Hybrid materials and conical bolts for high-strength bolted joints

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German Aerospace Center (DLR)

DLR

Outline

- Company introduction and motivation
- RAX-Connection
- Fibre Metal Laminates (FML)
- Design results
- FML infusion
- Bearing tests results

German Aerospace Center (DLR)

- 10,000 employees
- 55 research institutes and facilities
- 34 locations
- Research fields

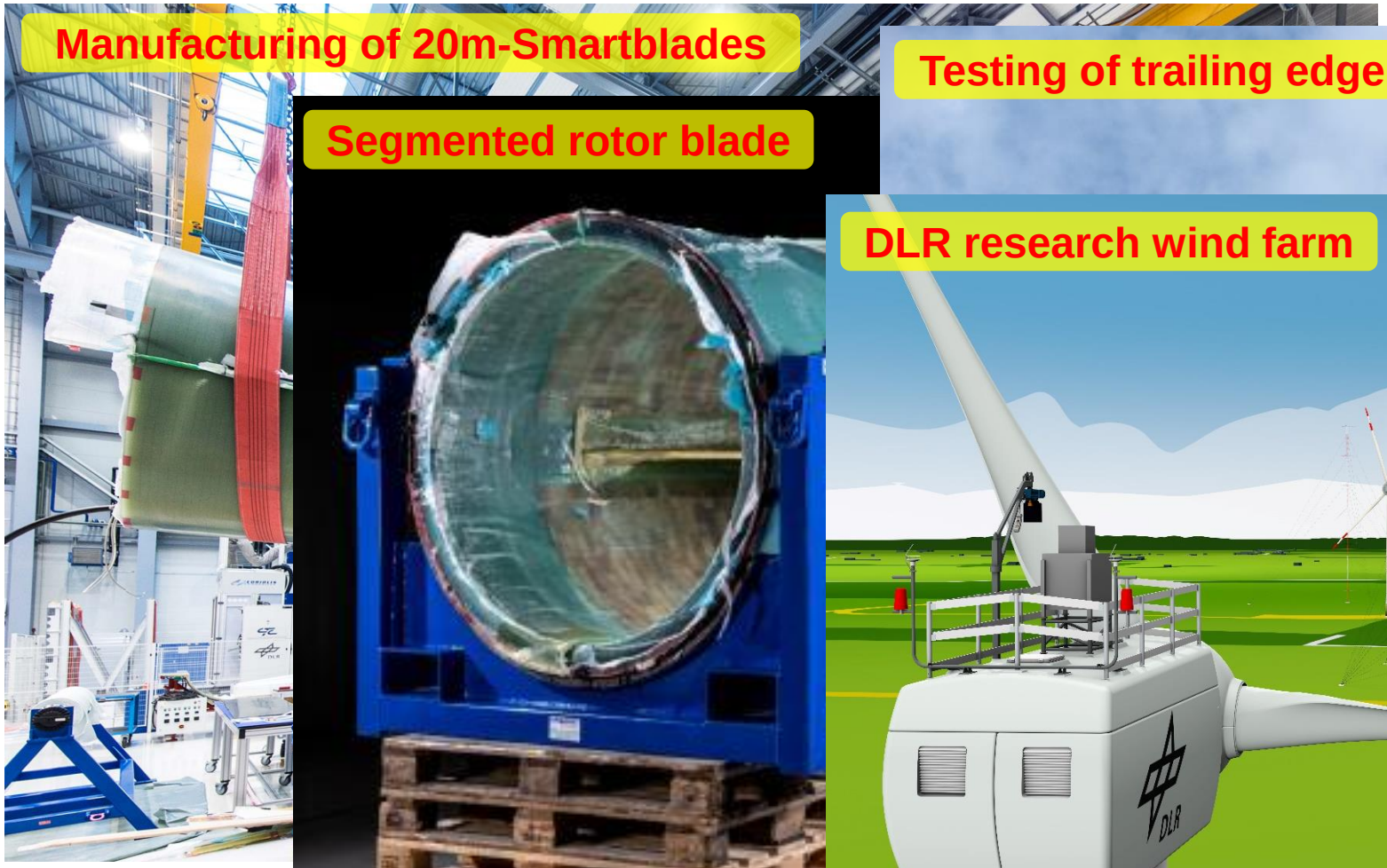
Space **Energy**

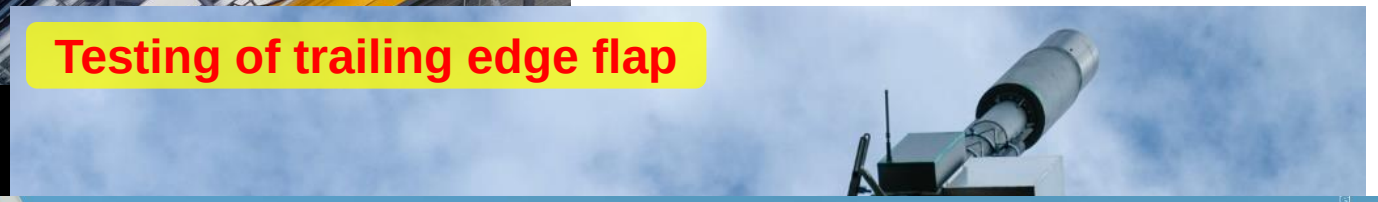
Aeronautics **Digitalisation**

Transport **Security**

- Institute of Composite Structures and Adaptive Systems
  - Braunschweig, Stade
  - 180 employees

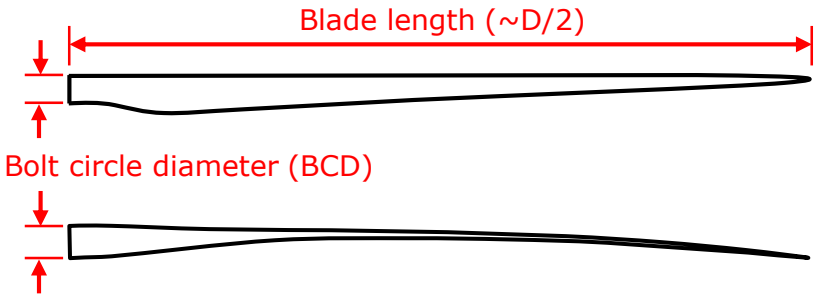
Wind Energy Research at DLR

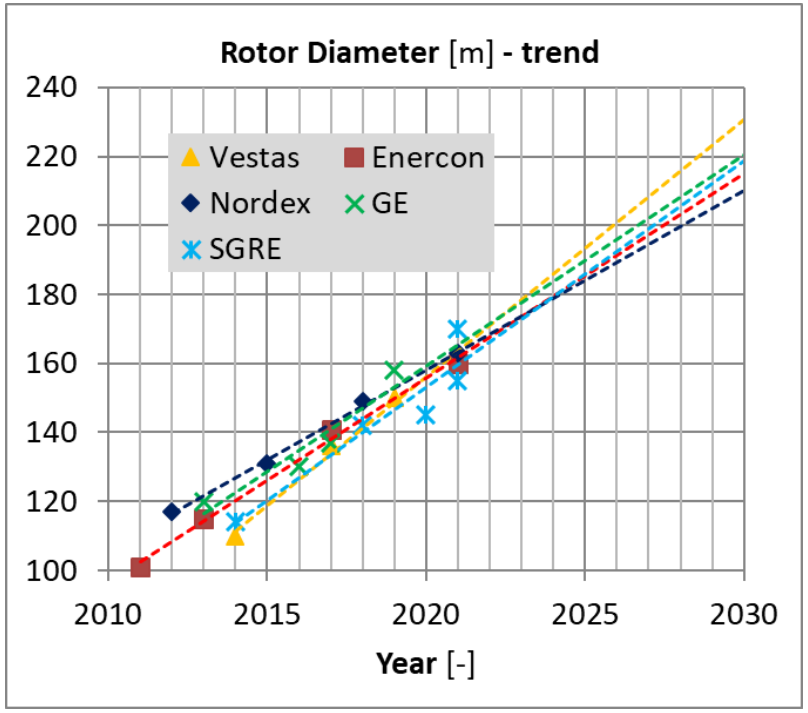


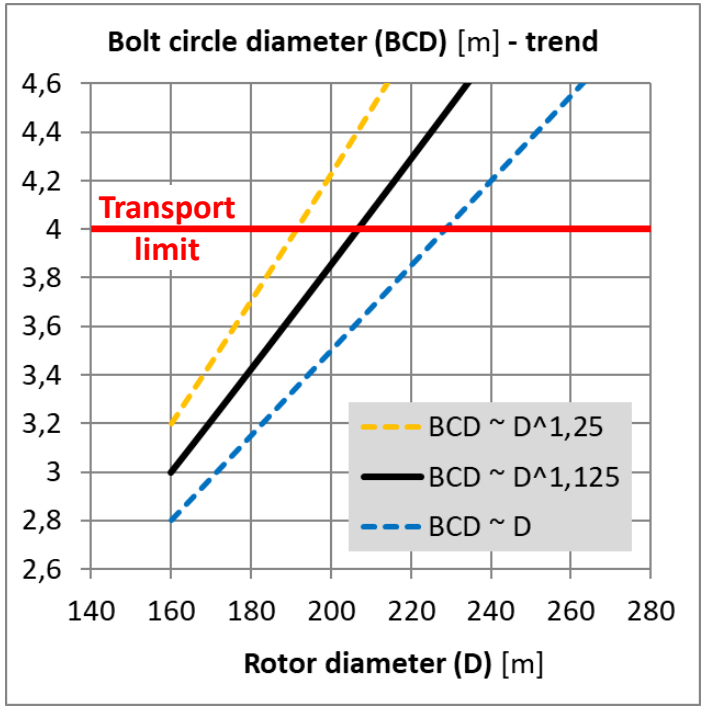


Motivation

- Onshore trend: 200 m rotors in 2026 – 2028
- Blade roots are increasing exponentially
- Onshore transportation limit: 4 m blade root

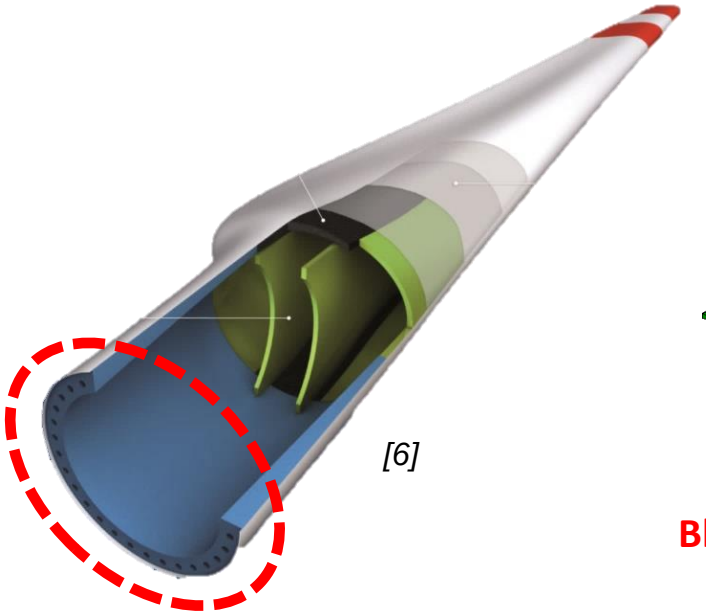


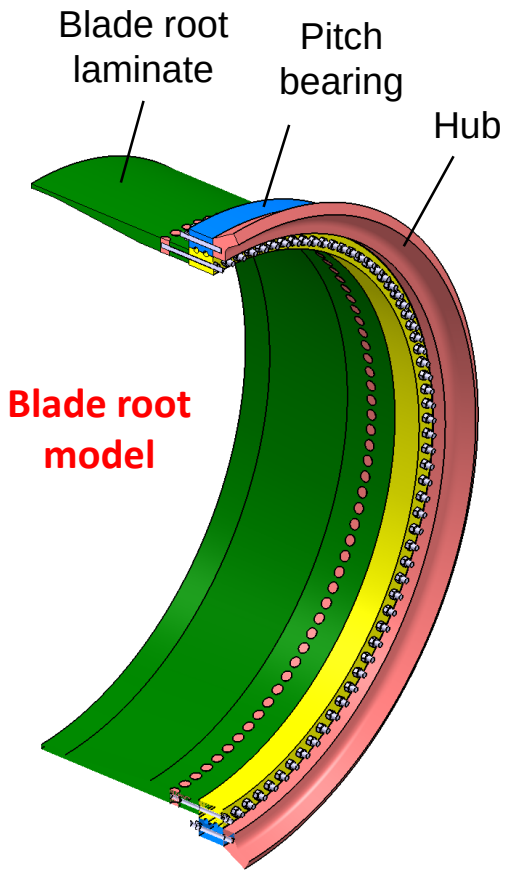




Typical bridge clearance

Blade root connection – state of the art

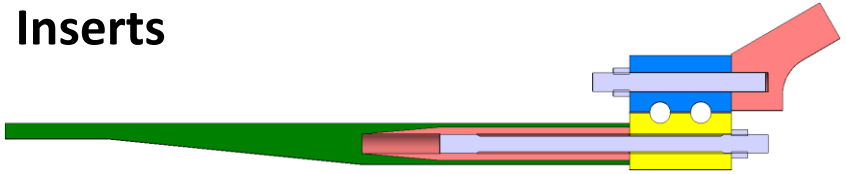




T-Bolts

- Load transfer by bolt bearing
- Simple, but limited strength

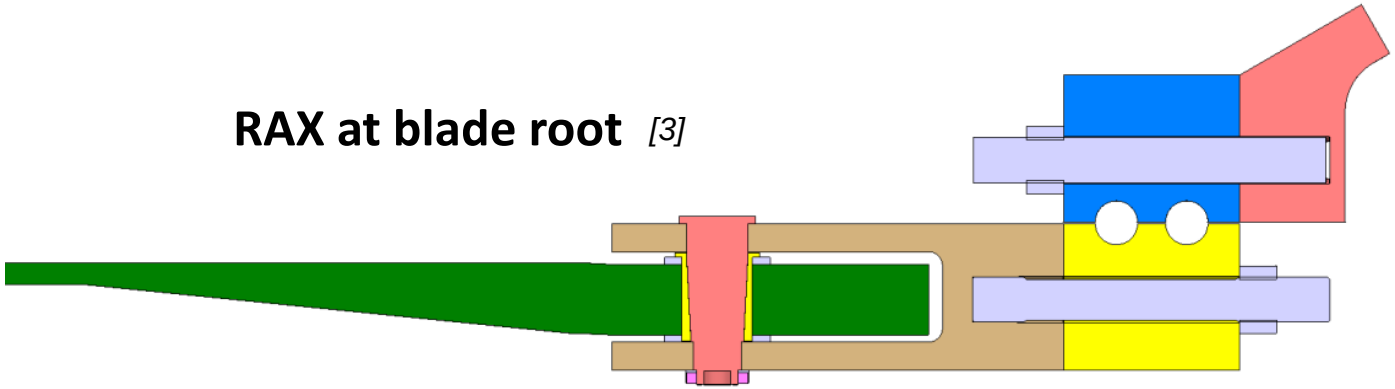
Inserts

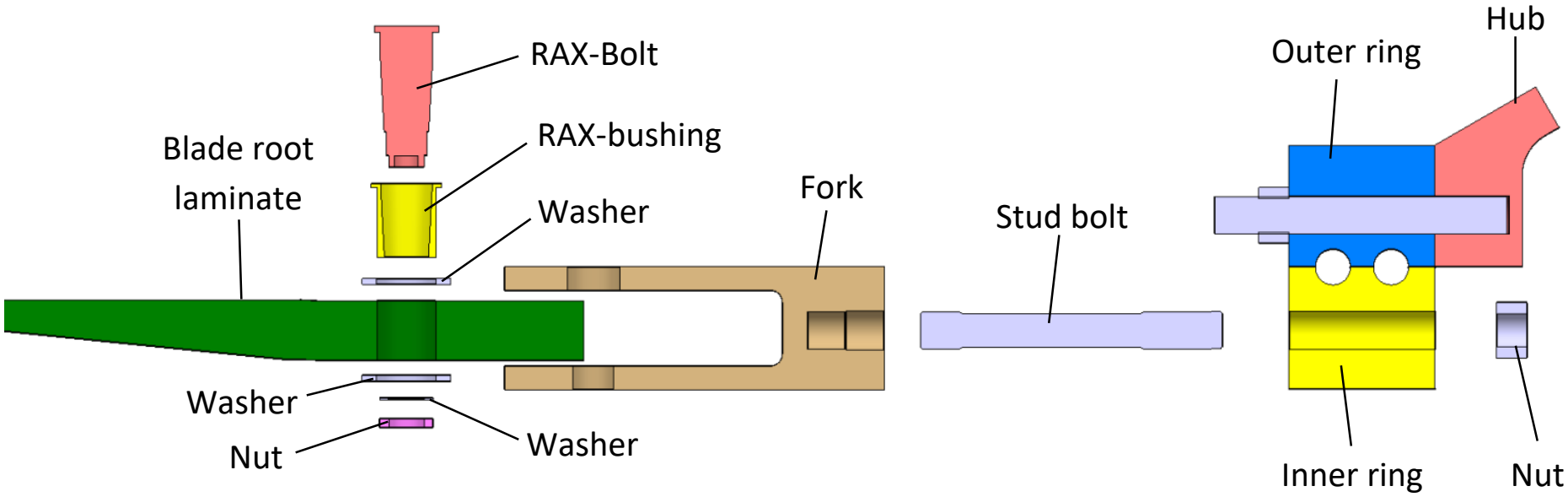


- Load transfer by (co-)bonding of insert
- Higher packing rate than T-bolts

Radial and axial pretension (RAX)

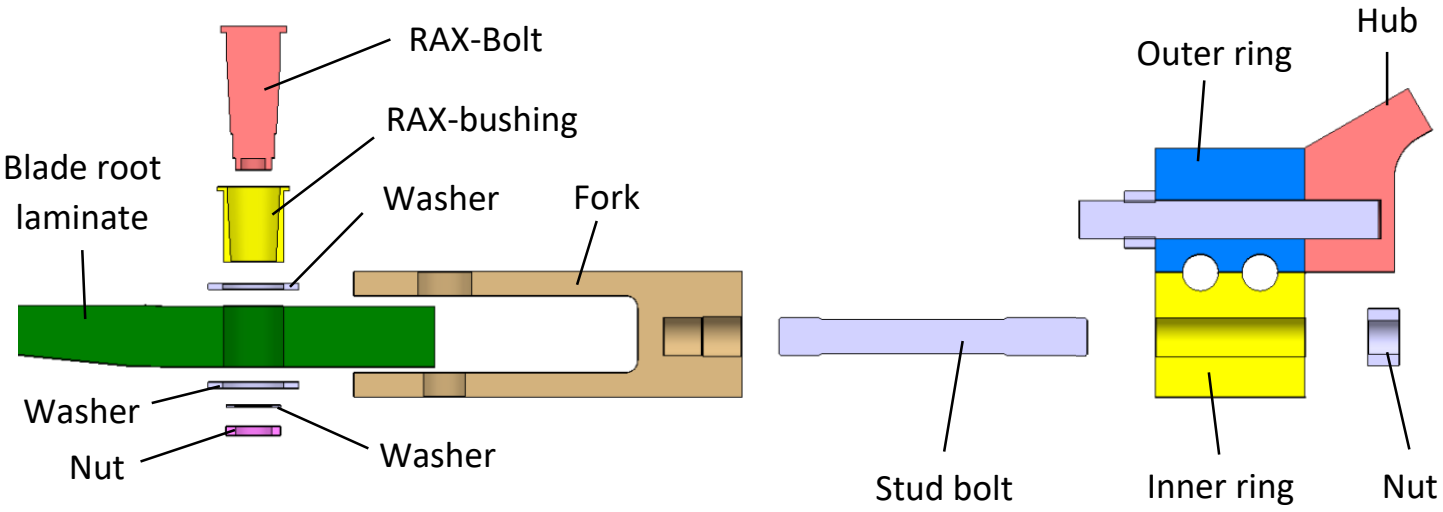
RAX at blade root *[3]*

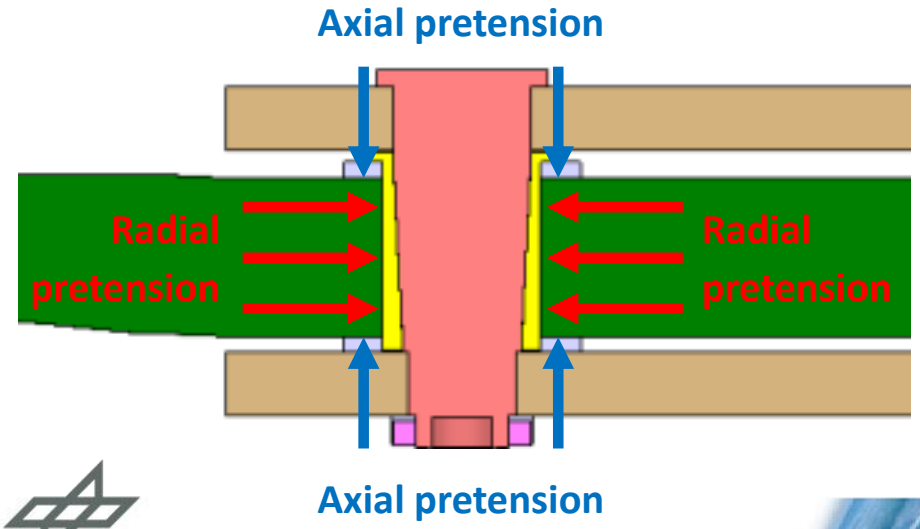


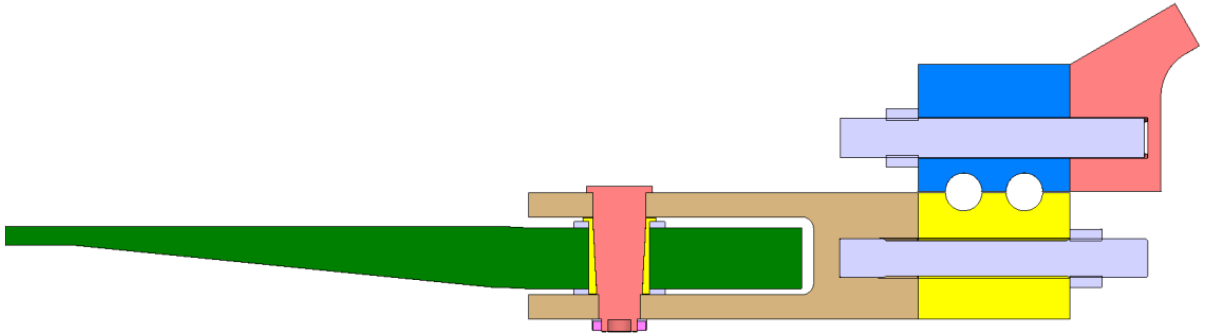


Radial and axial pretension (RAX)

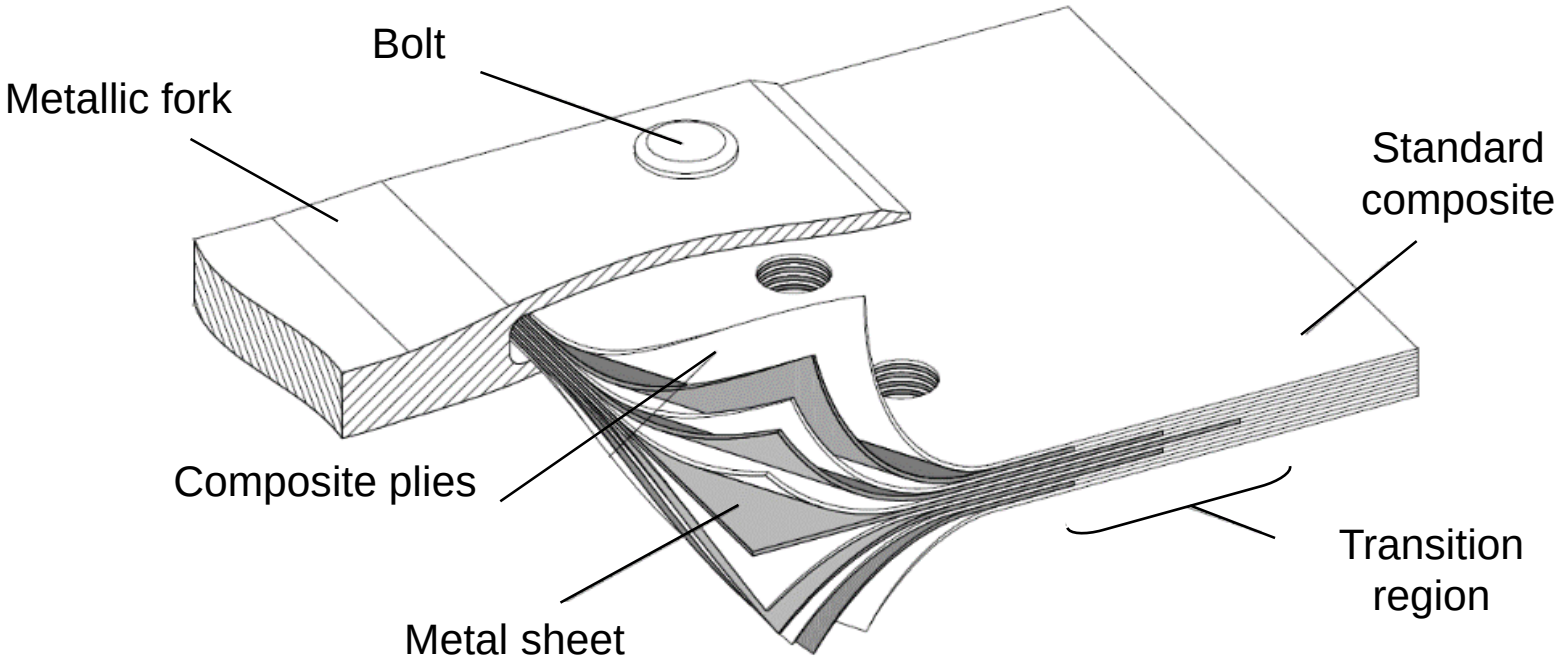
- Conical bolts and bushings introduce **radial pretension**
  - Bearing contact area is doubled
  - Fatigue strength increases
- Washers introduce **axial pretension**
  - Delamination is restrained
  - Static strength increases



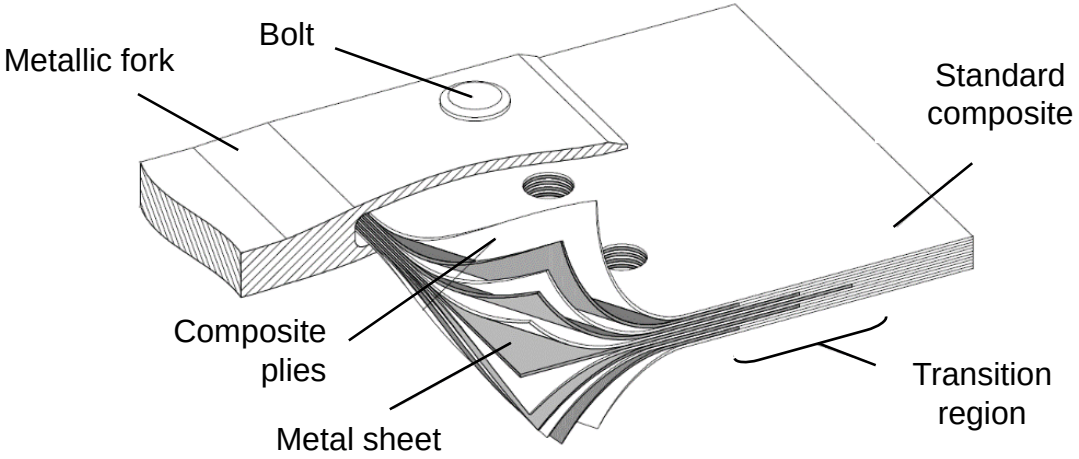




Fibre metal laminates (FML)



Fibre metal laminates (FML)

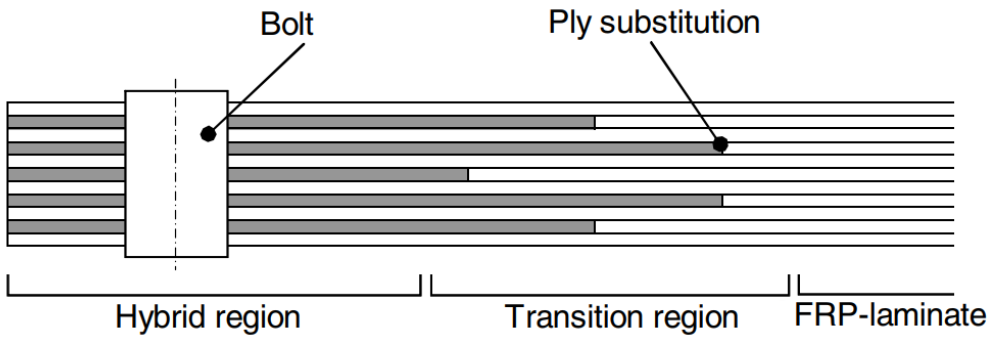


Objective

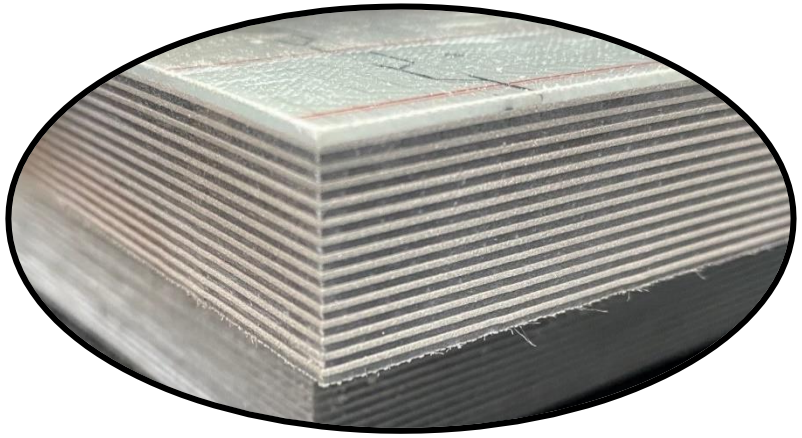
- Improve the mechanical efficiency of bolted joints
  - Strength / mass / space

Approach

- Reinforce joining area with metal (steel, titan, aluminium)
- Substitute some composite plies with metal sheets

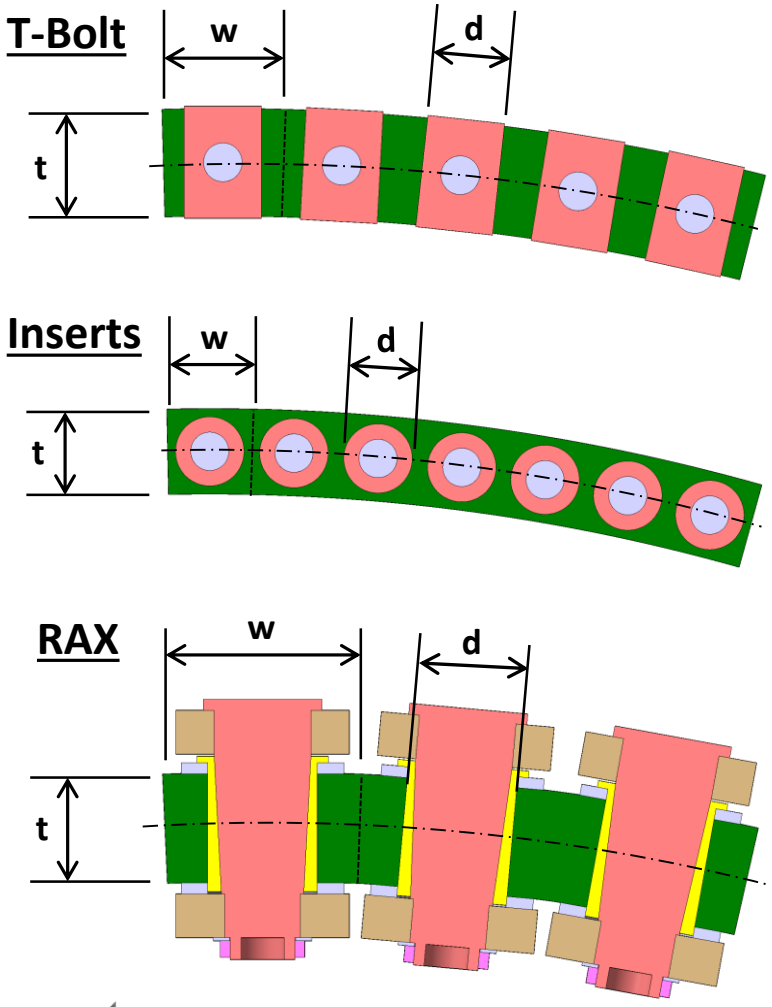


[1], [2]



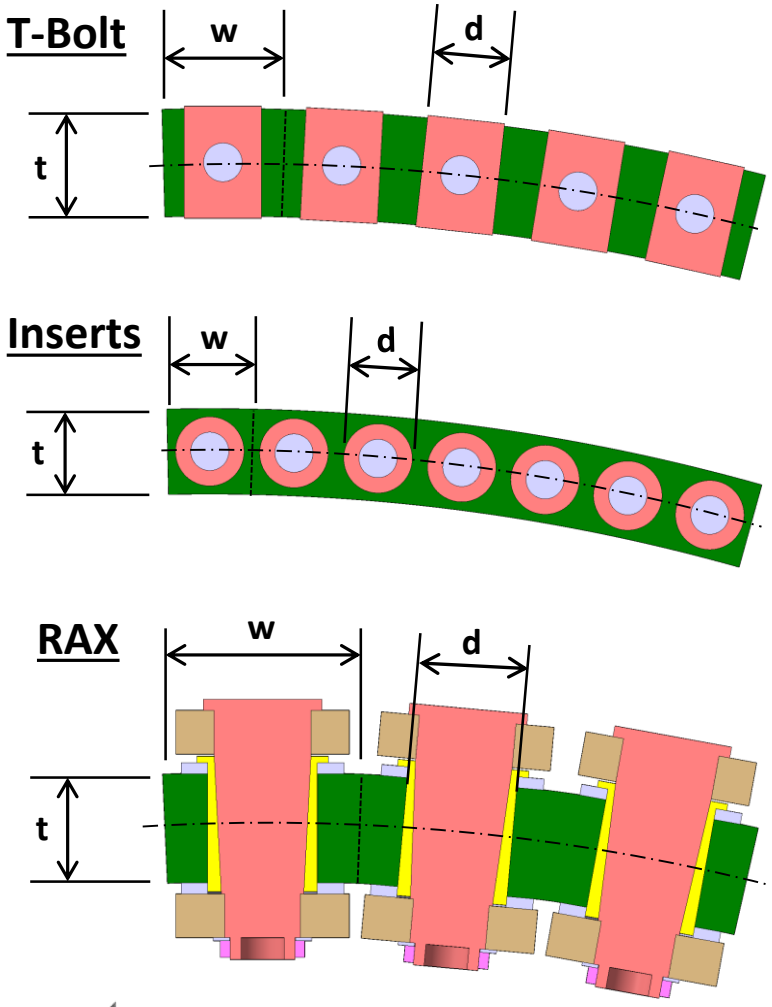
GFRP-steel-laminate

Design results of 4 m blade roots



	Concept	w [mm]	t [mm]	d [mm]
[4], [5]	T-Bolt	110	100	70
[5]	Insert	80	80	65
	RAX	180	90	90
	RAX + FML	200	80	100

Design results of 4 m blade roots



	Concept	w [mm]	t [mm]	d [mm]	F_{all} [kN]	σ_{all} [MPa]	D_{max} [m]
[4], [5]	T-Bolt	110	100	70	330	**30**	170 – 180
[5]	Insert	80	80	65	350	**55**	200 – 220
	RAX	180	90	90	1450	**90**	260 – 280
	RAX + FML	200	80	100	2200	**137**	300 – 320

F_{all} = allowable load per segment (including safety factors)
- Blade root laminate (bearing and tension)
- Steel parts (studs, bolts, bushings, …)

$\sigma_{all} = F_{all} / wt$ = allowable stress at the laminate gross section
- For comparison of different concepts

D_{max} = Rotor diameter at 4 m bolt circle diameter

Infusion of thick-walled FML

Objective

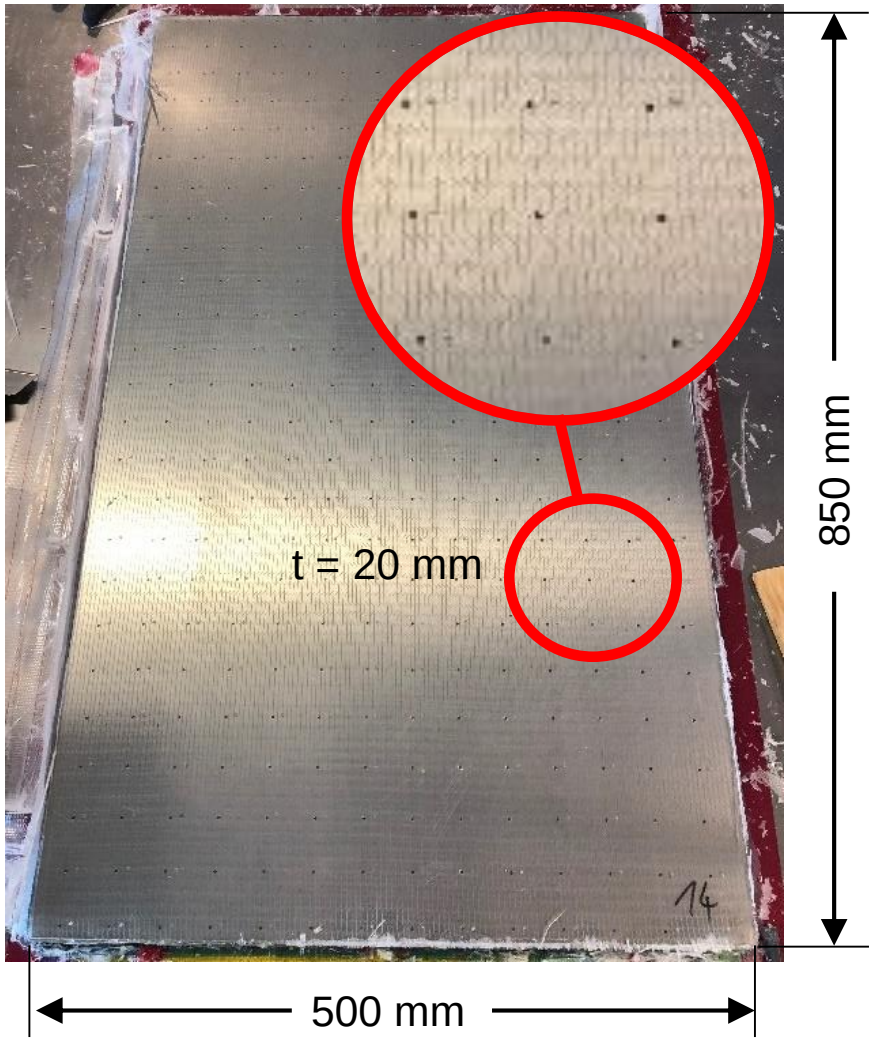
- Define infusion process for thick-walled FML

Material	Description	Thickness	No of layers
Steel	1.4310 spring steel	0,5 mm	14
Glass fiber	Saertex U-E-1182g/m²	0,83 mm	15
Resin	Hexion RIMR035c / RIMH037	-	-

Approach

- Perforate steel sheets with little holes
  - Hole diameter = 2 mm, hole spacing = 30 mm
  - Laser cutting or punching
- Alternating hole position vs. aligned hole position

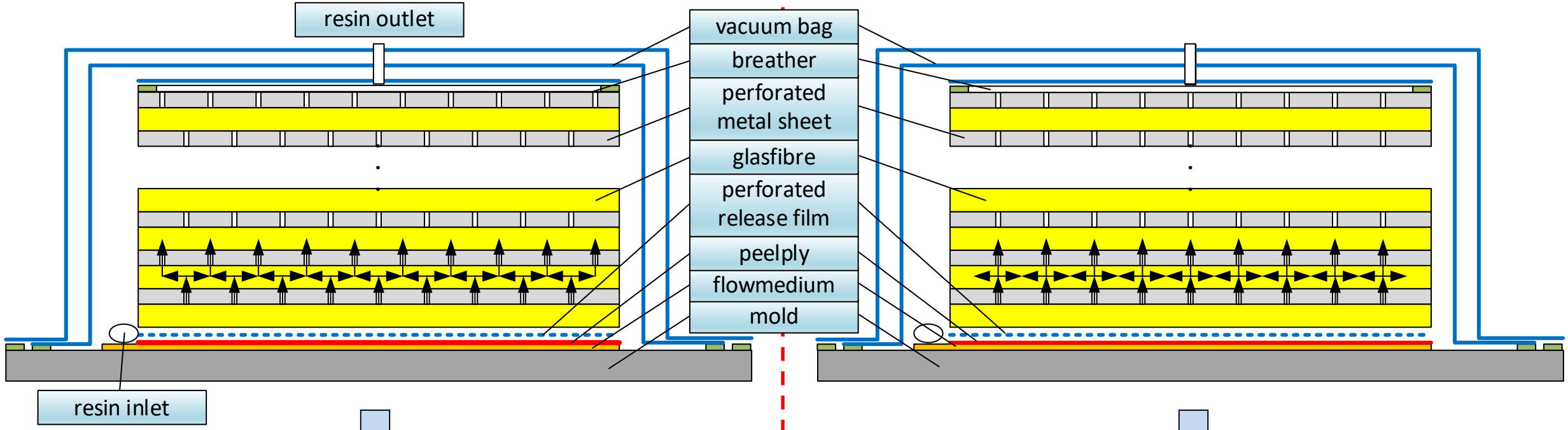
Plate for infusion trials



Infusion strategies for thick walled FML

Alternating holes

Aligned holes



- No Voids expected
- Pot life sufficient?

- Faster infusion expected
- Voids?

Infusion of thick-walled FML: Results of layer-by-layer demoulding

Alternating holes

Ply 17

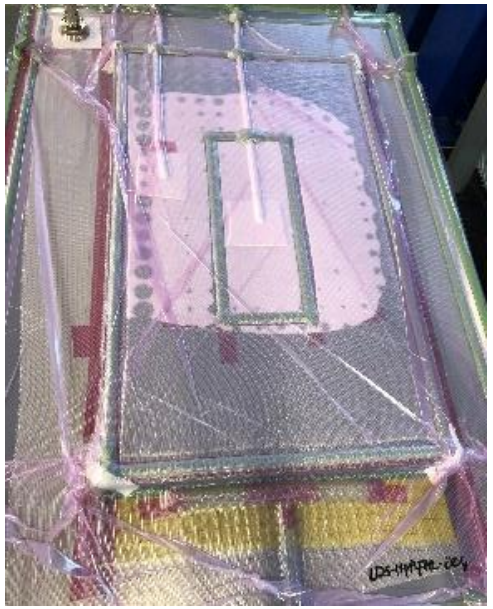
Ply 19

Ply 21

Results

- Dry spots in upper plies
- Limit: 10-mm-Layup (9 glass + 8 steel) successfully impregnated

Aligned holes

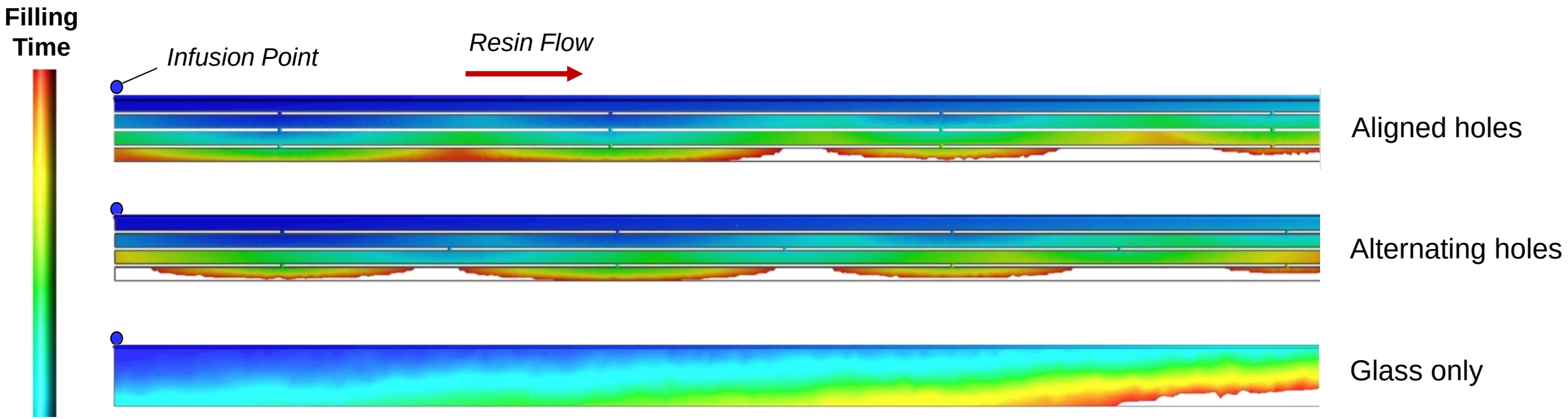


Ply 33

Results

- No dry spots or voids
- 20-mm-Layup (17 glass + 16 steel) successfully impregnated

Infusion simulation of perforated FML

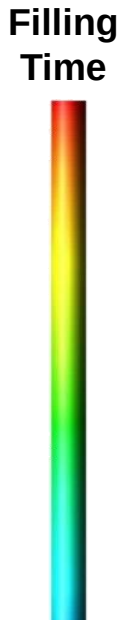


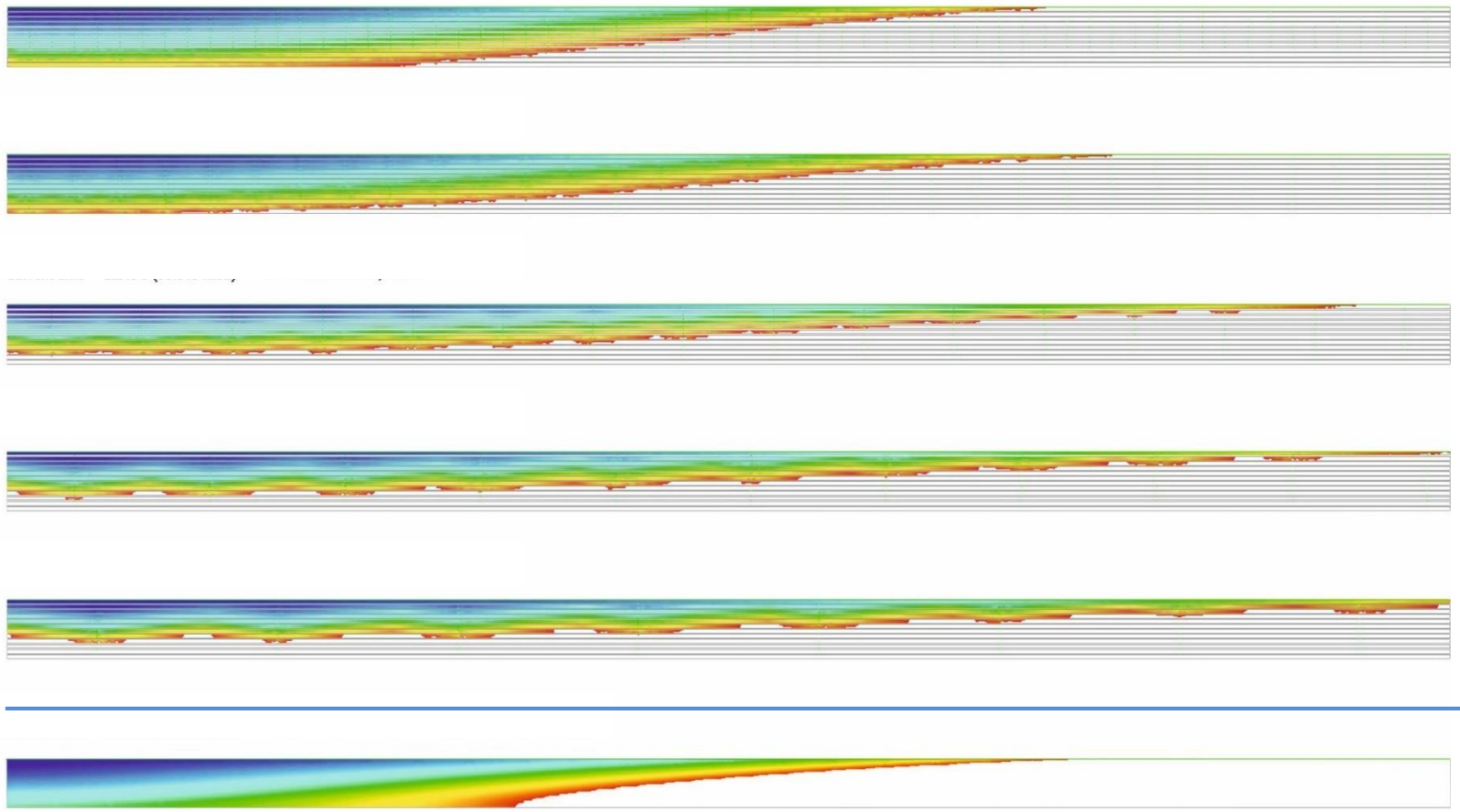
Results

- Both aligned and alternating holes show a reasonable infusion behaviour
- Alternating holes increase the filling time
- Aligned holes chosen for further investigations

Infusion simulation of perforated FML

Variation of hole spacing for 0,5 mm hole diameter

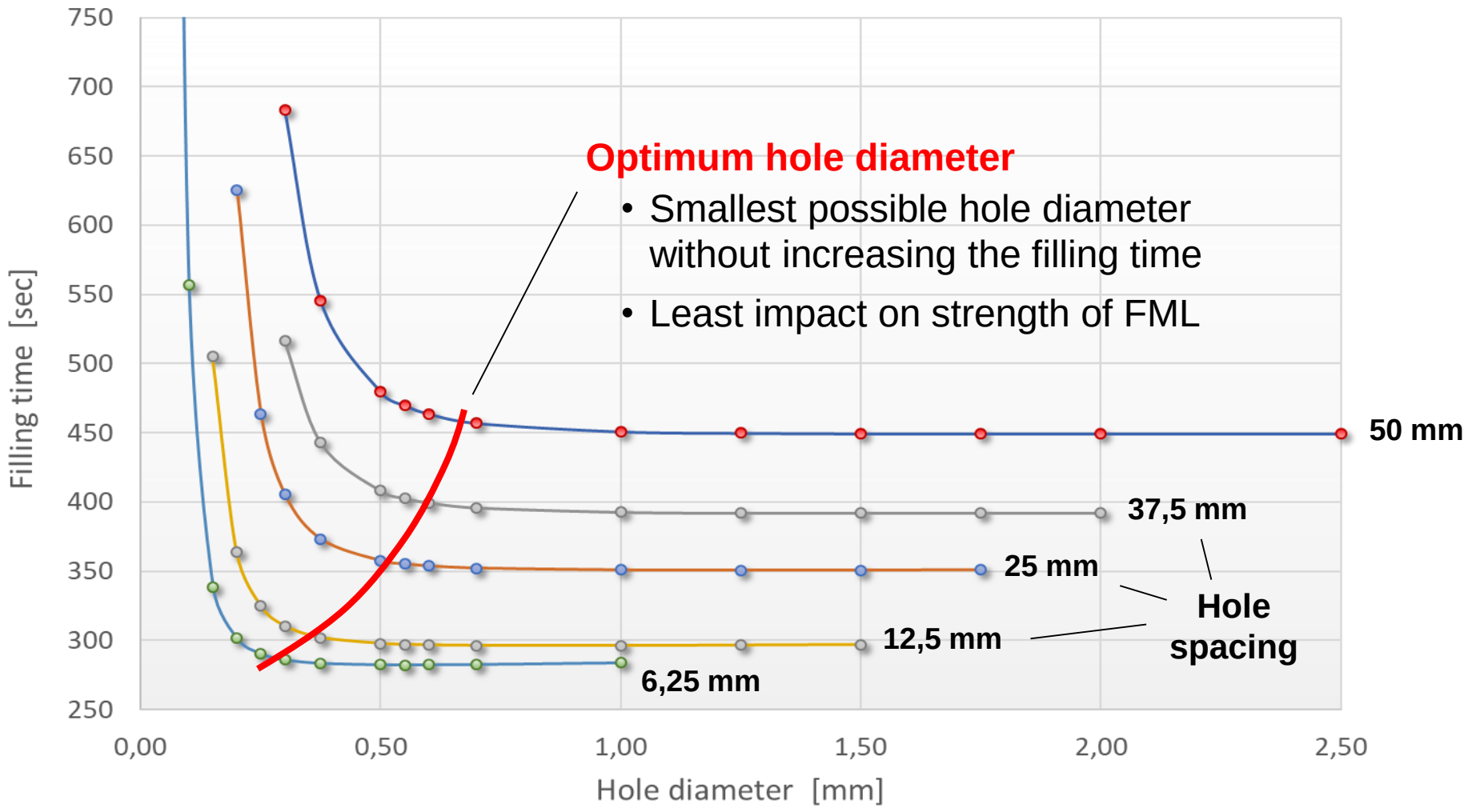




Hole spacing	Filling time
6,25 mm	92 sec
12,5 mm	100 sec
25 mm	130 sec
37,5 mm	148 sec
50 mm	167 sec
Glass only	131 sec

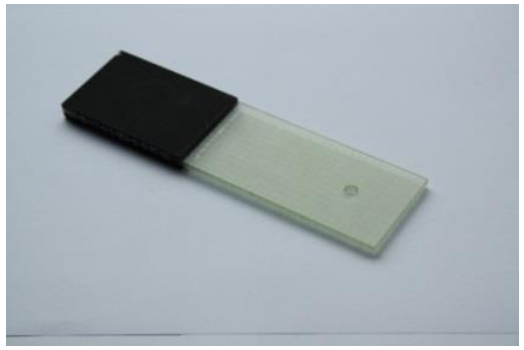
Increasing filling time

Infusion simulation of perforated FML



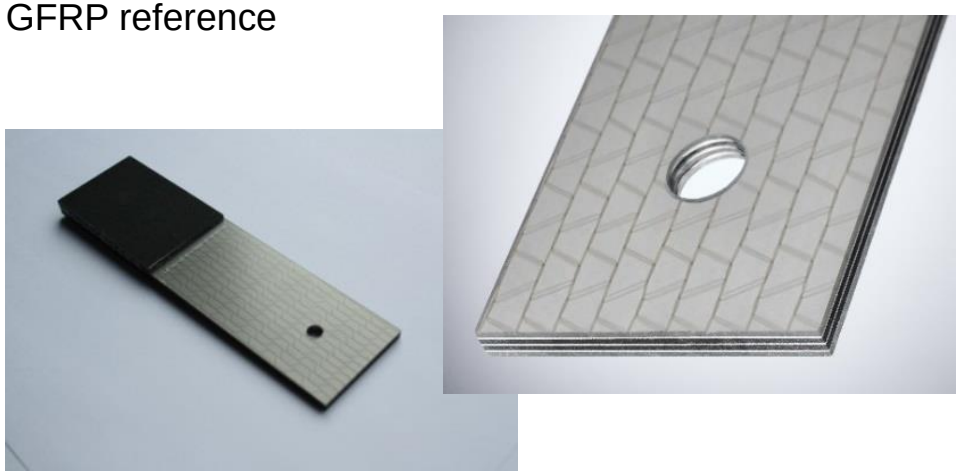
FML bearing tests on coupon level

Specimens



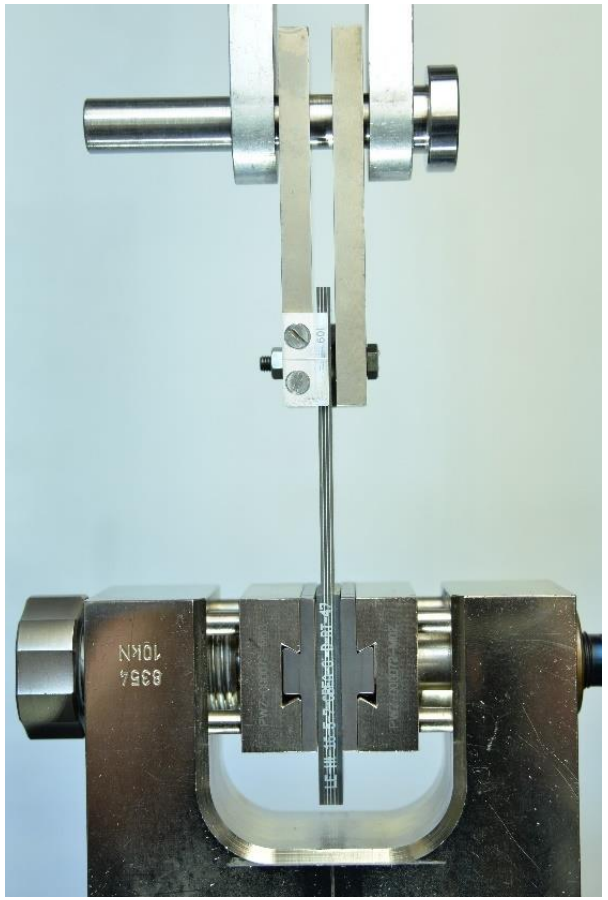
GFRP reference

- 150 x 45 x 4 mm
- 6,35 mm bore hole
- 4 glass plies
- 1 to 3 steel sheets, thickn. 0,12 / 0,25 mm

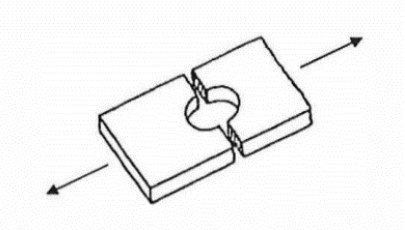


FML specimen

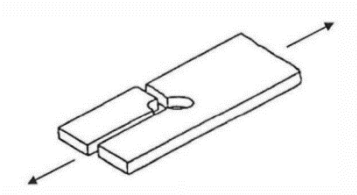
Test setup



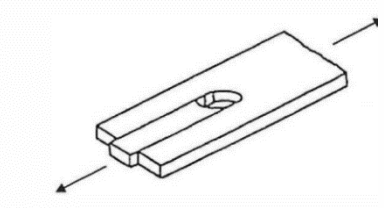
Failure modes



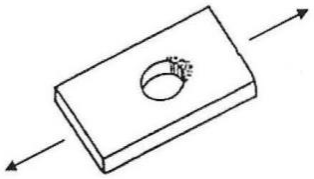
Net tension



Cleavage-tension



Shear out



Bearing

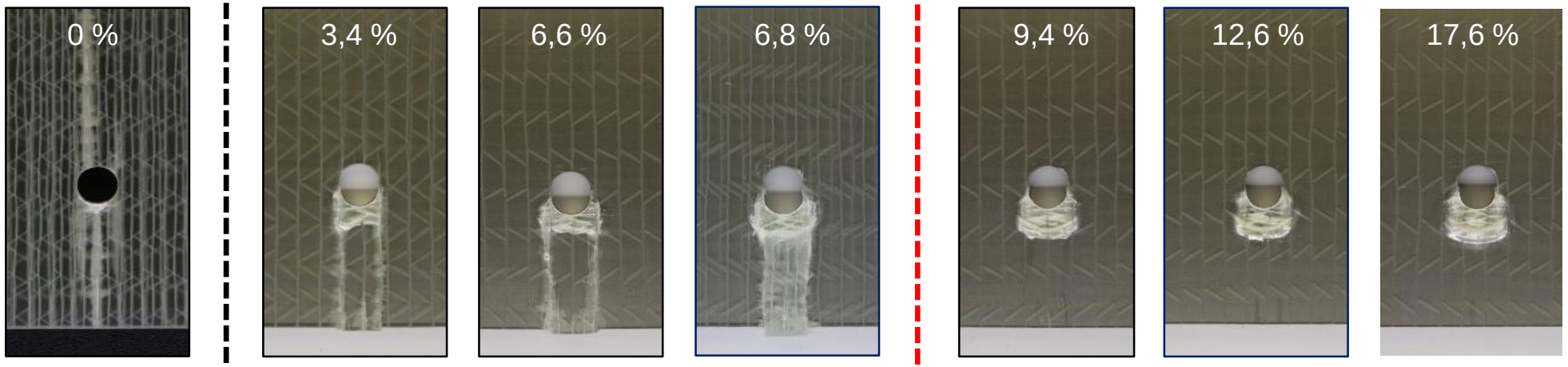
FML bearing tests on coupon level – failure modes

Steel volume content (SVC)

0% **ca. 10%** **18%**

GFRP | FML →

UD $[0°]_4$



cleavage | **shear out** | **bearing failure**

Failure mode of UD FML depends on steel volume content (SVC)

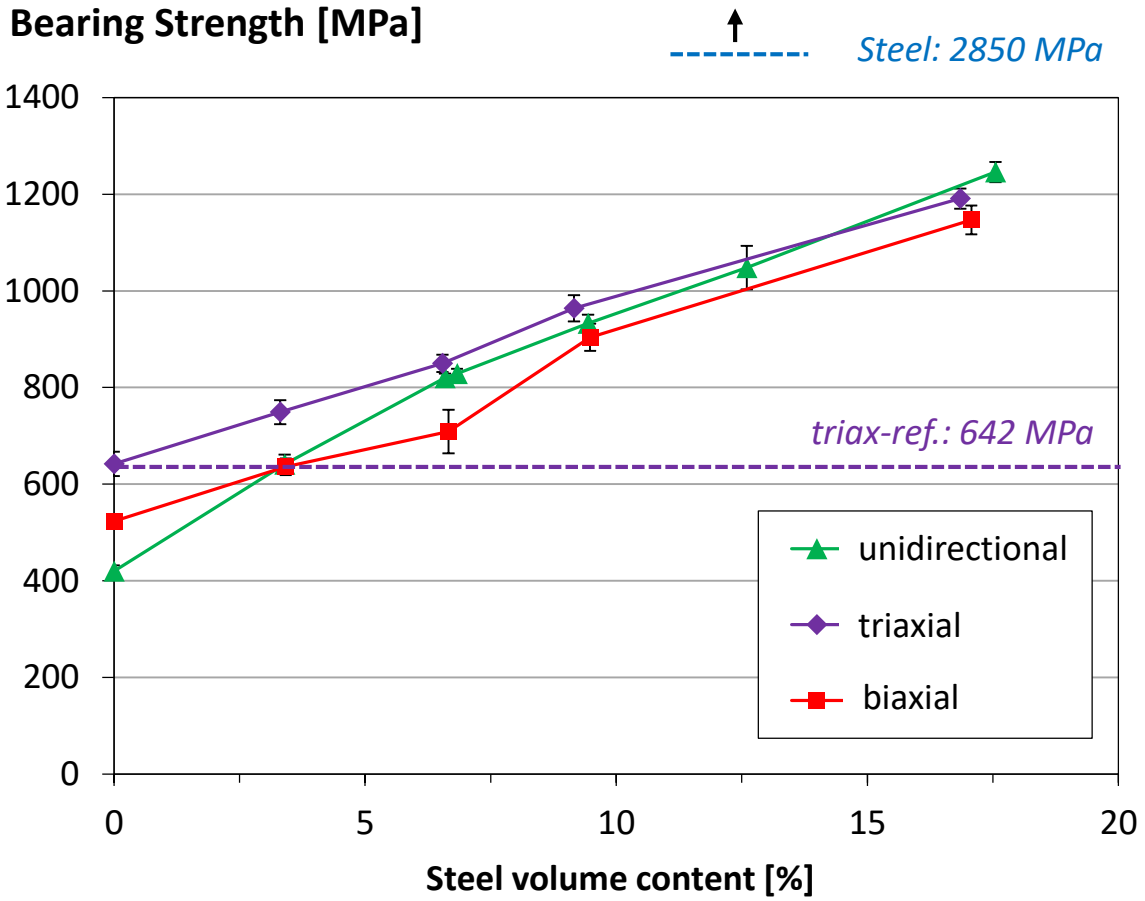
FML bearing tests on coupon level – Static results

Samples

- Up to 18 % Steel
- 3 laminate configurations:
  - UD
  - Triaxial
  - Biaxial

Results

- Bearing strength without steel: Triax > Biax > UD
- Bearing strength is significantly improved by intrinsic steel hybridization



FML bearing tests on coupon level – Fatigue results

Samples

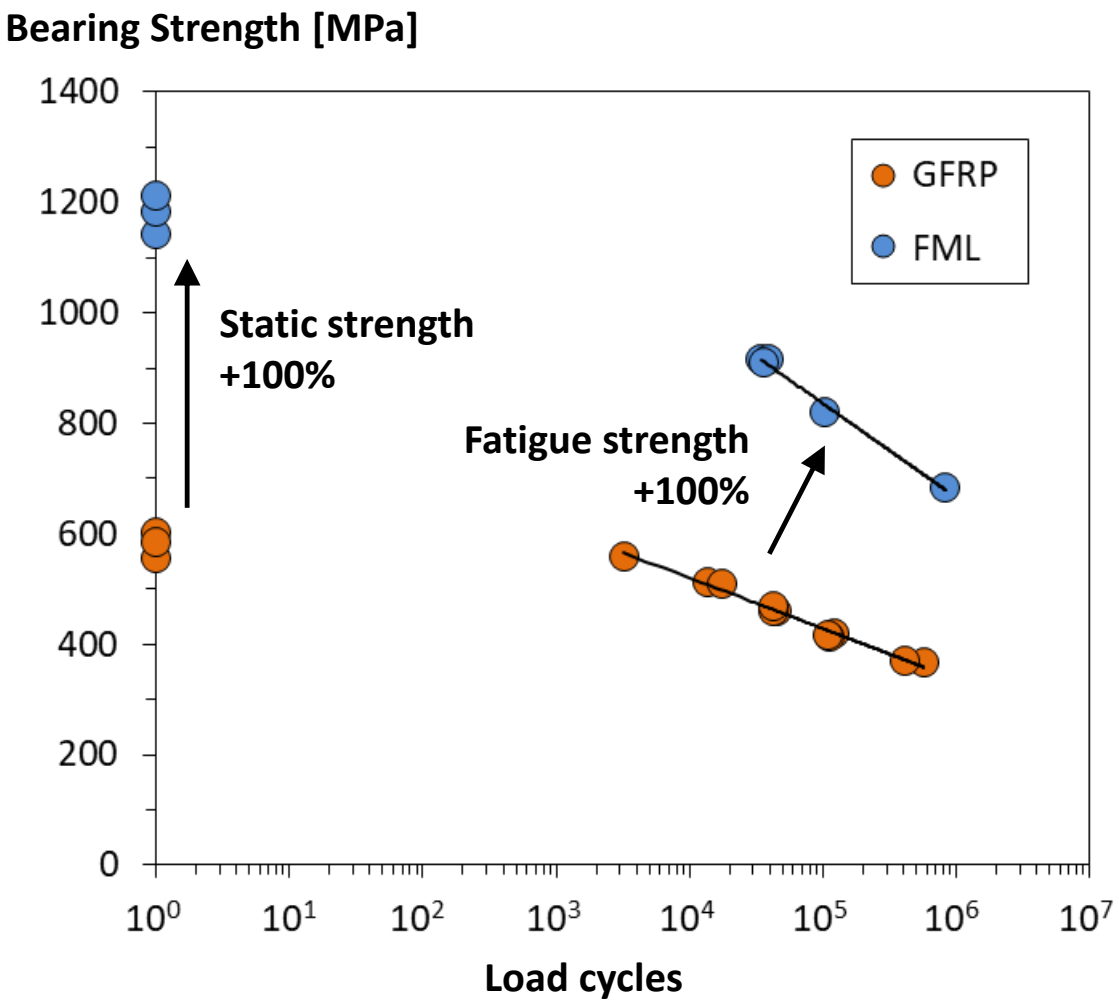
- Triax-GFRP as reference
- Triax-FML (SVC: 18 %)

Test conditions

- Tensile (R=0.1)
- Load cycles up to 1.000.000

Result

- FML withstand about twice the static and cyclic loads compared to the Triax-GFRP reference



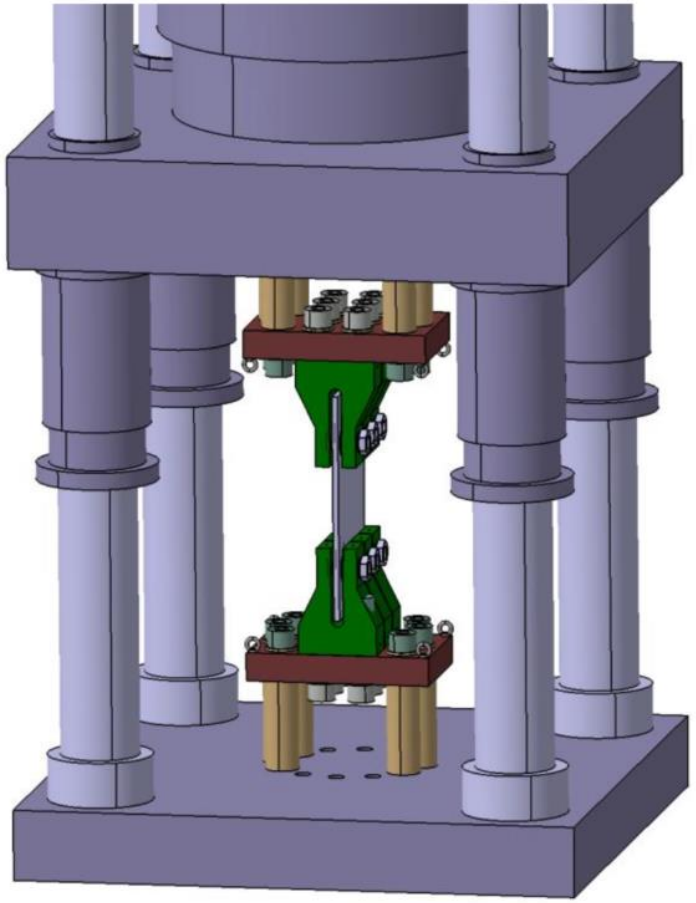
Test of big bearing specimens

- 10 MN servo-hydraulic test machine
- Institute of Building Materials Science, Leibnitz University Hannover

- Static and fatigue tests up to 1,5 Hz

- Specimen:
  800 x 450 x 20 mm
- Hole diameter: 70 mm

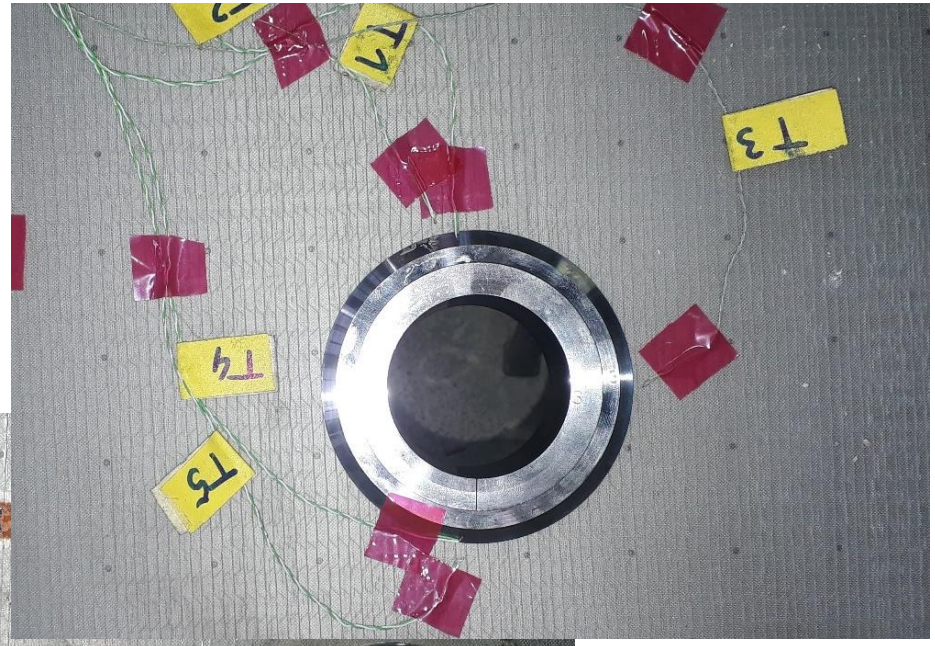
- RAX + FML
  vs.
  GFRP reference

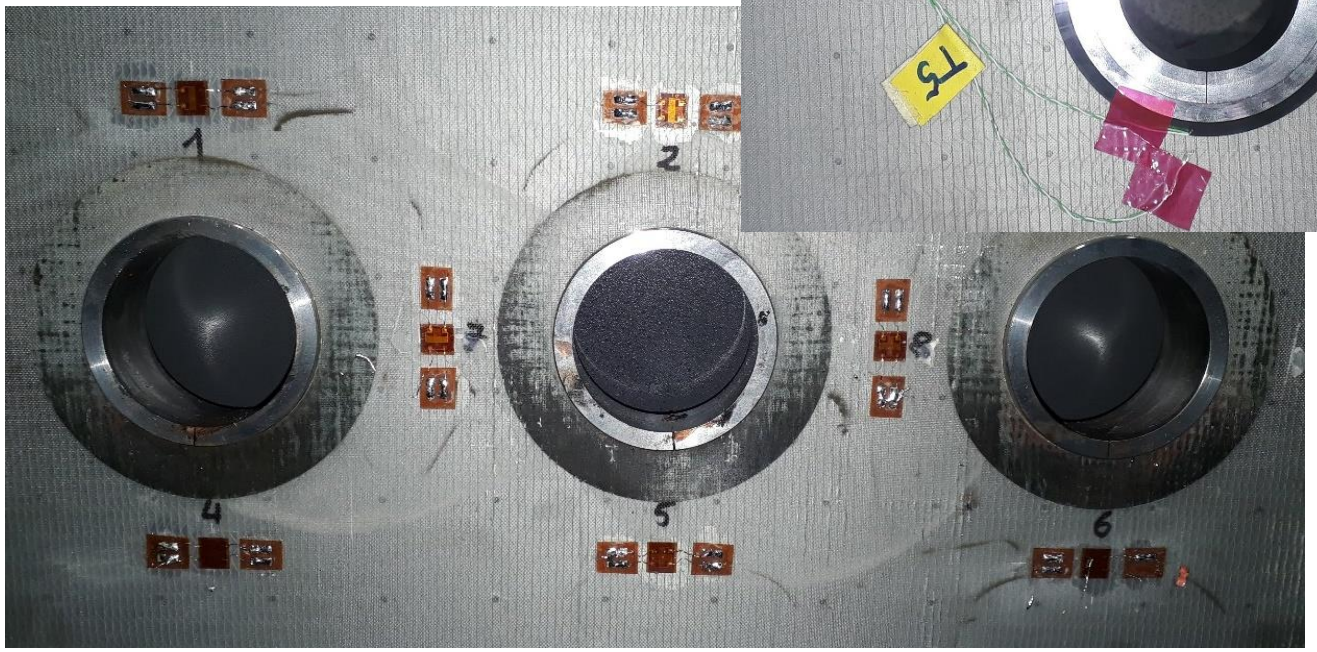


Sensors

- Up to 32 strain gauges per specimen
- Up to 12 thermocouple sensors per specimen

Thermocouple sensors

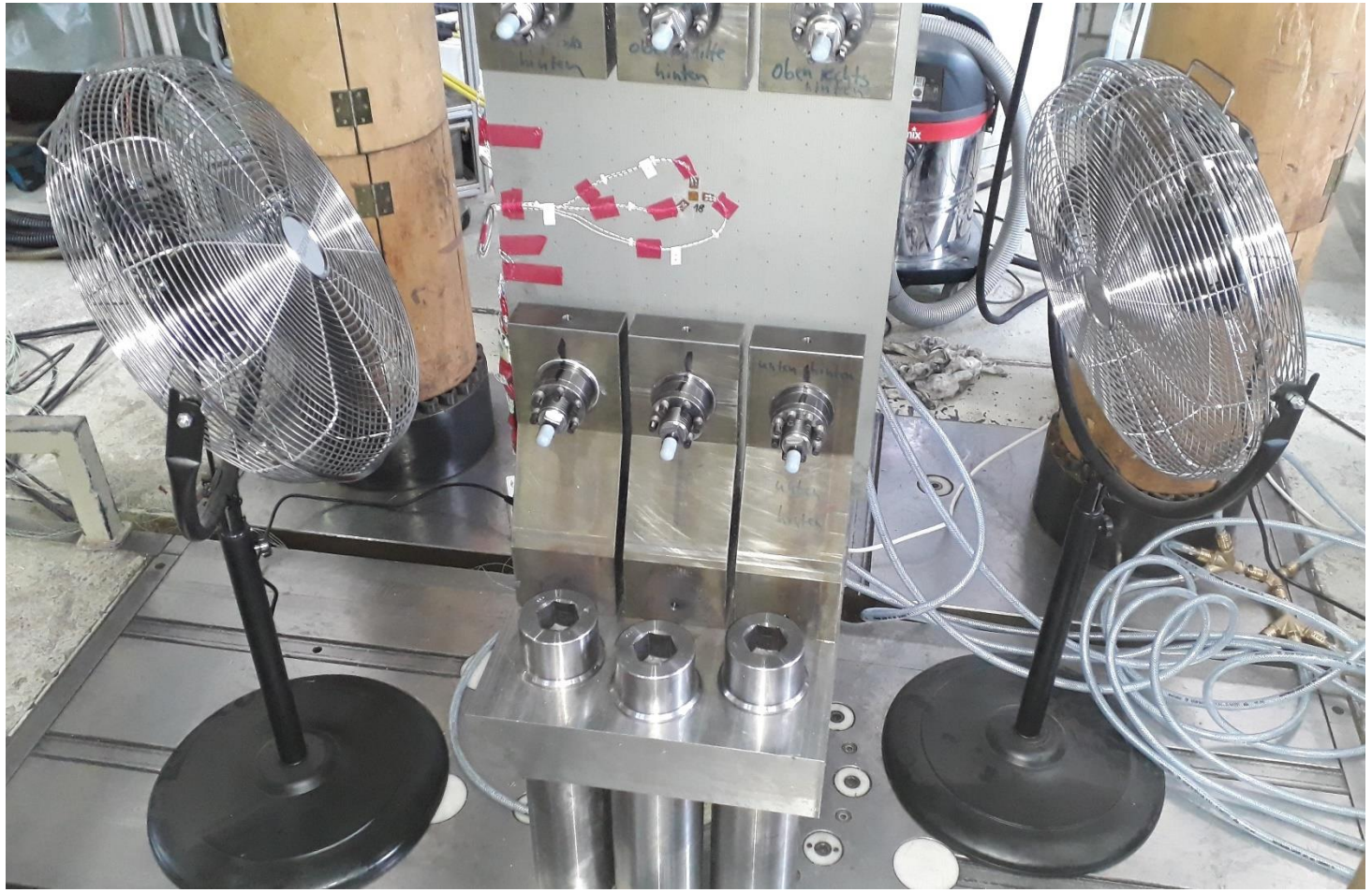




Strain gauges

Air cooling during fatigue tests

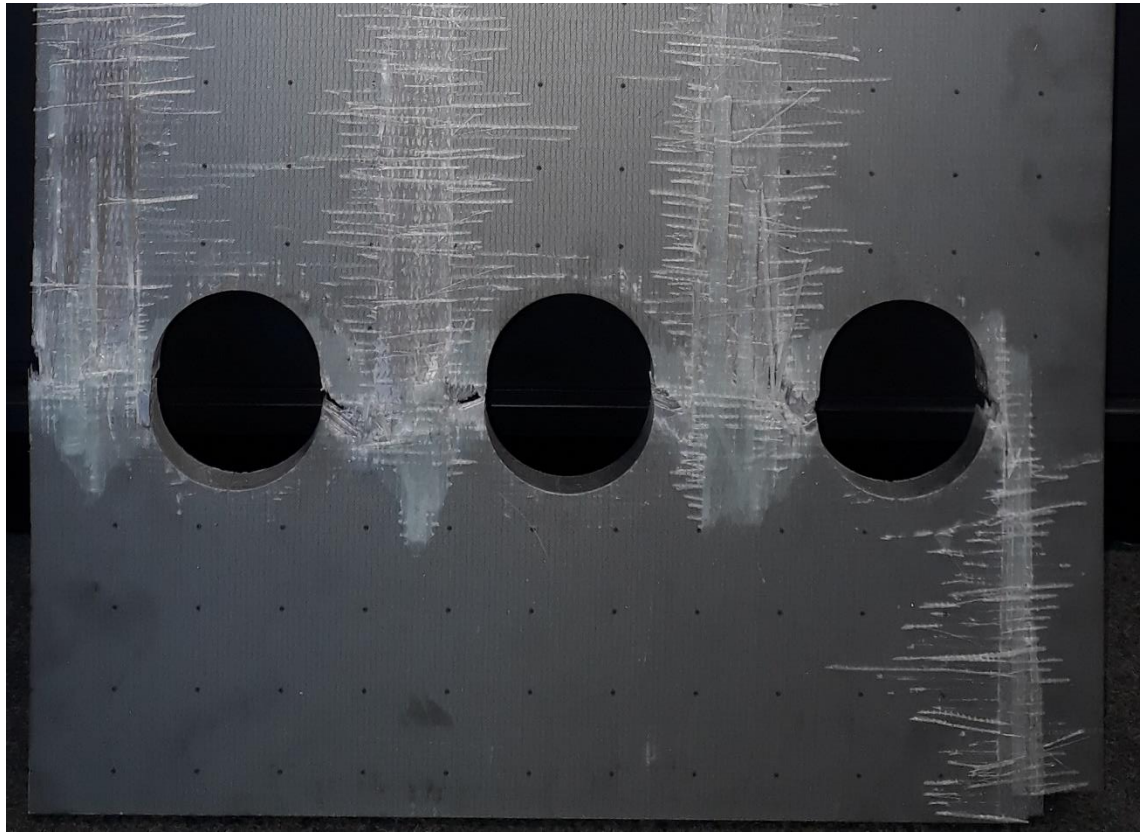
Pneumatic hoses at bolts' bore holes



Conventional fans

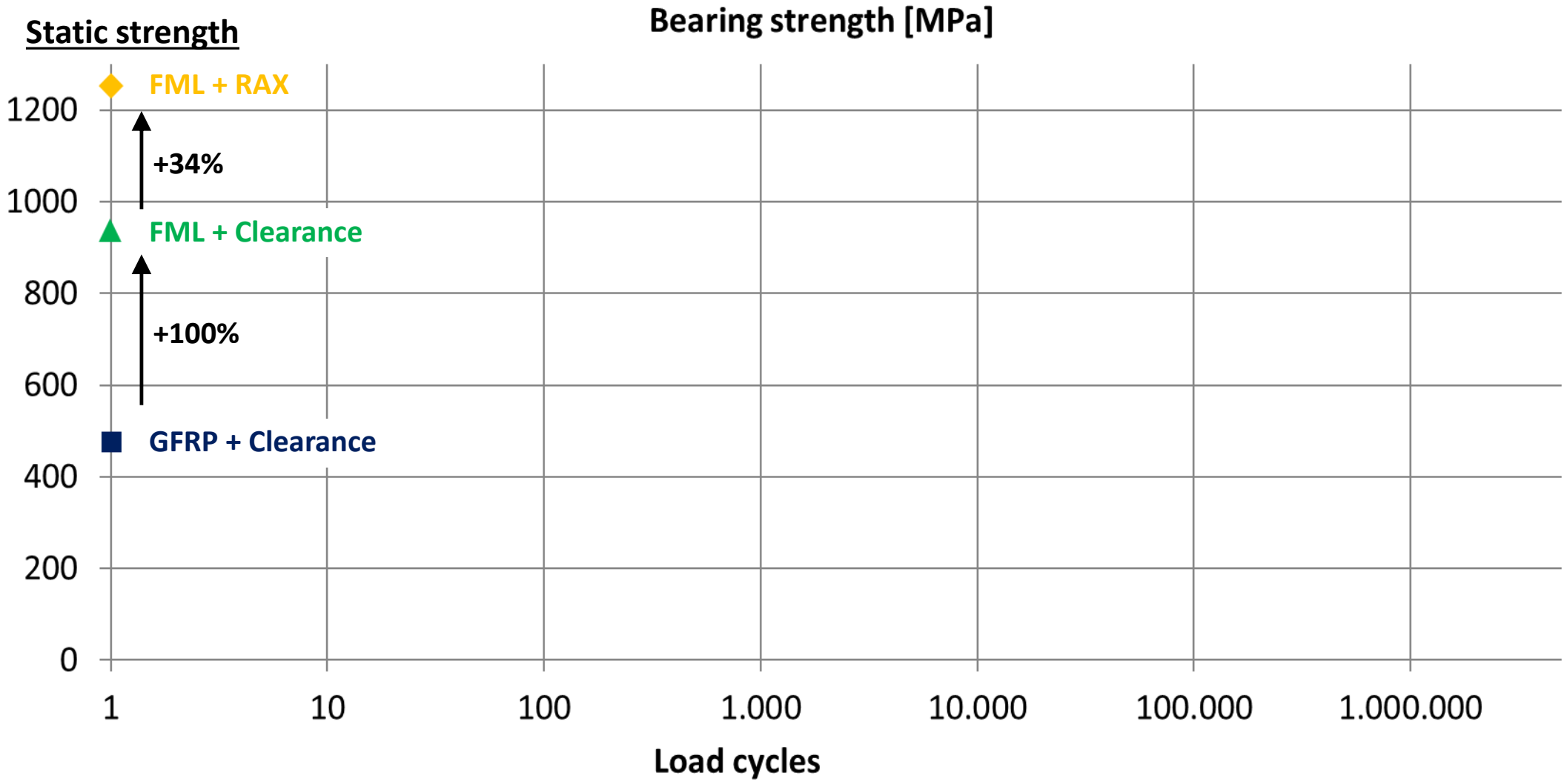
Failure types at static tests

Bearing failure



Net tension failure

Test results for big bearing specimens



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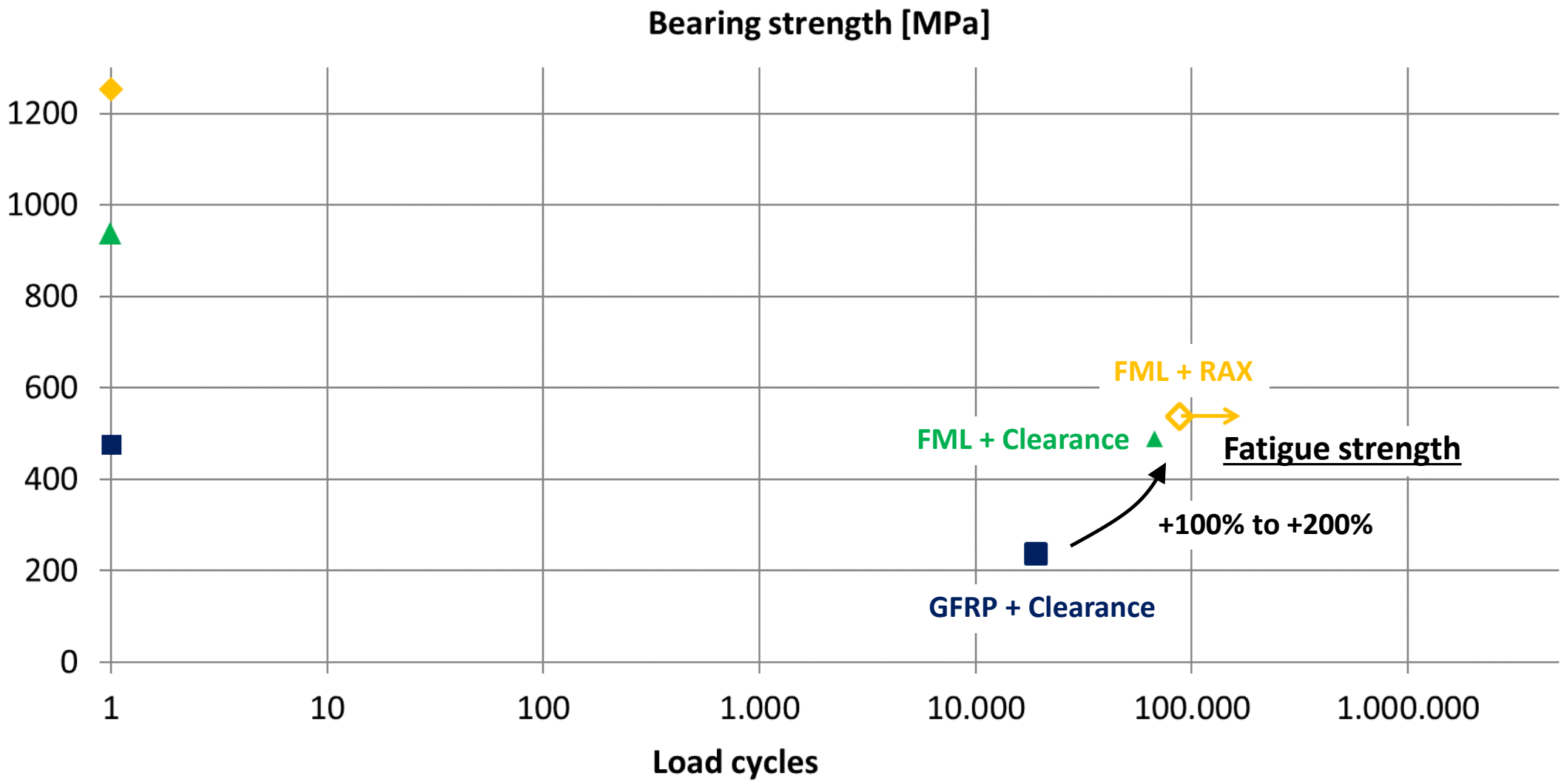

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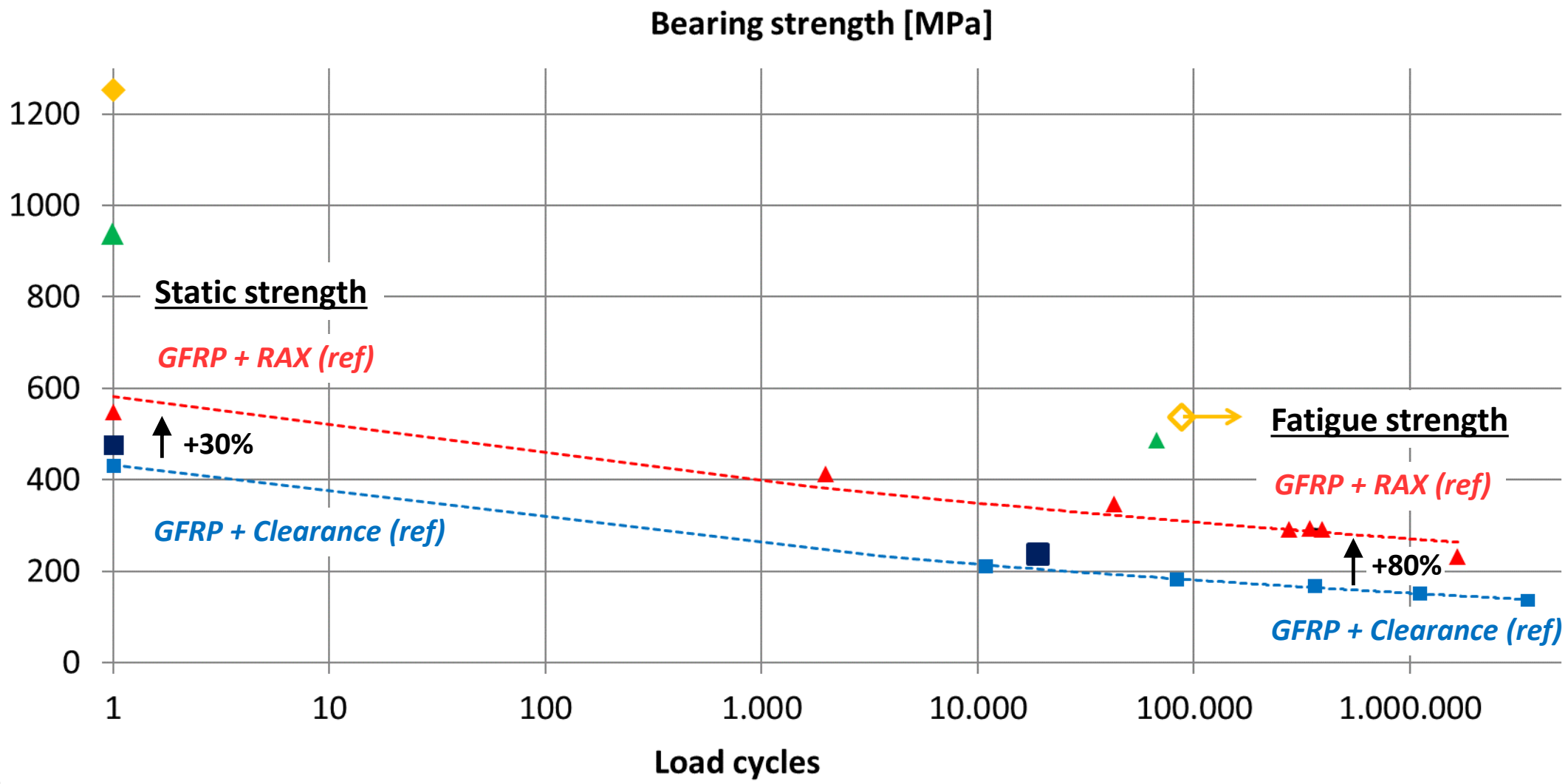
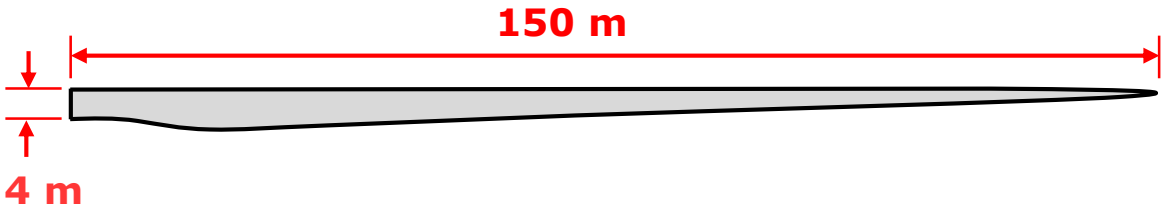


Conclusion

Results

- Novel Technologies “RAX” and “FML” can push the limits for onshore rotor blades
- High static and fatigue bearing strength verified by small and big scale bearing tests
- Infusion of FML can be simulated realistically
- Successful infusion of 20 mm FML



Outlook

- Quantification of environmental impacts on FML
- Infusion of a blade root
  - Mould with 1,35 m in diameter
  - FML of about 40 mm thickness as proof of concept

- Novel design concepts
  - Blade root – pitch bearing – hub
  - Segmented rotor blades

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Thank you!

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