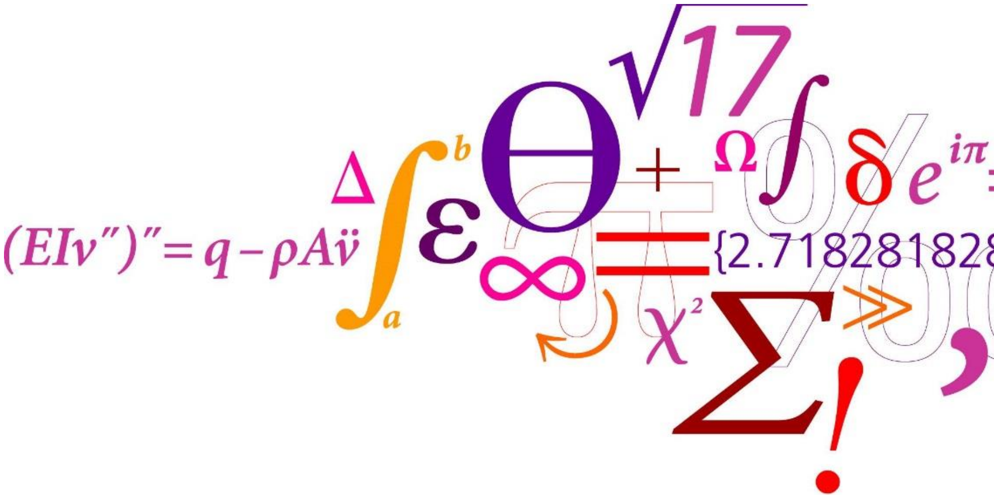
CASMaT
Villum Center for Advanced Structural and Material Testing

DTU

Multi-scale testing of composite steel interfaces for blade root bushing connections

<u>Mohsen Rezaei</u>, Mads Borgnæs, Christian Berggreen

Researcher, lightweight structures group

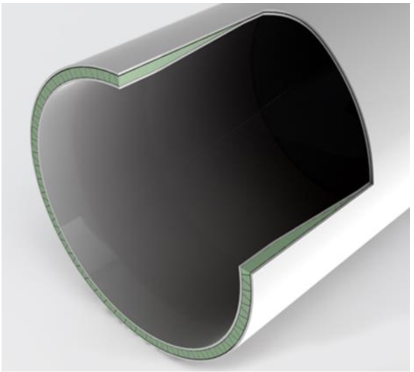


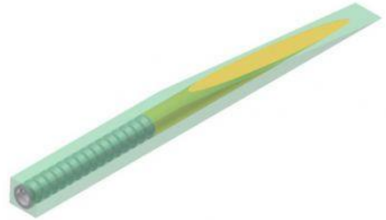
DTU Mechanical Engineering

Department of Mechanical Engineering

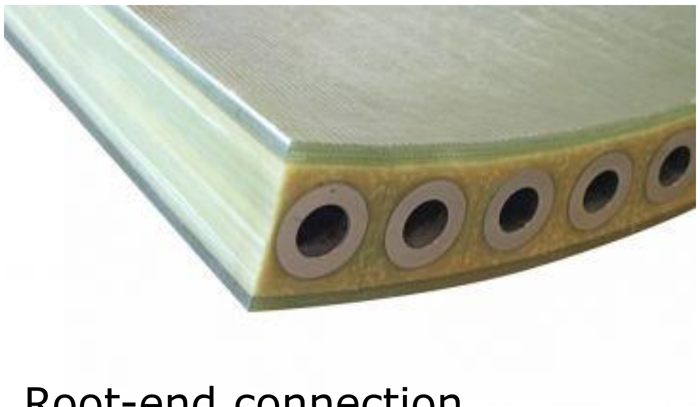
Agenda

- Introduction
- Materials & Manufacturing
- Theory
- DCB-UBM Test & Results
- DSL Test & Results
- Bushing Test & Results
- Bushing FE Model
- Conclusion & Future Works



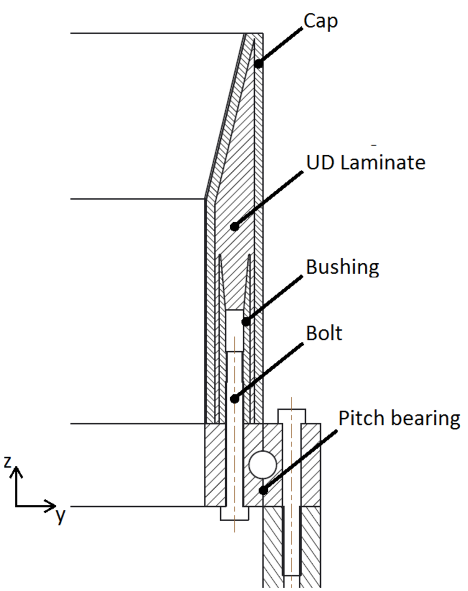


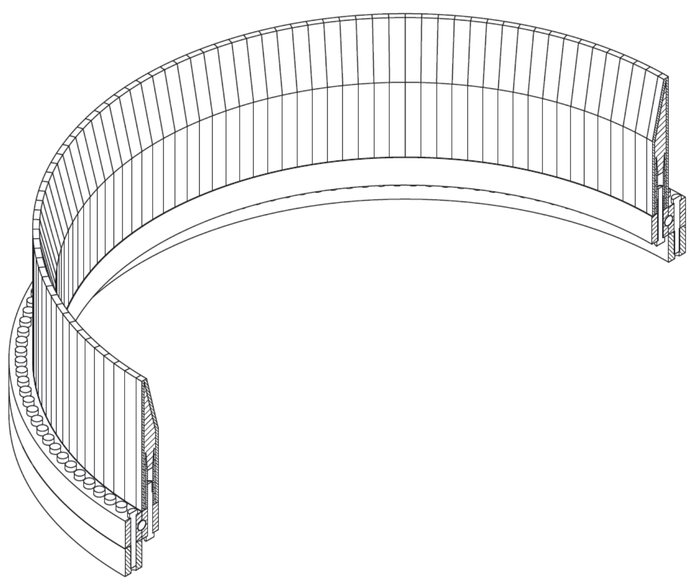
Introduction: **Bushing solution from Fiberline Composites A/S**



Root-end connection

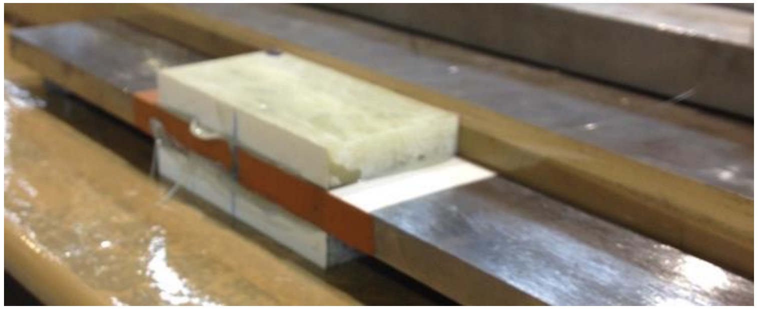
Cross-section of one bushing

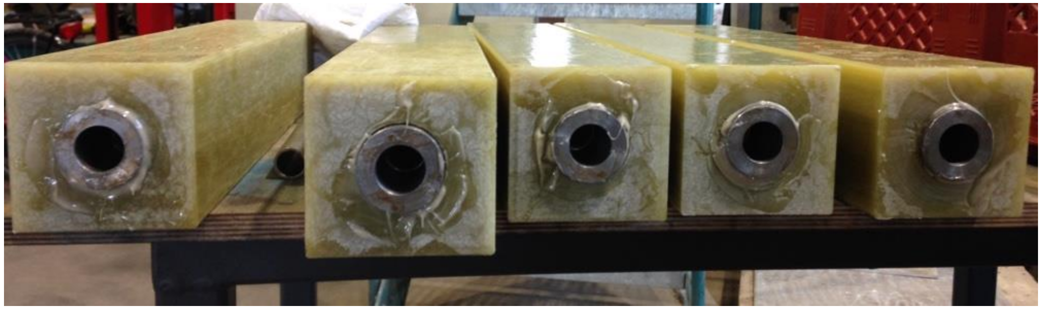




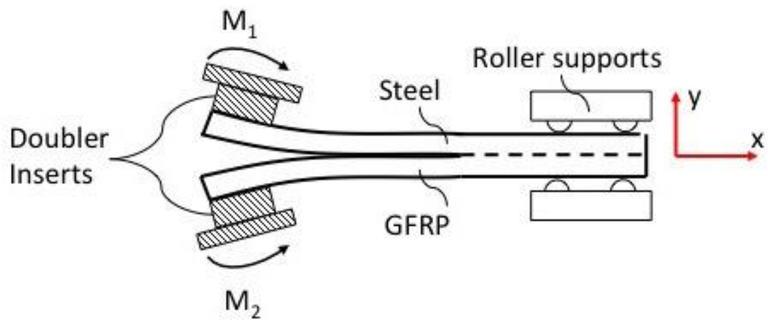
Goal/Objective:

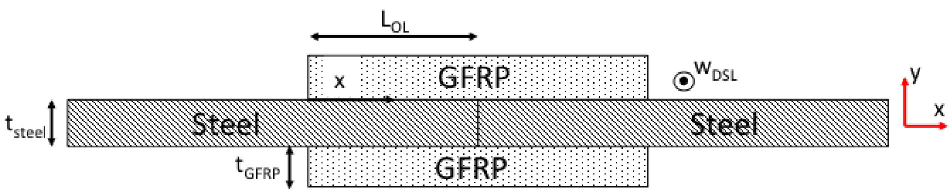
- By obtaining the cohesive law experimentally and compare the results with the finite element analysis it is aimed to determine/be able to predict the static pull-out strength and finding the locus of failure of the in-situ condition root-end bushings of a wind turbine blade.

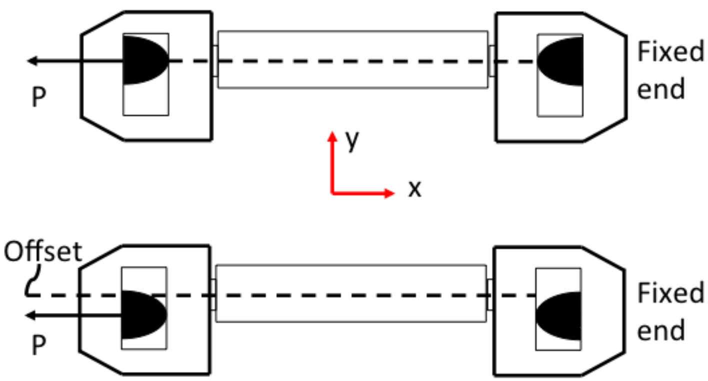




Project Description

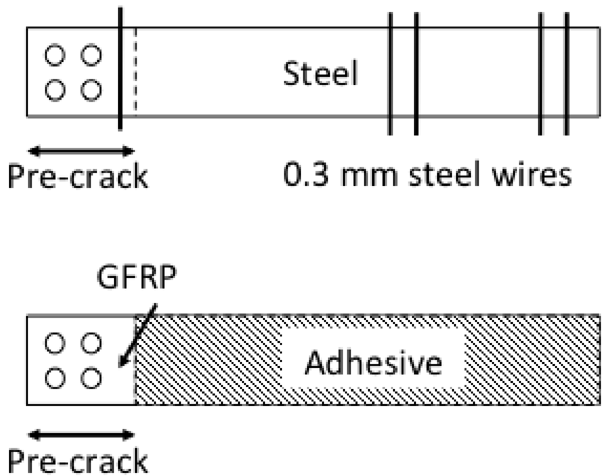


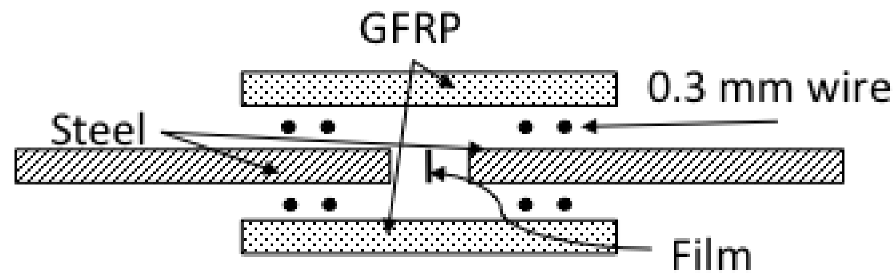


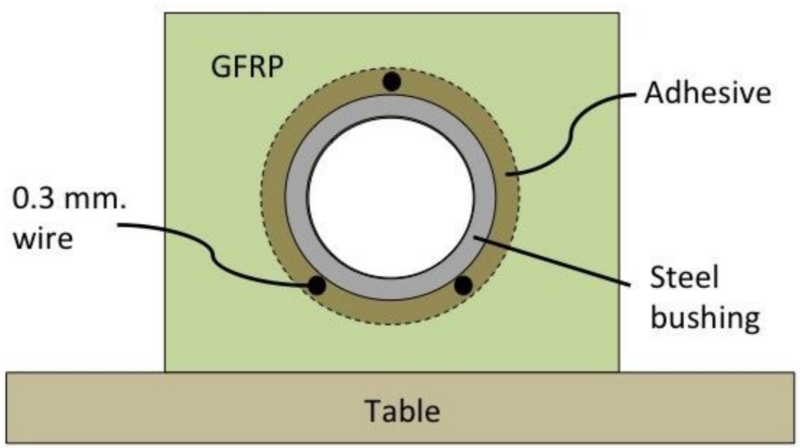


Material Properties of GFRP
↓
Mode-Mixity Analysis (Ψ-angle)
↓
DCB-UBM Test
↓
Extract Cohesive Laws
↓
DSL Intermediate Tests
↓
2D FE Analysis of DSL Specimen
↓
Static Load Test of Root-End Bushing
↓
2D & 3D FE Analysis of Root-End Bushing
↓
Compare Test with Numerical Results
↓
Conclusion

Material & Manufacturing:



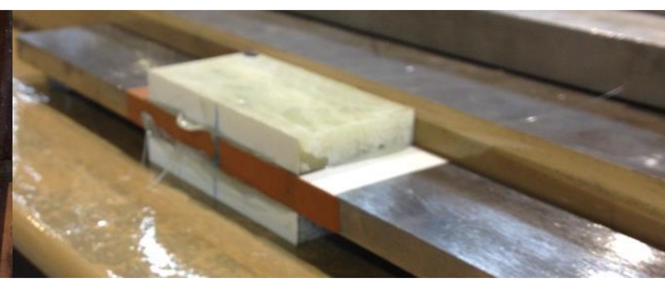




Material & Manufacturing:

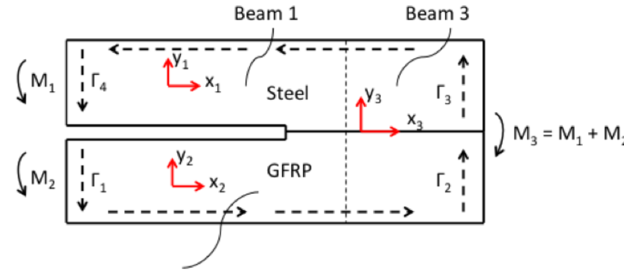




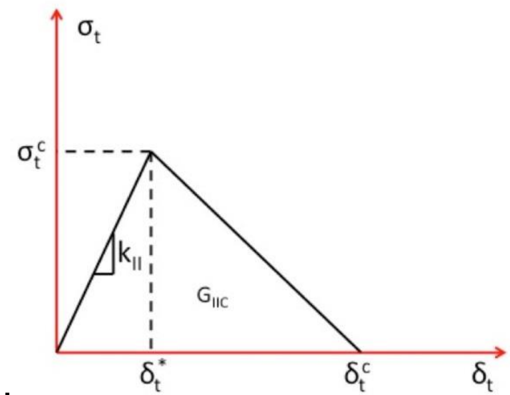



DCB-UBM Test and Analysis

Test Method & Theory:



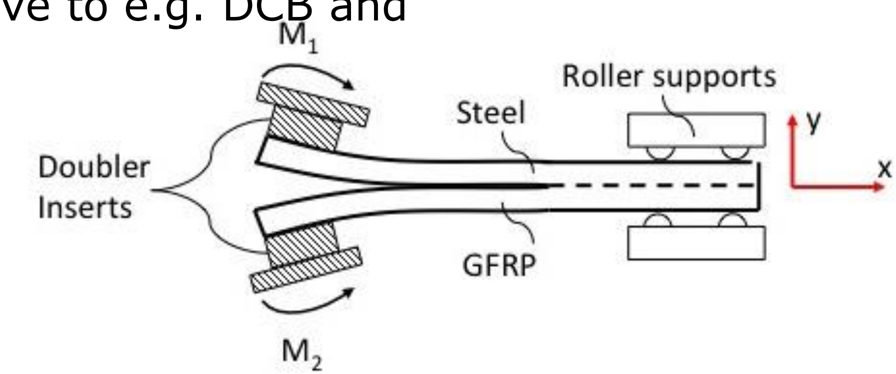
- Using bi-material *J*-integral to obtain $G_c(\Psi)$



- Differentiation of J_R & Nominal Cohesive Zone Length

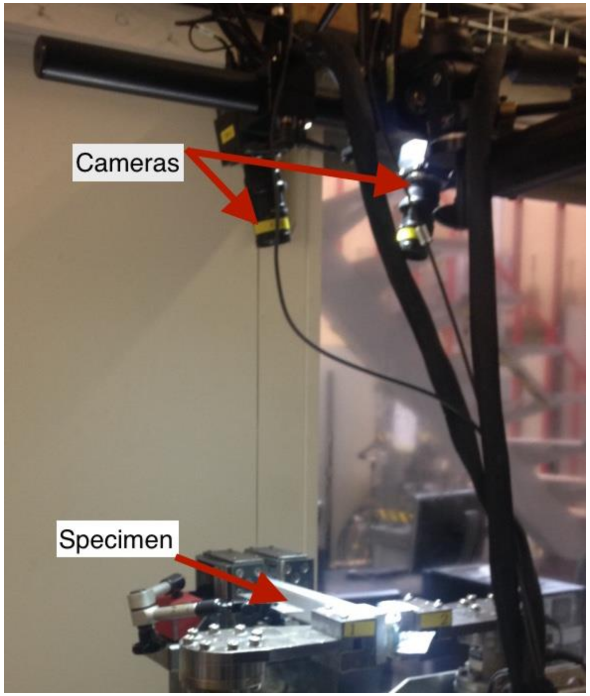
- CZM & VCCT (FE analysis)

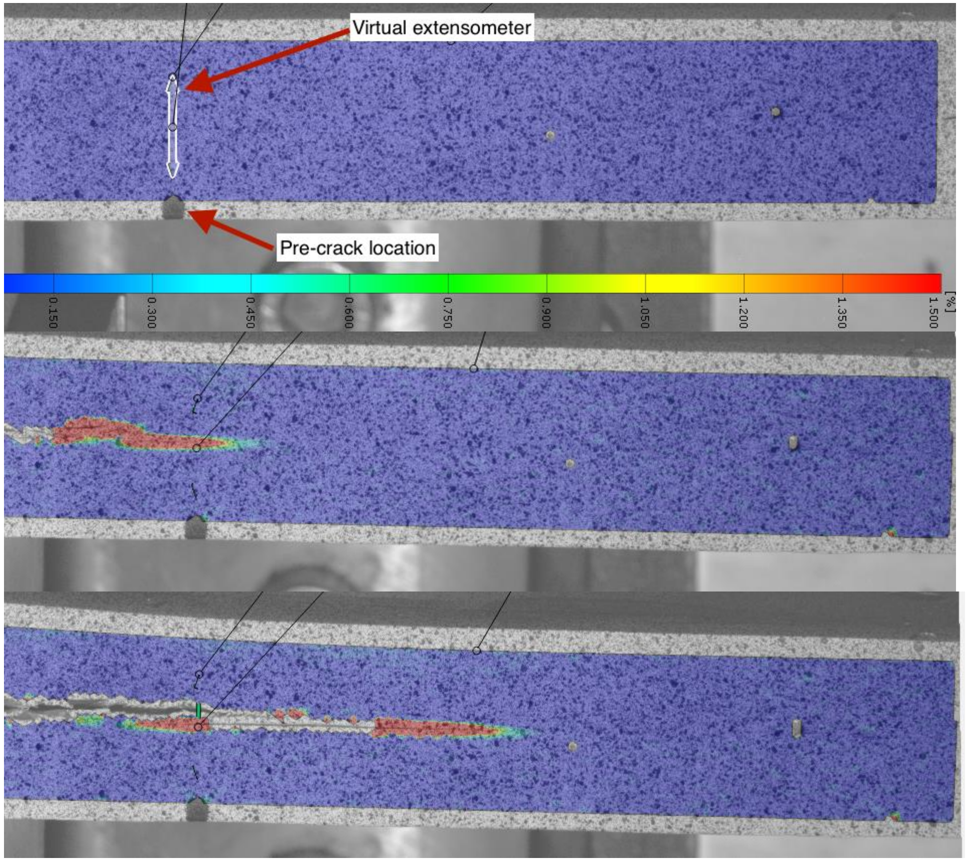
- DCB-UBM Test – An alternative to e.g. DCB and ENF tests



- Testing and Results

DCB-UBM Test & Results:

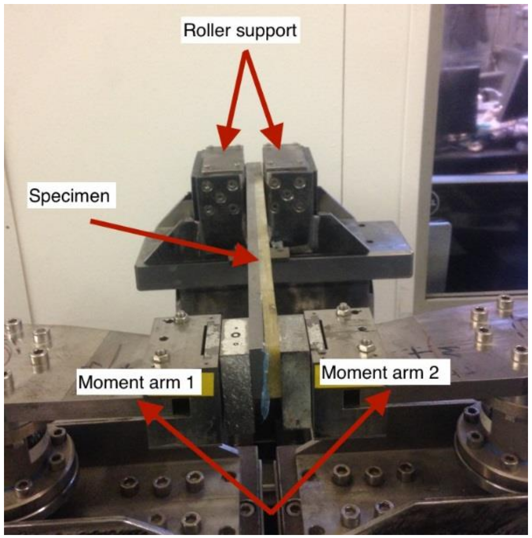


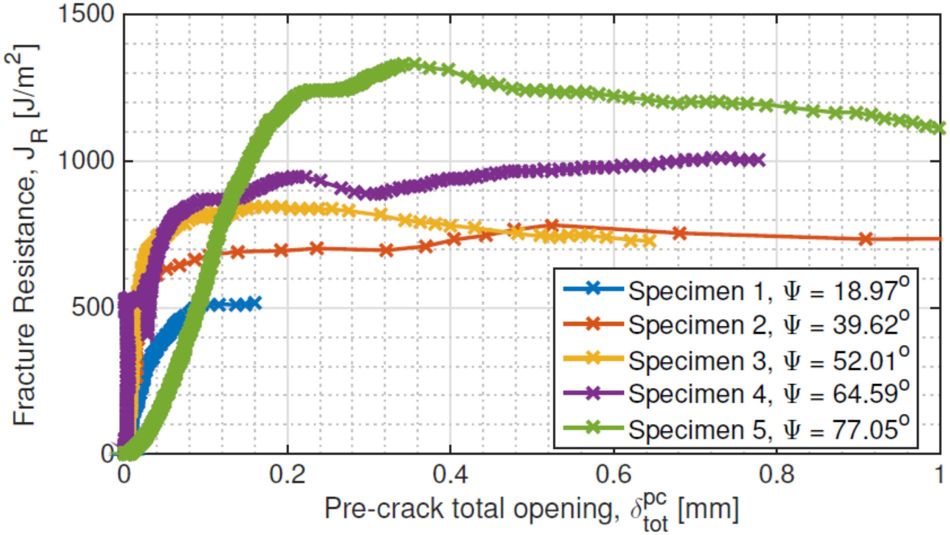


DCB-UBM Test & Results:

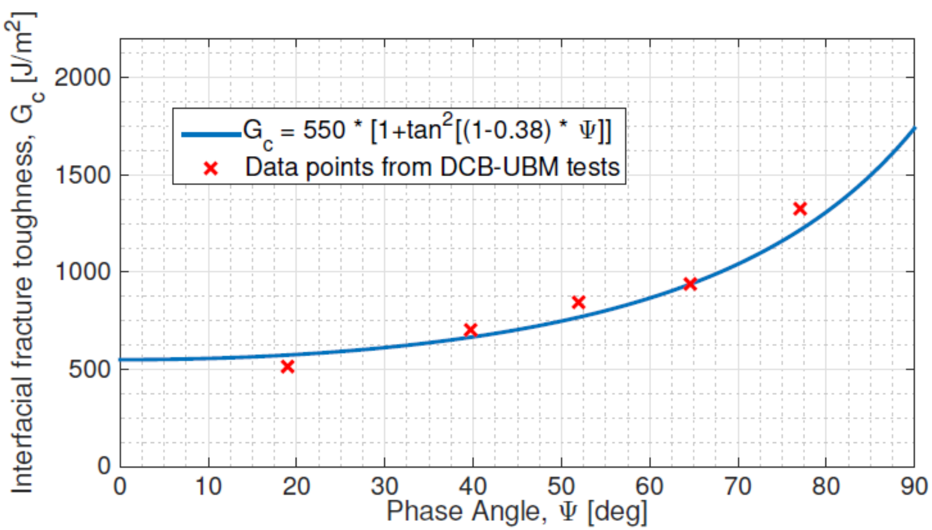
Testing & Results

Interfacial fracture toughness:





#	Ψ (VCCT)	G_c [J/m²]
1	18.97	511.5
2	39.62	701.6
3	52.01	844.4
4	64.59	944.1
5	77.05	1325.0



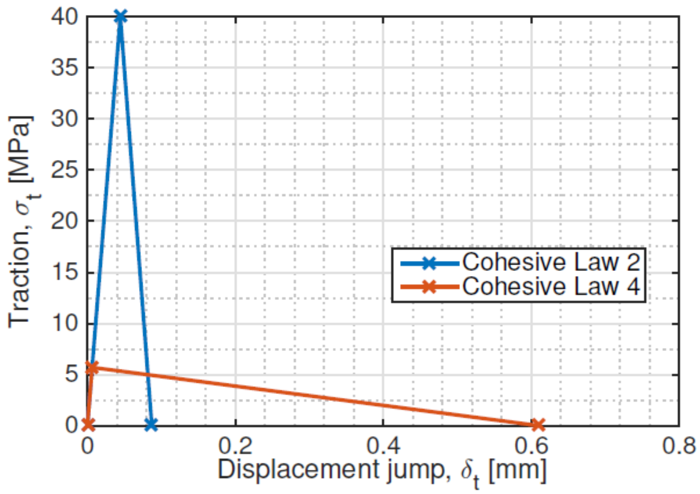
DCB-UBM Test & Results:

Cohesive Law suggestions

Cohesive Law	G_{Ic} [J/m^2]	σ_n^c [MPa]	ζ_I [-]	δ_n^* [mm]	δ_n^c [mm]
#1	550	28.1	22.0	0.031	0.039
#2	550	22.5	34.4	0.025	0.050
#3	550	8.4	244.5	0.0093	0.131
#4	550	3.2	1693.5	0.0036	0.344

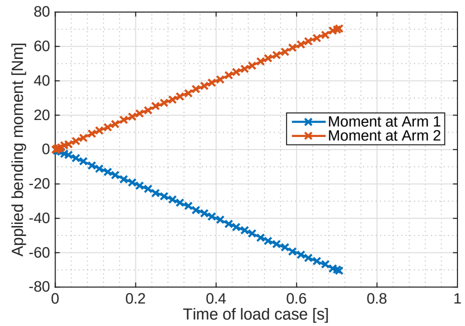
$$G_{Ic} = 550\,\mathrm{J/m^2} \quad , \quad G_{IIc} = 1740.8\,\mathrm{J/m^2}$$

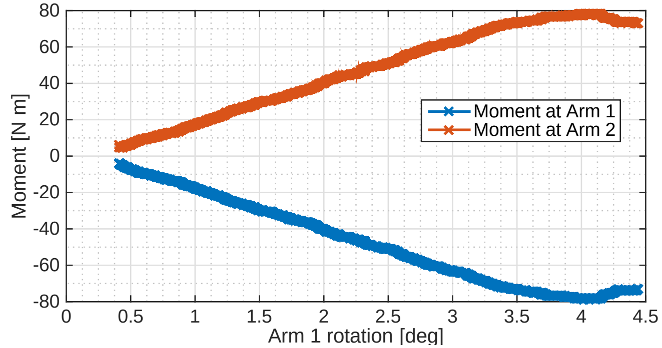
Cohesive Law	G_{IIc} [J/m^2]	σ_t^c [MPa]	ζ_{II} [-]	δ_t^* [mm]	δ_t^c [mm]
#1	1740.8	50	22.0	0.056	0.070
#2	1740.8	40	34.4	0.044	0.087
#3	1740.8	15	244.5	0.017	0.232
#4	1740.8	5.7	1693.5	0.006	0.611

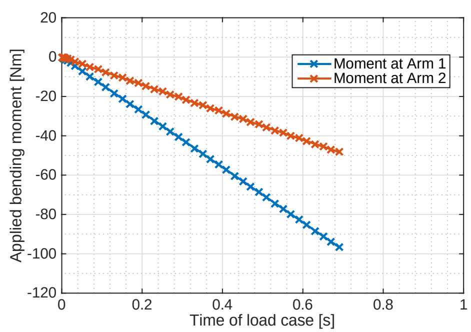


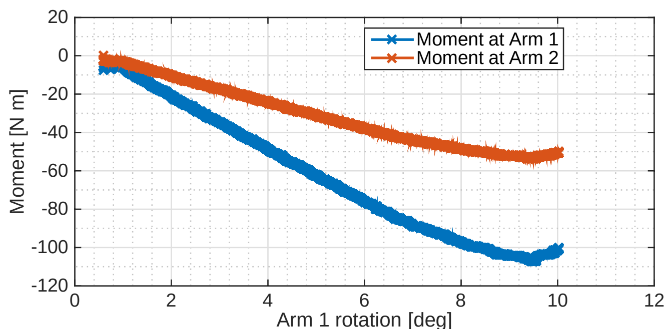
DCB-UBM Test & Results:

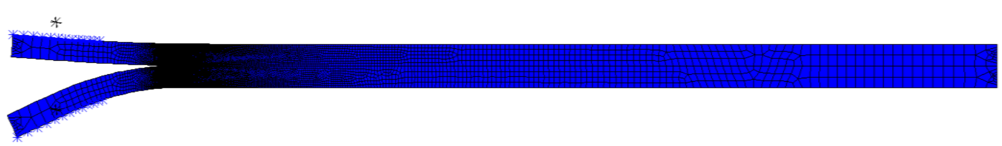
FEA vs. Experiment, DCB-UBM (using cohesive law#2):





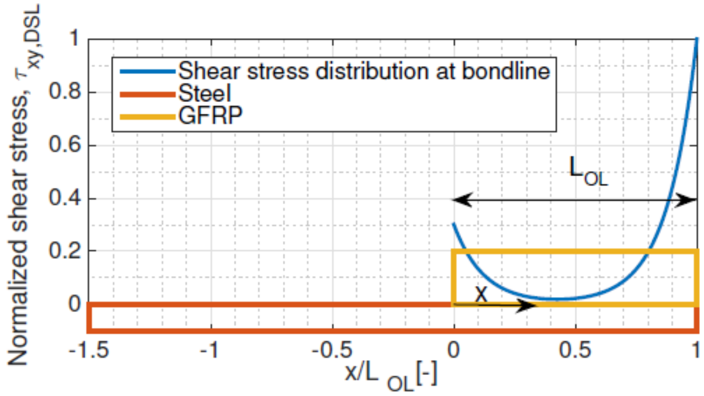


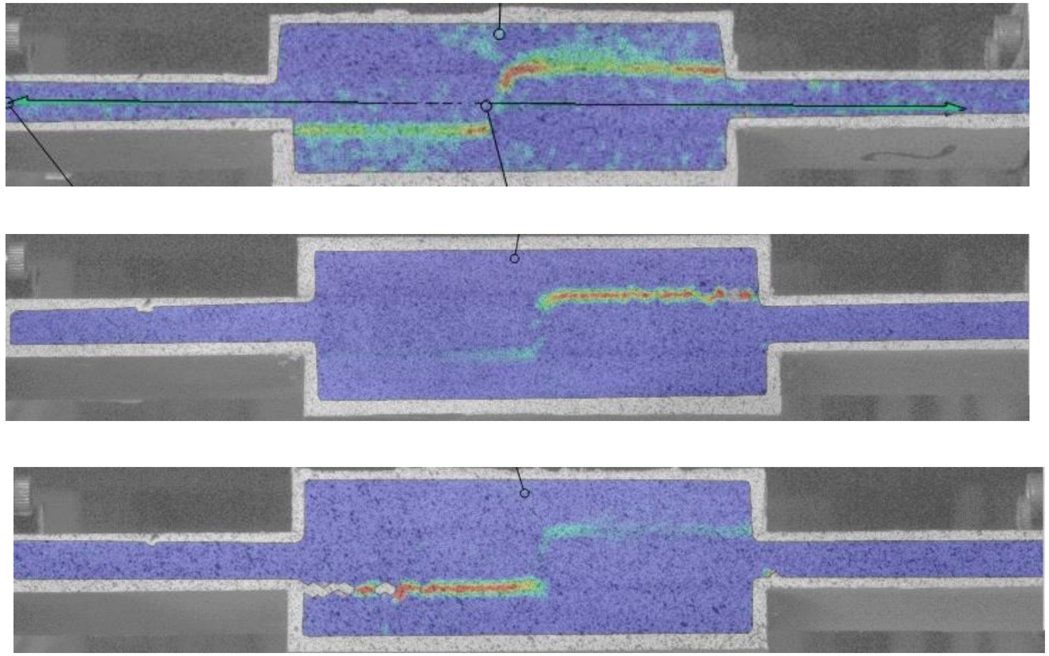




DSL Test & Results:

Theory and crack initiation

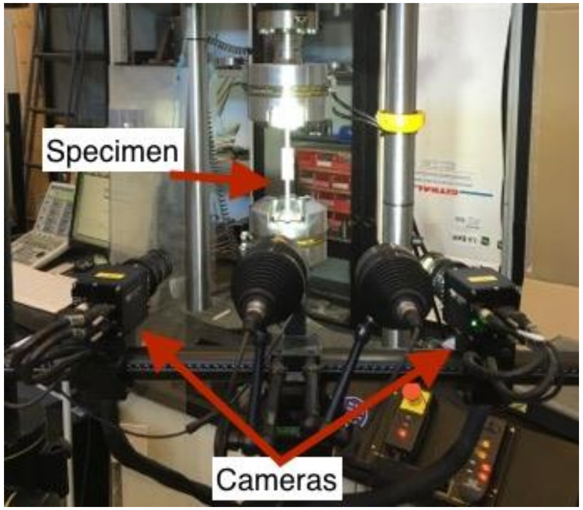


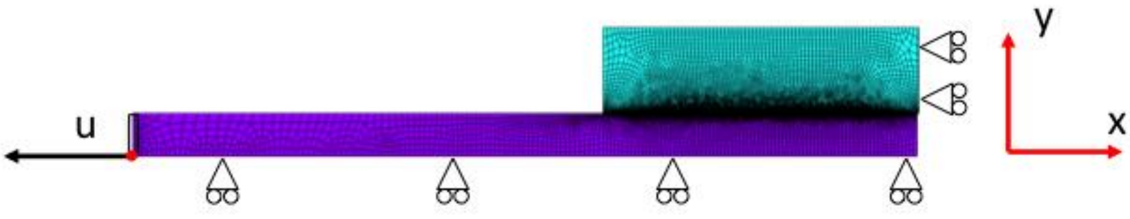


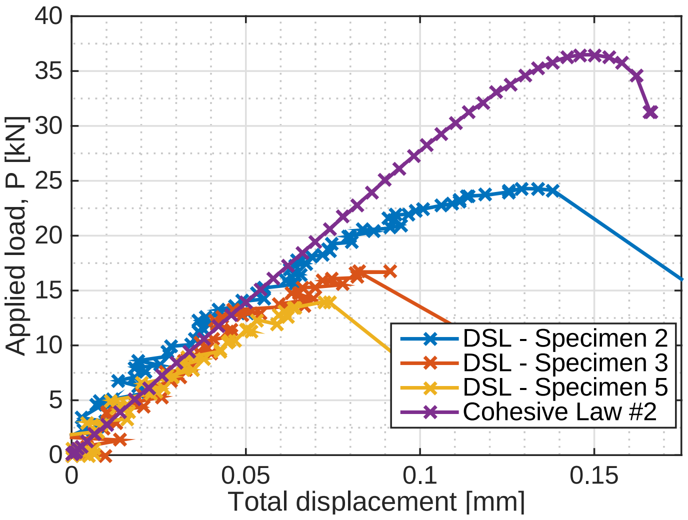
$$\xi = \frac{E \cdot t_{steel}}{2E_x \cdot t_{GFRP}}$$

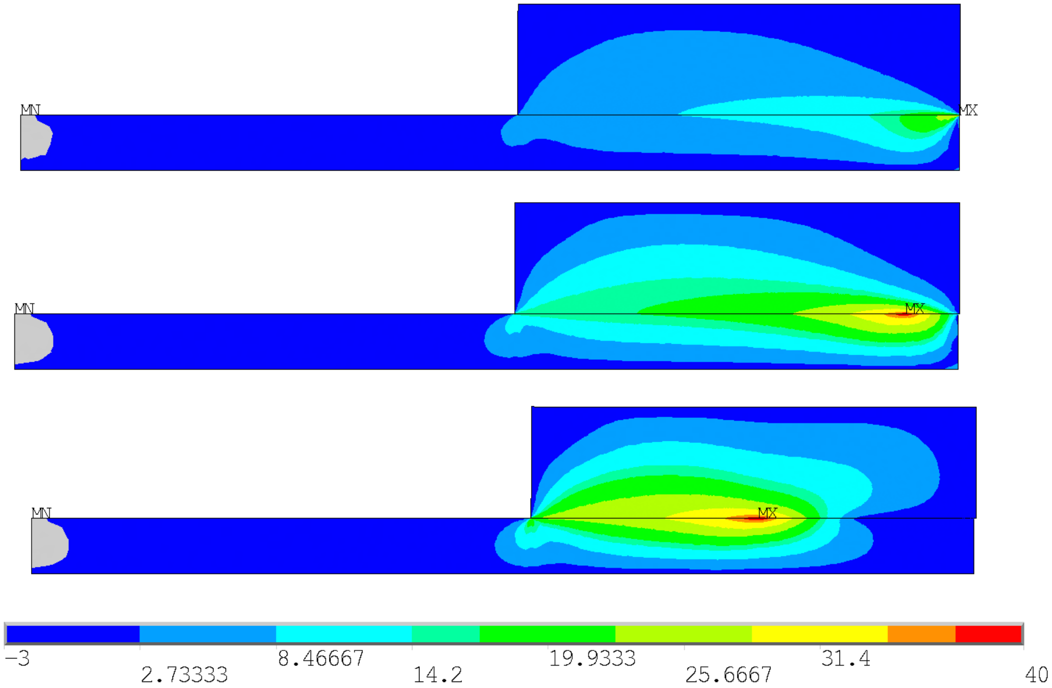
$\xi = 3.32 > 1$ Crack initiates from the middle

DSL analysis

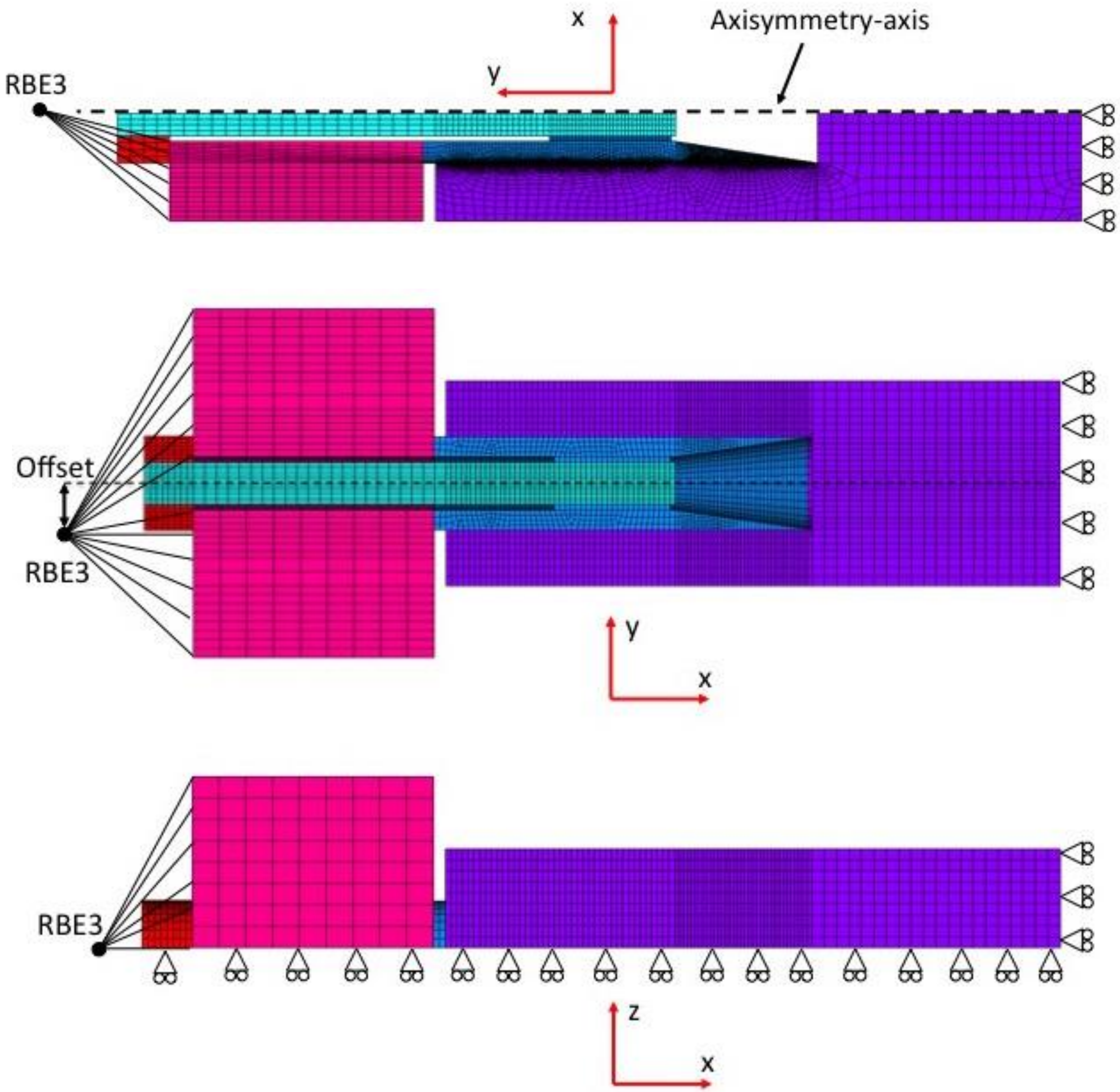




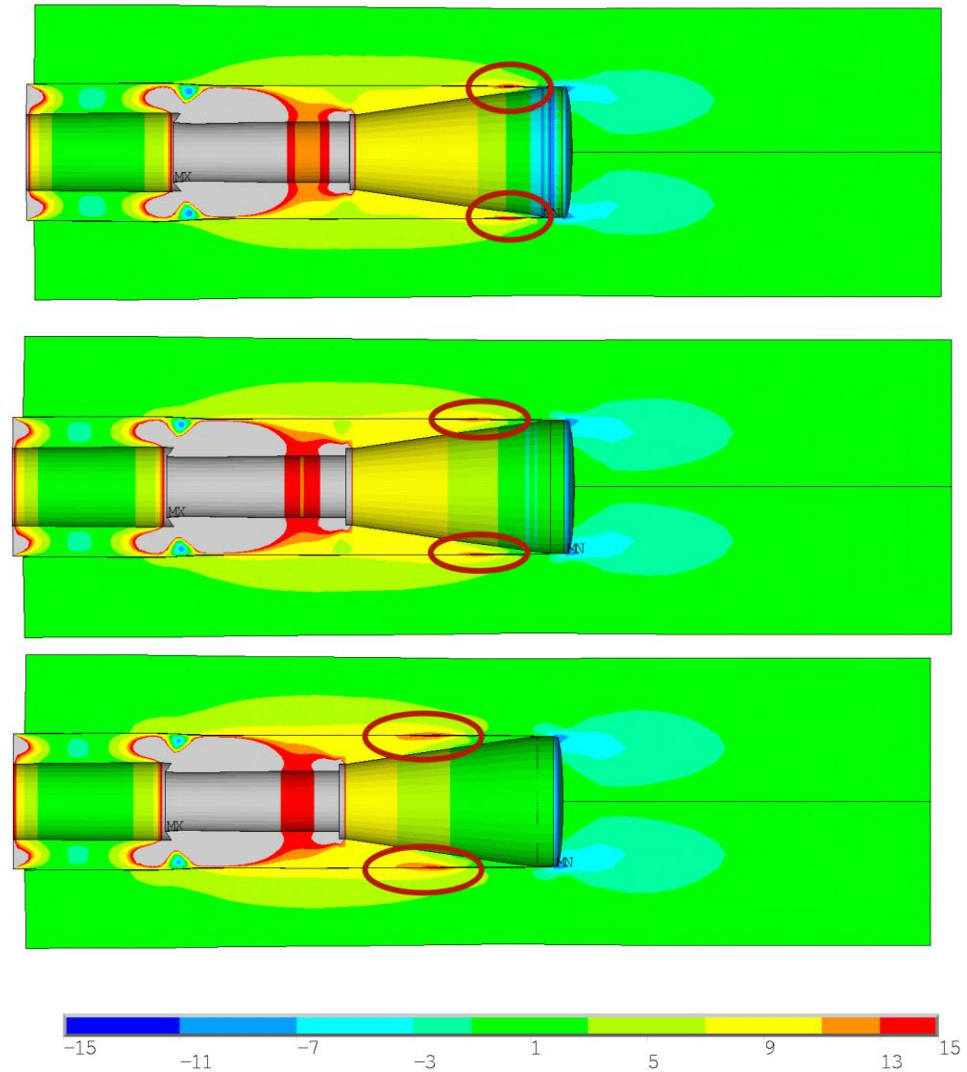




Bushing FE model:



Bushing FE model:



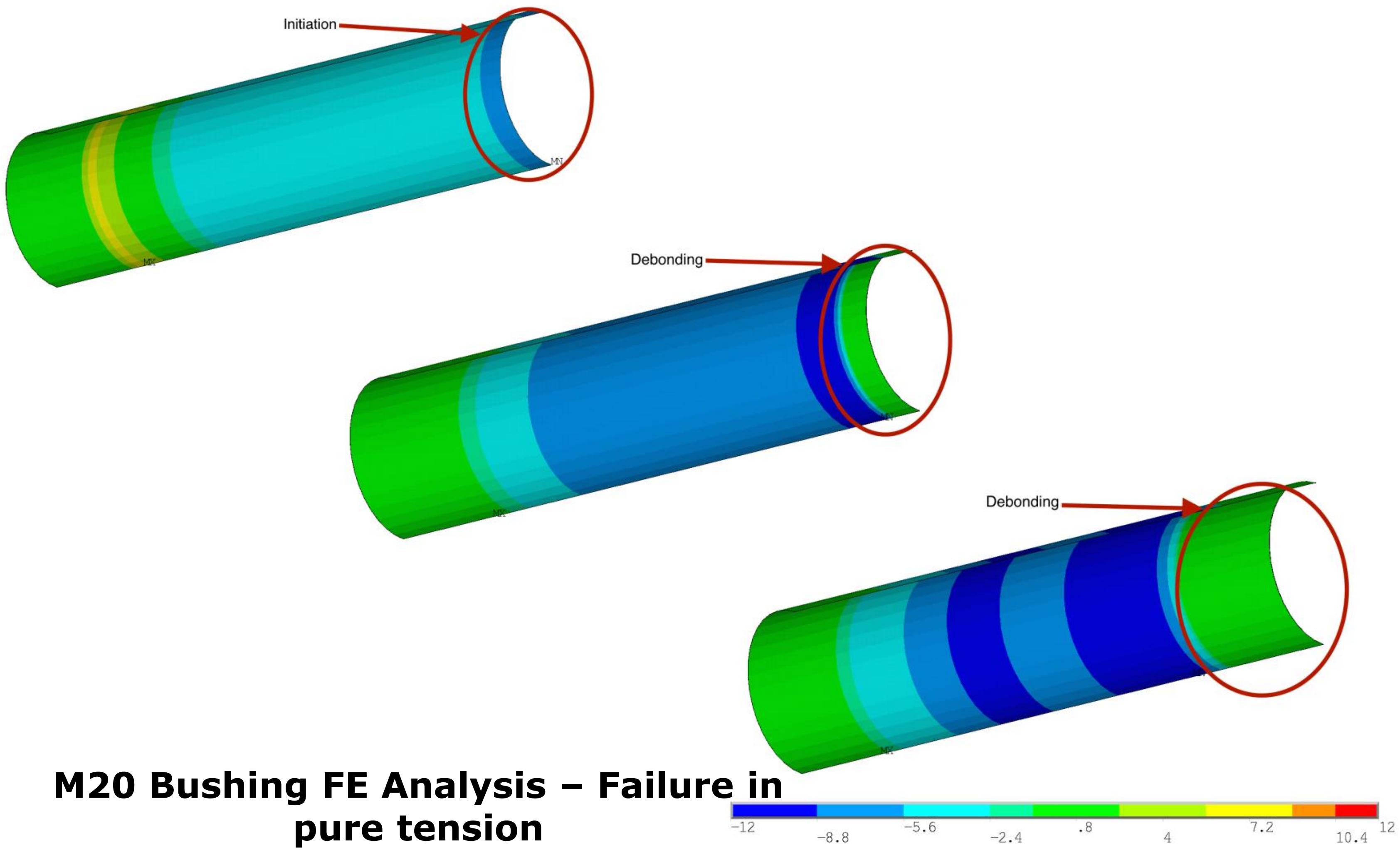
$$G_{Ic} = 550\,\mathrm{J/m^2} \cdot 0.08 = 44.0\,\mathrm{J/m^2}$$

$$G_{IIc} = 1740.8\,\mathrm{J/m^2} \cdot 0.08 = 239.3\,\mathrm{J/m^2}$$

C1	C2	C3	C4	C5	C6
σ_n^c	δ_n^c	σ_t^c	δ_t^c	α	β
[MPa]	[mm]	[MPa]	[mm]	[-]	[-]
6.4	0.014	14.8	0.032	0.5	1.0

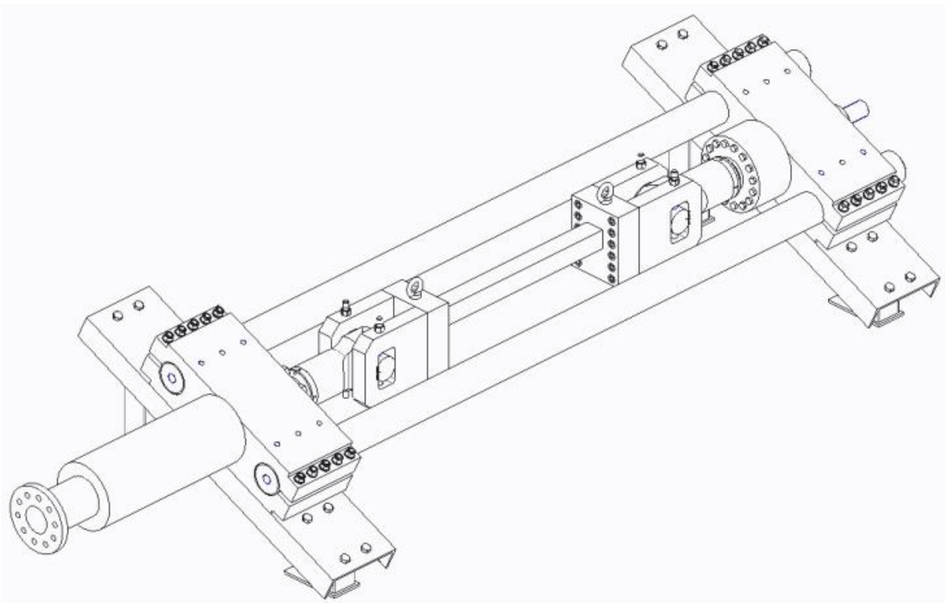
- Running the FE analysis corresponding to applied load of 108.2 kN.

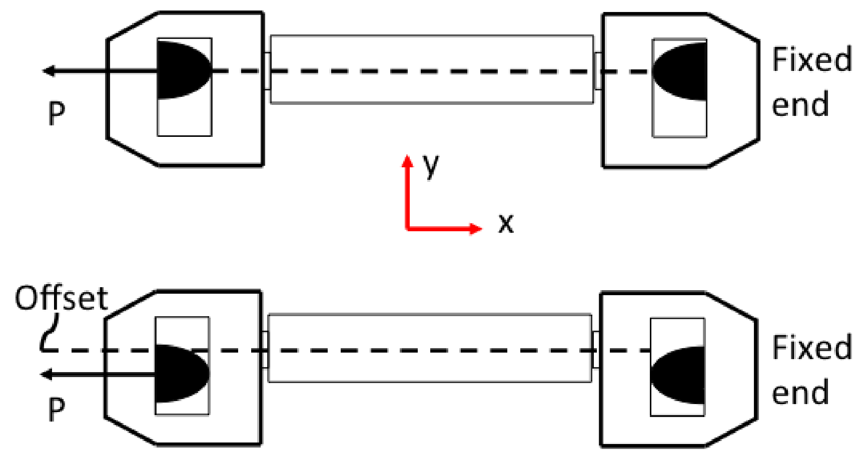
Bushing FE model:



M20 Bushing FE Analysis – Failure in pure tension

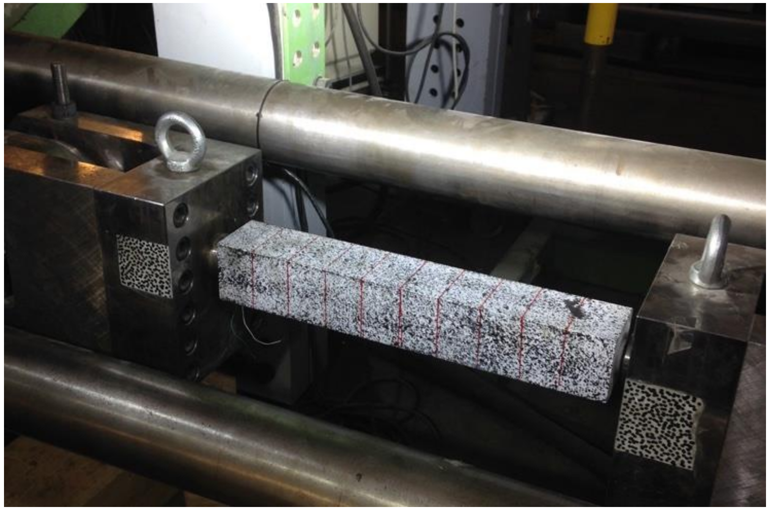
Bushing Test :

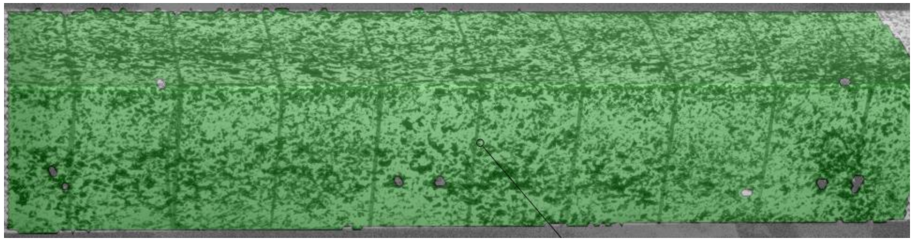


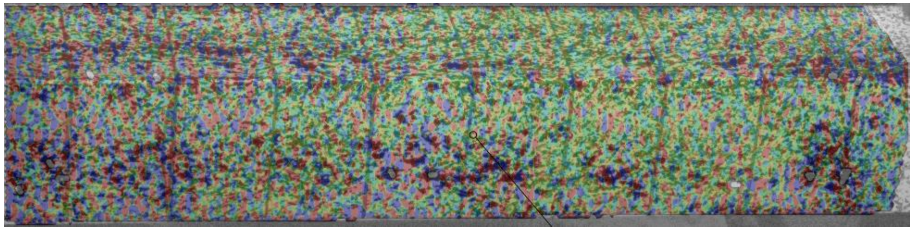


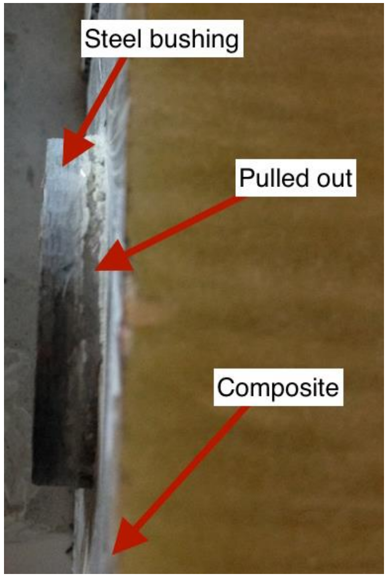
M20 Bushing Test

Bushing Test & Results:



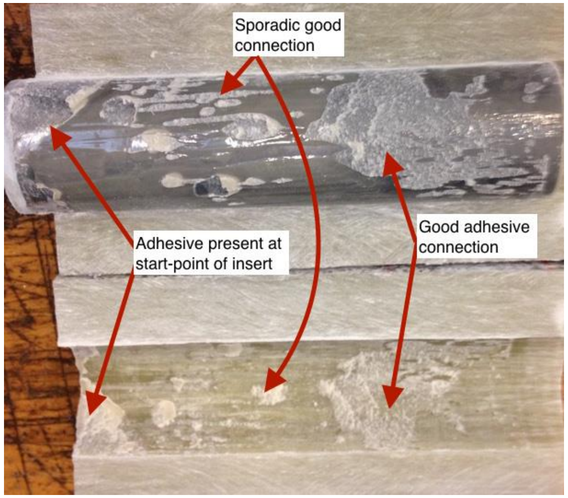


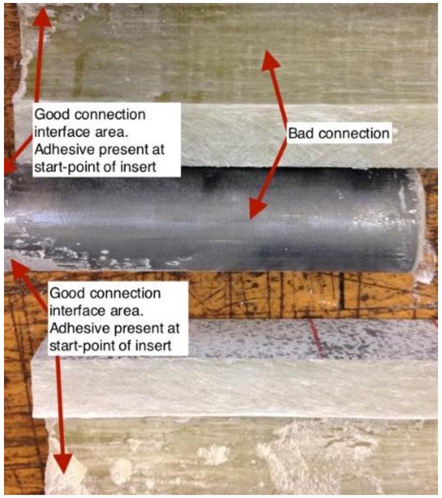


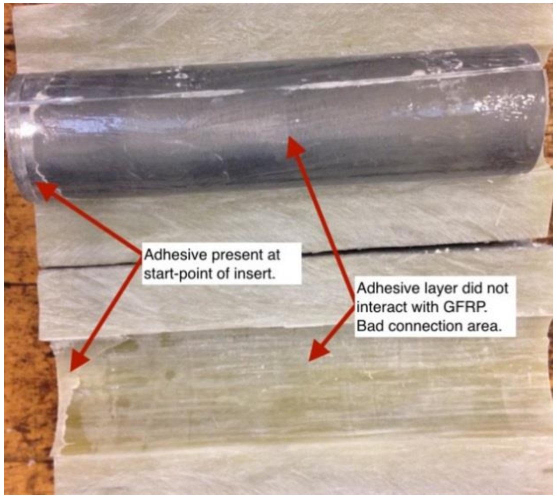


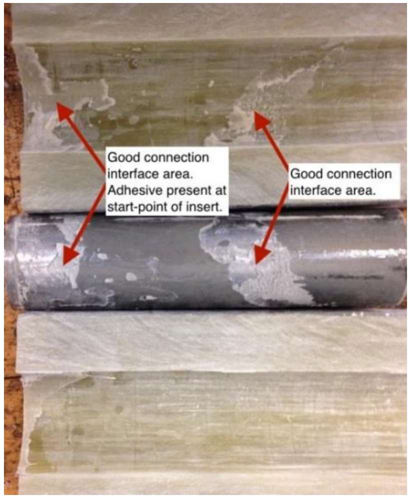
Bushing specimen	#1	#2	#3	#4	#5
Failure load [kN]	70.38	36.42	33.08	36.50	40.80

Bushing Test & Results:









M20 Bushing, Failed specimens

Conclusions and Future works

- Developed FE model to determine phase angle based on VCCT

- Determination of interfacial fracture toughness as a function of mode mixity

- New and updated FE model of root-end bushing w. contact- and cohesive elements

- More static pure tension tests for root end bushings with better manufacturing process are needed

- potential for future research on Fatigue life prediction of root-end bushing