Efficient simulation of multiple impacts on double-curved composite structures

presented by
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Composite aircraft structures are vulnerable to impacts by foreign objects, e.g.

- in-flight & ground hail
- ice-shedding
- tool-drop (production & maintenance)

... leading to barely visible impact damage (BVID), potentially

- remaining undetected in the structure
- accumulating up to the next maintenance date

adapted from [1]
**Project objectives**

- Assessment of multiple impact damage in composite aircraft components
- Simulation methodology to evaluate the impact response and the residual properties of the structure
Low-fidelity simulation methodology...

Structural modeling
- Contact modeling by using contact laws
- Discretization with a single layer of shell elements

Material modeling
- Three-dimensional stress state recovery
- Use of modern three-dimensional failure criteria (Puck, Cuntze, LaRC04)
- Material degradation with a lookup table

... in a nutshell

Experimental vs. virtual testing

Application in a multiple impact simulation
II. Eye candy

- Application in a multiple impact simulation

**Example:**
- 5 unique impactors with isotropic material behavior (stainless steel & aluminium alloy)
- Kinetic energies 25 J – 60 J
I. Introduction
    The Big Picture
    Project objectives
    Low-fidelity simulation methodology in a nutshell

II. Eye candy

III. Numerical experiments
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    Verification by means of literature results
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    Verification of the extended 2D method
III. Numerical experiments

- **Modeling strategy**

  **Three-dimensional stress state recovery:**
  - Transverse shear stresses
  - Transverse normal stress \( \rightarrow \) Rolfes & Rohwer [4]

  **Damage initiation:**
  - Fiber breakage = Maximum Stress criterion
  - Matrix cracking = Cuntze [5]
  - Delamination = Choi & Chang [6]

  **Damage evolution:**

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<th>Elastic constants in Pa</th>
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III. Numerical experiments

- **Modeling strategy**

  **Contact modeling:**
  - Loading phase = Hertz
  - Unloading phase = Crook
  - Reloading phase = Tan & Sun [7]

  **Element type:**
  - S8R (quadrilateral shell with eight nodes)

  **Boundary conditions \((u_i, v_i = 0)\):**
  - \(u_x, u_y, u_z, v_x, v_y, v_z\) at edges T & R (*clamped*) or
  - \(u_x, u_y, u_z\) at edges T & R (*simple supported*)
  - \(u_x, v_y, v_z\) at edge L (*symmetry in x-direction*)
  - \(u_y, v_x, v_z\) at edge B (*symmetry in y-direction*)
III. Numerical experiments

- **Modeling strategy**

  **Contact modeling:**
  - Loading phase = Hertz
  - Unloading phase = Crook
  - Reloading phase = Tan & Sun [7]

  **Element type:**
  - S8R (quadrilateral shell with eight nodes)

  **Boundary conditions** \( u_i, v_i = 0 \):
  - \( u_x, u_y, u_z, v_x, v_y, v_z \) at edges T & B (clamped)
  - \( u_x, u_y, u_z \) at edges L & R (simple supported)
  - \( u_y \) in the red-shaded area
III. Numerical experiments

- Verification by means of literature values

**Impactor:**
- stainless steel
- 32.67 g
- \( v = 1 \, \text{m/s} \)
- \( \phi 20 \, \text{mm} \)

**Target:**
- 8 mm thickness
- stainless steel
- clamped
III. Numerical experiments

- Verification by means of literature values

Impactor:
- stainless steel
- $8.84\, g$
- $v = 3\, m/s$
- $\phi 12.7\, mm$

Target:
- $2.69\, mm$ thickness
- $[(0,90)_{2}, 0]_{s}$
- simple supported
III. Numerical experiments

- Validation by means of single-drop tests

**Impactor:**
- stainless steel
- 3.95 kg
- Ø 16 mm

**Target:**
- 4 mm thickness
- [(±45)_5, 45]_s

[Graphs showing contact force over time for different energies (10 J, 15 J, 25 J, 35 J)]
III. Numerical experiments

- Validation by means of single-drop tests

- Projected delamination areas:
  - LHS → C-scan result
  - RHS → Simulation
III. Numerical experiments

- Validation by means of single-drop tests

**Impactor:**
- stainless steel
- 3.95 kg
- ø 16 mm

**Target:**
- 4 mm thickness
- [(±45, 0,90)₂, ±45,0]ₜ
III. Numerical experiments

- Validation by means of single-drop tests

Projected delamination areas:
- LHS → C-scan result
- RHS → Simulation

10 J

15 J

25 J

30 J
IV. Conclusion

**Verification by means of literature results:**
- All results are in line with literature results

**Validation by means of single-drop tests:**
- Very satisfying results w.r.t. the projected delamination areas
- Good agreement between the measured & simulated contact force history

**Points to optimize:**
- Simulated contact stiffness is slightly too soft in all cases → explains the right-shift
- The effect of material degradation on the contact force history is slightly too small → results in overestimated contact force maxima

**Next challenges:**
- Validation of simulation methodology for multiple impact problems
- Implementation of an expression for brittle impact behavior (hail, ice-shedding)
- Implementation of subsequent analysis steps to assess the residual strength or fatigue behavior of the damaged structure
V. Acknowledgements

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Thank you for your attention!

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VII. References

VIII. Appendix

- Verification of the material degradation lookup table

Damage evolution:
- Degradation model causes stress redistribution in cases of damage
VIII. Appendix

- Verification of the extended 2D method

**Double-cosine load:**
- Amplitude of +1

**Rectangular plate:**
- 1 mm thickness
- 0.128 mm layer thickness
- $[(0,90)_2]_s$