University of Stuttgart
Institute for Structural Mechanics

A comparative analysis of the improved stress prediction with higher-order 3D-shell finite elements for laminated structures

Ansys Innovation Conference & 17th LS-DYNA Forum

October 16th, 2024
in Leinfelden, Germany

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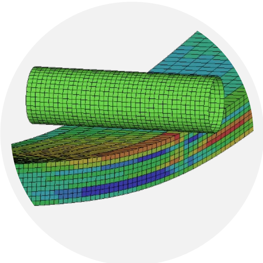
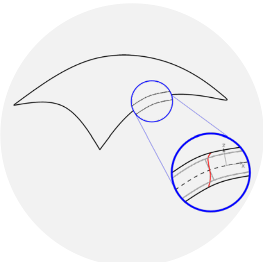
DigiTain

Baustatik und Baudynamik

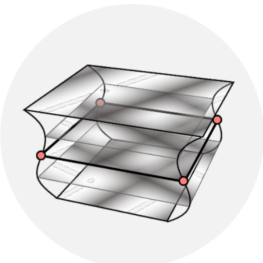
Outline



Simulation of laminated structures



Shell theories



Improved stress prediction with higher-order 3D-shell finite elements

Conclusion and outlook

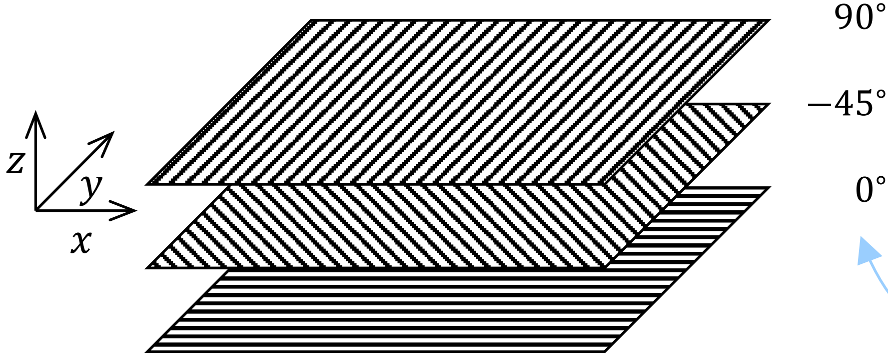
1

Simulation of laminated structures

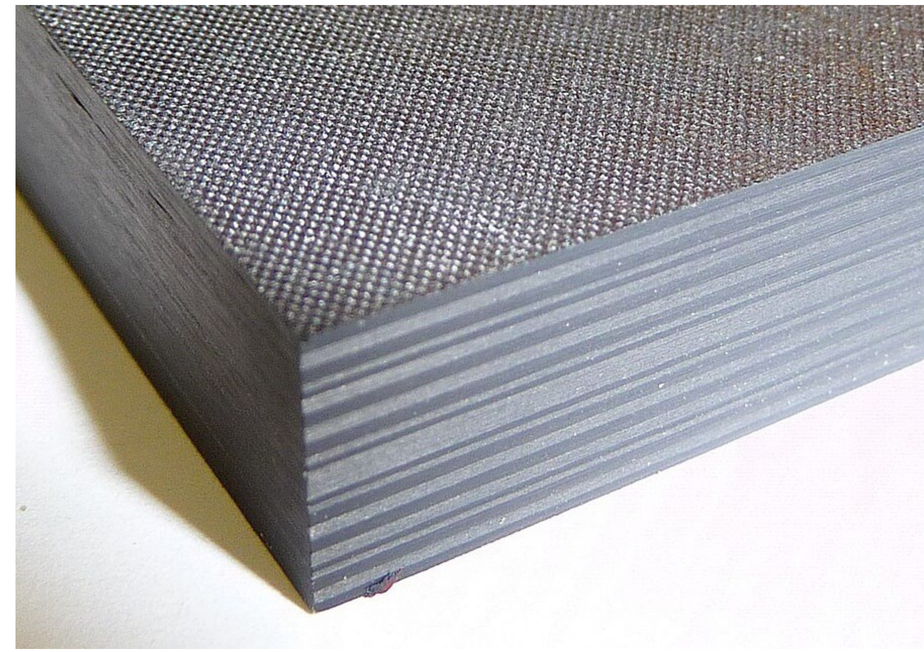
Simulation of laminated structures

Fundamentals of laminates

- Layers of fiber-reinforced material
- Orientation of fibers in each layer controls material properties
- Tailorable properties, high strength, and high stiffness of interest



Laminate made of 3 layers

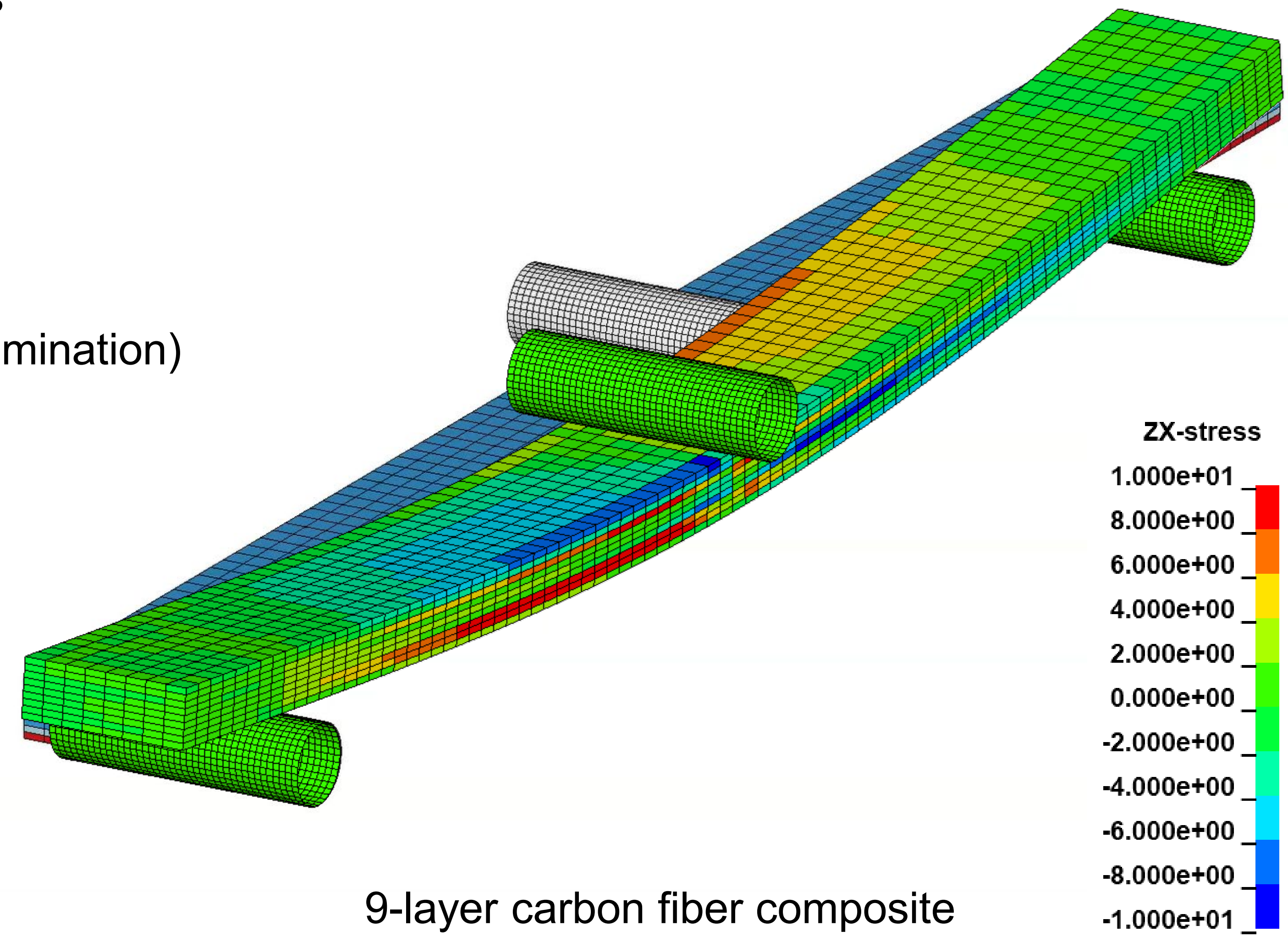


Fiber angle β relative to x-direction

Simulation of laminated structures

Challenges in finite element analysis of laminates

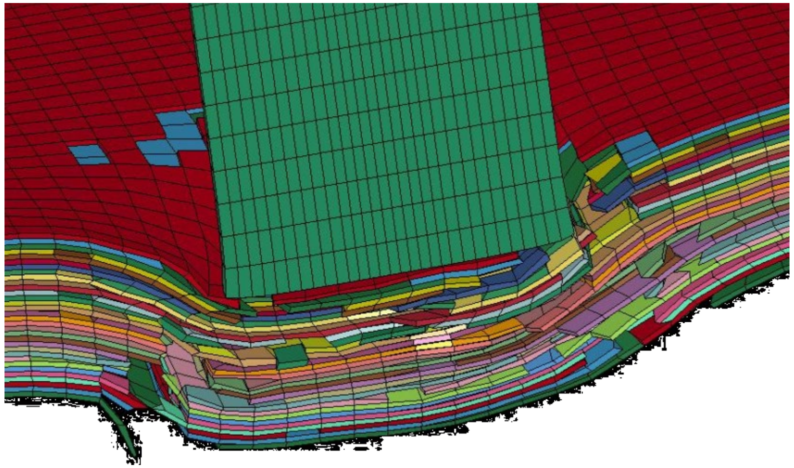
- Complex stress and strain fields
- Multiscale complexity
- Nonlinearities
  (e.g., intralaminar damage, delamination)



9-layer carbon fiber composite

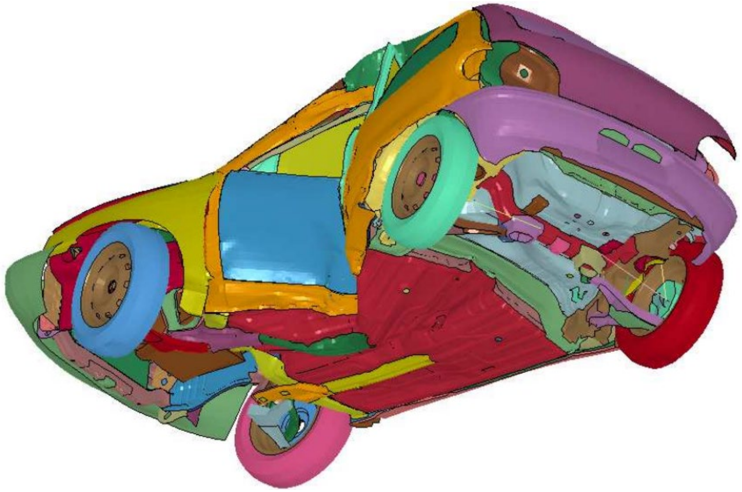
Simulation of laminated structures
Current finite element modelling approaches

- **Meso scale: Components** (e.g. pressure vessel)
  - Laminate as multiple layers of solid elements
  - Complex, fully 3D stress state
  - Higher accuracy



M.J. Loikkanen et al., Simulation of ballistic impact on composite panels, 10th LS-DYNA Users Conference

- **Macro scale: Complete structures** (e.g., full vehicle crash)
  - Laminate as a single layer of shell elements
  - Reduced stress state
  - Lower accuracy



E. Nassiopoulos et al., Finite element dynamic simulation of whole rallying car structure: Towards better understanding of structural dynamics during side impacts, 8th European LS-DYNA Conference
Pressure vessel: https://www.asme.org/topics-resources/content/fea-only-as-good-as-the-operator

Simulation of laminated structures
Current finite element modelling approaches

- **Meso scale: Components** (e.g. pressure vessel)
  - Laminate as a multiple layers of solid elements
  - Complex, fully 3D stress state
  - Higher accuracy

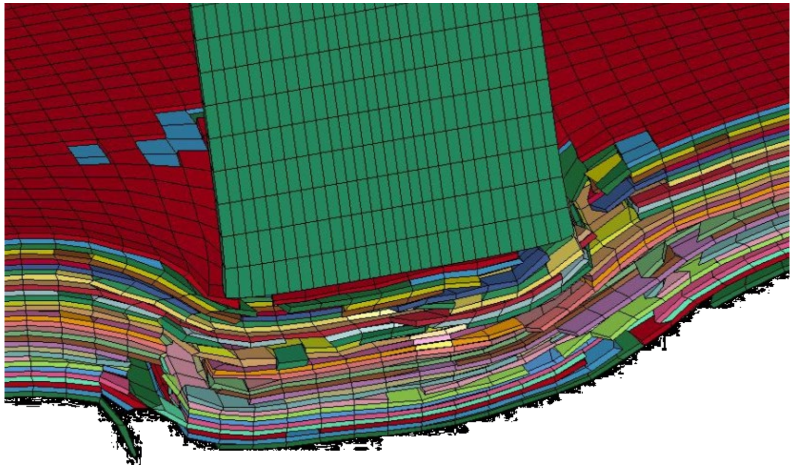
What we would like:

→ Cheap, higher accuracy modelling approach for laminates in large-scale simulations.

One solution:

→ Higher-order 3D-shell elements

- **Macro scale: Complete structures** (e.g., full vehicle crash)
  - Laminate as a single layer of shell elements
  - Reduced stress state
  - Lower accuracy



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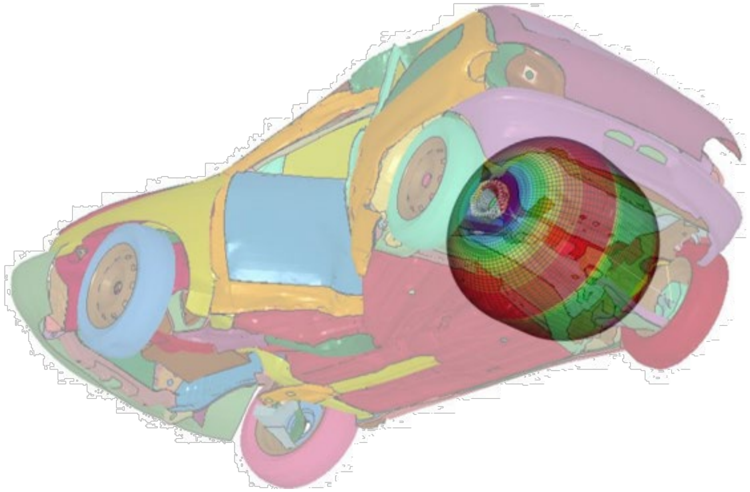

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2

Shell theories

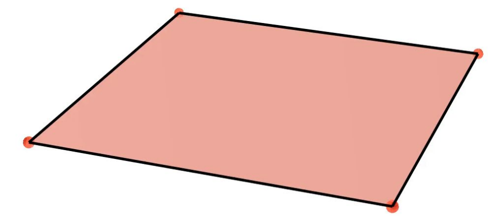
Shell theories

Reissner–Mindlin-shell (ELFORM={2, 16})

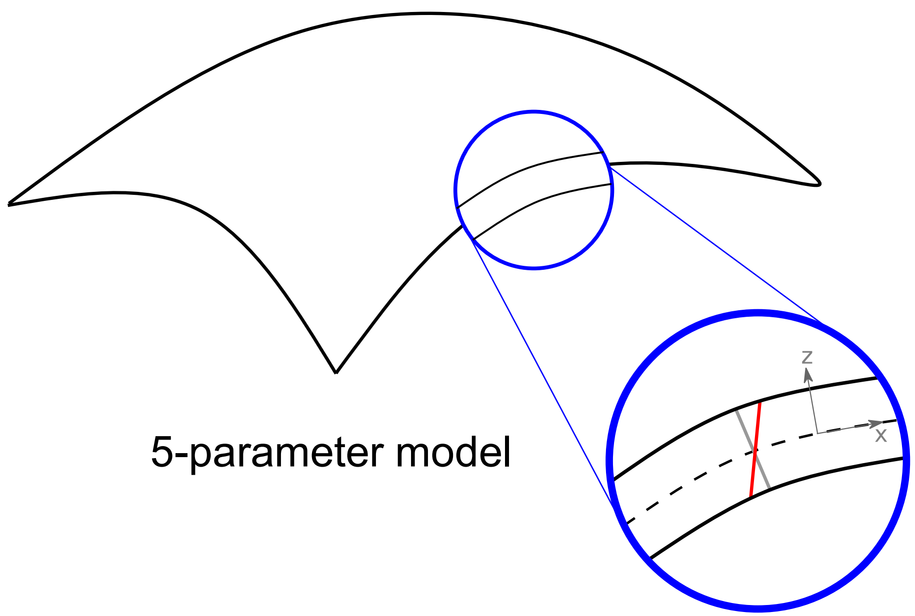
- Fibers transverse to the shell midface remain straight but not normal to the midface
- Transverse normal stress is zero

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & 0 \end{bmatrix}$$

- Modification of the material law



Reissner-Mindlin shell element



5-parameter model

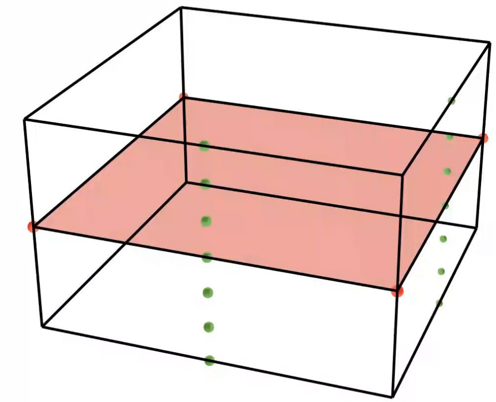
Shell theories

Shell with thickness stretch (ELFORM={25, 26})

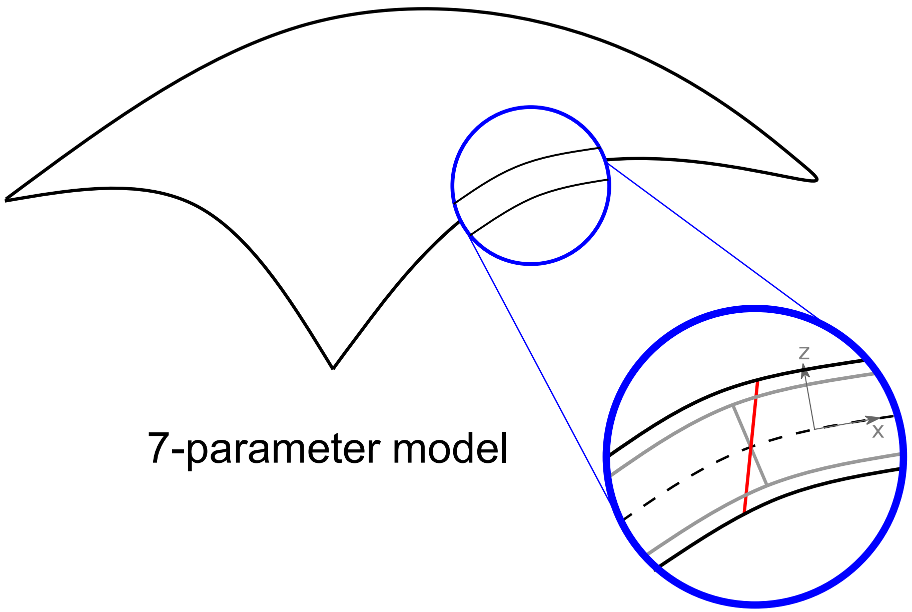
- Fibers transverse to the shell midface remain straight but not normal to the midface
- Transverse normal stress is unequal to zero
- Thickness stretch and transverse normal strain

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

- Fully three-dimensional material laws



7p shell element



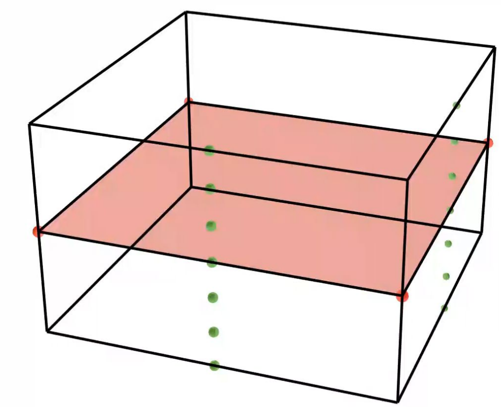
7-parameter model

Shell theories

Higher-order 3D-shell

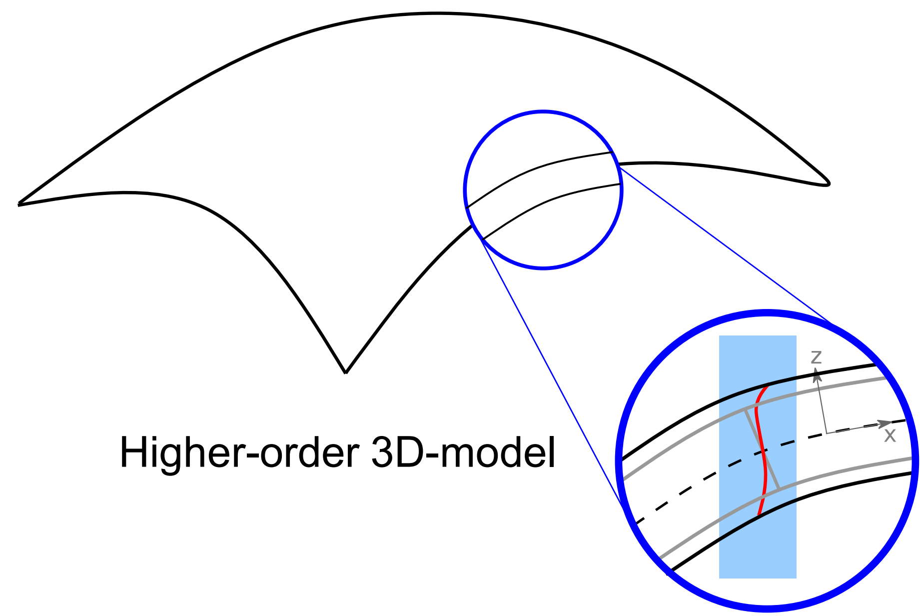
- Fibers transverse to the shell midface do not remain straight and not normal to the midface
- Transverse normal stress is unequal to zero
- Nonlinear thickness stretch and nonlinear transverse normal strain

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



Higher-order 3D-shell element

- Fully three-dimensional material laws
- Originally for sheet metal forming simulations
- Here: *Cubic 3D-shell element* (3DSH-cub) used

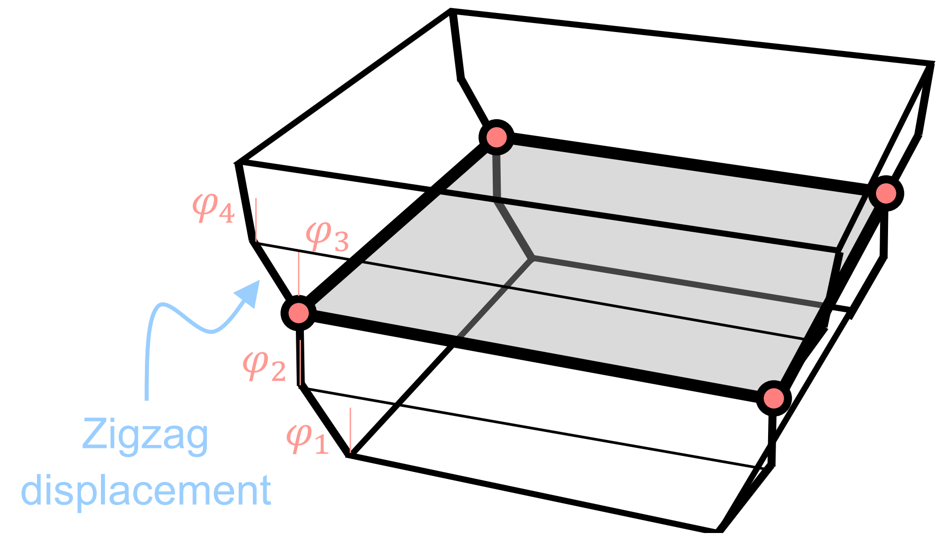


Higher-order 3D-model

Willmann, T. & Bischoff, M. (2019). Shell Models with Enhanced Kinematics for Finite Elements in Sheet Metal Forming Simulations. 12th European LS-DYNA Conference 2019, Koblenz, Germany.

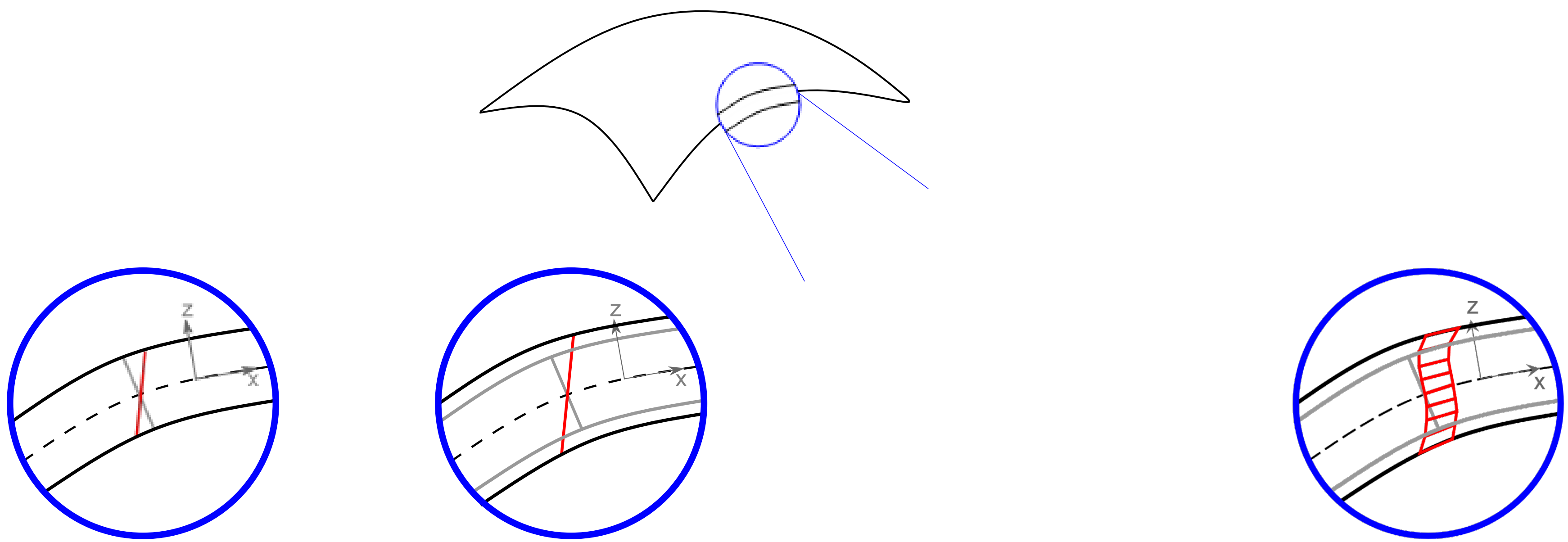
How to model laminates with shell finite elements

1. **Kinematic layers**
   - Enhanced kinematics
   - Additional degrees of freedom for each layer
   - Computationally prohibitive



2. **Numerical layers** (quadrature points)
   - Standard kinematics, no additional degrees of freedom
   - ≥1 quadrature point per layer
   - Fiber angle → material properties at quadrature point
   - Computationally cheaper

Shell theories
Overview



Reissner–Mindlin shell elements	Shell elements with thickness stretch	**Higher-order 3D-shell elements**	Solid elements
(ELFORM={2, 16})	(ELFORM={25, 26})		(ELFORM=–2)

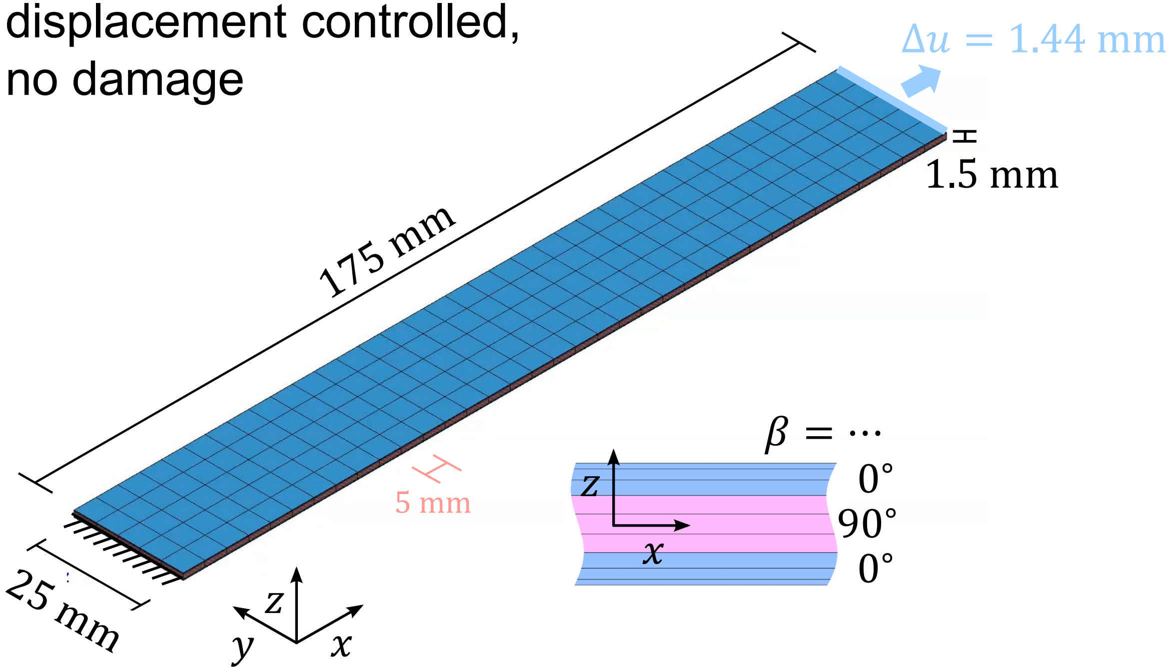
3

Improved stress prediction with higher-order 3D-shell finite elements

Improved stress prediction with cubic 3D-shell finite elements

Tensile test (verification model)

3-layer carbon fiber composite (**`*MAT_022`**),
displacement controlled,
no damage



SCHILLING, M., USTA, T., WILLMANN, T., VON SCHEVEN, M., & BISCHOFF, M.: "INVESTIGATING THE POTENTIAL OF HIGHER-ORDER 3D SHELL FINITE ELEMENTS IN STRESS ANALYSIS OF LAMINATED STRUCTURES", PROCEEDINGS OF THE STUTTGART CONFERENCE ON AUTOMOTIVE PRODUCTION (ACCEPTED), 2024.

Improved stress prediction with cubic 3D-shell finite elements

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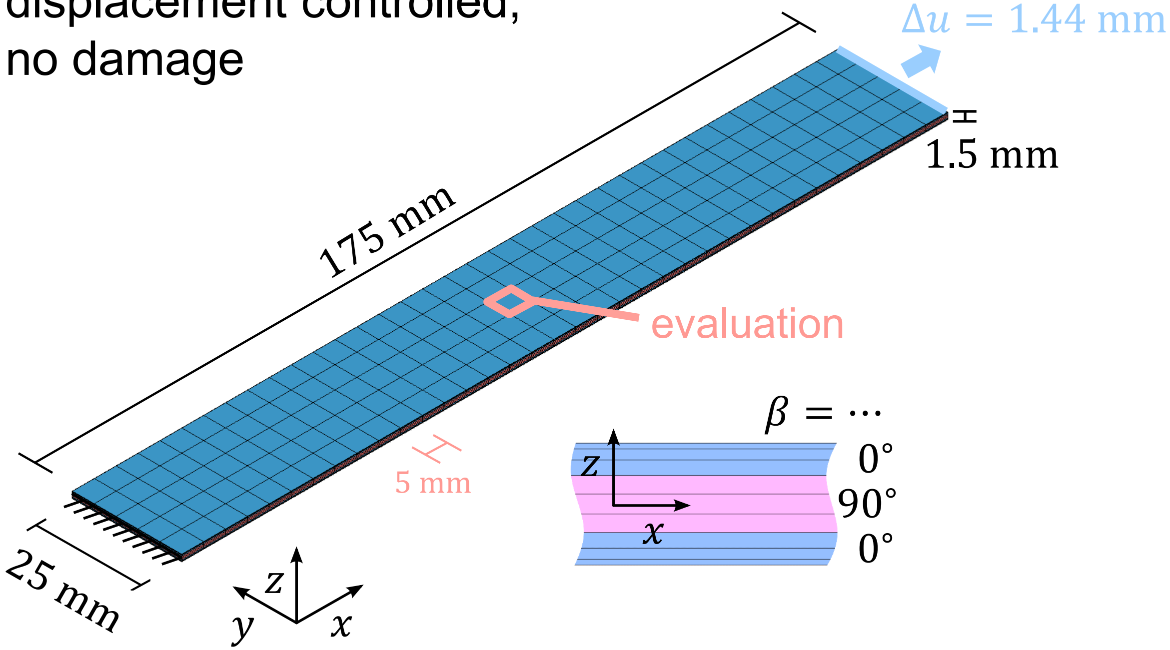

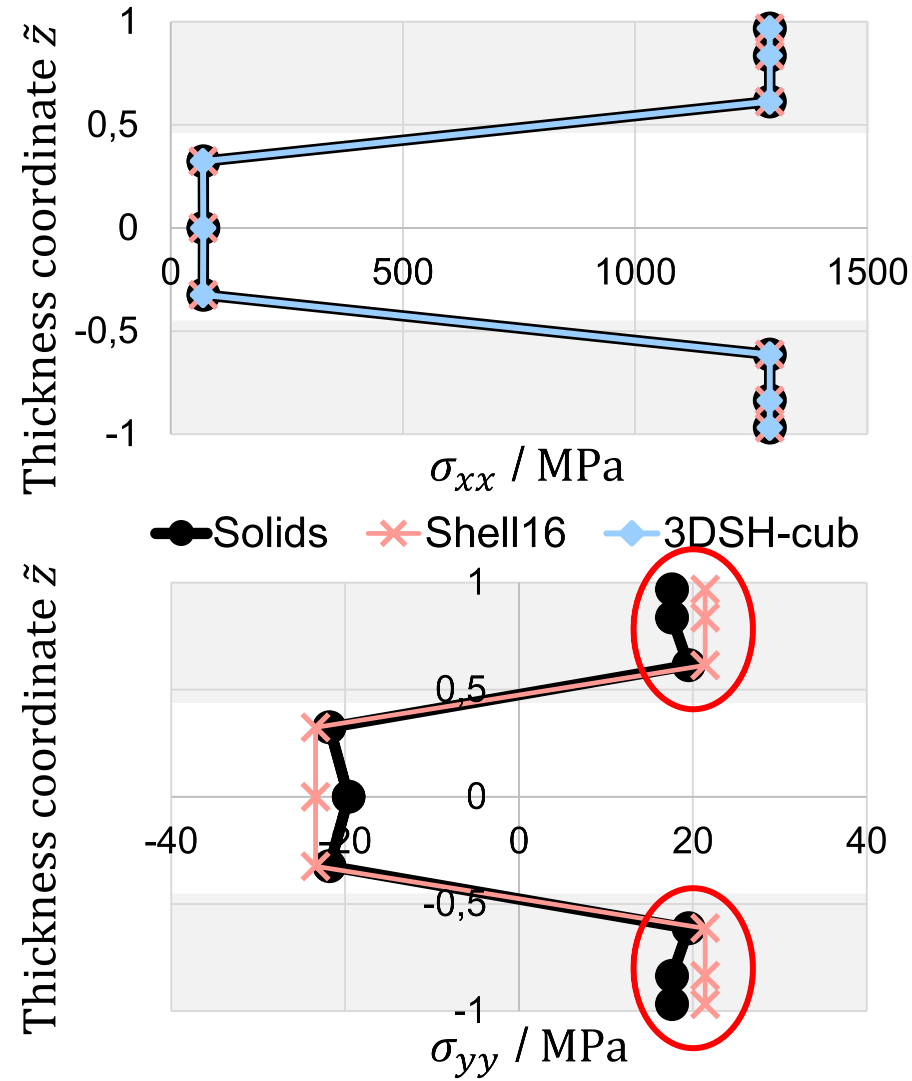

Element formulations:

- 9 solids in thickness direction (reference) (**`ELFORM=-2`**)
- Reissner–Mindlin shell (**`ELFORM=16`**)
- Cubic 3D-shell (**`3DSH-cub`**)

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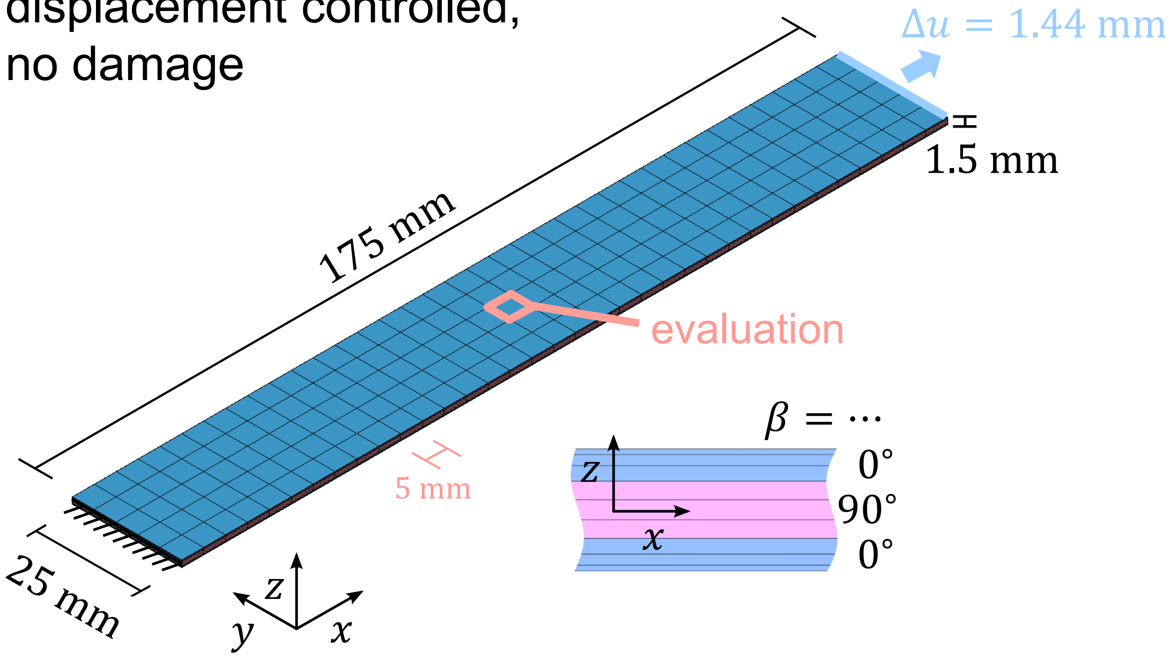

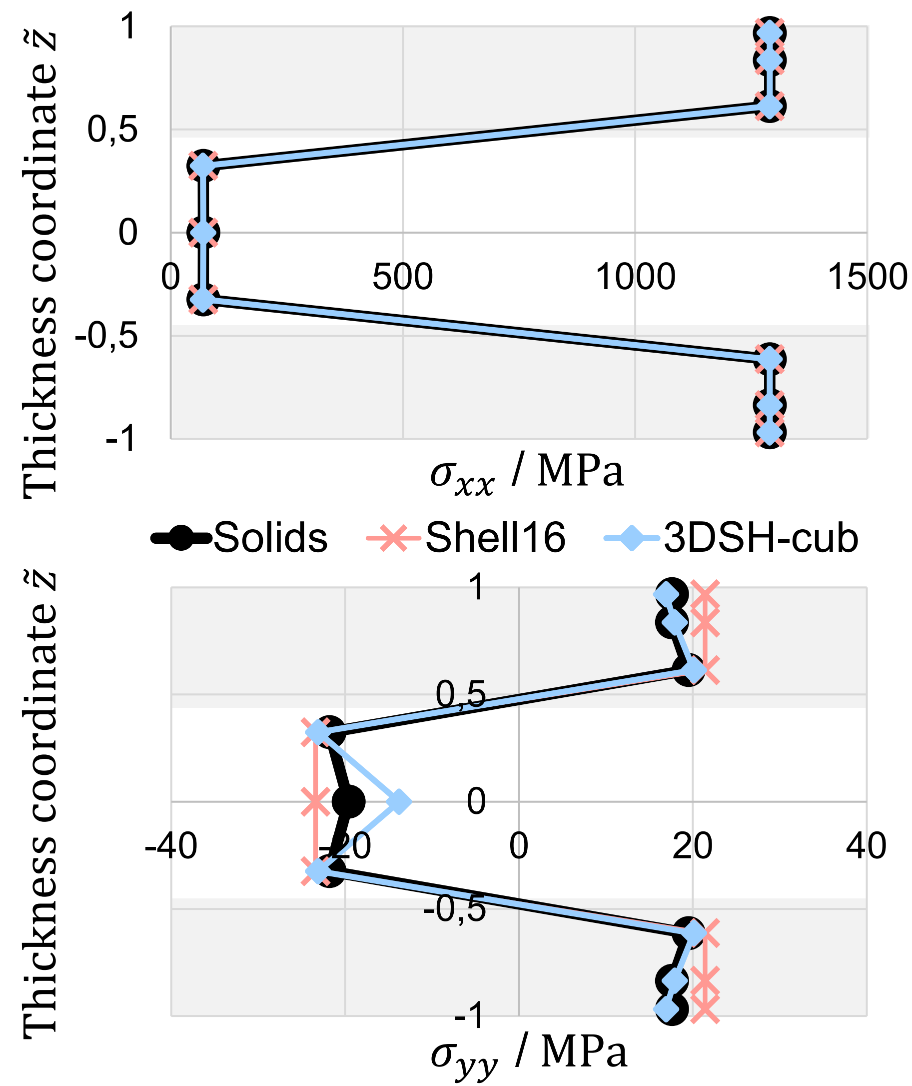

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Three-point bending test (3 layers)

3-layer carbon fiber composite (**`*MAT_022`**),
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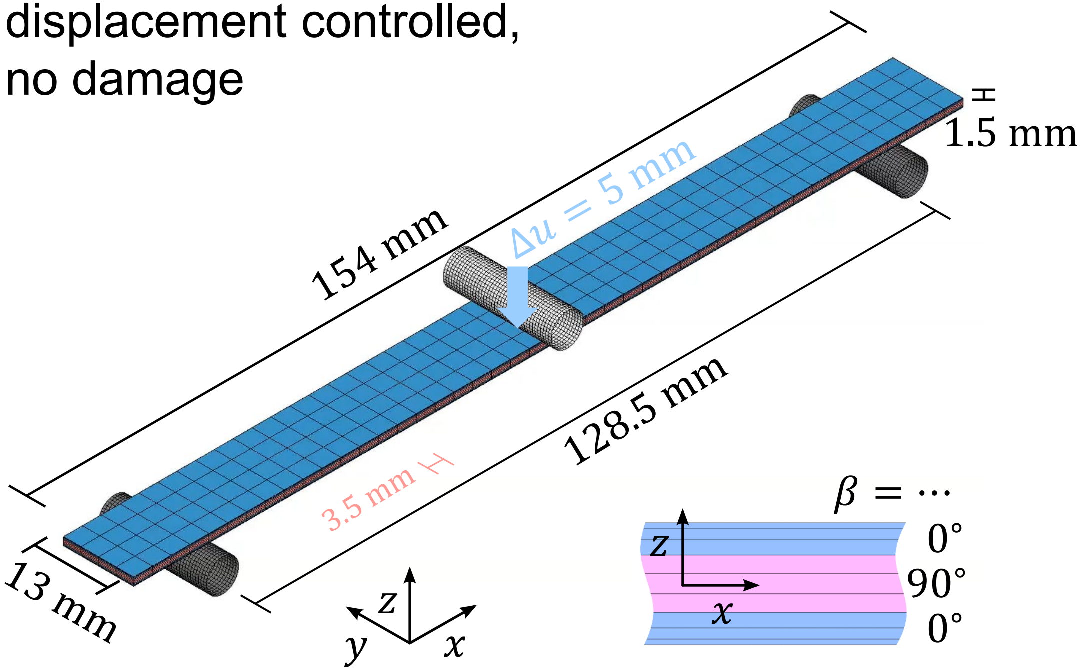

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Baustatik und Baudynamik

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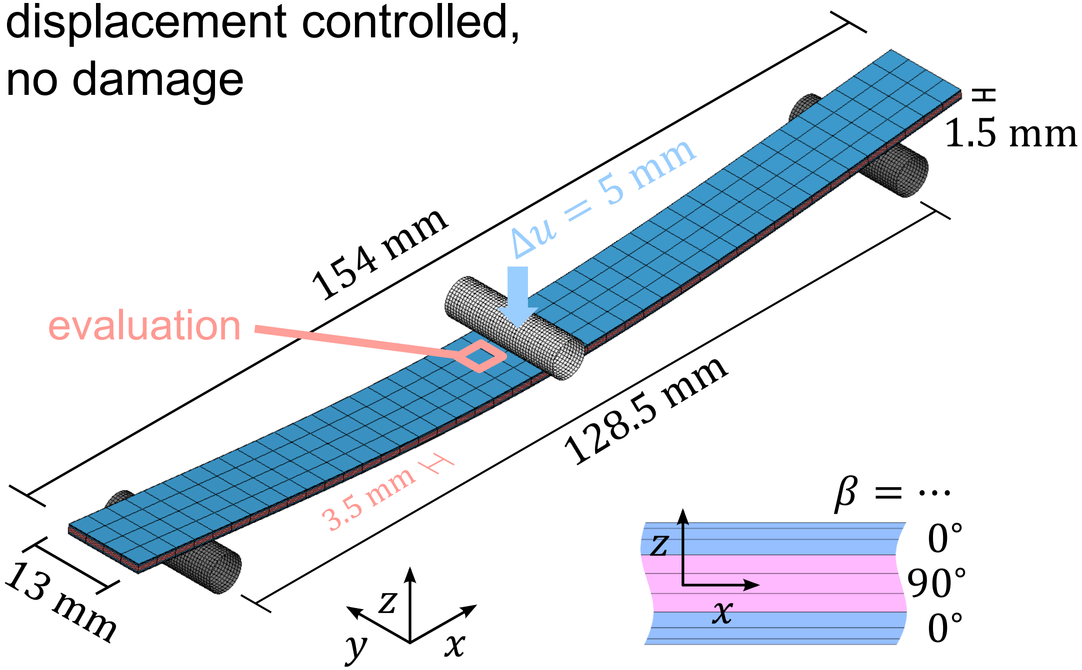

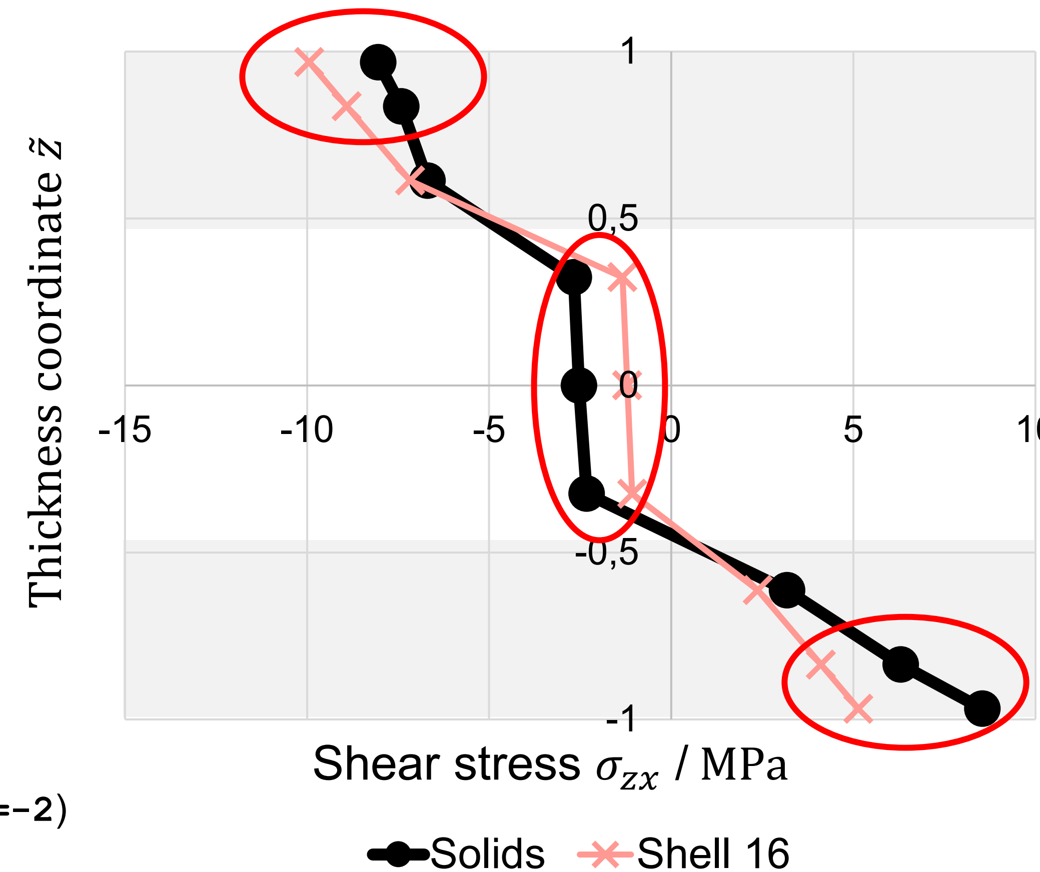

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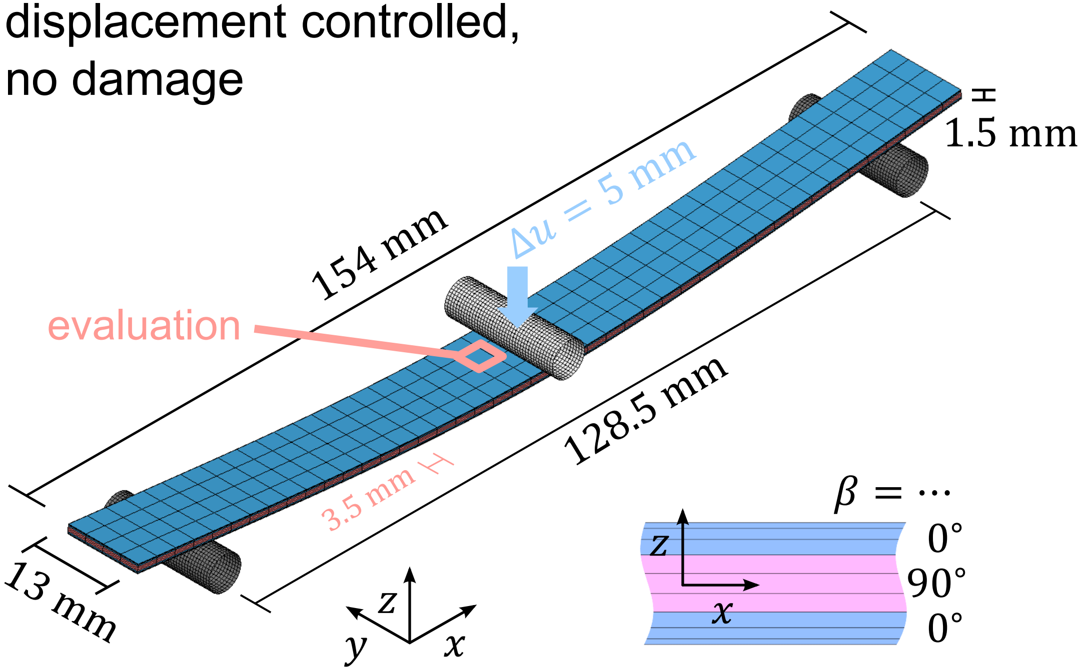

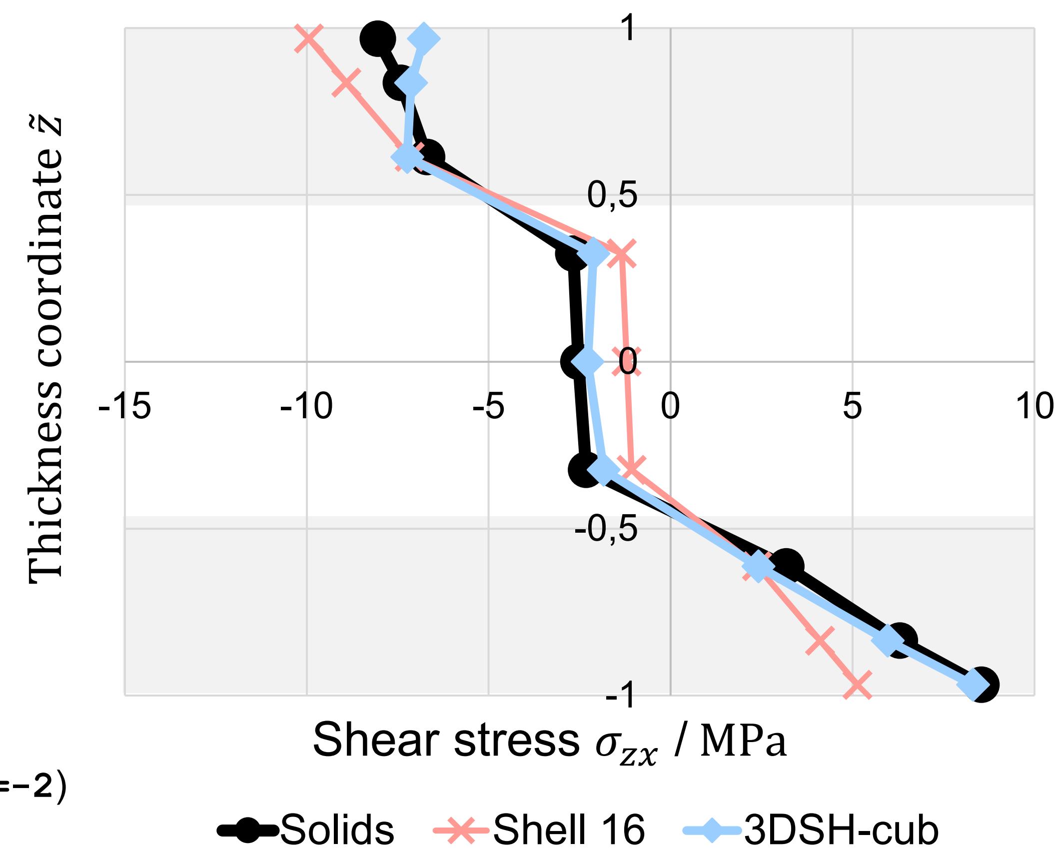

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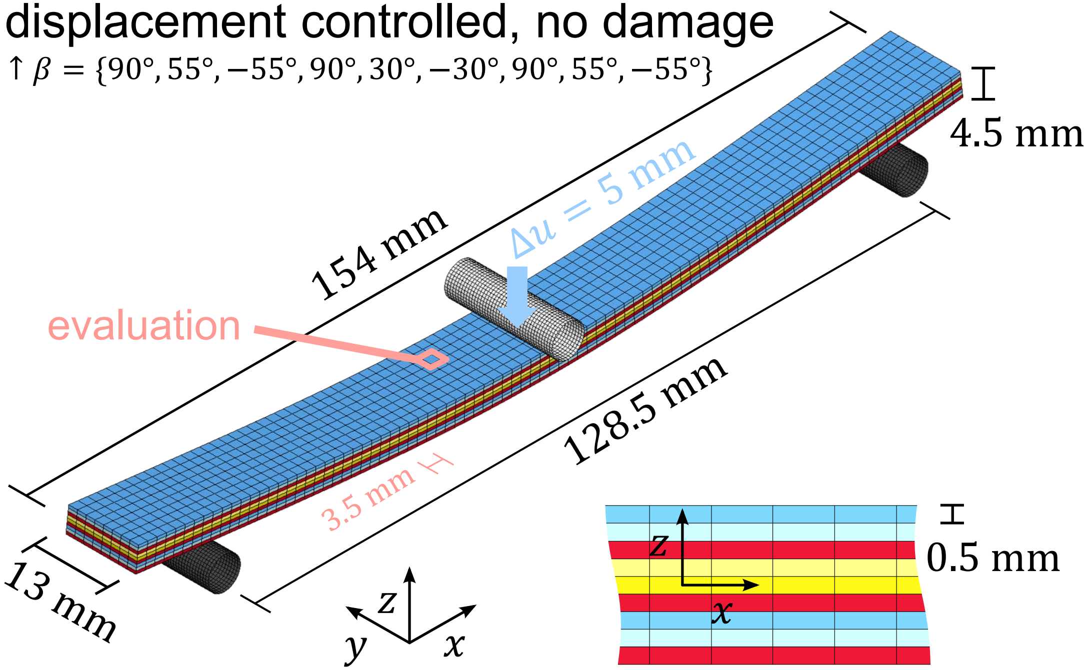
Improved stress prediction with cubic 3D-shell finite elements

Three-point bending test (9 layers)

9-layer carbon fiber composite (**`*MAT_022`**), displacement controlled, no damage

$\uparrow \beta = \{90°, 55°, -55°, 90°, 30°, -30°, 90°, 55°, -55°\}$



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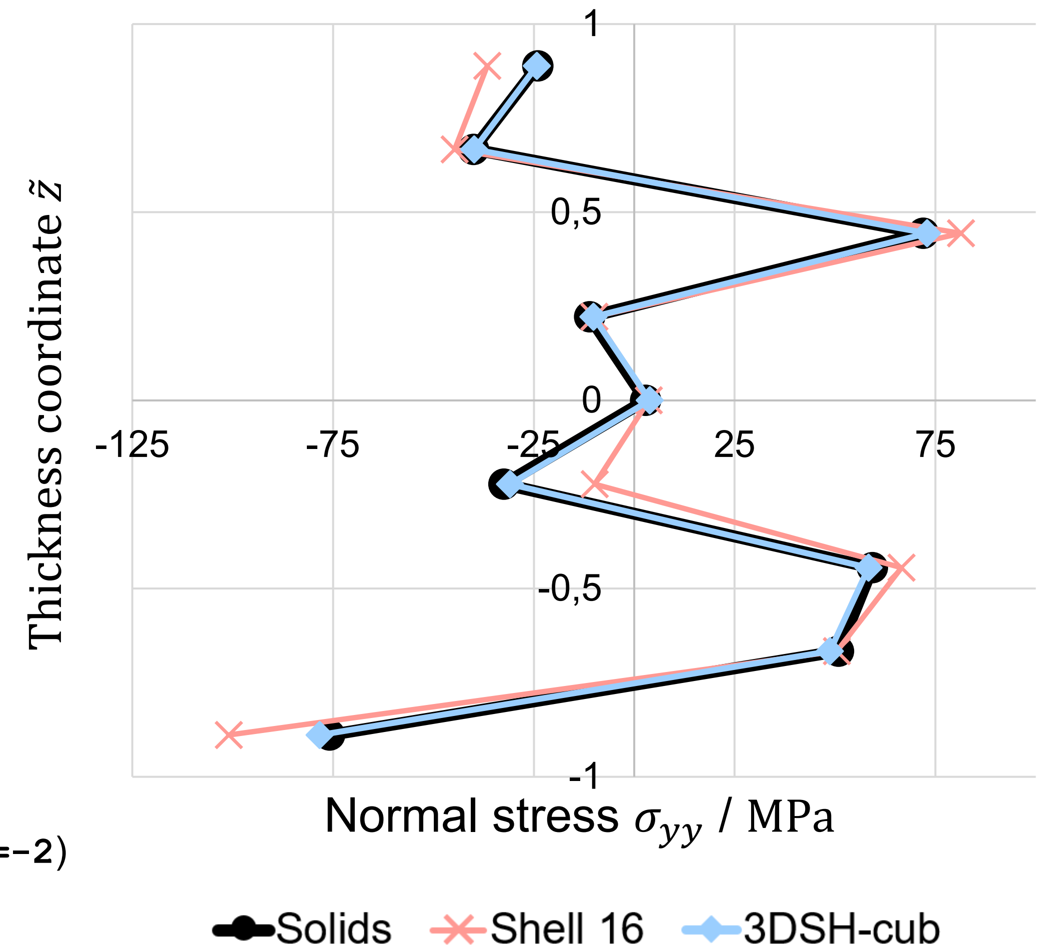

Improved stress prediction with cubic 3D-shell finite elements

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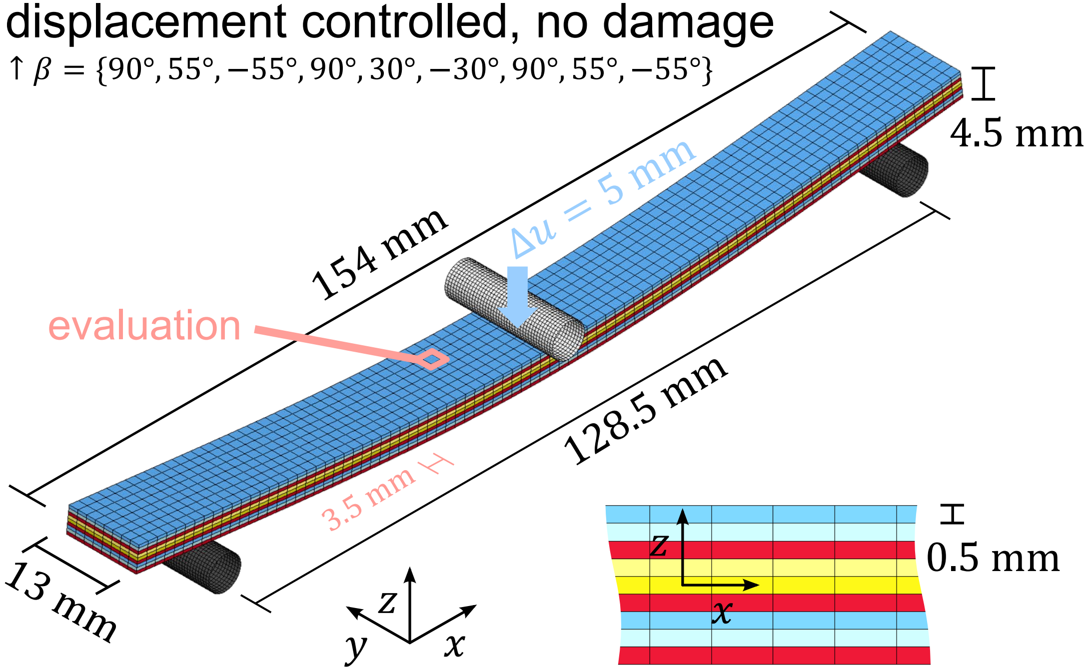

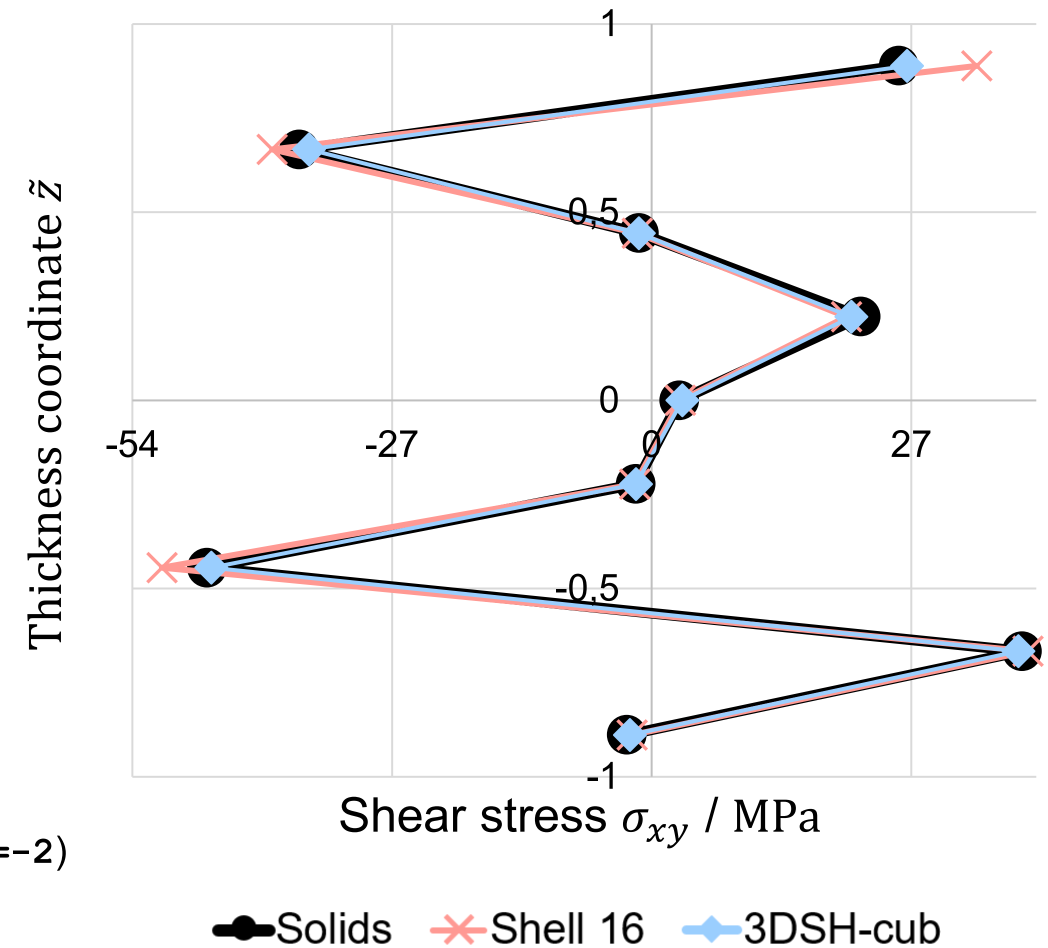

Element formulations:

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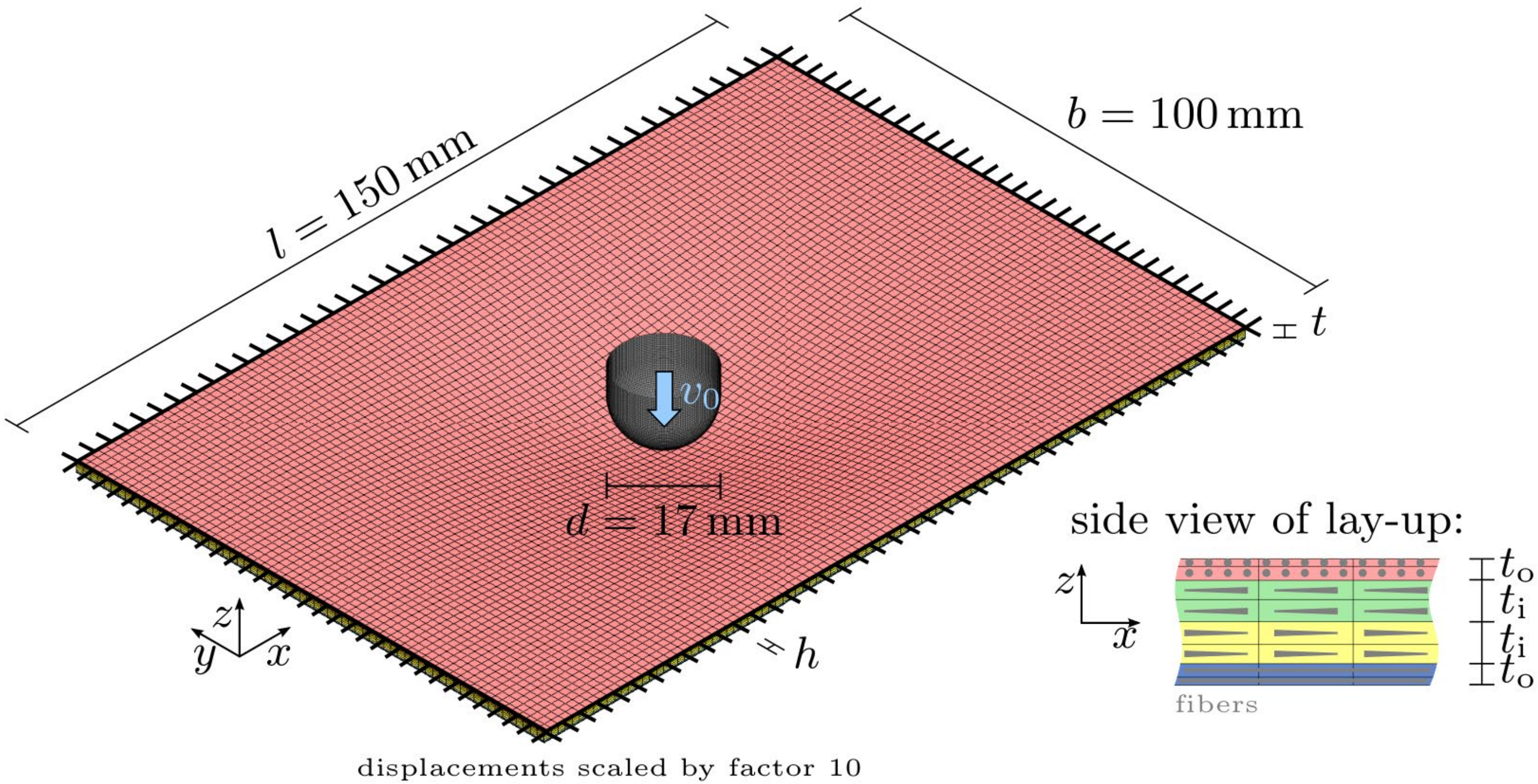
- Reissner–Mindlin shell (**`ELFORM=16`**)
- Cubic 3D-shell (**`3DSH-cub`**)

Improved stress prediction with cubic 3D-shell finite elements
Impact test

4-layer carbon fiber composite (**`*MAT_022`**),
impactor with initial velocity v_0 (slow impact)

$\uparrow \beta = \{0°, 45°, -45°, 90°\}$



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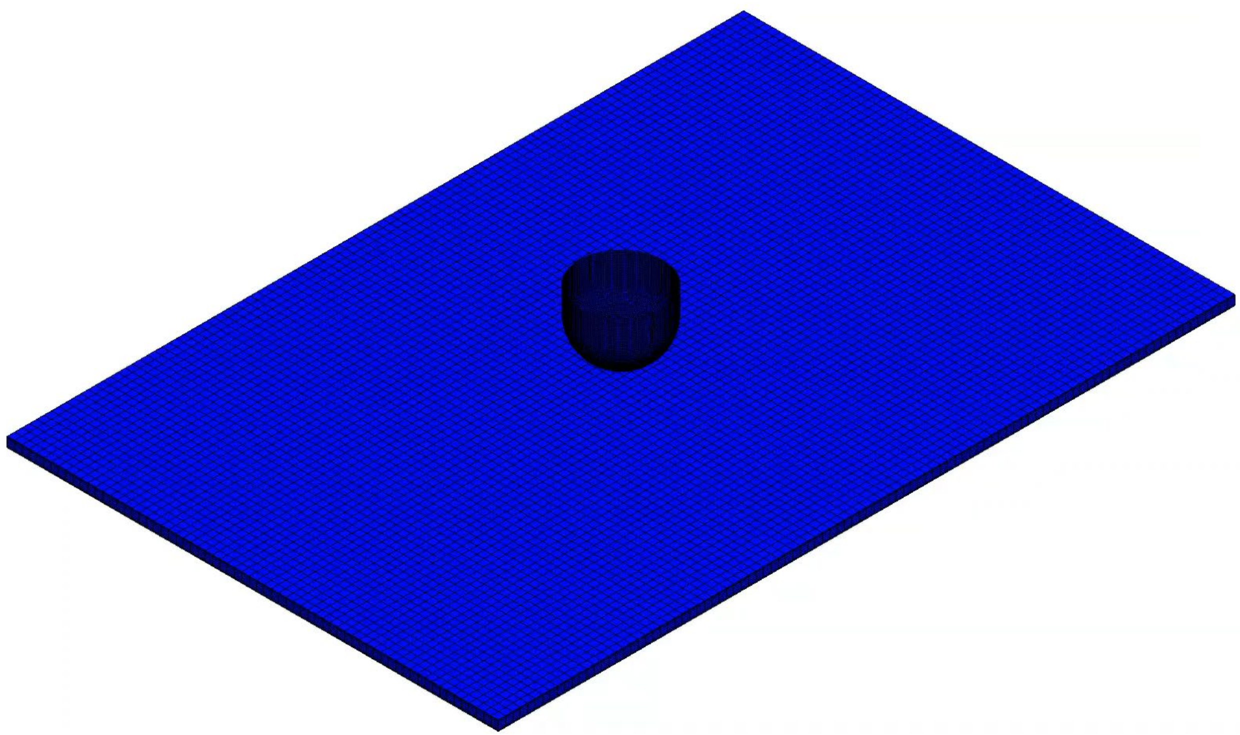
Improved stress prediction with cubic 3D-shell finite elements

Impact test

4-layer carbon fiber composite (**`*MAT_022`**),
impactor with initial velocity v_0 (slow impact)

$\uparrow \beta = \{0°, 45°, -45°, 90°\}$



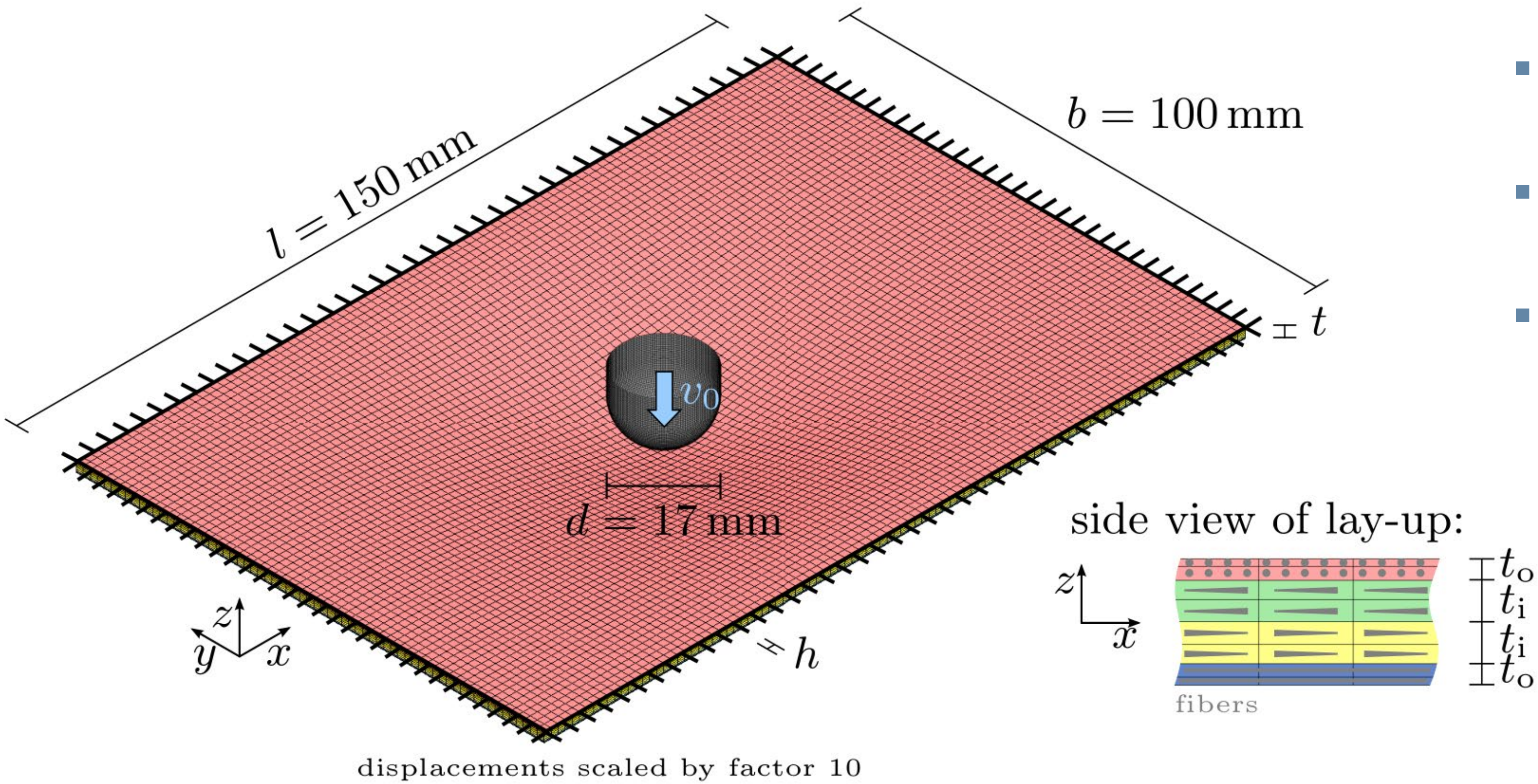
displacements scaled by factor 10

Improved stress prediction with cubic 3D-shell finite elements

Impact test

4-layer carbon fiber composite (**`*MAT_022`**), impactor with initial velocity v_0 (slow impact)

$\uparrow \beta = \{0°, 45°, -45°, 90°\}$



Element formulations:

- 8 solids in thickness direction (reference) (**`ELFORM=-2`**)
- Reissner–Mindlin shells (**`ELFORM=16`**)
- Conventional 3D-shells (**`ELFORM=26`**)
- Cubic 3D-shells (**`3DSH-cub`**)

Improved stress prediction with cubic 3D-shell finite elements

Impact test

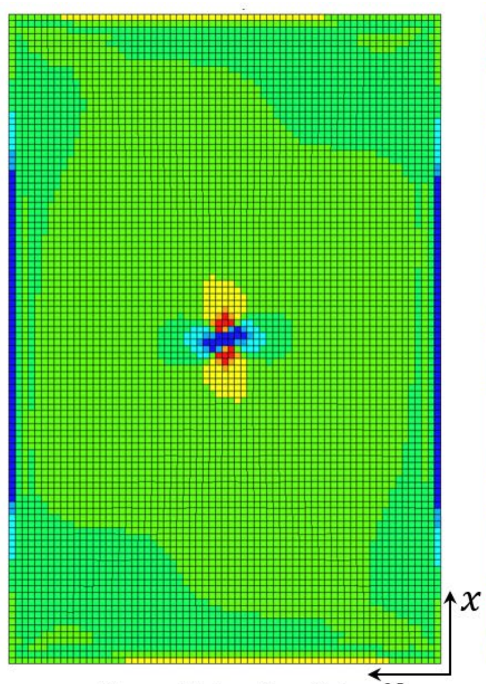
Baustatik und Baudynamik

4-layer carbon fiber composite (**`*MAT_022`**),
impactor with initial velocity v_0 (slow impact)

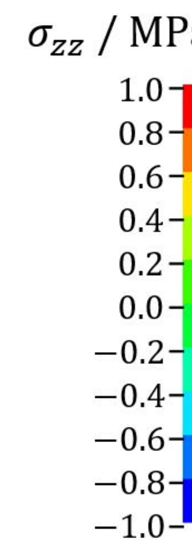
$\uparrow \beta = \{0°, 45°, -45°, 90°\}$

Only shell element to qualitatively align with reference solution

Contour plot of normal stress σ_{zz} in $45°$ layer



8 solids (ref.)



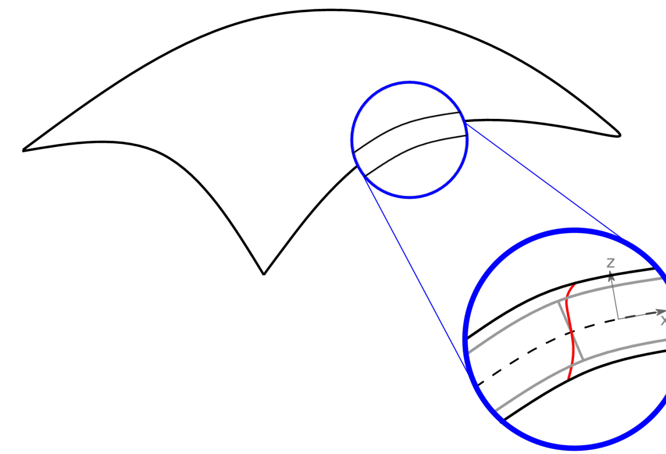
4

Conclusion and outlook

Conclusion and outlook

Higher-order 3D-shell elements…

- **… can offer an improved prediction quality for stress in laminated structures.**
- … enable large scale simulations with a 3D material law, taking into account all stress components.



Industrial scale examples,
detailed analysis of impact scenarios,
enhancements for delamination.

Acknowledgement

This research has been funded by the project DigiTain 19S22006K by the Federal Ministry of Economic Affairs and Climate Action based on a resolution of the German Bundestag. This support is gratefully acknowledged.

DigiTain

Funded by the European Union
NextGenerationEU

Supported by:
Federal Ministry for Economic Affairs and Climate Action
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Universität Stuttgart

Thank you!

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