Additive Layer Manufacturing will enable new design concepts for hybrid joints

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ALM’d Hybrid Joints

- EPSRC First Grant project starting in January 2016:
  - Virtual Testing of Additively-Manufactured Hybrid Metal-Composite Structures (EP/M021963/1)

- Objectives:
  - Build the numerical framework required for the optimisation of future ALM’d hybrid joints
  - Consider complex cases without periodicity or representative volumes
  - Validate models using braided and woven fibre architectures
Summary

- Virtual testing can enable more efficient test pyramids
- ACCIS has developed and validated novel tools for virtual testing at intermediate levels of complexity in the test pyramid
- These tools have been used successfully by industrial partners (mostly in aerospace)
- Potential for further / new collaborations in:
  - Validation at higher levels in the pyramid
  - Virtual testing for probabilistic / machine learning approaches
  - ALM of metals (titanium, steel, aluminium) and hybrid joining

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