Probabilistische Bewertung der Integrität gewickelter CFK-Wasserstoffdruckbehälter mit inhärenten fertigungsbedingten Ungänzen

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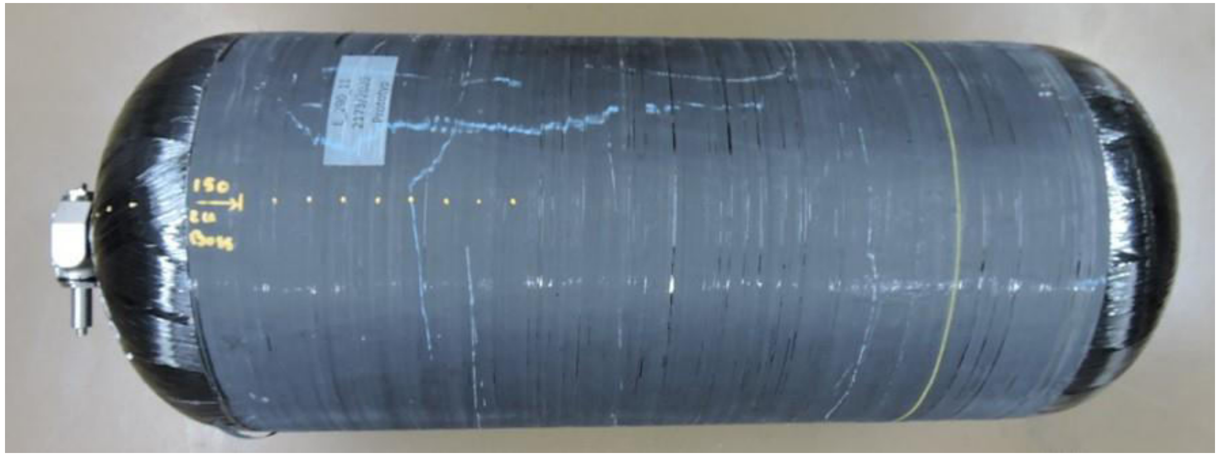
Probabilistic integrity assessment of filament wound CFRP pressure vessels

Introduction

- type 4 pressure vessels
  - polymeric liner
  - load bearing filament wound CFRP overwrap
  - high pressure storage of gaseous hydrogen and other media
  - design for high internal pressures up to 1000 bar
- manufactured by filament winding
  - inherent manufacturing induced defects
  - current laminate designs heavy and expensive

➢ enhanced concepts for assessment considering presence of inherent manufacturing induced defects necessary



reference vessel

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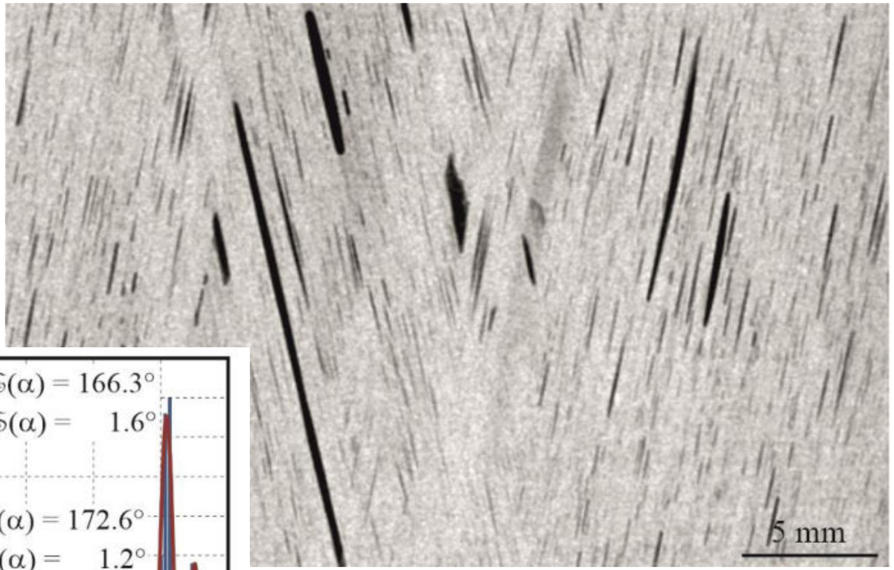
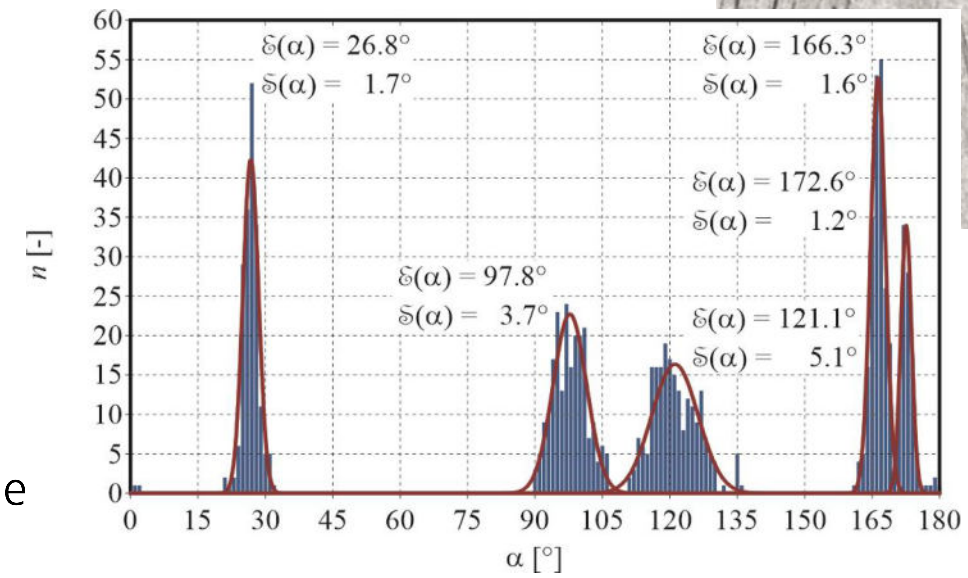
Reference material

- material
  - carbon fiber reinforced epoxy matrix material
  - filament wound using standard process used in industrial scale production
- nondestructive inspection
  - X-ray computed tomography
  - worm pores between filaments
  - preferably located in outer plies
  - limited variations in the fiber angle





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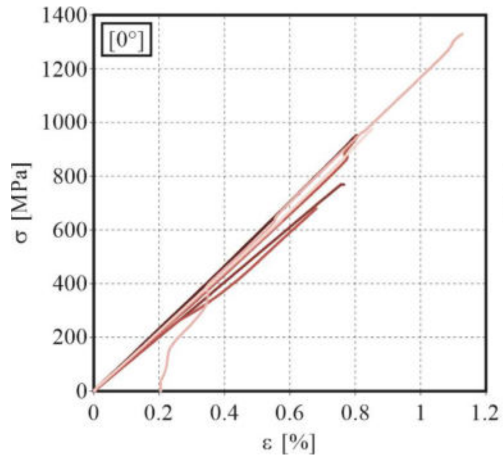
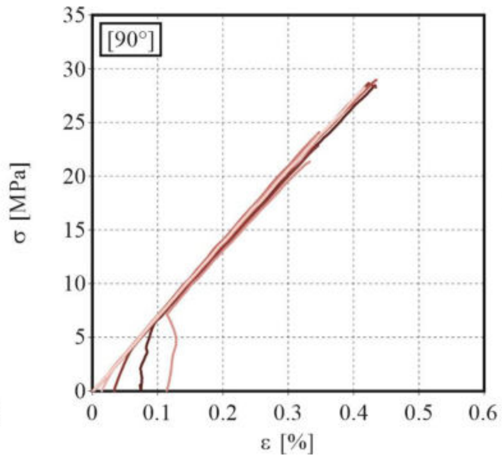
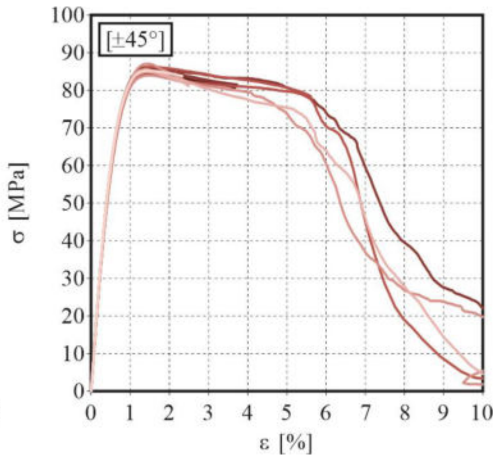
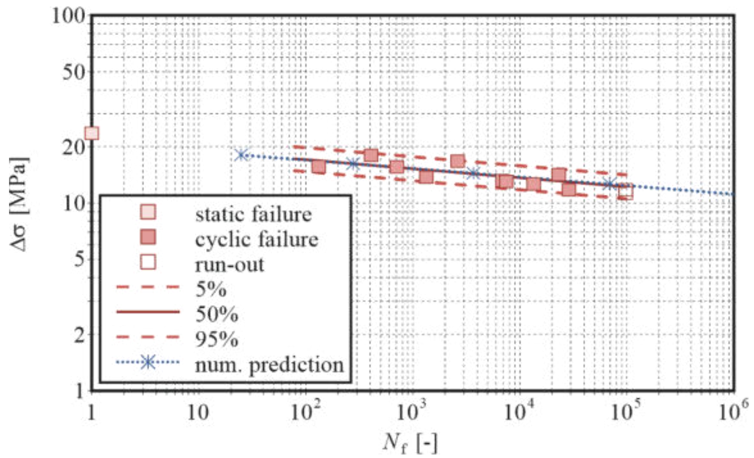
Experimental material characterization

- data base for material model development, data identification and validation
  - quasi-static coupon experiments (UD [0°] and [90°], [±45°]-laminates)
  - fatigue experiments under cyclic loading conditions
- results
  - significant uncertainty with respect to strength









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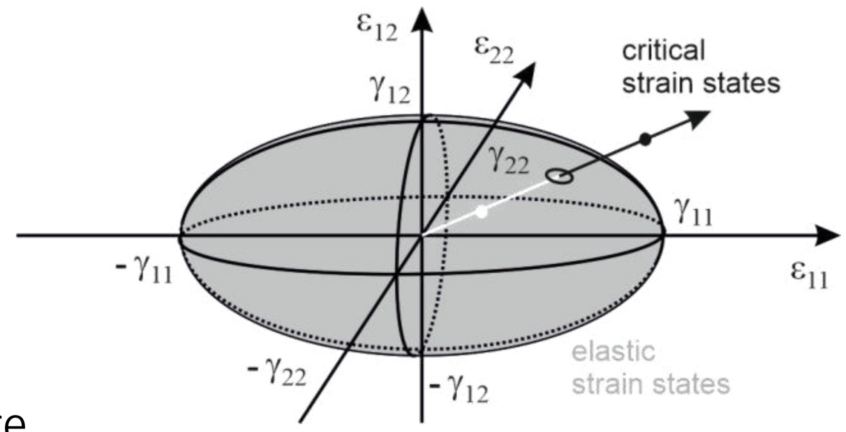
User-defined continuum damage mechanics material model

- material model to be defined
- base material model on [±α]-ply level: Hooke's law with single Kachanov-Lemaitre type damage variable

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{(1-D)E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-D)E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{(1-D)E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-D)G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-D)G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-D)G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{pmatrix}$$



- elastic domain bounded by a Tsai-Wu-type failure envelope in strain space

$$\Phi = \left(\left(\frac{\varepsilon_{11}}{\gamma_{11}^{t}}\right)^2 - \frac{\varepsilon_{11}\,\varepsilon_{22}}{\gamma_{1122}^{t}} + \left(\frac{\varepsilon_{22}}{\gamma_{22}^{t}}\right)^2 - \frac{\varepsilon_{22}\,\varepsilon_{33}}{\gamma_{2233}^{t}} + \left(\frac{\varepsilon_{33}}{\gamma_{33}^{t}}\right)^2 - \frac{\varepsilon_{33}\,\varepsilon_{11}}{\gamma_{1133}^{t}} + \left(\frac{\varepsilon_{23}}{\gamma_{23}^{s}}\right)^2 + \left(\frac{\varepsilon_{13}}{\gamma_{13}^{s}}\right)^2 + \left(\frac{\varepsilon_{12}}{\gamma_{12}^{s}}\right)^2 \right)^{\frac{1}{2}} \leq 1$$

- damage driven by approach of the failure envelope by actual strain state

$$\Rightarrow \mathrm{d}D = \begin{cases} A\,\phi^n\,\mathrm{d}\phi & \text{if } \mathrm{d}\phi \geq 0 \\ 0 & \text{else} \end{cases}$$

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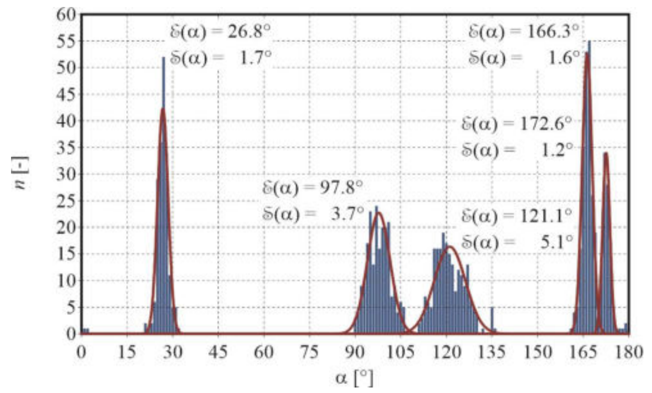
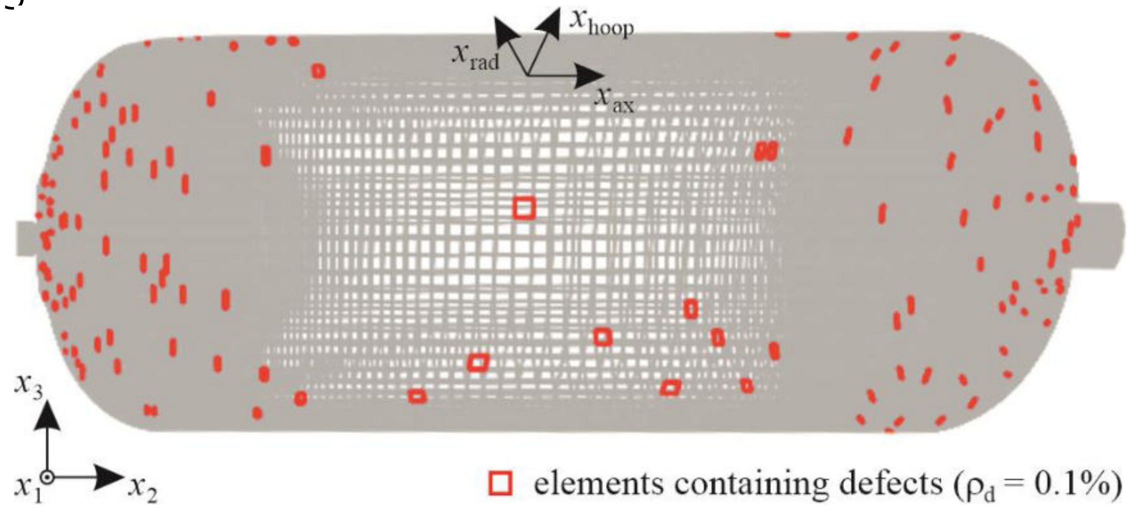
Probabilistic simulation strategy

- manufacturing induced defects distributed stochastically through the vessel
- explicit consideration of worm pores and fiber angle variation
- reduction of strength by presence of pores

- strategy
  - definition of material parameter sets with reduced strengths
  - consideration of different defect sizes and geometries
  - stochastic mapping of defects onto vessel finite element model using random number generation
  - thereby taking observed probability distributions into account
  - repeated execution using Monte-Carlo simulation





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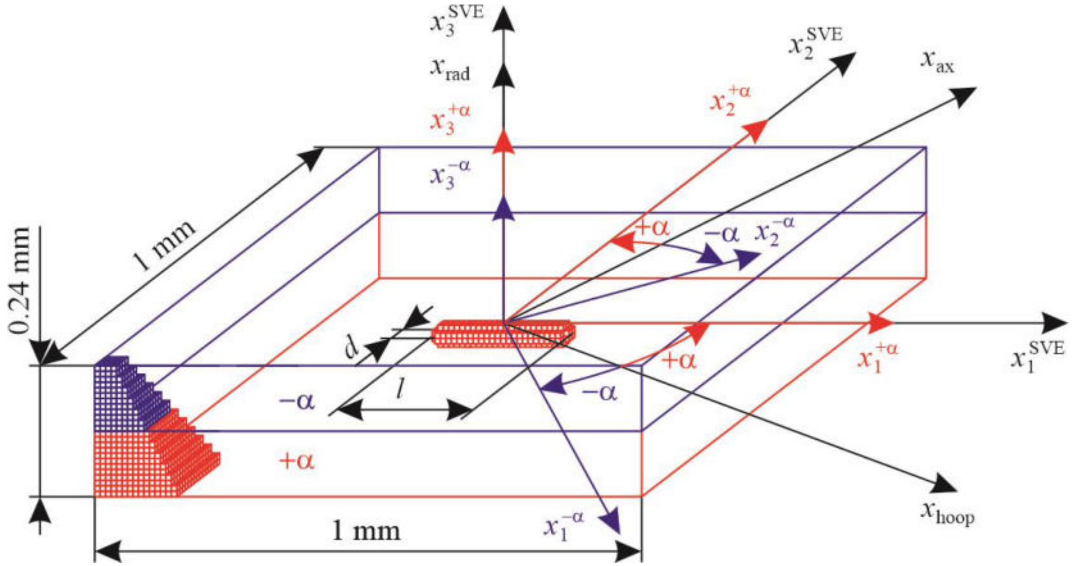
Multiscale analysis to determine effects-of-defects

- determination of reduced strengths for different pore sizes and geometries
- numerical analyses of representative volume elements containing selected defects
  - voxel based finite element model
  - two plies ([+α] and [-α])
  - loaded by different selected effective reference strain states $(\bar{\varepsilon}_{11}, \bar{\varepsilon}_{22}, \bar{\varepsilon}_{12})$
  - periodic boundary conditions
  - failure prediction for individual plies using Puck's criterion
  - load increase till first prediction of failure



➢ failure strains $\gamma_{11}^{t}, \gamma_{22}^{t}, \gamma_{12}^{s}$ on the effective material level

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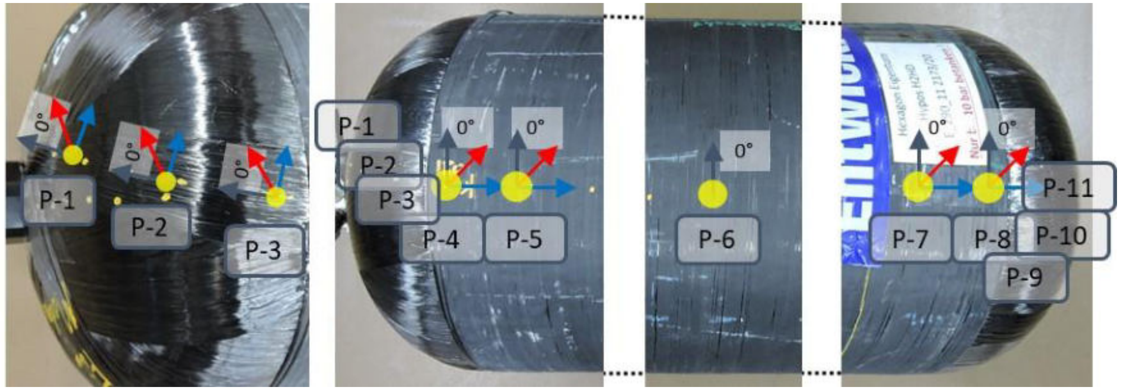
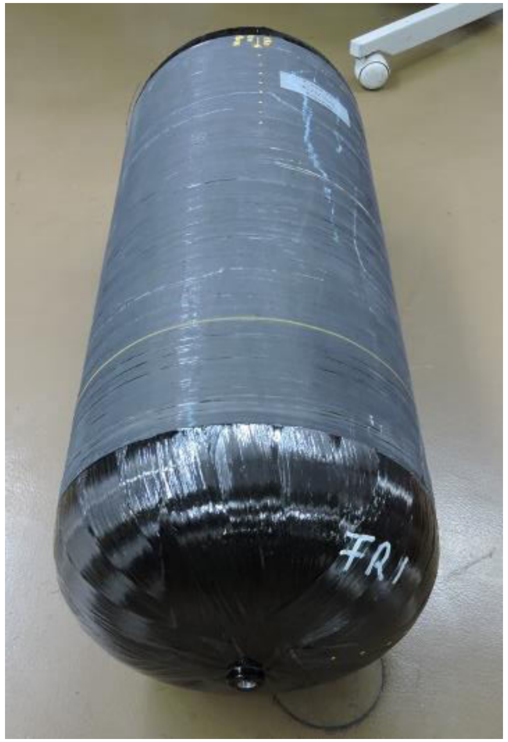
Validation and demonstration example

- instrumented burst tests
  - reference vessel with simplified stacking sequence (two outer circumferential plies, single central helical ply)
  - instrumentation with resistance strain gauges
  - two burst tests
  - burst loads 158.8 bar and 185.2 bar





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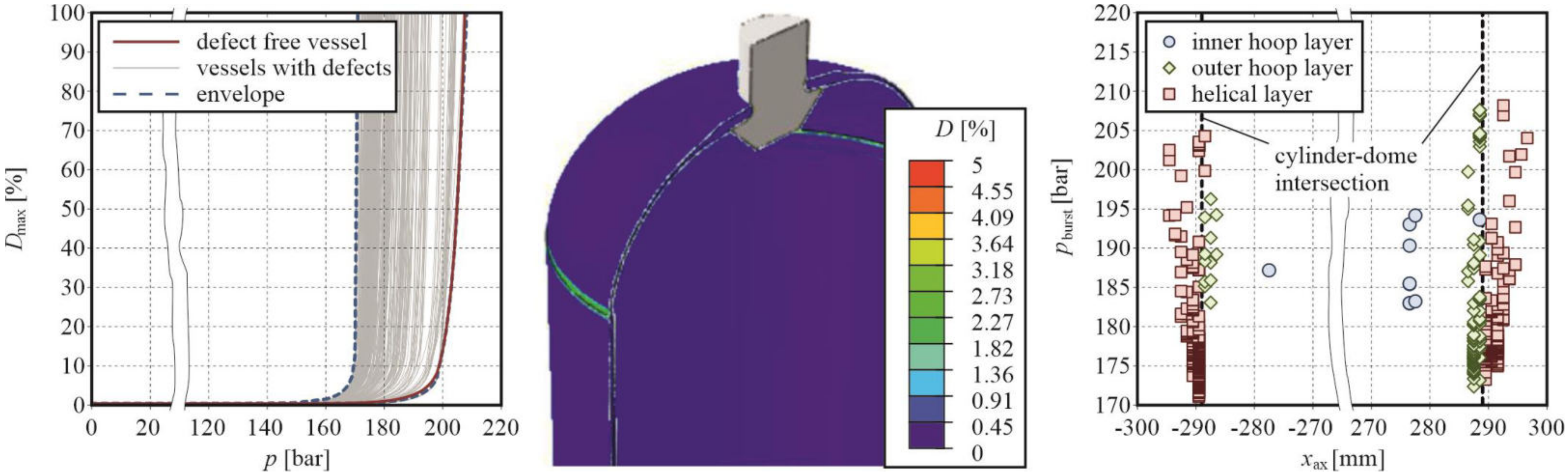
Structural simulation

- integrity assessment
  - different defect fields and distributions



  - failure position and location of failure initiation accurately predicted

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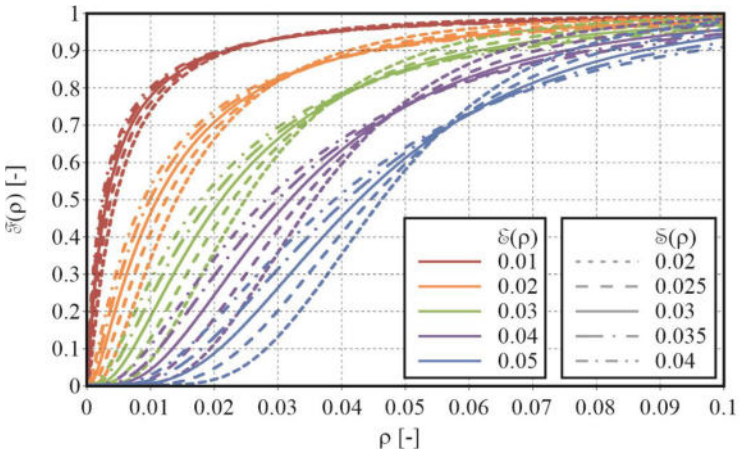
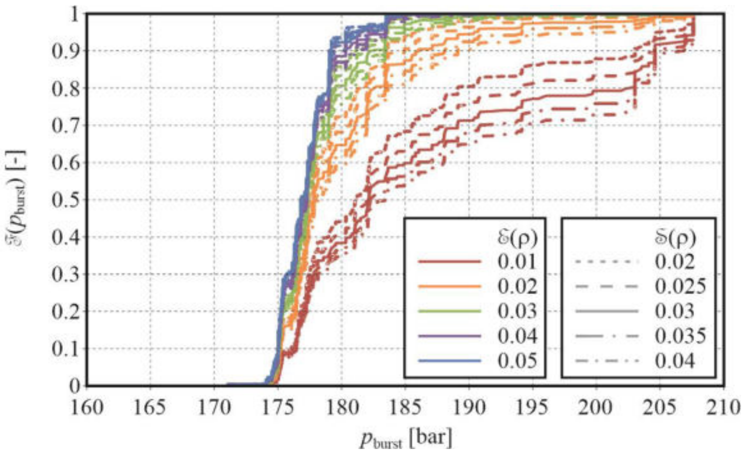
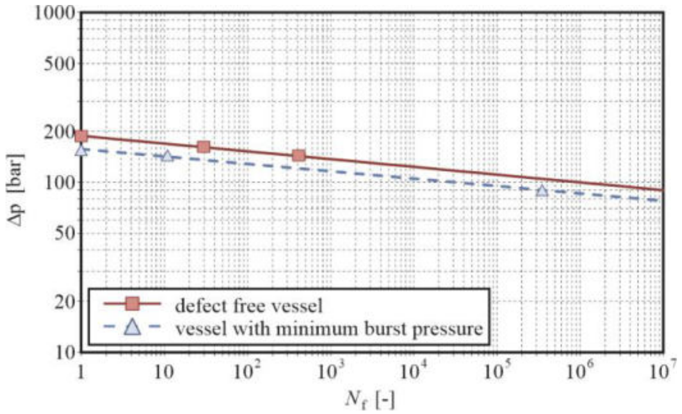
Stochastic assessment

- sampling procedure:
  - analysis of selected, pre-defined cases
  - weighting of the individual results with the individual probability of the underlying case





- fatigue assessment
  - structural response under harmonic internal pressure load ($R = 0$)



  - similar to coupon experiments gently declined S-N curve
  - constant scatter band width

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Conclusions

- integrity assessment of filament wound CFRP type 4 pressure vessels under static and fatigue loads
- probabilistic simulation strategy
  - reduced strengths due to inherent manufacturing induced defects analyzed numerically on RVE level
  - defects mapped statistically onto structural FE model using random number generation
  - stochastic analysis based on sampling procedure
- continuum damage mechanics material model
  - strain space Tsai-Hill type failure envelope
  - damage evolution driven by approach of strain state towards the failure envelope
- experimental validation
  - material tests on coupon level
  - burst tests on simplified reference vessel
- good agreement between experimental and numerical results

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