ESI VPS based multiscale modelling of the performance of laser structured composite-metal interfaces

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Introduction

• **COMMUNION** European Research Project
  ‣ Development of productive and cost effective manufacturing of 3D metal/CFRTs multi-material components
    • Automatic tape placement of CFRTs with controlled laser-assisted heating
    • High-speed laser texturing and cleaning
    • On-line monitoring and inspection
    • Multi-stage robot solution for joining
    • Quality diagnosis and decision support
  • Computational multi-scale modelling

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Motivation

“The right material at the right place.”

• Why composite materials?
  ‣ High stiffness, strength and durability
  ‣ High specific energy absorption

• Why metals?
  ‣ Great experience on design and manufacturing
  ‣ Good joinability and load introduction

Efficient lightweight design requires the combination of multiple materials
But how to join them?
Motivation

• Automated Tape Placement (ATP)
  ‣ Systematic local reinforcement with composite tapes
  ‣ Automated process

• Laser Texturing and Cleaning of Surfaces
  ‣ Elimination of undesired substances
  ‣ Creation of controlled structures on the metal surface for the anchorage of the TPCs
  ‣ Improved wettability and mechanical interaction

Laser assisted joining can help to secure the required performance of a hybrid joint

*But how to design the process?*
Outline

1. Introduction and Motivation
2. Multiscale analysis of metal / composite interfaces
   1. Scale bridging
   2. Model generation
3. Material modelling
   1. Progressive interface damage
   2. Polymeric matrix failure
4. Demonstration
5. Conclusion
Multiscale analysis of metal / composite interfaces

- How to predict the adhesive performance of laser structured metal / composite interfaces numerically?
  - Interface consists of a periodic repetition of unique geometric features
  - Periodicity allows for the extraction of representative parts of the interface
  - High contrast of length scale between the microscopic geometrical interface features and the macroscopic dimension of the hybrid structure
  - Scale bridging based on the HILL averaging principle
    - The macroscopic virtual work density equals the volume average of the total virtual work on the microscale
Multiscale analysis of metal / composite interfaces

- **Model generation**
  - Cumbersome generation of a numerical FE model of the microscopic interface structure
  - Automated model generation process
    1. Idealized CAD models of the local interface structure
    2. Mapping of the geometry on a homogeneous voxel mesh
    3. Extraction of the local material coordinate system
    4. ESI VPS model preparation
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Material modelling

- **Progressive interface damage**
  - 3D cohesive damage approach
    - Linear degradation of the interface traction
      \[
      \sigma_{nn} = (1 - D^{CZ}) K_{nn} \delta_{nn} \\
      \sigma_{ns} = (1 - D^{CZ}) K_{ns} \delta_{ns} \\
      \sigma_{nt} = (1 - D^{CZ}) K_{nt} \delta_{nt}
      \]
  - Damage initiation based on quadratic failure criteria
    \[
    \left( \frac{\sigma_{nn}}{X_n} \right)^2 + \left( \frac{\sigma_{ns}}{Y_s} \right)^2 + \left( \frac{\sigma_{nt}}{Y_t} \right)^2 = 1
    \]
  - Damage evolution controlled by effective mixed-mode separation and fracture criterion
    \[
    \delta_m = \sqrt{\langle \delta_{nn} \rangle^2 + \delta^2_{ns} + \delta^2_{nt}} = \sqrt{\langle \delta_{nn} \rangle^2 + \delta^2_{shear}}
    \]
    \[
    \left( \frac{G_I}{G_{IC}} \right) + \left( \frac{G_{II}}{G_{IIC}} \right) + \left( \frac{G_{III}}{G_{IIIC}} \right) = 1
    \]
Material modelling

• Continuum damage model for the polymeric matrix
  ‣ Nonlinear elastic material behavior with isotropic damage
    \[ \sigma_{ij} = (1 - D^{CDM}) \hat{\sigma}_{ij} \]
    \[ \hat{\sigma}_{ij} = \frac{2G}{1 + \alpha_G \| e_{kl} \|} e_{ij} + \frac{2K}{1 + \alpha_K \| \varepsilon_{mm} \|} \varepsilon_{mm} \delta_{ij} \]
  ‣ Damage initiation defined by Christensen failure criterion
    \[ \left( \frac{1}{T} - \frac{1}{C} \right) (\sigma_{11} + \sigma_{22} + \sigma_{33}) + \]
    \[ \frac{1}{2TC} \left[ (\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 \right] \leq 1 \]
  ‣ Scalar damage driven by equivalent displacement
    \[ D^{CDM} = \frac{\delta_v^f (\delta_v^{max} - \delta_v^0)}{\delta_v^{max} (\delta_v^f - \delta_v^0)} \]
    \[ \delta_v = I^{elem} \left( k_1 l_1 + \sqrt{(k_1 l_1)^2 + k_2 l_2} \right) \]
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Demonstration

- Analysis of idealized interface structures
- Each structure corresponds to a specific laser structuring process setup
- Automated generation of the VPS models for the virtual characterization
Demonstration

- Empirical set of material parameters

- Analysis of different loading conditions
  1. $\alpha = 90^\circ$ Mode I loading
  2. $\alpha = 0^\circ$ Mode II loading
  3. $\alpha = 45^\circ$ Mixed Mode loading

- Extraction of effective Force-Separation curves and local damage patterns

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<th>Material</th>
<th>Parameter</th>
<th>Value</th>
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| Polymer - PA66 | $E$      | 1.7  |
|                | $\nu$    | 0.3  |
|                | $X_a$    | 0.01 |
|                | $Y_a$    | 0.01 |
|                | $Y_c$    | 0.01 |
|                | $G_{IC}$ | 9e-5 |
|                | $G_{IC}$ | 2e-4 |

| Interface | $G_{IC}$ | 9e-5 |
|           | $G_{IC}$ | 2e-4 |
Demonstration

- Local damage distribution under different loading conditions

Mode I
- Pure adhesive failure

Mixed Mode
- Combined adhesive and cohesive failure

Mode II
Demonstration

- Local damage distribution under different loading conditions

Pure adhesive failure

Combined adhesive and cohesive failure
Demonstration

- Local damage distribution under different loading conditions

Mechanical interlock  Combined adhesive and cohesive failure
Demonstration

- Effective Stress-Separation curves

**Type 3**
Increased stress level due to mechanical interlock

Adhesive failure followed by cohesive failure

**Type 2 & 3**
Increased shear strength
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Conclusion

• Modern lightweight design requires the combination of multiple materials
• Laser structuring of metal / composite interfaces can enhance the mechanical performance of local ATP based reinforcement
• Multiscale modelling can be applied to analyze microscopic material interface geometries
• Efficient simulation based on automated model generation
• Characteristic damage phenomena need to be modeled properly
• Simulation can help to analyze the mechanical performance effects of different laser structuring process parameters