Extended Finite Element Method for Damage Modelling of Composite

Presented by Dr. Peter Linde, Airbus

Herausforderungen und Methoden bei der Simulation von Faserverbund-Werkstoffen

3. Fachkongress Composite Simulation
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20. März 2014, Schwabenlandhalle, Fellbach

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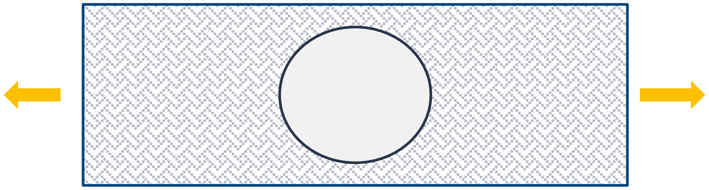
Motivation

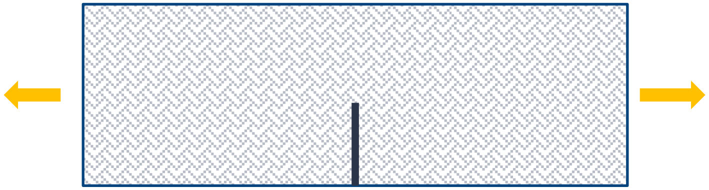
Sizing flight structures

-Damage cases:

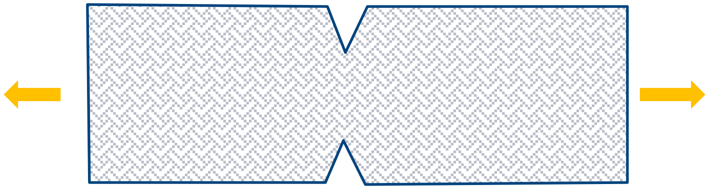
a) Net section by OHT (open hole tension)



b) Sharp cut, e.g. Discrete Source Damage



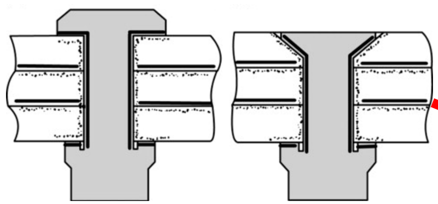
c) Notched cut



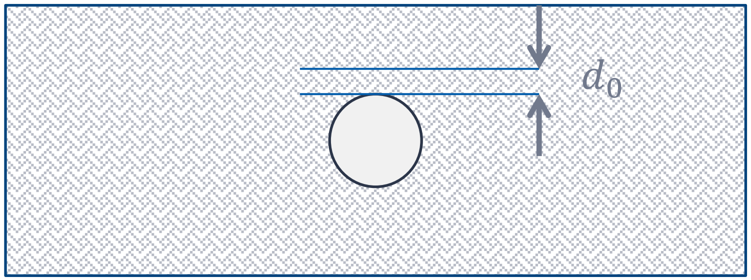
All 3 cases are high stress concentrators.

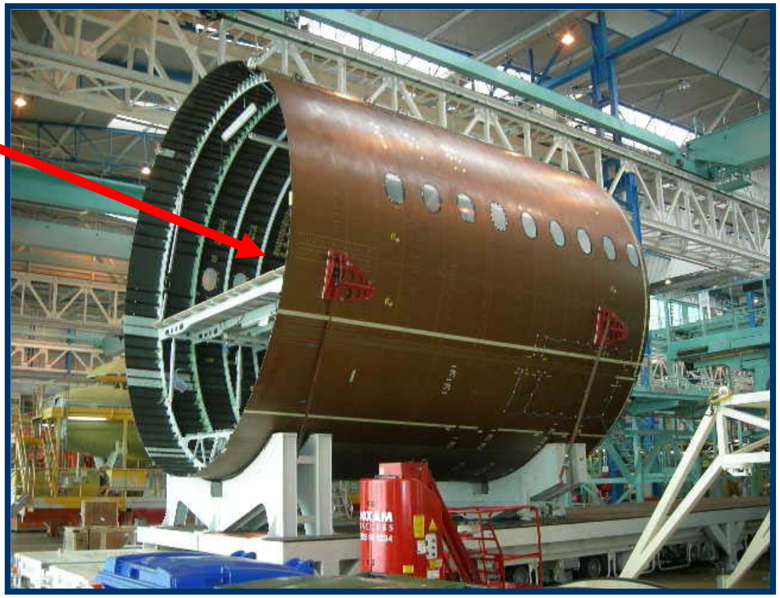
Motivation

Sizing ↔ Strength Analysis ↔ Degradation



Bolted Joints are high stress regions in composite materials

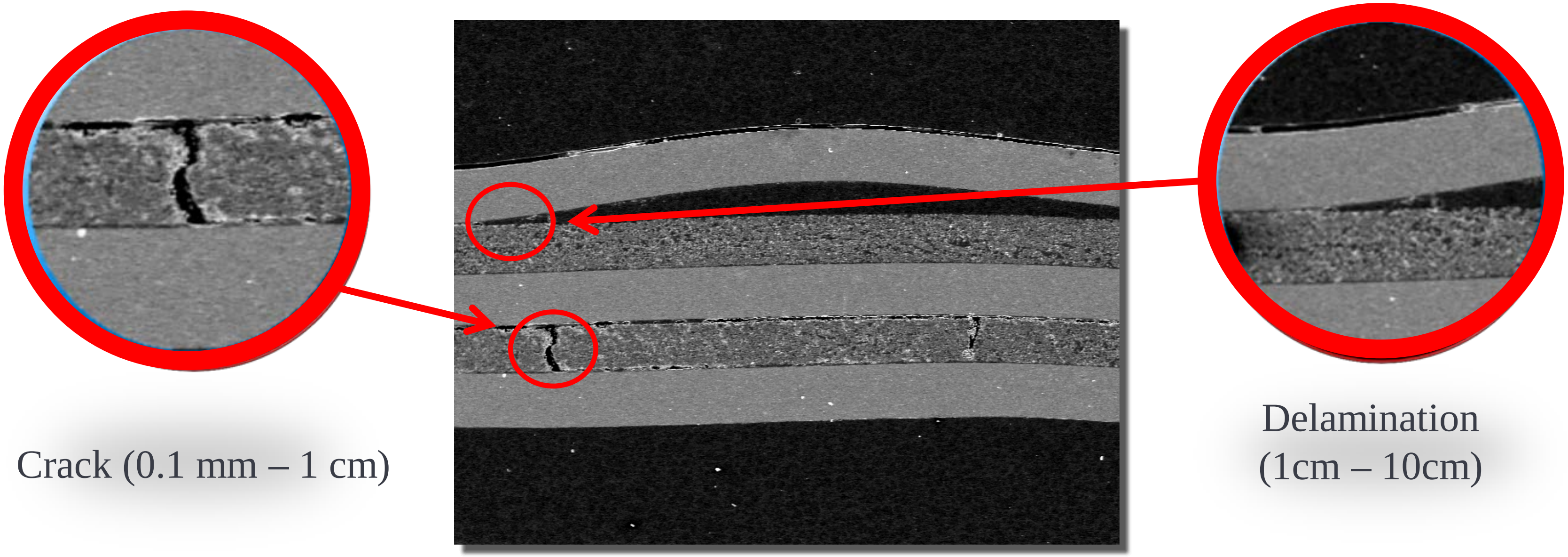




- Degradation may take place over a distance d_0
- Need of a better understanding of the process causing the degradation
- Predicting d_0 and realistic damage

Intro to damage modeling of CFRP

Physical damage types:



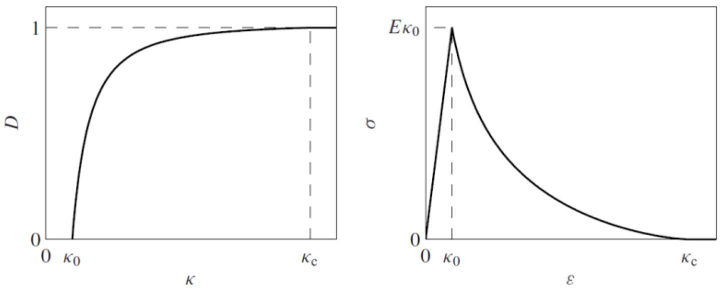
- Intra-ply damages, e.g. matrix cracking, transverse cracks
- Inter-ply damages, e.g. delamination

Numerical damage models

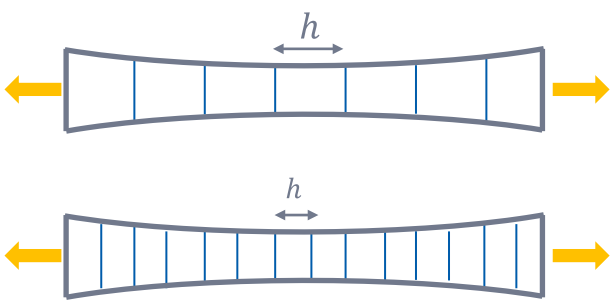
Continuous element approach:

1. Intra-ply
   - Matrix cracking by ‘classical’ damage model:

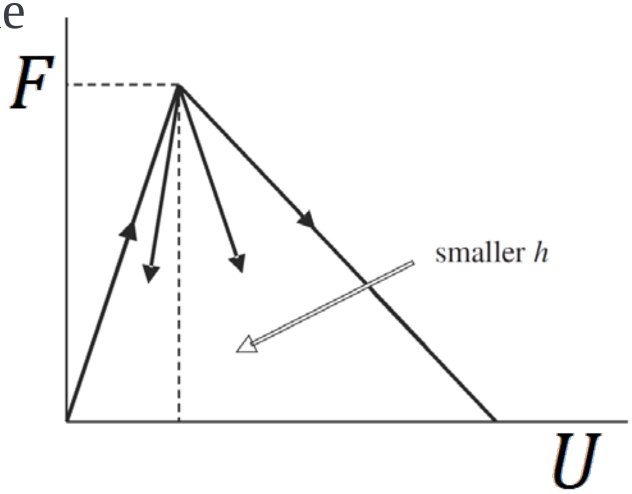
     i.e. κ is stored in the Gauss points of the elements, at κ_o damage is initiated. Complete fracture (D=1) at κ_c



   - Mesh sensitivity plays an important role

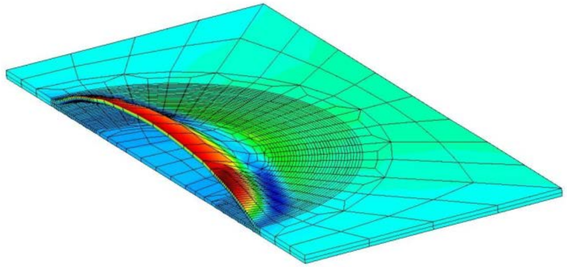


h = Finite element size

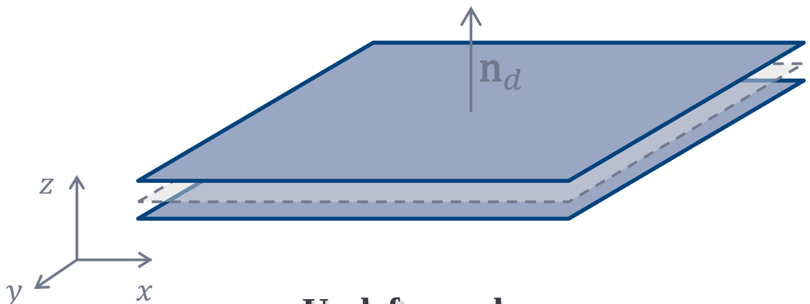


Numerical damage models

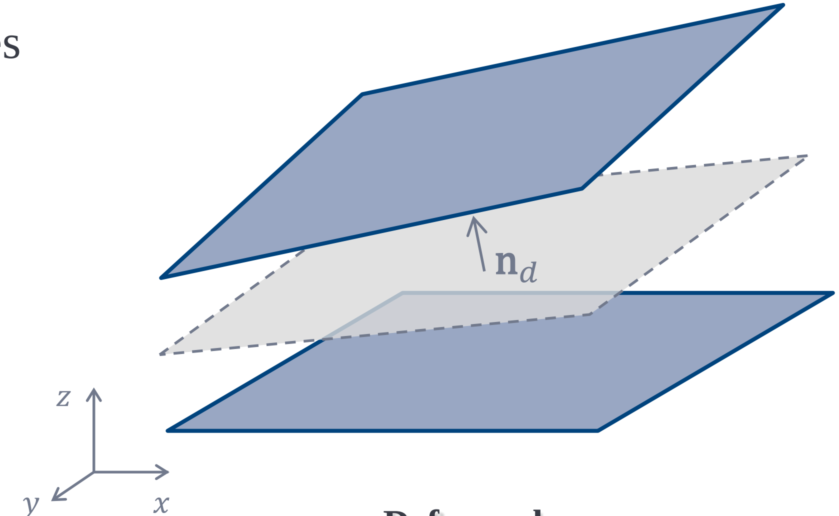
Continuous element approach:



2. Inter-ply
   a) Interface element (Hashagen)
      - Implemented as UEL in Abaqus
      - Is often used in delamination studies in FML/CFRP



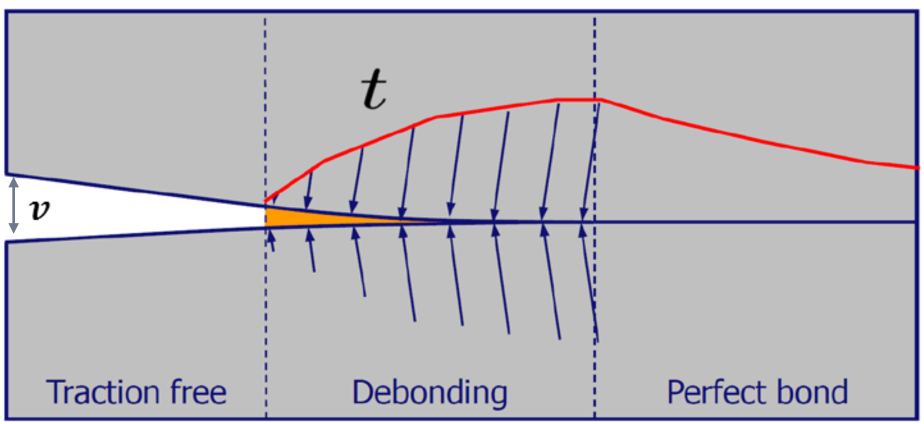
Undeformed

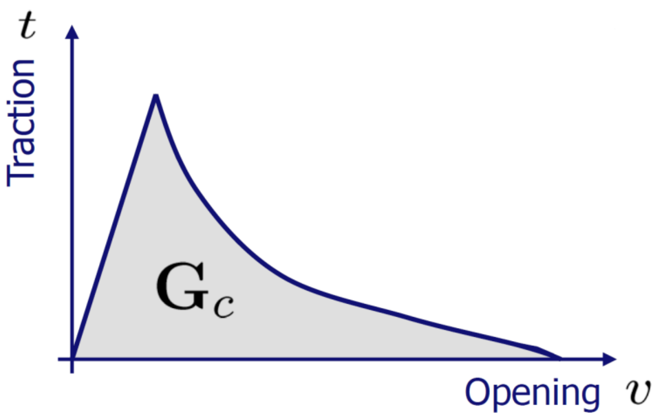


Deformed

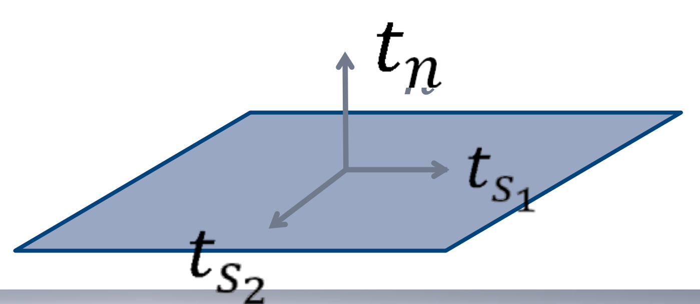
Numerical damage models

In later version implemented as “cohesive zone” elements: an interface element with a cohesive relationship.





Cohesive constitutive relation

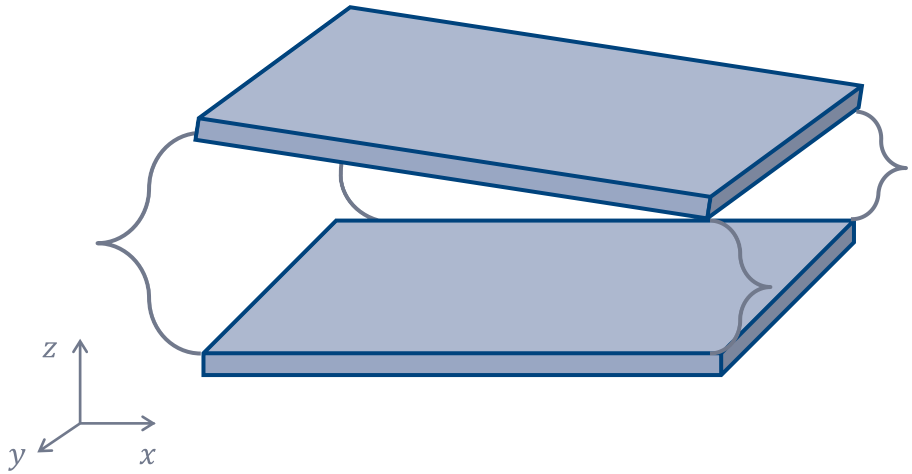


Numerical damage models

b) Nonlinear inter-element-relation

User subroutine to define surface interaction behavior for contact surfaces implemented; delamination is implemented as user defined contact law.

Considerable benefit is the improved convergence obtained by the implementation of fully consistent tangent operators. Numerical efficiency as well very competitive.

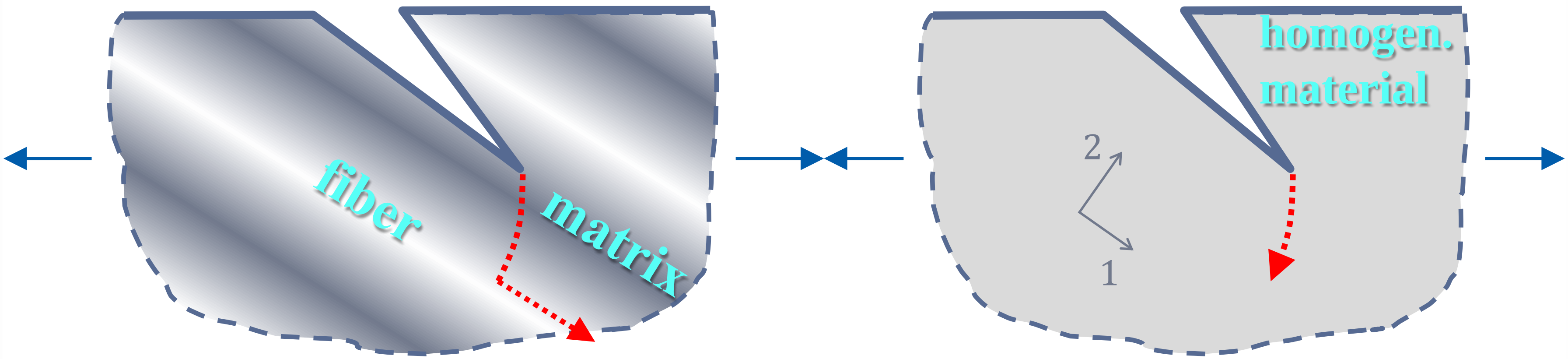


‘ } ’ = represents user subroutine UINTER (ABAQUS) defining the nonlinear interaction relation between the surfaces

Numerical damage models

Continuous element approach; discussion:

- Several (continuous) methods available for crack propagation and failure inside the ply, most suffer from mesh related problems. Also it is doubted whether these methods are suitable to capture these phenomena correctly.



- Reason: In CFRP failure will occur in weaker matrix domain, while homogenized continuum material models do not offer domain separation
- Proposed solution: Use discontinuous approach to model failure.

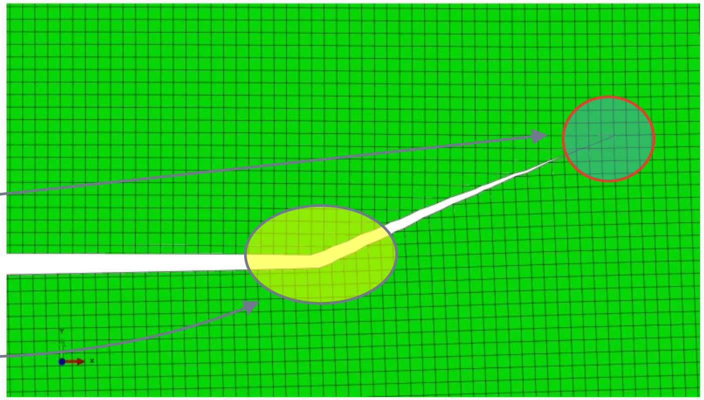
: represents crack propagation. For fiber-matrix material, the crack will align with the fiber direction

Numerical damage models

Discontinuous element approach:

- XFEM (extended finite element method) is able to model discontinuities at an arbitrary location in the mesh, independent of the mesh size.
- Original XFEM is based on the partition of unity approach
- A discontinuity is introduced by an enrichment of the shape functions with the Heaviside step function *H(x)*.
- XFEM is also suitable for additional enrichment of the displacement field around the crack tip to capture the singular field, $\sum_{\alpha=1}^{4} F_\alpha(x)\boldsymbol{b}_I^\alpha$

$$\boldsymbol{u} = \sum_{I=1}^{N} N_I(x)[\boldsymbol{u}_I + H(x)\boldsymbol{a}_I + \sum_{\alpha=1}^{4} F_\alpha(x)\boldsymbol{b}_I^\alpha]$$

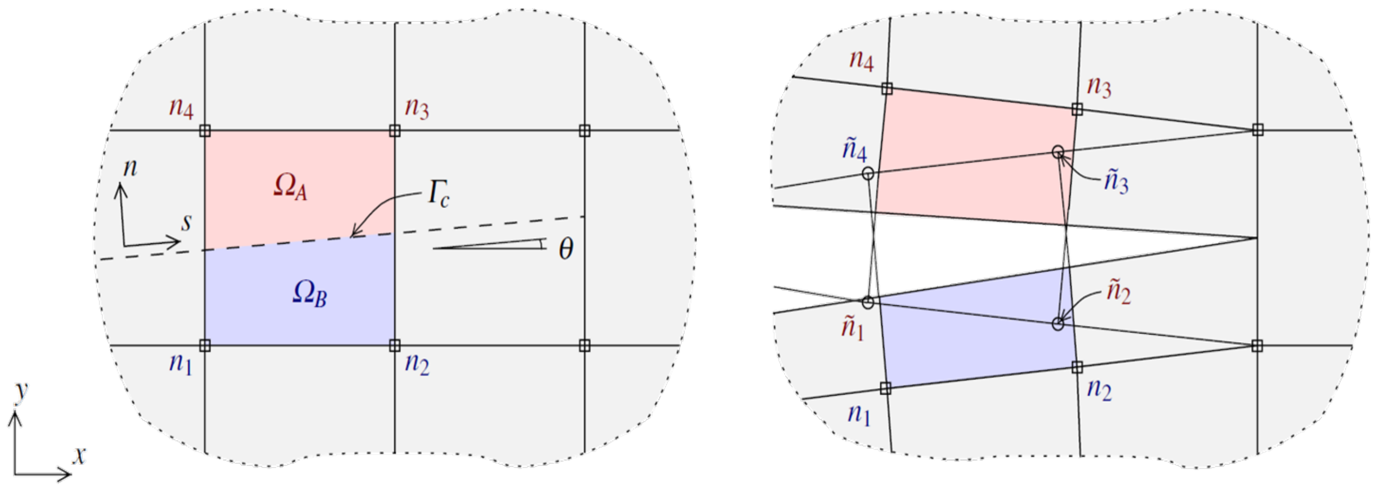


Applies to all nodes in the model

Numerical damage models

Discontinuous element approach:

- A simplified XFEM-method was first introduced by Hansbo & Hansbo (2004) based on the phantom node method:



- The displacement jump over the discontinuity is defined as the difference between the displacement fields of element A and B: $u(x) = N(x)(u_A - u_B)$
- Crack modeling in the phantom node method is only element wise and the tip is always located at an element boundary.

Approach in past studies

Several combinations considered:

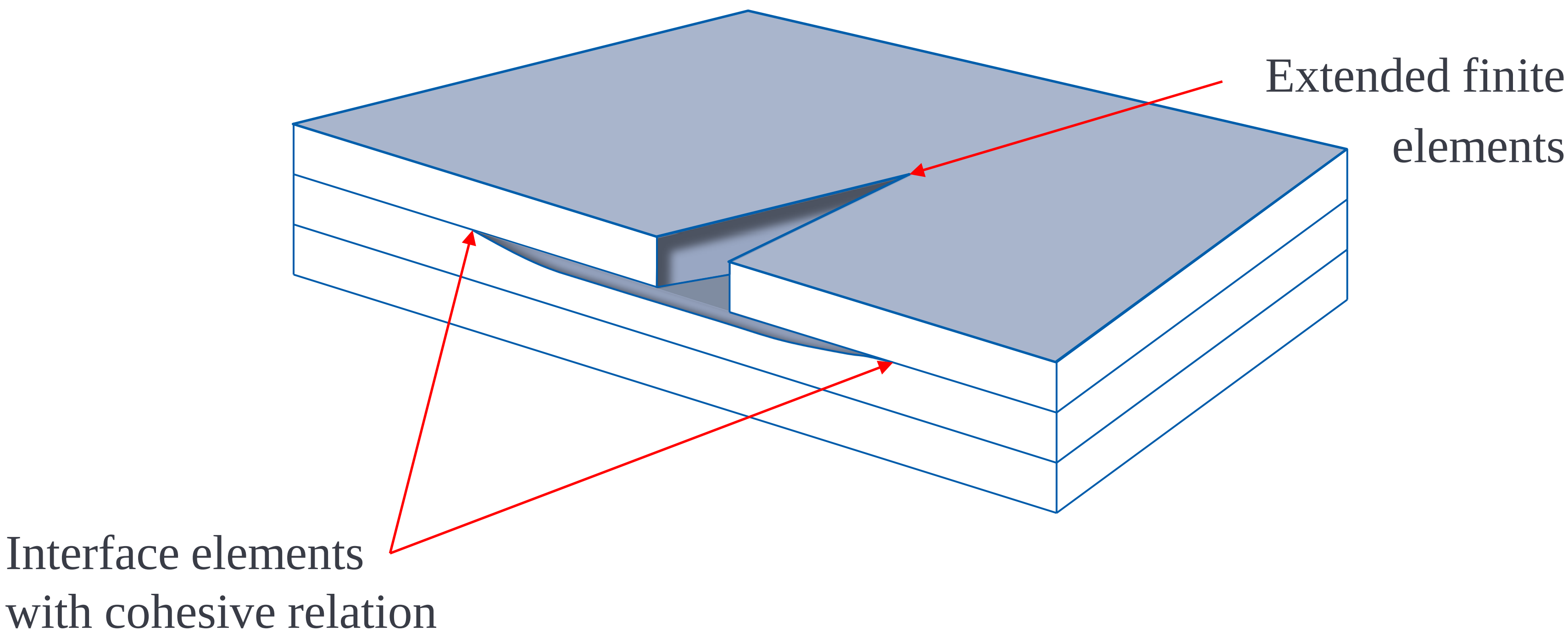
a) For Intra-ply: Classical damage modeling (continuum damage model) + For Inter-ply: interface elements with cohesive relation or contact/interface material law. The combination of these two classical models is from the onset of damage propagation numerically very challenging

b) For Intra-ply: Classical damage modeling (continuum damage model) + For Inter-ply: extended finite elements. This is what often is considered, but it offers no essential benefit vs. a) since direction if inter-ply damage already given by the interface (its extension only, can be increased)

Continued:

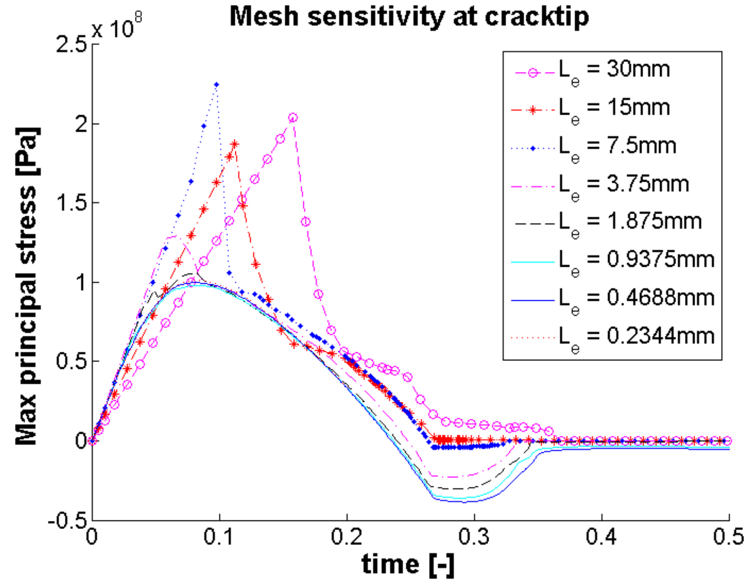
Approach in present study

c) Combination: For intra-ply damage extended finite elements are used, for inter-ply damage, interface elements with a cohesive relationship (a classical damage model) :

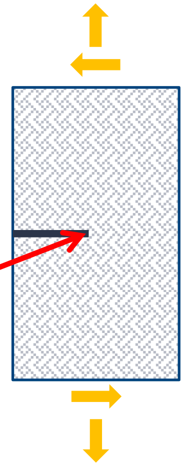


Application

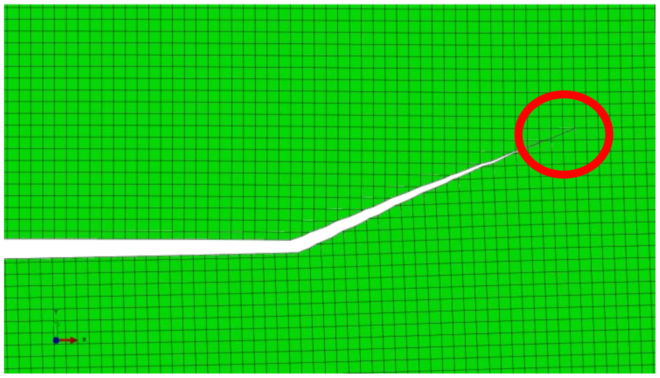
- NL FEA program ABAQUS V. 6.12 is used to study XFEM in simulation of CFRP failure
- In ABAQUS for XFEM, two types of cracks can be identified:
  a) Stationary; uses partition of unity approach with full enrichment function
  b) Propagating; uses phantom node method



Using the phantom node method may lead to mesh dependent results. Convergence was however achieved well.

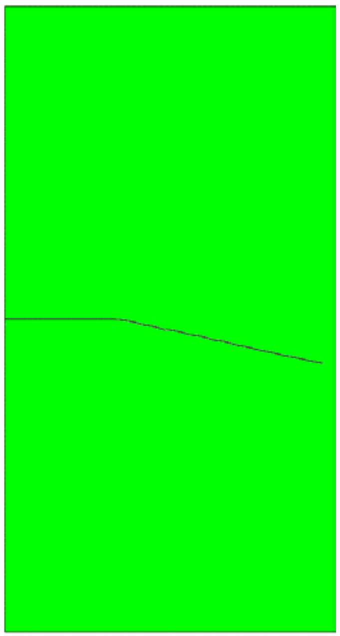


Location of original crack tip

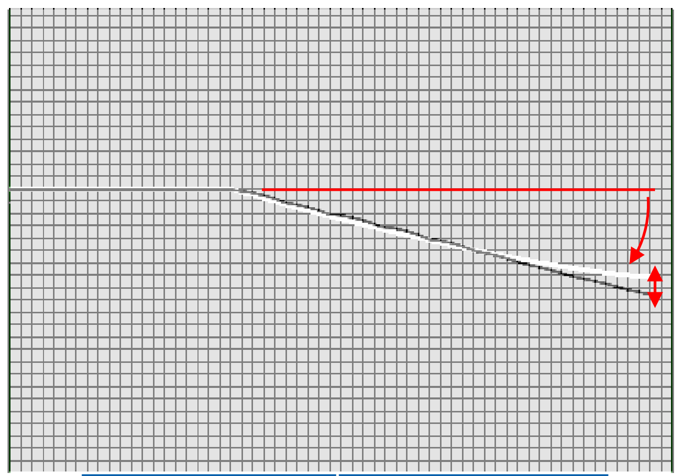


Application at Airbus

- Crack propagation was compared for partition of unity and phantom node method
- Convergence was obtained for both methods
- Overall crack propagation paths are in agreement

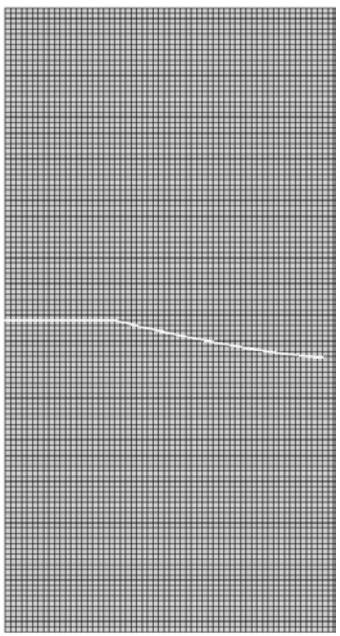


Phantom node method



	Angle (deg)
Black line	12.6
White line	11.2

	Angle difference (deg)	Height difference at end position (mm)
Value	1.4	7e-2



Partition of unity method

Conclusions

1. The original approach for the extended finite element method was introduced: partition of unity approach, as well as the industry-approach: the ‘phantom node method’. ABAQUS uses a combination of both methods

2. The combination chosen here; intra-ply damage with extended finite elements and inter-ply damage with interface elements with a cohesive relationship (a classical damage model) was introduced.

3. The chosen combination appears to mirror the physical reality by providing a similar magnitude of difference in crack width as exists between real intra-ply and inter-ply damage.

4. In an example problem: a notched plate, both approaches were employed and full convergence was obtained.

5. There is a certain mesh-dependency for the phantom node approach. Well converged solutions could however be obtained.

6. There were fine differences between the approaches: they may be attributed to the fact that the phantom node approach cuts a whole element in a single increment.

Acknowledgement

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Thank you for your attention

Questions?