4A TECHNOLOGY DAYS
WERFENWENG (AUSTRIA), MARCH 3TH-4TH 2020

SIMULATION AND VALIDATION OF FATIGUE PERFORMANCE OF WELD LINES FOR SHORT FIBER-REINFORCED PLASTIC PARTS

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Fatigue behavior of weld lines for short fiber-reinforced plastics
Outline

1 Introduction
- Publicly funded project VMAP and its use cases
- Integrative simulation chain for virtual product development
- Goals of use case “Fatigue”

2 Weld lines in short fiber-reinforced thermoplastics
- Weld lines and effects on strength
- Approach to consider weld lines in fatigue lifetime assessment

3 Material characterization
- Influence of fiber orientation
- Fatigue behavior of weld lines in AdBlue

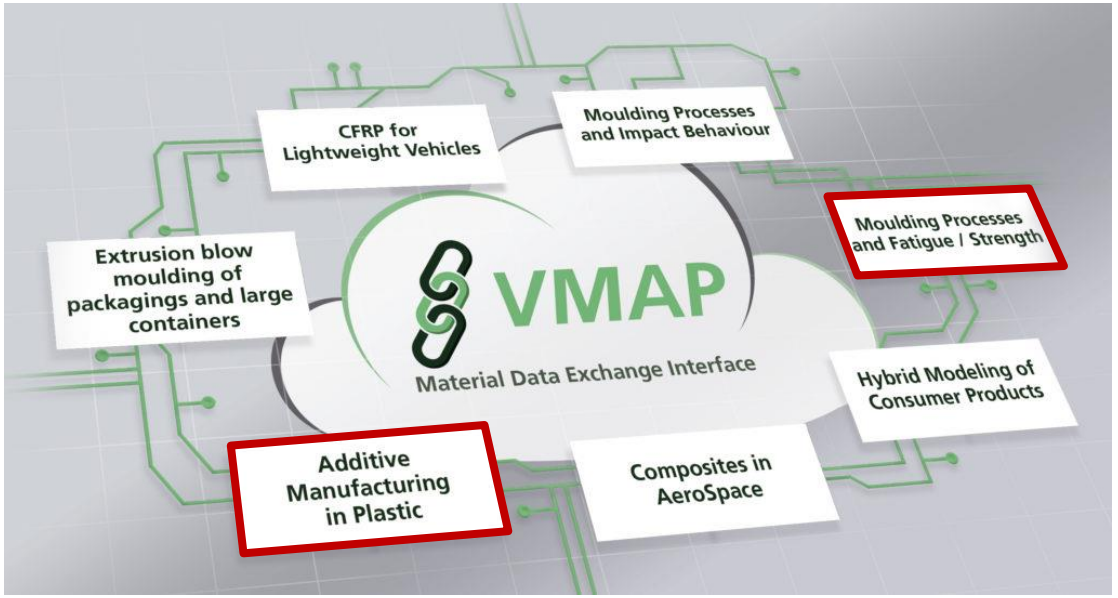
4 Fatigue lifetime assessment
- Simulation workflow
- Failure in bulk vs. failure at weld line

5 Concept validation on demonstrator

6 Summary and outlook

Fatigue behavior of weld lines for short fiber-reinforced plastics
Introduction: VMAP – industrial use cases

- Robert Bosch is participating in two use cases
  - Use case 2.3: (Injection) Molding Processes
  - Use case 2.4: Additive Manufacturing in Plastics



- Use case 2.3 is divided into sub use cases
  - Presentation focuses on sub-use case “Fatigue”

Use case 2.3
Molding Processes

- Use case 2.3.1 Impact
- Use case 2.3.2 Foaming
- **Use case 2.3.3 Fatigue**
- Use case 2.3.4 Anisotropic Creep

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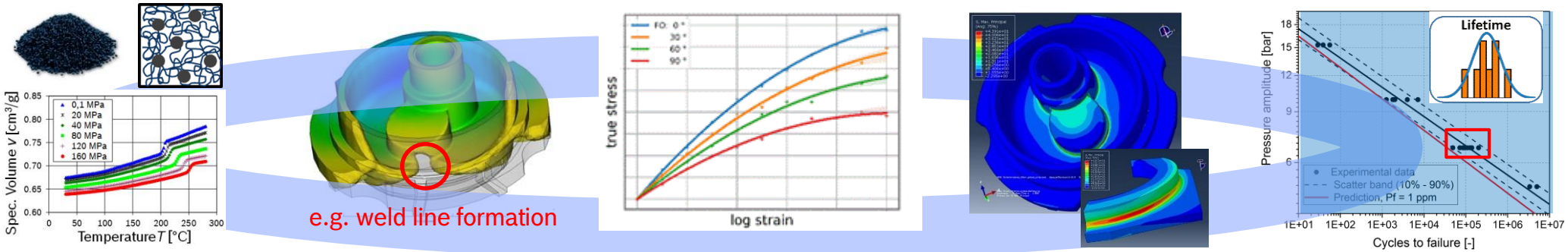
Fatigue behavior of weld lines for short fiber-reinforced plastics

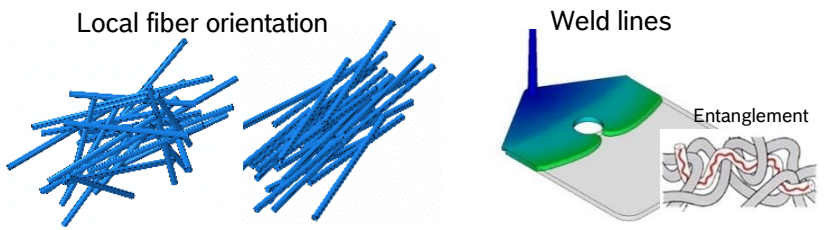
Integrative simulation chain for virtual product development

Virtual Material Characterization | ***Virtual Production Process*** | ***Local Material Behavior*** | ***Stress and Strain Analysis*** | ***Reliability Assessment***



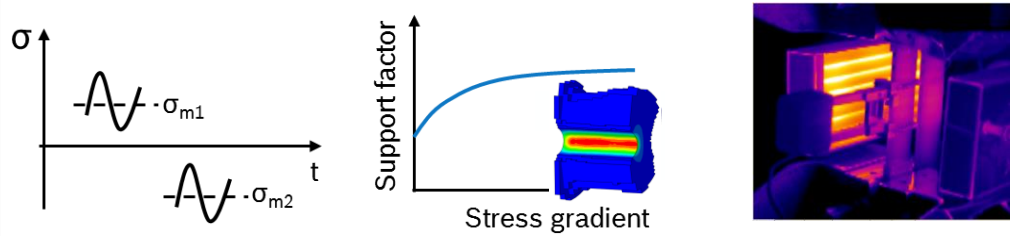
Material, Process and Design Optimization

Material and production process



Microstructure & surface

Load, design and environment



Mean stress | **Notches & fillet radii** | **Temperature** | **Medium**

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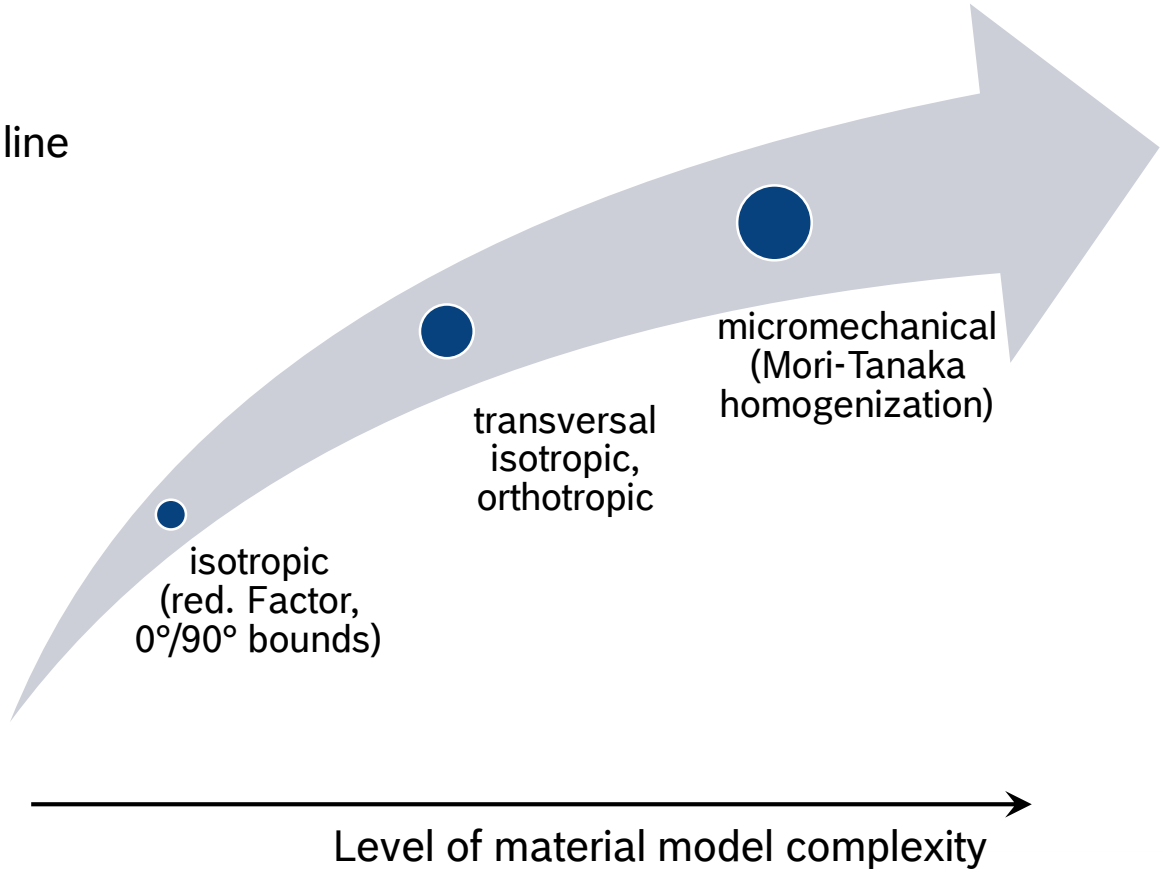
Fatigue behavior of weld lines for short fiber-reinforced plastics

Introduction: goals of use case “Fatigue”

Goals of use case “Fatigue”

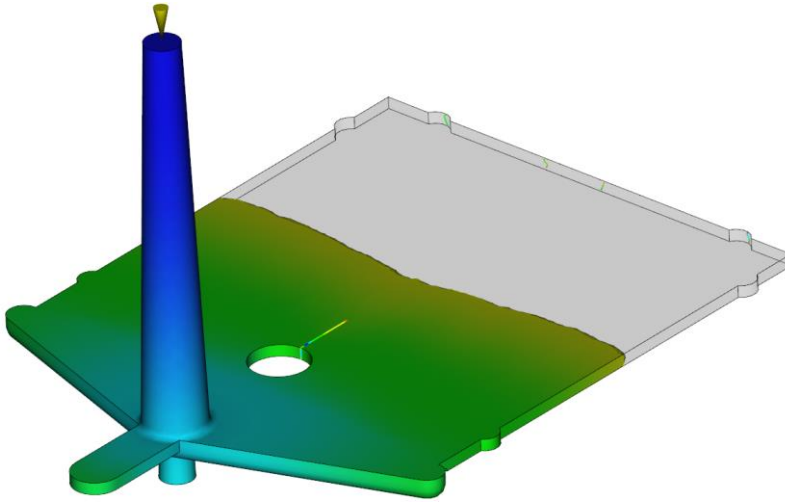
- Consider weld lines in fatigue lifetime assessment
- Evaluate, whether failure will occur in bulk or at weld line
- Simplify simulation chain
  - keep similar accuracy
  - use standard material models
  - as simple as possible and as complex as necessary



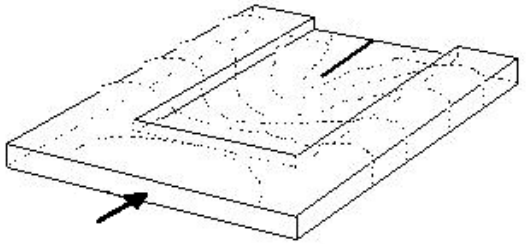
Fatigue behavior of weld lines for short fiber-reinforced plastics

Weld lines: how do they arise?

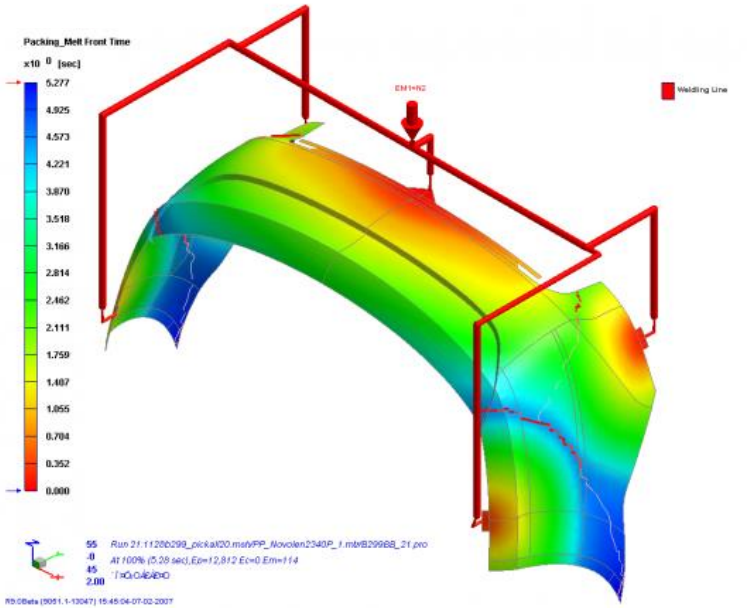
OBSTRUCTION



DIFFERENT WALL THICKNESSES

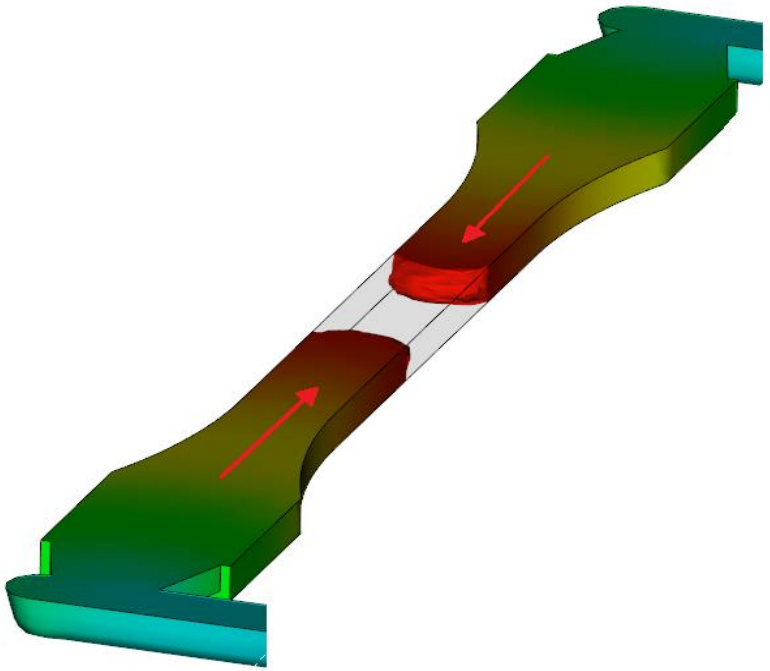


MULTIPLE GATING

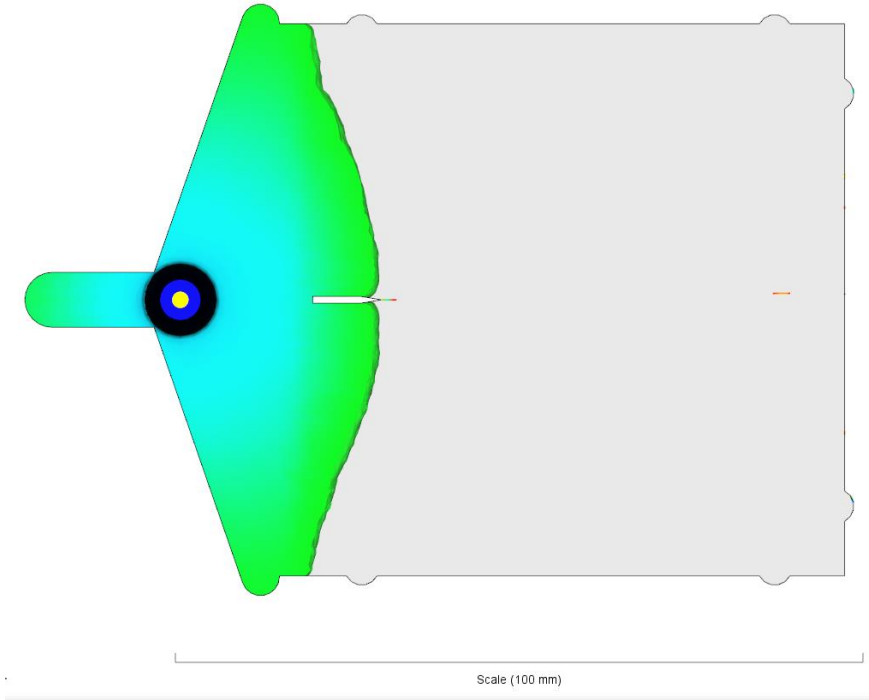


Fatigue behavior of weld lines for short fiber-reinforced plastics
Frontal vs. flowing weld lines

FRONTAL WELD LINE

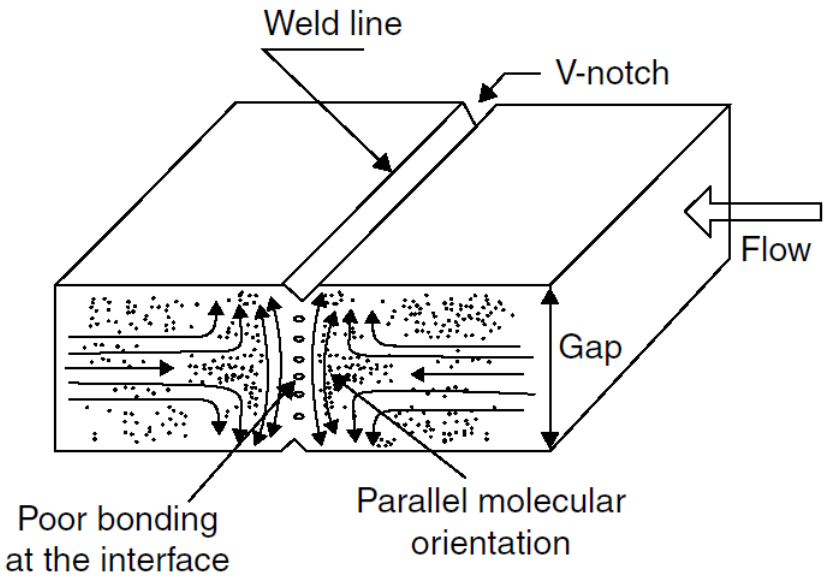


FLOWING WELD LINE



Fatigue behavior of weld lines for short fiber-reinforced plastics

Factors affecting weld line strength



i. Bonding at the interface


perfect


partial/poor

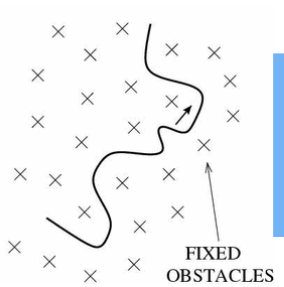

none

ii. Molecular/fiber orientation

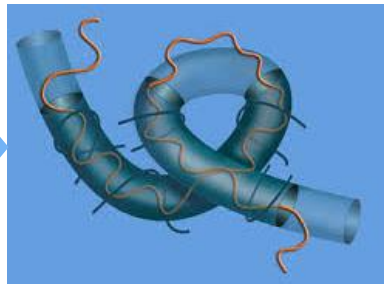
iii. V-notch at the surface

Fatigue behavior of weld lines for short fiber-reinforced plastics
Degree of bonding at the interface (weld line quality)

- Assumption: no fibers crossing the weld line surface
- The degree of bonding at the interface depends solely on matrix healing occurring at temperature above $T_{crystallization}$ for semi-crystalline polymers
- Matrix healing: determined by the inter-diffusion of the polymer chains at the weld line surface
- Can be described by the reptation theory*



An entangled polymer is confined into a "tube".



Initial configuration of the tube is lost after one reptation time (t_R) → i.e. It has diffused out of the "tube"

- Polymer chain can only move along the curvilinear length of the tube.
- *Reptation time*

$$t_R \propto \eta \propto M_w^{\,3}$$

$$Q_{local} = \int_{t_{contact}}^{t_{solidification}} \frac{d\tau}{t_R\left(T(\tau), P(\tau)\right)}$$

Criterion

$Q \geq 1$ **Bulk**

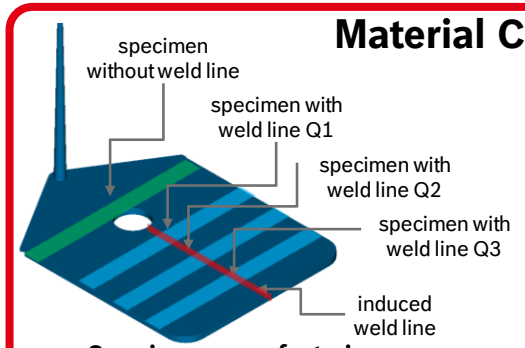
$Q < 1$ **Incomplete healing**

* De Gennes, Doi & Edwards

Fatigue behavior of weld lines for short fiber-reinforced plastics

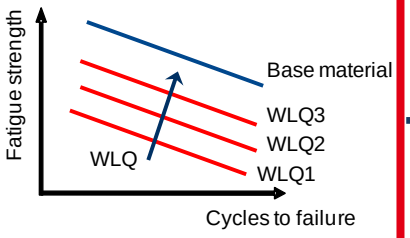
Material characterization: approach

Material Characterization



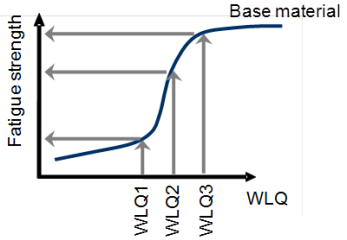
Specimen manufacturing

Fatigue testing in fuel



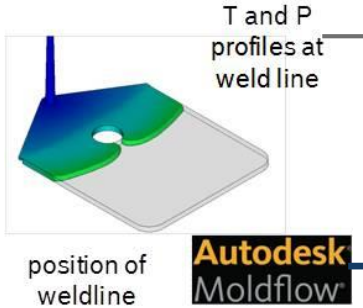
Fatigue behavior

Lifetime Assessment

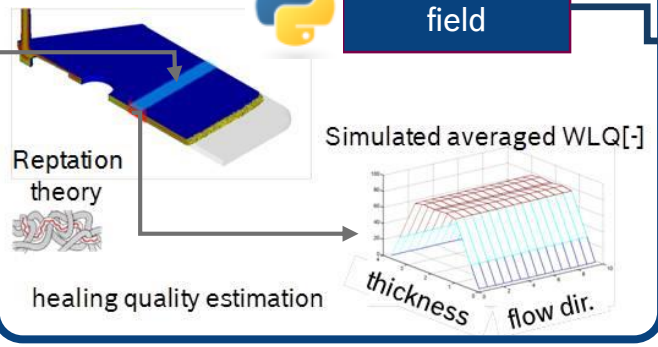


Calibration curve for WLQ

Injection Molding Simulation



Weld Line Quality Computation



Struct. Analysis

Mapping (FO, WLQ)

WL as node set

SIMULIA ABAQUS ANSYS

Focus of the presentation

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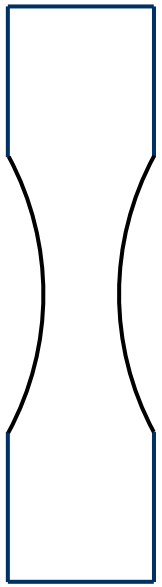
Fatigue behavior of weld lines for short fiber-reinforced plastics

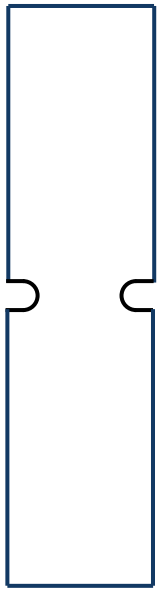
Material characterization: specimens for material characterization

Plain (PL)



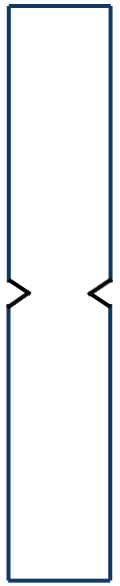
Gross width: 20
Radius: 40

Mildly Notched (MN)



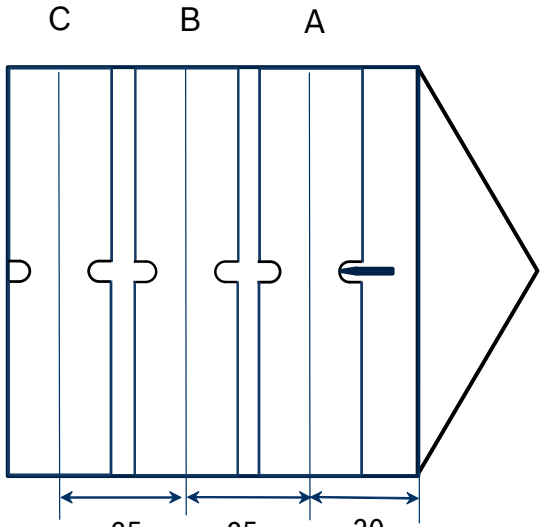
Gross width: 20
Radius: 2
Opening angle: 0°

Sharply Notched (SN)

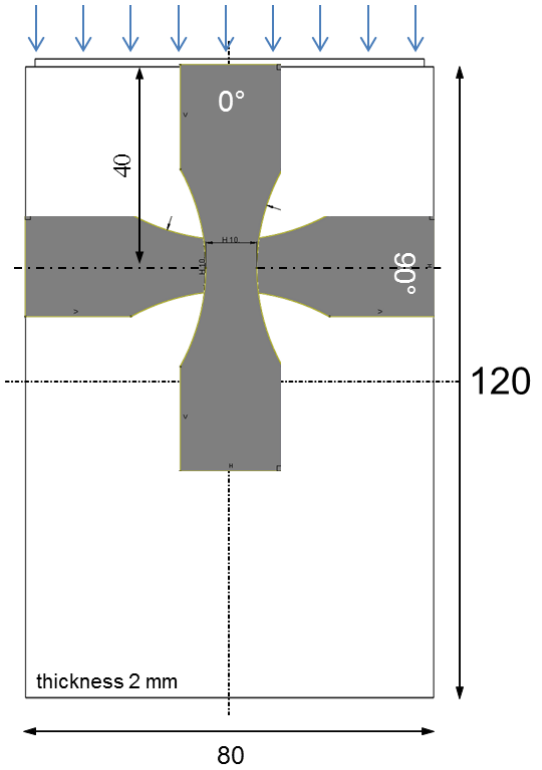


Gross width: 14
Radius: 0.1 (weld line), 0.05 (bulk)
Opening angle: 60°

Dimensions (in mm)
Length: 80
Thickness: 2
Net width: 10



Plates for investigation of anisotropy



Specimens milled out from plates

Fatigue behavior of weld lines for short fiber-reinforced plastics

Material characterization: weld line qualities

Insert	T_{mold} [°C]	Flow rate [ccm/s]	Label
MI3	160	15	Reference
MI3	160	60	Flow rate +
MI3	160	10	Flow rate -
MI3	190	15	MoldT +
MI3	130	15	MoldT -
MI3	130	10	WLQ -
MI3	190	60	WLQ +

Packing profile: 600bar-10s; T_{melt}=340°C

Fatigue behavior of weld lines for short fiber-reinforced plastics

Material characterization bulk material: influence fiber orientation

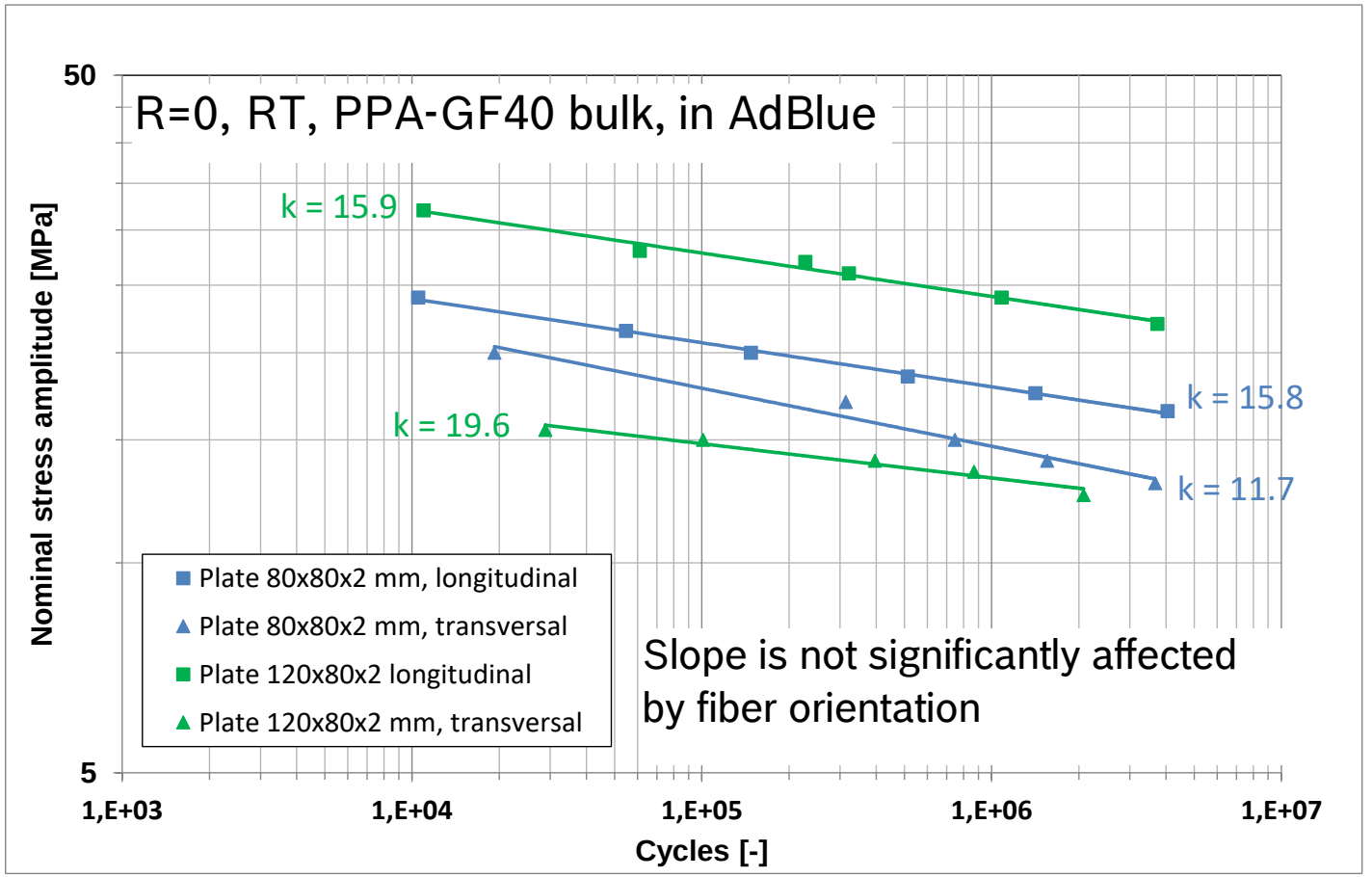


Plate 120x80x2 mm

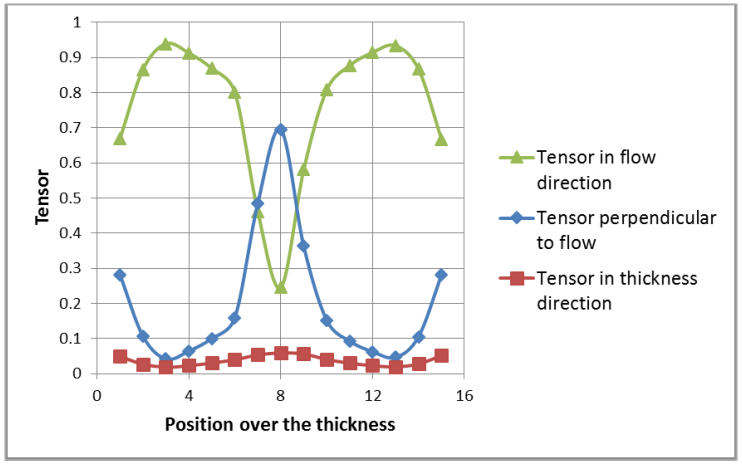
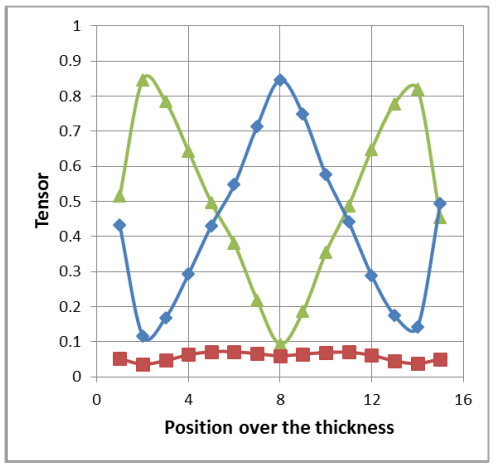


Plate 80x80x2 mm



Pre-aging: 1000 h @ 80°C in AdBlue

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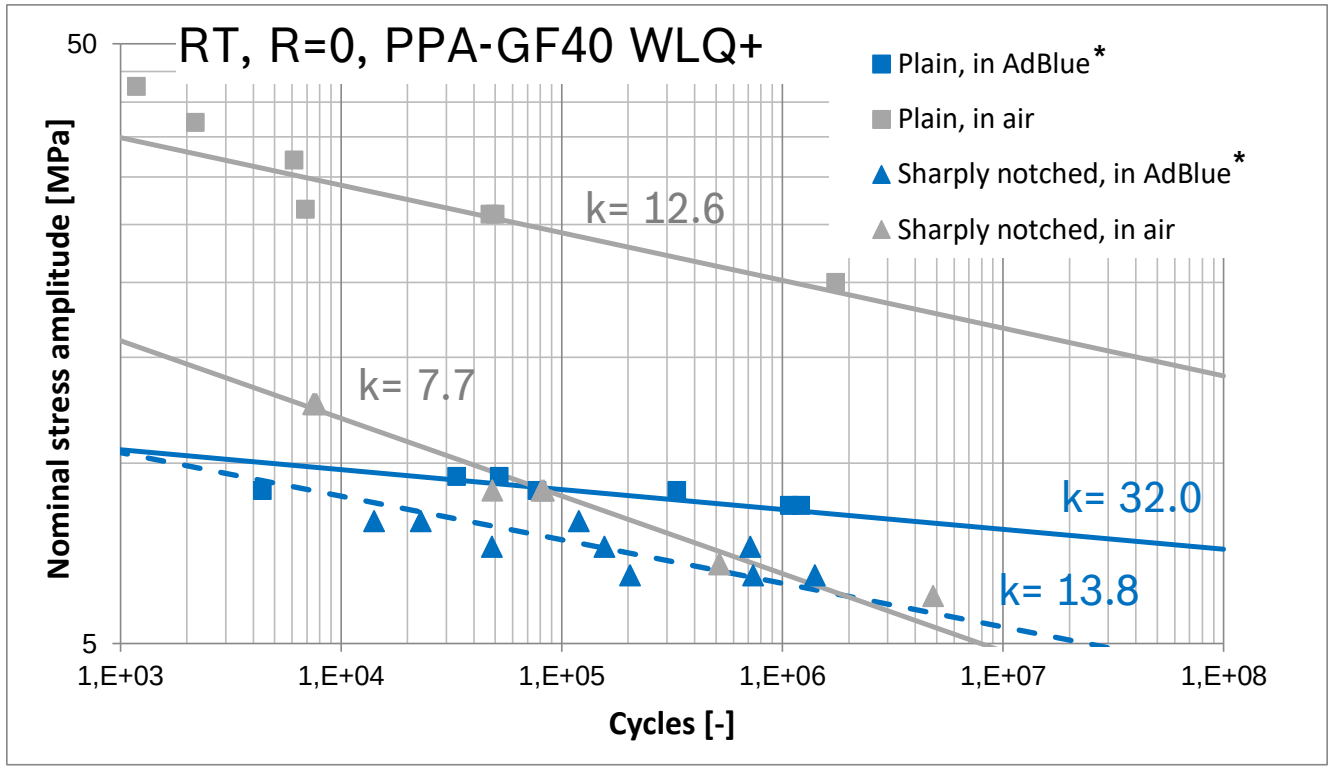
Fatigue behavior of weld lines for short fiber-reinforced plastics

Material characterization weld line: fatigue behavior AdBlue vs. air



- Scatter larger than for bulk material
- Behavior in air:
  - Very pronounced notched sensitivity (strength decrease at N=106 cycles by 87%
  - Steeper S-N curve for notched specimes
- Behavior in AdBlue:
  - Plain specimen: fatigue strength at N=106 cycles decreases by 70% in AdBlue
  - Notched specimen: similar fatigue strength at N=106 cycles in AdBlue and in air
  - Notch sensitivity in AdBlue strongly reduced compared to air
- Fatigue curves in AdBlue are flatter than in air → compressive residual stresses due to increased local swelling at the

Strong influence of AdBlue for plain specimens, slight influence for notched specimens
Notch sensitivity in AdBlue strongly reduced compared to air

* Pre-aging: 1000 h @ 80°C in AdBlue WLQ: Weld Line Quality

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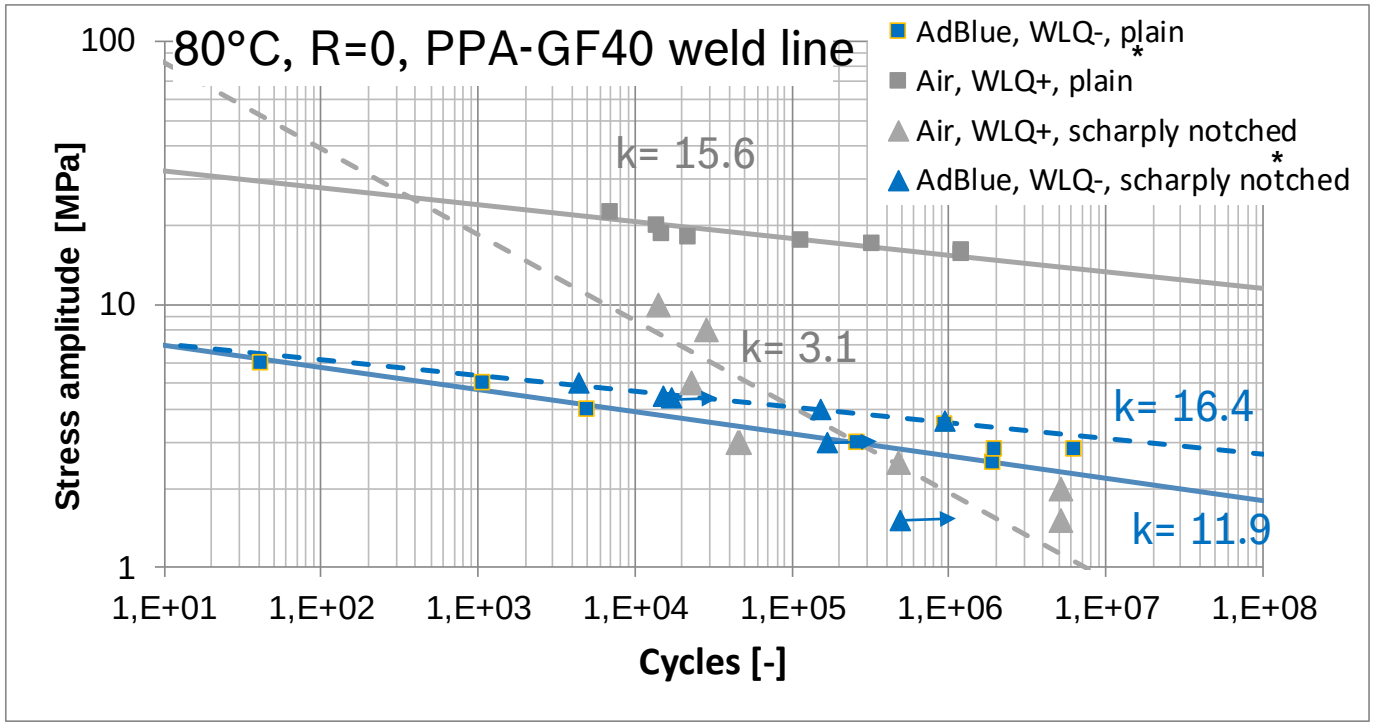
Fatigue behavior of weld lines for short fiber-reinforced plastics

Material characterization weld line: fatigue behavior AdBlue vs. air



- Scatter larger than for bulk material, observed also at 80°C
- Influence of temperature:
  - S-N curves are steeper than at RT
  - Notch influence is still very pronounced in air
  - Very steep curve for notched specimens in air
- Fatigue curves in AdBlue are flatter than in air → compressive residual stresses due to increased local swelling at the notch tip?

S-N curves at 80°C are steeper than at RT
Anomalous behavior of notched specimens in AdBlue

* Pre-aging: 1000 h @ 80°C in AdBlue

** weld line qualities in air and AdBlue are different

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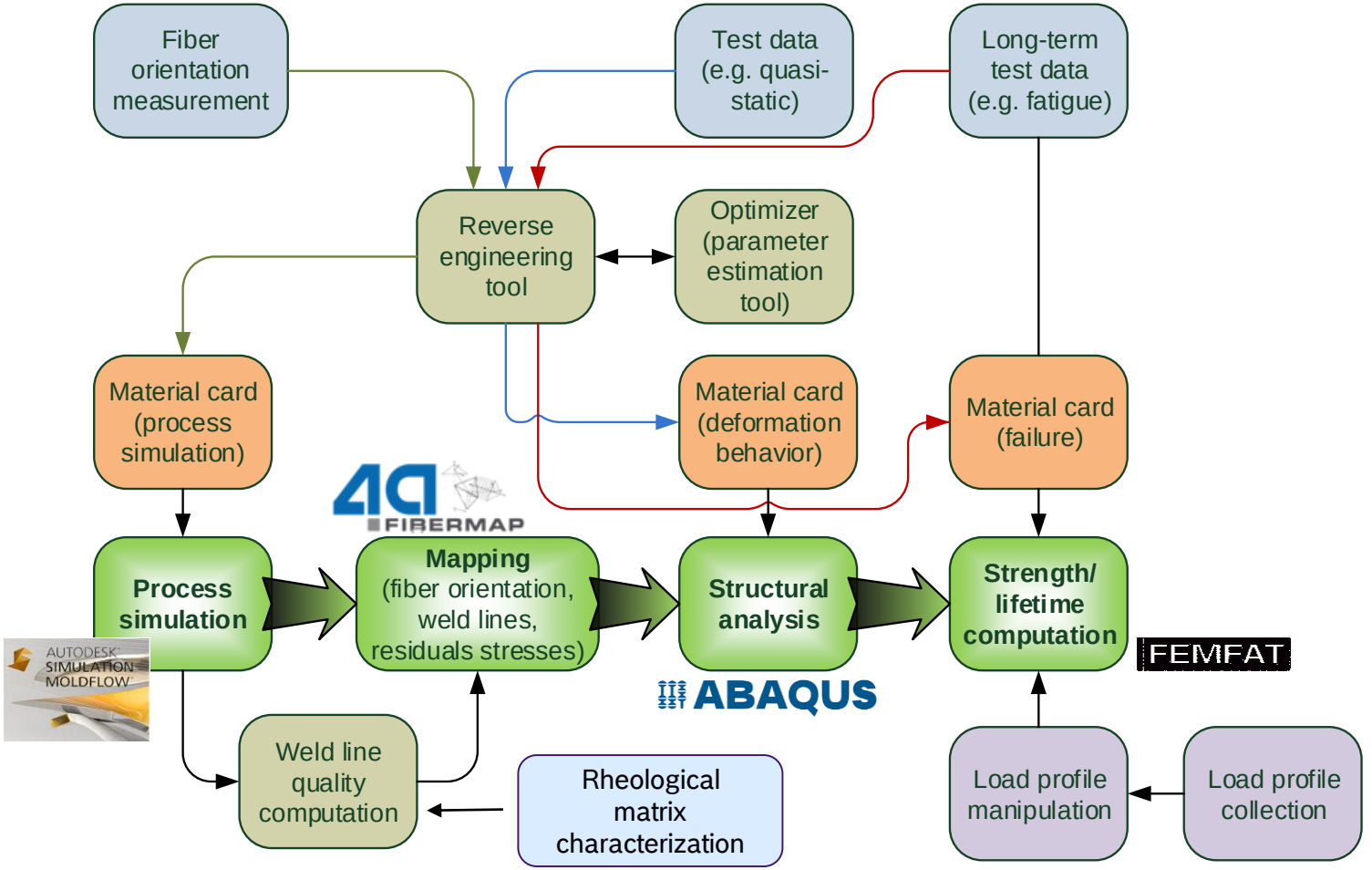
Fatigue behavior of weld lines for short fiber-reinforced plastics

Fatigue lifetime assessment: simulation workflow

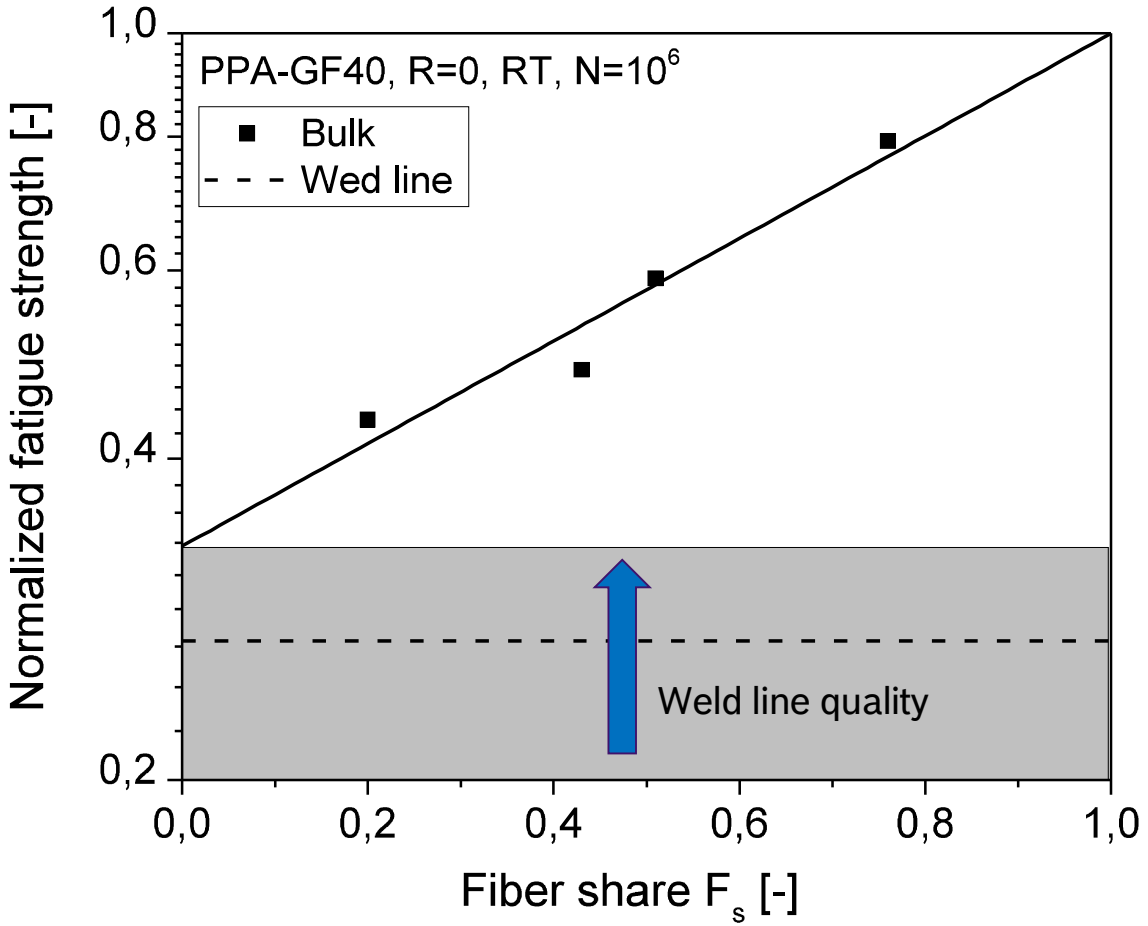


Considerations

- Rheological matrix characterization necessary for assessment of weld line quality
- Structural analysis: anisotropic linear-elastic (material model by Mori-Tanaka homogenization)
- Separate material characterization for fatigue behavior of bulk and weld line necessary
- Influences considered in fatigue
  - Support effect (stress concentrations)
  - Load ratio by Haigh diagram
  - Temperature by potential function

Fatigue behavior of weld lines for short fiber-reinforced plastics

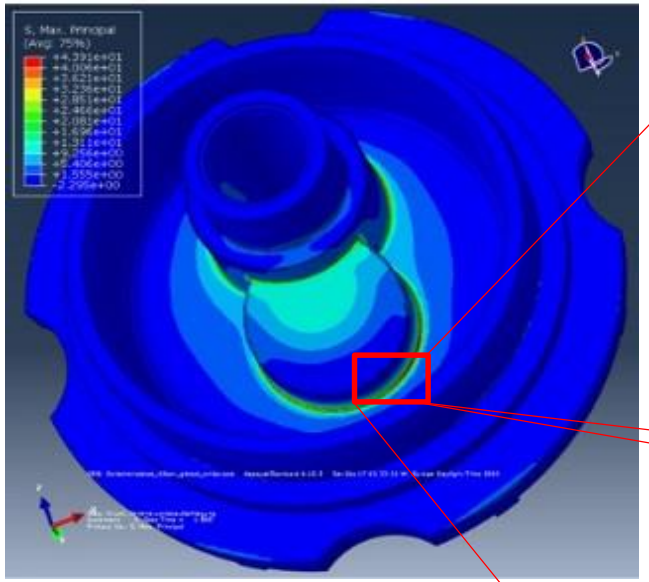
Fatigue lifetime assessment: fatigue strength bulk vs. weld line

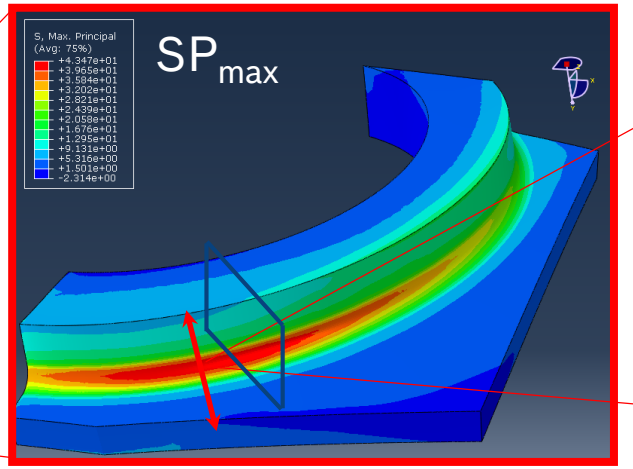


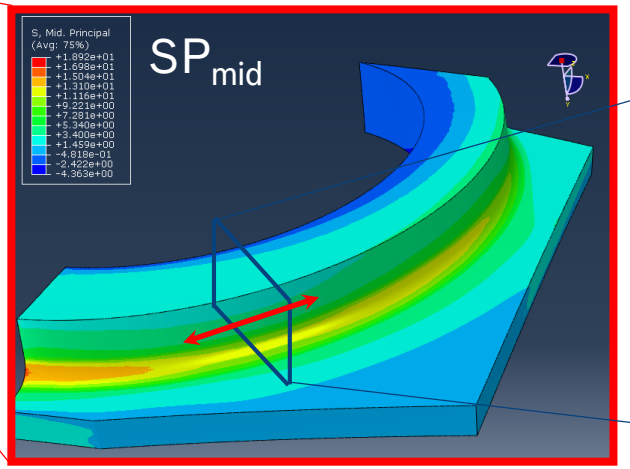
- A strength decrease up to 67% can result from a fiber orientation according to fiber share calibration curve.
- Weld line strength can however be even lower than perfectly transversally oriented specimens.
- A separate consideration of weld lines is necessary for safe design and dimensioning of parts.
- Material and process parameters play a key role regarding weld line strength.

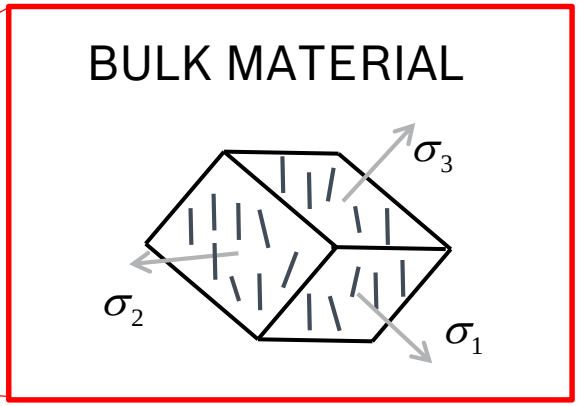
Fatigue behavior of weld lines for short fiber-reinforced plastics

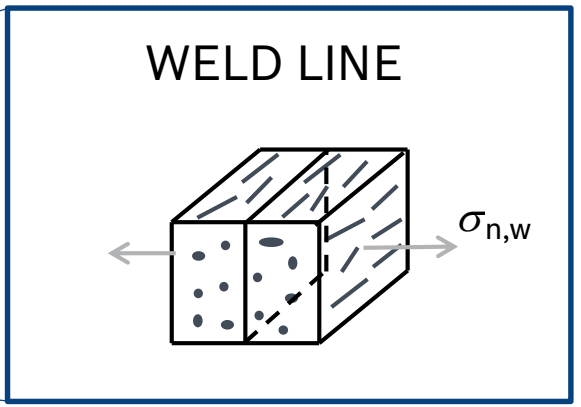
Fatigue lifetime assessment: failure assessment bulk vs. weld line



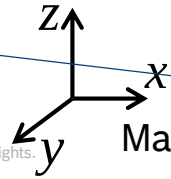








- Stress concentration occurs in proximity of weld line
- Two possible failure modes:
  - Bulk failure
  - Weld line



Material coordinate system

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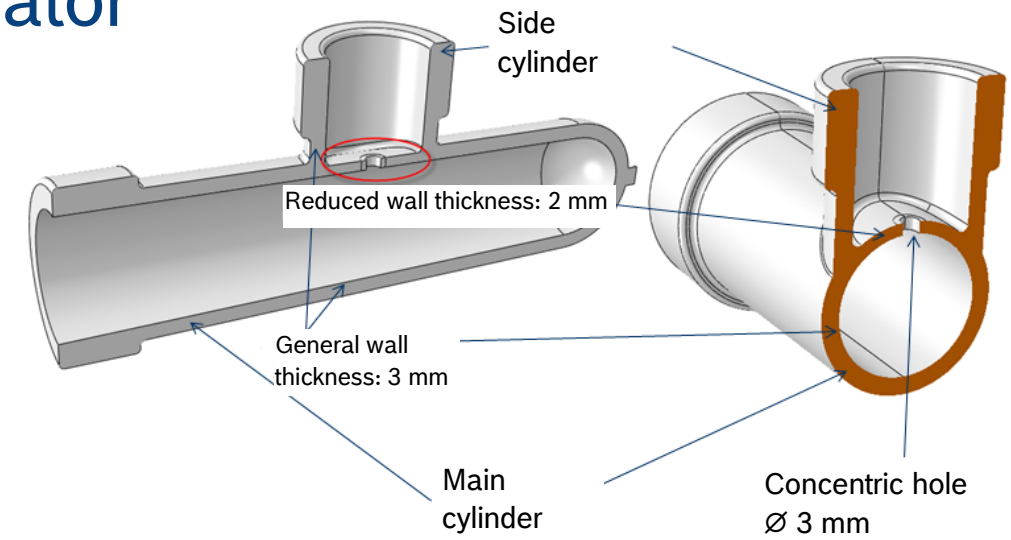
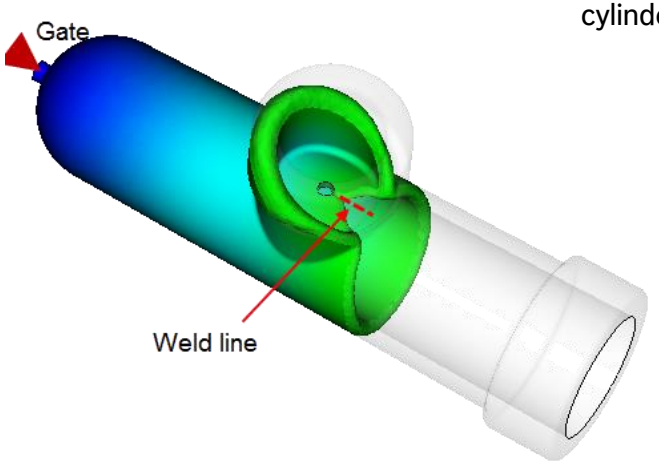
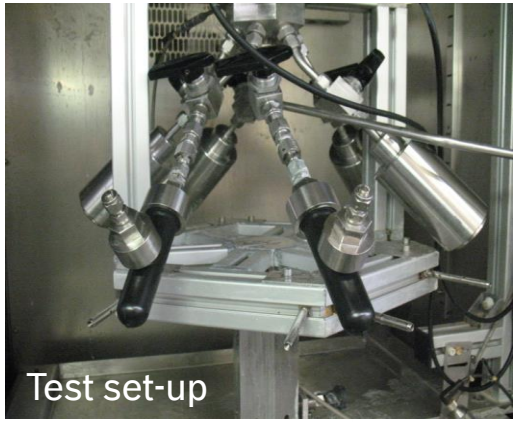
Fatigue behavior of weld lines for short fiber-reinforced plastics

Concept validation on demonstrator

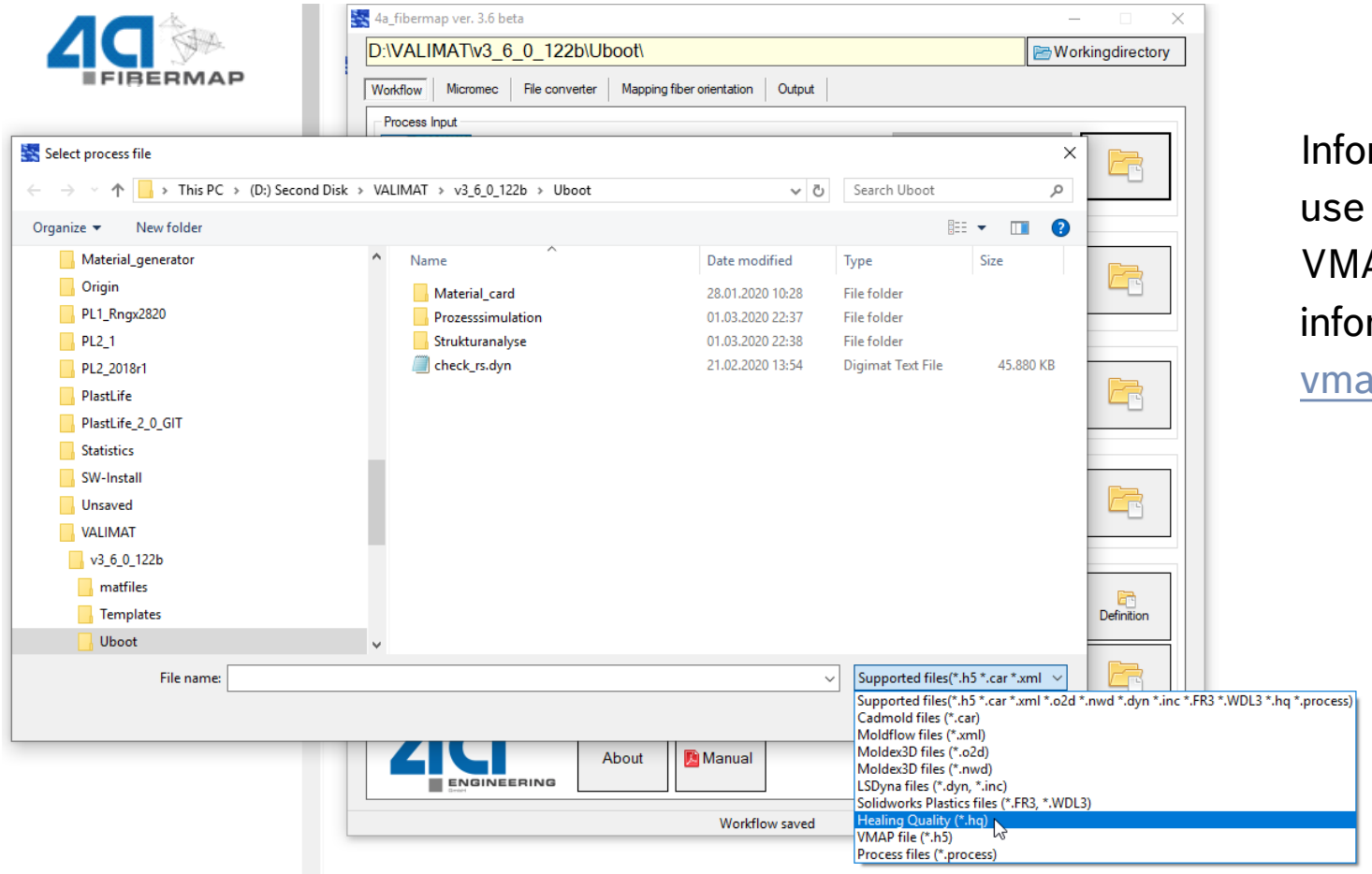
- Demonstrator: submarine specimen
- Weld line created by circular insert
- Testing conditions
  - Pulsating inner-pressure
  - Max. pressure level: 10 – 46 bar
  - Simultaneous testing of up to 6 parts
  - Pre-aging: 1000 h at 80°C in AdBlue
  - Medium: AdBlue
  - R = 0.1
  - T = 80 °C
  - f = 4-10 Hz (depending on pressure level)







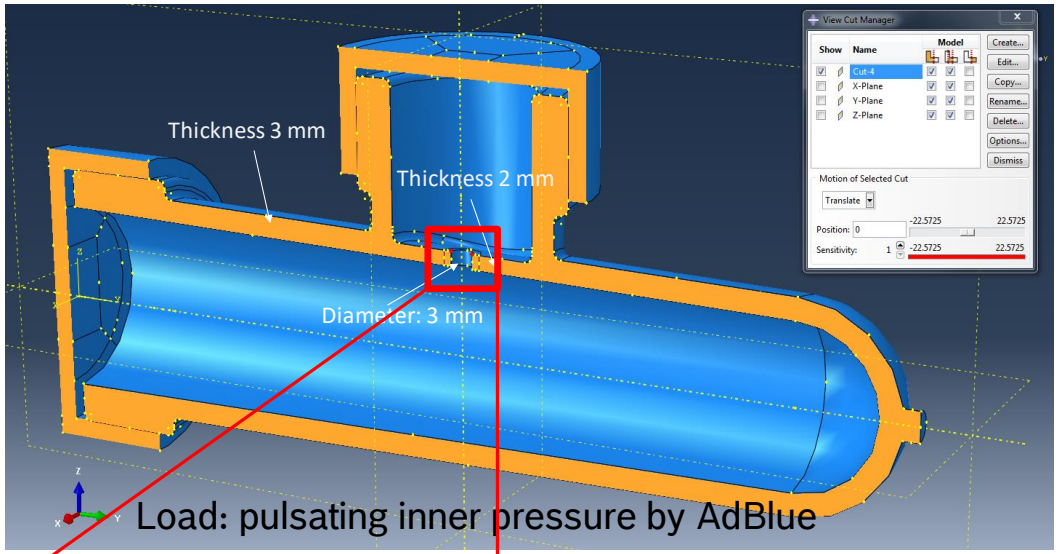
Fatigue behavior of weld lines for short fiber-reinforced plastics
Concept validation on demonstrator: healing quality in FiberMap

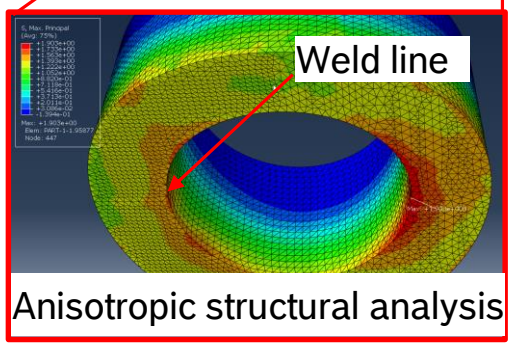


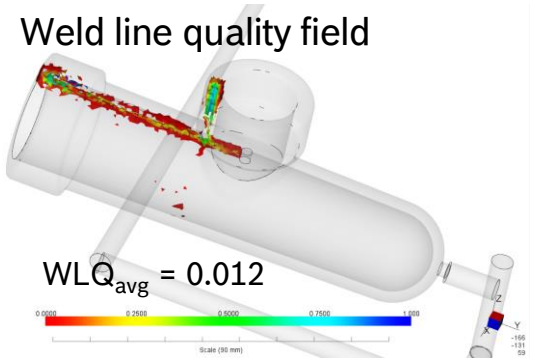
Information transferred in this use case will be included in VMAP specification (for further information refer to vmap.eu.com)

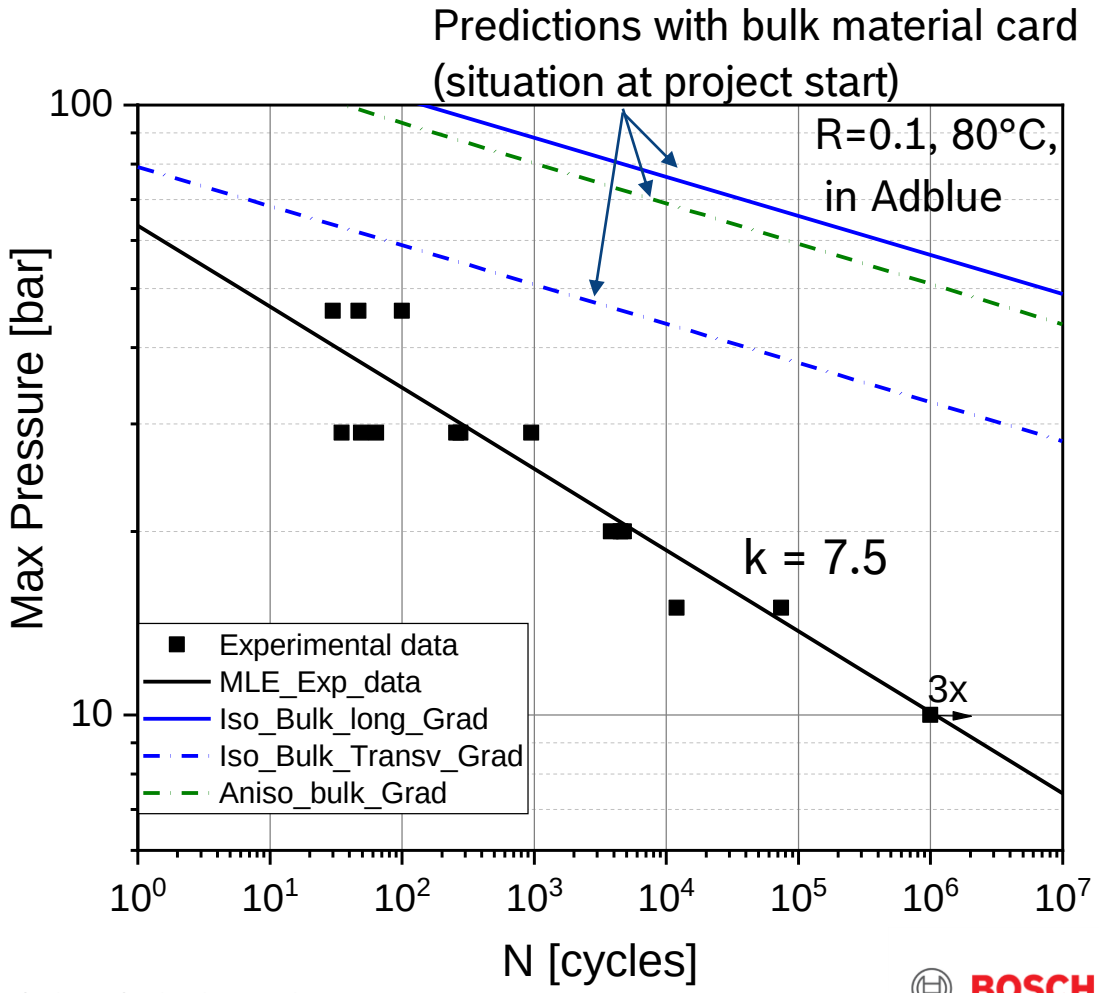
Fatigue behavior of weld lines for short fiber-reinforced plastics

Concept validation on demonstrator









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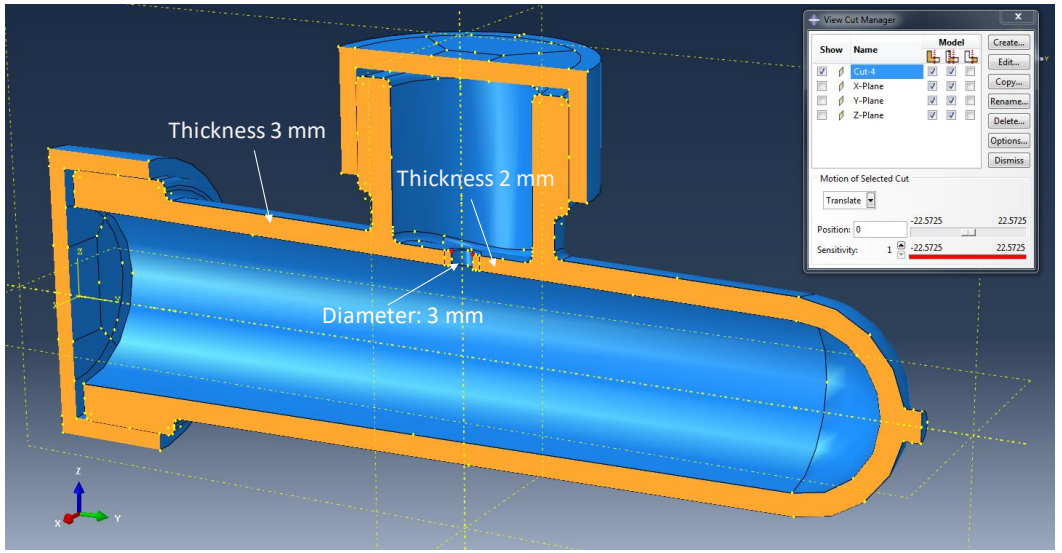
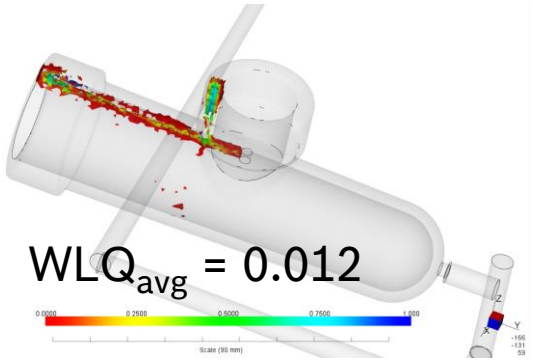
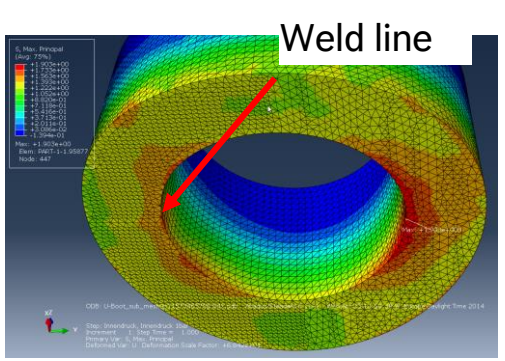
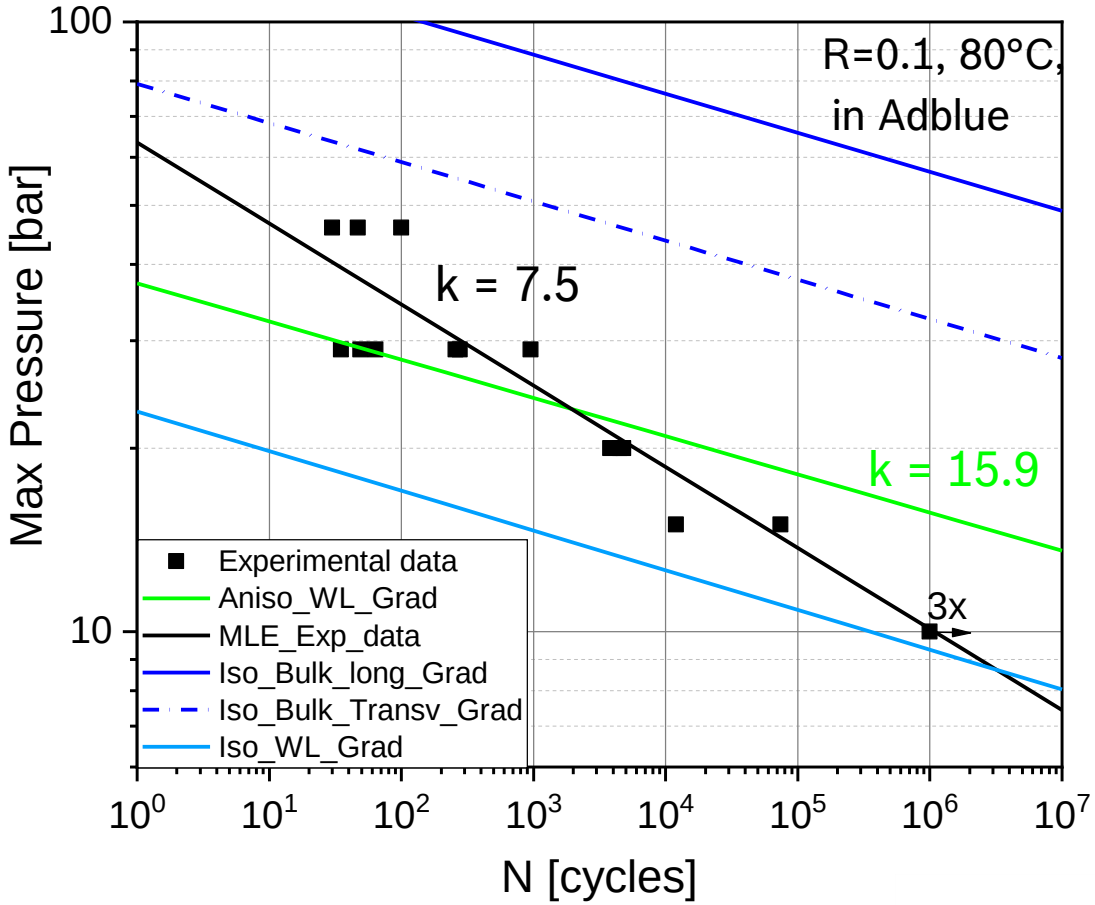
Fatigue behavior of weld lines for short fiber-reinforced plastics

Concept validation on demonstrator









Fatigue behavior of weld lines for short fiber-reinforced plastics
Summary and outlook

- Integrative simulation chain for lifetime assessment of reinforced plastics
  - Concept to consider influence of local fiber orientation and weld lines available
  - Distinction between bulk and weld line failure
  - Weld line quality can be computed by taking into account pressure and temperature history
- Fatigue behavior of PPA-GF40 weld lines
  - Higher uncertainty for material parameters compared to bulk material due to larger scatter
  - Very pronounced notched sensitivity in air (still evident at 80°C)
  - S-N curves increased support effect in case of operation in AdBlue environment
  - S-N curves at 80°C significantly steeper than at RT
- Concept validation (preliminary)
  - Substantial accuracy improvement in lifetime assessment compared to situation of project start
  - Improvement on prediction of slope of S-N curve necessary
  - Further validation on submarine demonstrators with enhanced weld line quality planned
  - Extension to other simulations workflows (Ansys, other approaches to consider anisotropy, ...) planned

4A TECHNOLOGY DAYS
WERFENWENG (AUSTRIA), MARCH 3TH-4TH 2020

SIMULATION AND VALIDATION OF FATIGUE PERFORMANCE OF WELD LINES FOR SHORT FIBER-REINFORCED PLASTIC PARTS

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