Efficient Postbuckling Progressive Failure Analysis of Stiffened Composite Panels Using a Two-Way Loose Coupling Approach

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Outline

1. Motivation
   - How can the structural failure loads and total behavior be evaluated with reasonable economical costs?

2. Two-way loose coupling approach
   - How can an efficient approach for structural failure analysis be realized?

3. Application and verification
   - How can the procedure be applied to a concrete example - progressive damage analysis for a 1-Stringer and Two-Stringer stiffened composite panel?

4. Enhancements to the method
   - How can the method be improved in terms of computational time and reliability?

5. Conclusions and Outlook
   - What is the status and what are the next steps?
Motivation

Coarse whole model = global model
- fast computation
- buckling and post buckling behavior (global effect)

Investigation of interaction between global and local effects

detailed fine model = local model
- accurate computation
- damage progression
- fast computation (local effect)

coupling
Overview of the procedure

1. Global analysis
   Material properties from local part tests for damaged global elements
   Local part = 1 global element = 1 laminate layer

2. Local analysis
   Local model = critical global area
   Material properties from local analysis for local part

3. Local part tests for determination of global material properties for each damaged global element

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Reduced material properties from the local part tests do not correspond to the initial displacements of the global model:

- Update of global displacements required
- Updated properties at global level applied by steps
Coupling models

Model description

- Flat stiffened panel with one T-stringer
- Layup with 4 composite layers: \([0^\circ, 90^\circ]_s\)
- Compression in axial direction
Reference models

Reference model
Solid elements (C3D8)

Reference model
Shell elements (S4R)

<table>
<thead>
<tr>
<th></th>
<th>Reference Solid</th>
<th>Reference Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix failure, mm</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>Fiber failure, mm</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>Total failure, mm</td>
<td>0.63</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Performance of four coupling loops with progressing damage

<table>
<thead>
<tr>
<th>Loop 1 (u = 0.56 mm)</th>
<th>Loop 2 (u = 0.60 mm)</th>
<th>Loop 3 (u = 0.63 mm)</th>
<th>Loop 4 (u = 0.67 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix damage initiation</td>
<td>Damage</td>
<td>Damage progression</td>
<td>Fiber damage initiation</td>
</tr>
</tbody>
</table>

Global model with critical areas

Plot overlay of separated models
Loop 4 \( (u = 0.670 \text{ mm}) \)
Fiber damage initiation

<table>
<thead>
<tr>
<th>Iteration 1</th>
<th>Iteration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global model</strong></td>
<td><strong>Global model</strong></td>
</tr>
<tr>
<td>Local model</td>
<td></td>
</tr>
<tr>
<td>Engineering constants</td>
<td></td>
</tr>
<tr>
<td>Homogenized properties</td>
<td></td>
</tr>
<tr>
<td>Loop 4 ( (u = 0.616 \text{ mm}) )</td>
<td></td>
</tr>
<tr>
<td>Fiber damage initiation</td>
<td></td>
</tr>
</tbody>
</table>

- New displacements at local model’s boundaries
- Check if there are no additional damaged areas

Total failure
\( u = 0.630 \text{ mm} \)
Reaction force - displacement curve

- Reference Volume
- Coupling. Loop 1
- Coupling. Loop 2
- Coupling. Loop 3
- Coupling. Loop 4
- Buckling
- Matrix damage initiation
- Fiber damage initiation

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Local models

New rule for local models:

- Elements adjacent to damaged element included
- If blade is not damaged – not examined

Advantages

1. Damage pattern is similar to reference solid model
2. Stress concentrations on edges are not considered
3. No risk of missing damage propagation

Disadvantages

1. Stress and displacement fields in current local models are more realistic

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Modifications and verification

Global model

- Shell elements
- Linear elastic material
- Damage initiation criterion determines critical areas

Critical area

Local models

- Previous approach
- New rules to define local model
- Verify mesh dependency, linear factor 2

Plot overlay

- Volume elements
- Degradation model by Linde
- Represents critical global area

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Coupling models

Mesh dependency
- 4 times more elements in local models
- Significant increase of computational time
- Relatively small increase in accuracy

New local models
- Only damaged elements and neighboring in-plane elements
- Significant decrease of computational time
- Relatively small decrease in accuracy
Coupling method applied to Academic Stiffened Panel:

- Local damage initiation => NO need to take all model into account => advantage of the Coupling method
- For 1-Stringer stiffened panel failure areas predicted by Linde criteria are similar for Reference Shell and Solid models => we can rely on shell model for the coarse analysis
- Total failure predicted by coarse Shell Reference Model with 13.72% accuracy (compared with Reference Solid Model)
- Total failure detected with Coupling Method with 0.53% accuracy (compared with Reference Solid Model), with 0.65% for new local models and with 0.19% for 4 times finer mesh applied to local models
Two-Stringer Stiffened Panel

Reference models

Reference model
Solid elements (C3D8)

Reference model 1, NE size=5
Shell elements (S4R)

Reference model 2, NE size=2.5
Shell elements (S4R)

Reaction force - displacement curve

<table>
<thead>
<tr>
<th></th>
<th>Reference Solid, NE=101600</th>
<th>Reference Shell, NE=560</th>
<th>Reference Shell, NE=21600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix failure, mm</td>
<td>0.434</td>
<td>0.413</td>
<td>0.392</td>
</tr>
<tr>
<td>Fiber failure, mm</td>
<td>0.532</td>
<td>0.525</td>
<td>0.511</td>
</tr>
<tr>
<td>Total failure, mm</td>
<td>0.559</td>
<td>0.579</td>
<td>0.568</td>
</tr>
</tbody>
</table>

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Performance of four coupling loops with progressing damage

Loop 1 (u = 0.42 mm)
Matrix skin damage initiation

Loop 2 (u = 0.45 mm)
Matrix foot damage initiation

Loop 3 (u = 0.48 mm)
Damage progression in foot area

Loop 4 (u = 0.54 mm)
Fiber skin damage initiation
Two-Stringer Stiffened Panel

Reaction force - displacement curve

- Reference Volume
- Coupling. Loop 1
- Coupling. Loop 2
- Coupling. Loop 3
- Coupling. Loop 4
- Buckling
- Matrix damage initiation
- Fiber damage initiation

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Two-Stringer Stiffened Panel

Model with local defect

- Local defect: between skin and foot (L=25 mm)
- New local model technique

![Reaction force - Displacement curve](image)

- Reference Solid
- Coupling 1
- Coupling 2
- Coupling 3
- Coupling 4
- Buckling Solid Model
- Matrix Damage Initiation Solid Model
- Fiber Damage Initiation Solid Model
- Matrix Damage Initiation Coupling
- Fiber Damage Initiation Coupling

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Coupling method applied to Two-Stringer Stiffened Panel:

Without defect

- Models with coarse mesh show no significant overestimation of load capacity:
  - 3.66% for Shell Model, NE=560
  - 1.10% for Shell Model, NE=2160

- Damaged areas are quite big => no advantages in computational time using Coupling method

Local defect

- Model with local defect demonstrated the advantages of the method during progressive damage analysis as total failure happened before local models started to be too large (compared with the size of the whole model)
Next steps

Global-local step

To be investigated

• Displacements difference on the driven nodes within 1 coupling loop

\[ \|u_k^{step \, i+1} - u_k^{step \, i}\| \leq \varepsilon, k = 1, NN \]

NN – number of driven nodes

step i – iteration step

Global coupling step
Next steps

Application to realistic and larger structures, including structures with local defects

• Advantages of the global-local approach to be assessed
• Available experimental results
• Realistic imperfections

Delamination

• Delamination between skin and foot
• Free edge effects
Conclusions

- A two-way loose coupling approach for investigation of local material damage in composite structures has been further verified and the efficiency has been improved for specific test cases.

- Larger structures have been examined (two-stringer panel).

- Application of the coupling procedure to a stiffened panel with local defect demonstrates the potential of the method.
Thank you for your attention!

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