The role of the cohesive law shape and mixed-mode interpolation when modeling delamination failure involving large fracture process zones

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Bas Tijs[3], Ivan R. Cózar[1], Said Abdel-Monsef[1], Laura Carreras[1], Iñaki Leciñana[2], Jordi Renart[1], C. Sarrado[1], Santiago García-Rodríguez[4]
Girona, 31st May 2023

Background

A Continuum Damage Model for the Simulation of Delamination under Variable-Mode Ratio in Composite Materials

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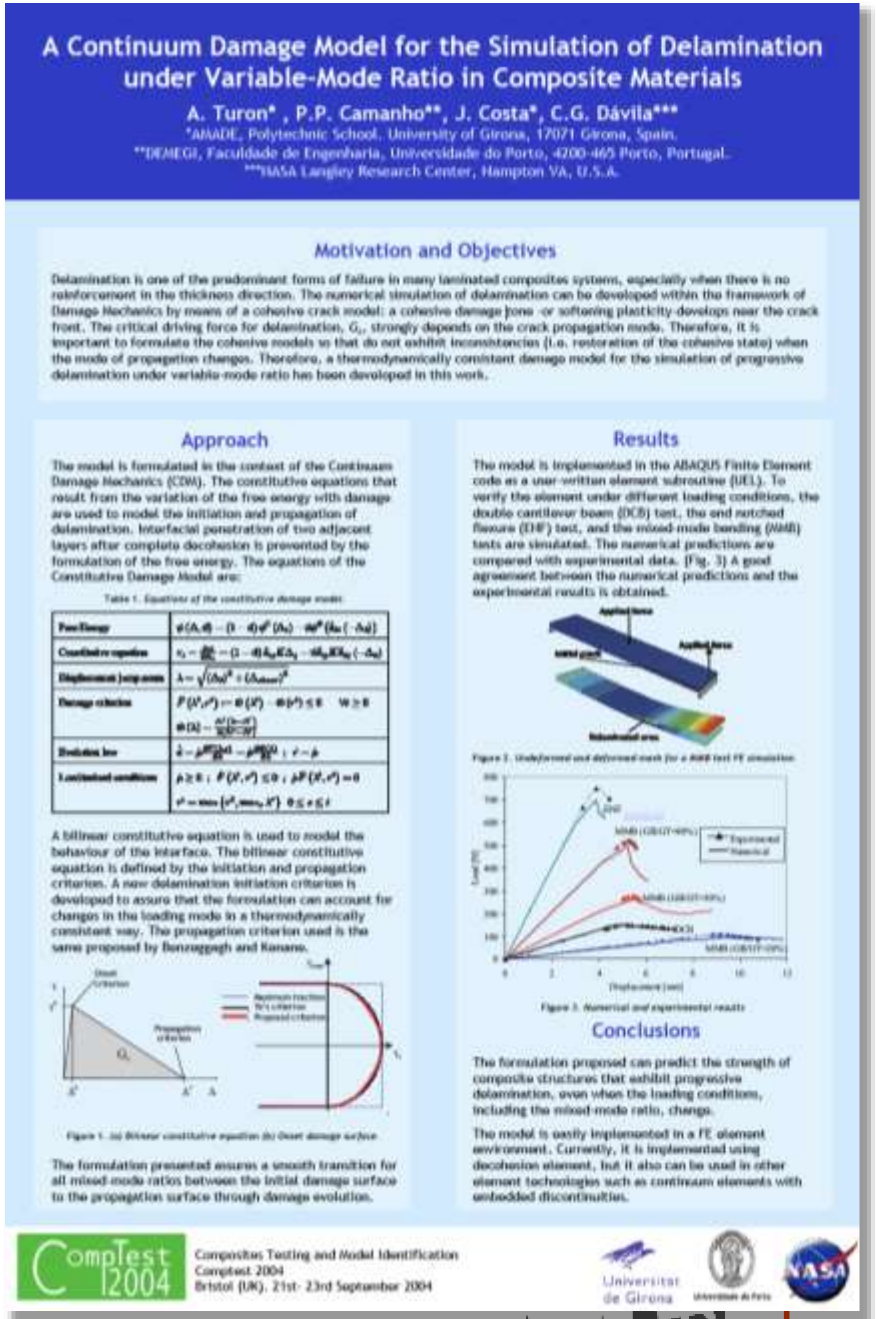
***NASA Langley Research Center, Hampton VA, U.S.A.

Best poster of the session ☺

Almost 20 years ago!!!



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Motivation and Objectives

Delamination is one of the predominant forms of failure in many laminated composites systems, especially when there is no reinforcement in the thickness direction. The numerical simulation of delamination can be developed within the framework of Damage Mechanics by means of a cohesive crack model: a cohesive damage zone -or softening plasticity- develops near the crack front. The critical driving force for delamination, G_c, strongly depends on the crack propagation mode. Therefore, it is important to formulate the cohesive models so that do not exhibit inconsistencies (i.e. restoration of the cohesive state) when the mode of propagation changes. Therefore, a thermodynamically consistent damage model for the simulation of progressive delamination under variable-mode ratio has been developed in this work.

Approach

The model is formulated in the context of the Continuum Damage Mechanics (CDM). The constitutive equations that result from the variation of the free energy with damage are used to model the initiation and propagation of delamination. Interfacial penetration of two adjacent layers after complete decohesion is prevented by the formulation of the free energy. The equations of the Constitutive Damage Model are:

Table 1. Equations of the constitutive damage model

Free Energy	[illegible]
Constitutive equation	[illegible]
Displacement jump norm	[illegible]
Damage criterion	[illegible]
Evolution law	[illegible]
Loading/unloading conditions	[illegible]

A bilinear constitutive equation is used to model the behaviour of the interface. The bilinear constitutive equation is defined by the initiation and propagation criterion. A new delamination initiation criterion is developed to assure that the formulation can account for changes in the loading mode in a thermodynamically consistent way. The propagation criterion used is the same proposed by Benzeggagh and Kenane.

Figure 1. (a) Bilinear constitutive equation (b) Onset damage surface

The formulation presented assures a smooth transition for all mixed-mode ratios between the initial damage surface to the propagation surface through damage evolution.

Results

The model is implemented in the ABAQUS Finite Element code as a user-written element subroutine (UEL). To verify the element under different loading conditions, the double cantilever beam (DCB) test, the end notched flexure (ENF) test, and the mixed-mode bending (MMB) tests are simulated. The numerical predictions are compared with experimental data. (Fig. 3) A good agreement between the numerical predictions and the experimental results is obtained.

Figure 2. Undeformed and deformed mesh for a MMB test FE simulation

Figure 3. Numerical and experimental results

Conclusions

The formulation proposed can predict the strength of composite structures that exhibit progressive delamination, even when the loading conditions, including the mixed-mode ratio, change.

The model is easily implemented in a FE element environment. Currently, it is implemented using decohesion element, but it also can be used in other element technologies such as continuum elements with embedded discontinuities.

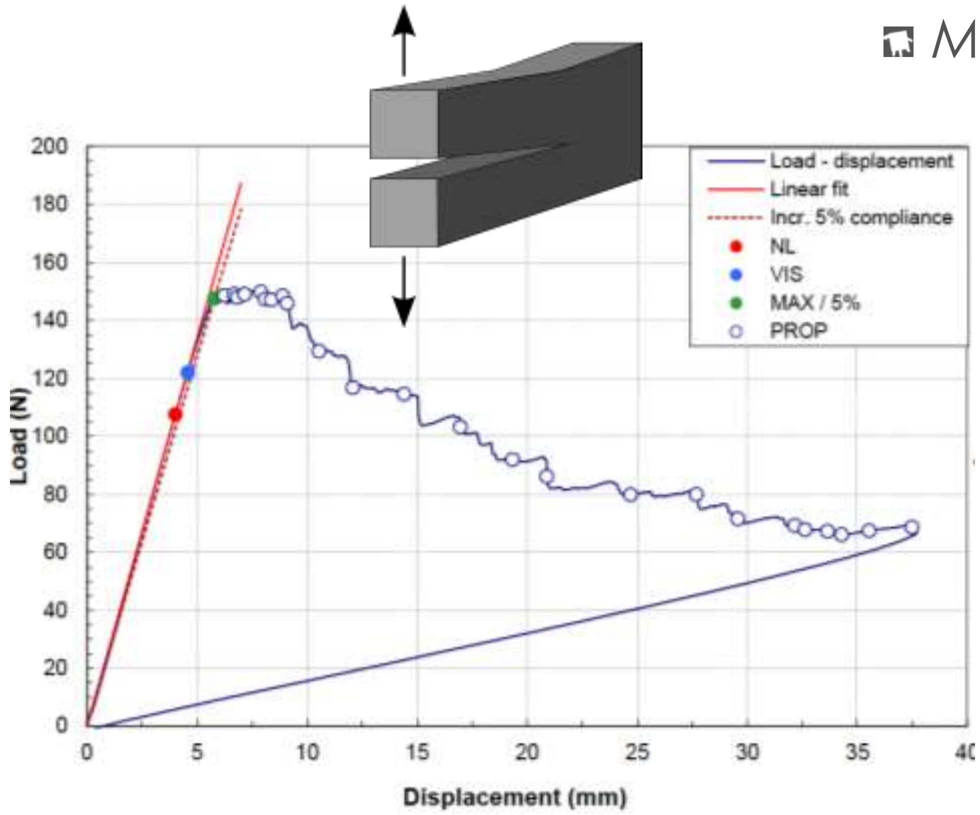
CompTest 2004
Composites Testing and Model Identification
Comptest 2004
Bristol (UK). 21st- 23rd September 2004
Universitat de Girona

Keynote speakers selection by the conference committee (Sept. 2022)

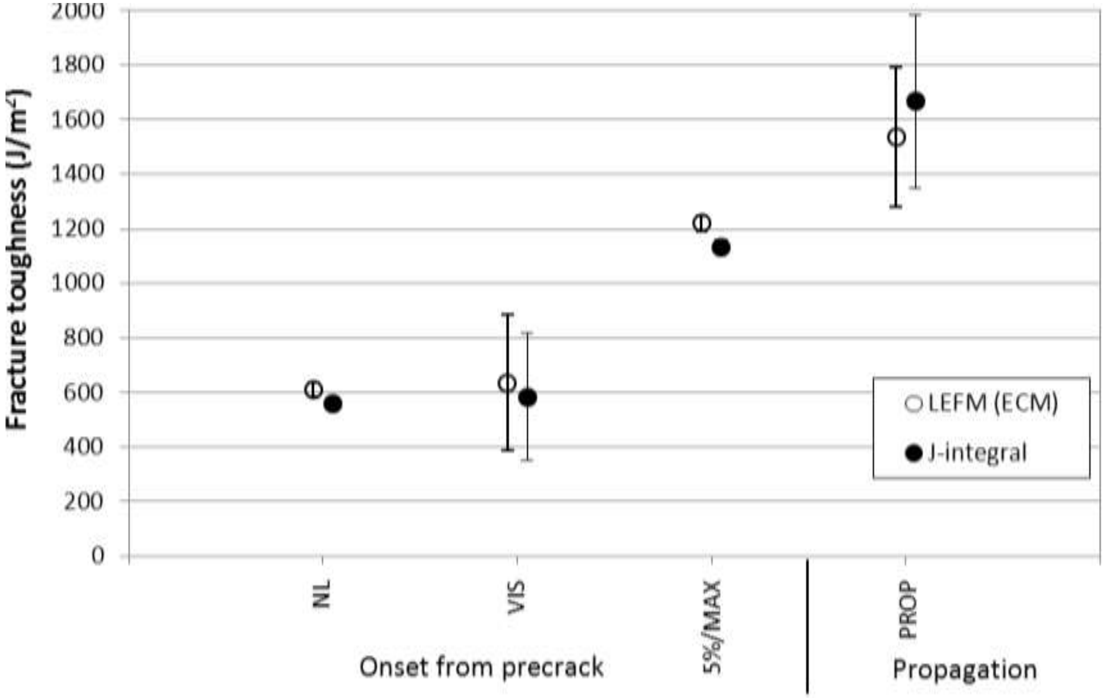
- *there are many researchers who use cohesive elements and never ask questions*
- *there is another (smaller) group that considers all this as nonphysical and rejects the method in spite of its applicability and practical usefullness*
- *there is a third group that HAS to use cohesive elements, but they want answers based on physics. (I hope we all belong to this group...)*

- *Obviously, the answer there is in experimental identification of cohesive laws (in elastic, viscoeleastic problems and also in the change of these laws in fatigue+ other things)*
- *I believe that the group in Girona (Josep or Albert) could prepare an excellent presentation of methodologies for experimental determination of cohesive laws in all these different cases.*

Prompt: I need to capture delamination with my FEM model



Material data



	Propagation data		Onset data from insert					
Specimen (internal code)	G_{IC} ECM (J/m^2) AVERAGE OF ECM PROPAGATION DATA*	J integral (J/m^2) AVERAGE OF PROPAGATION DATA*	G_{IC} ECM (J/m^2) NL	VIS	5%/MAX	J integral (J/m^2) NL	VIS	5%/MAX
14-1823	1354	1442	628	811	1240	577	750	1152
14-1824	1719	1891	591	460	1199	544	419	1116
Average	**1536**	**1667**	**610**	**635**	**1219**	**561**	**584**	**1134**
Standard deviation	**258.09**	**317.46**	**25.98**	**248.25**	**29.32**	**23.60**	**234.10**	**25.23**

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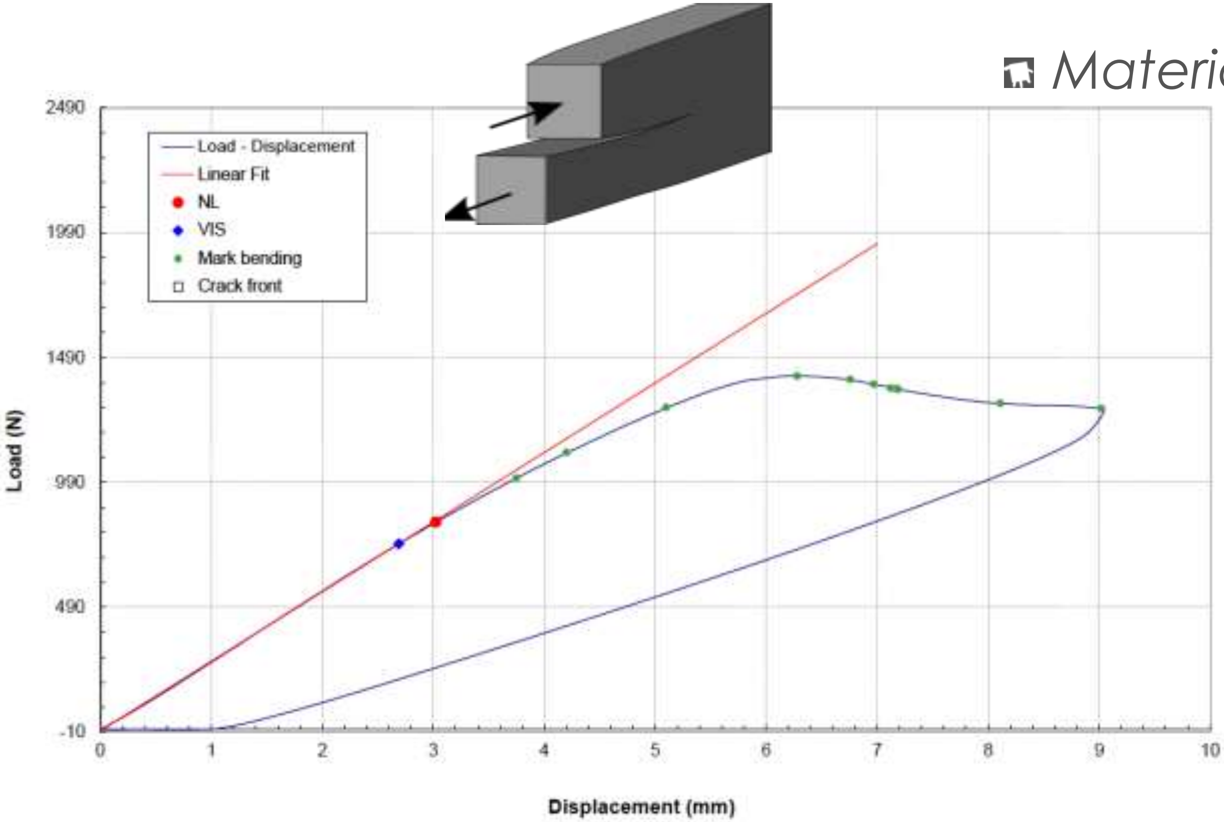

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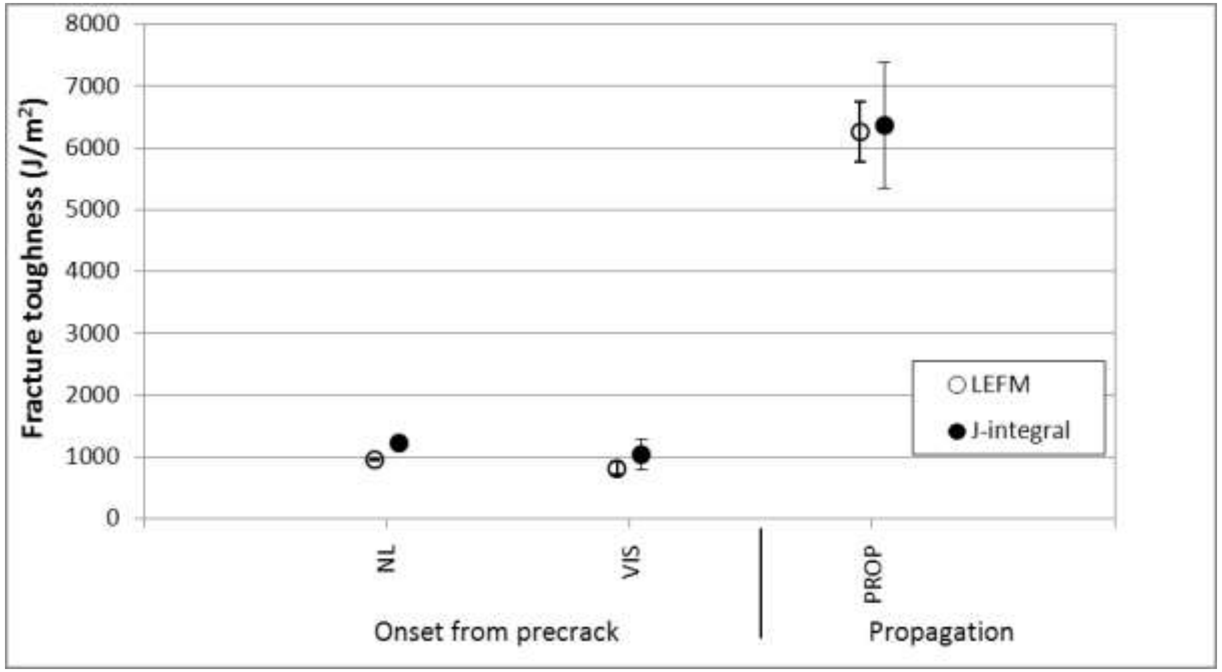

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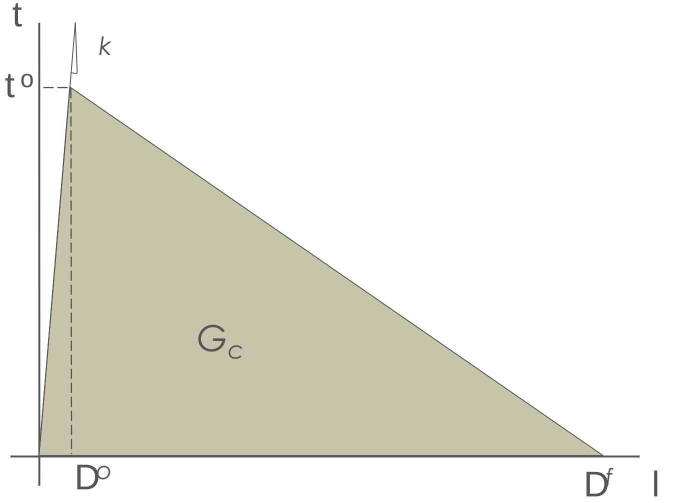
14-1829	5914	5638	968	743	1147	861
14-1830	6597	7083	953	896	1303	1220
Average	**6255**	**6360**	**960**	**819**	**1225**	**1041**
Standard deviation	**483,30**	**1021,86**	**10,24**	**107,86**	**110,67**	**253,69**

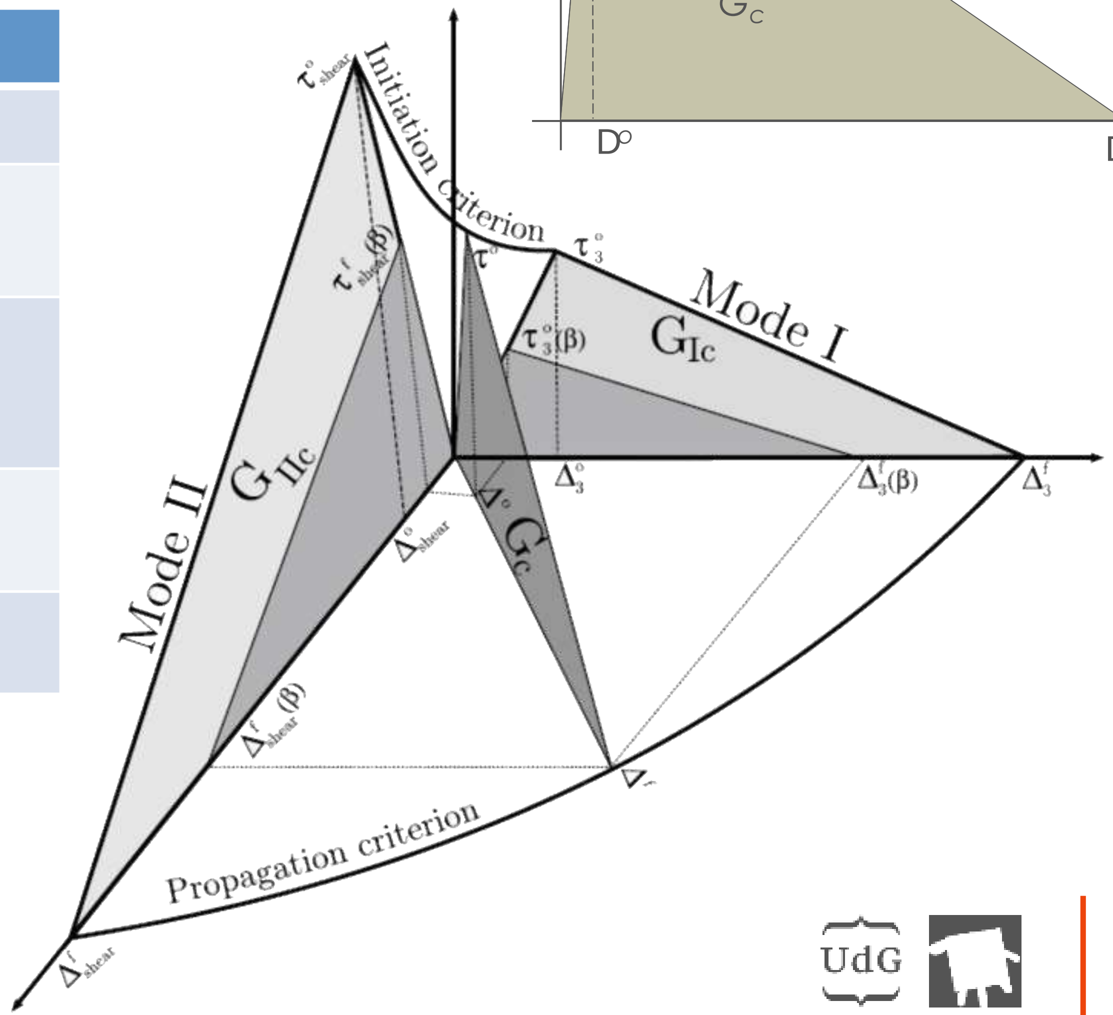
Prompt: I need to capture delamination with my FEM model

- *Input properties for my fem model?*

5+1 parameters:
G_{Ic}, G_{IIc}, τ_3, τ_{sh}, η, k

Reference	Test	Procedure/standard	Property
DCB	Mode I delamination test	ISO 25217	G_{Ic}
ENF CELS	Mode II delamination test	ASTM ESIS protocol	G_{IIc}
MMB	Mixed mode delamination test	ASTM D6671M:13	Power law: 〈 ,®,© BK:|
L-angle	Curved beam in for point bending	ASTM D6415	$\|_3$
ILSS	Intherlaminar shear strength	ASTM D2344	$\|_{sh}$





Prompt: I need to capture delamination with my FEM model

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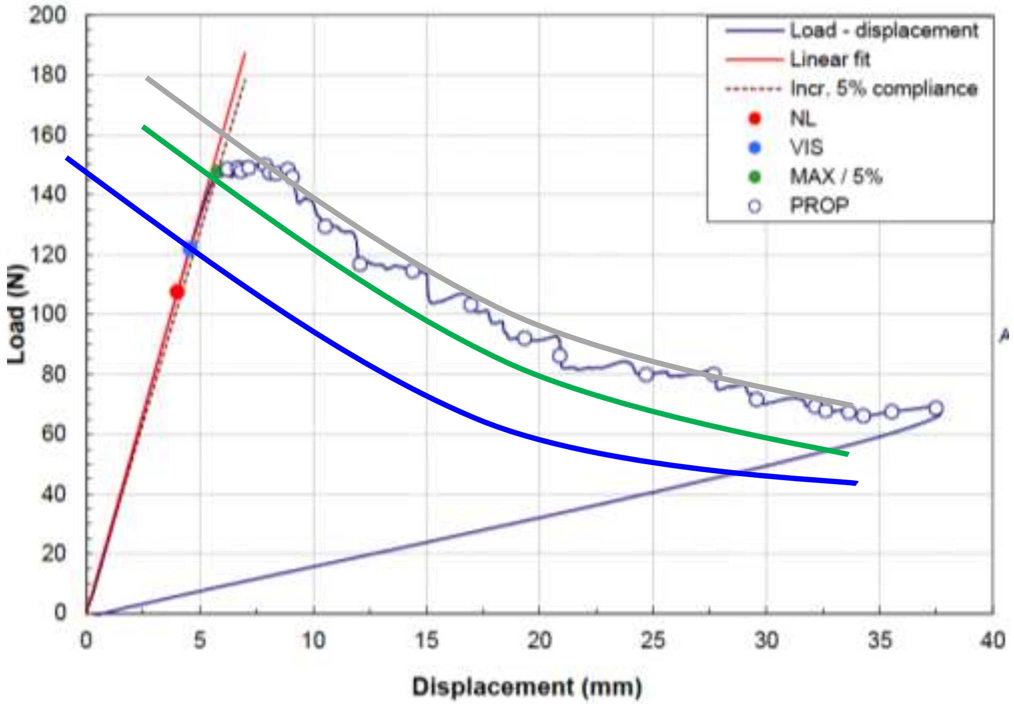

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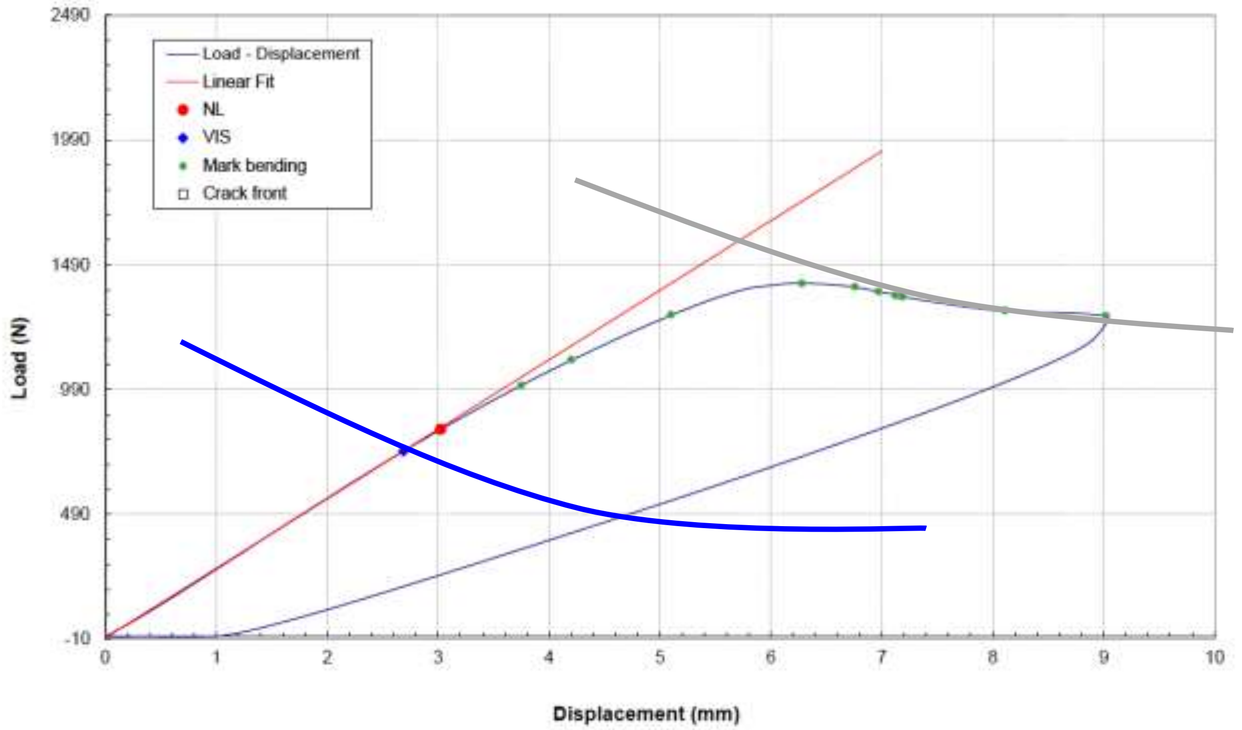

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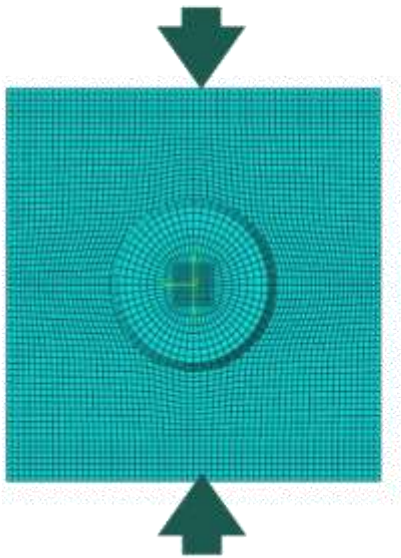
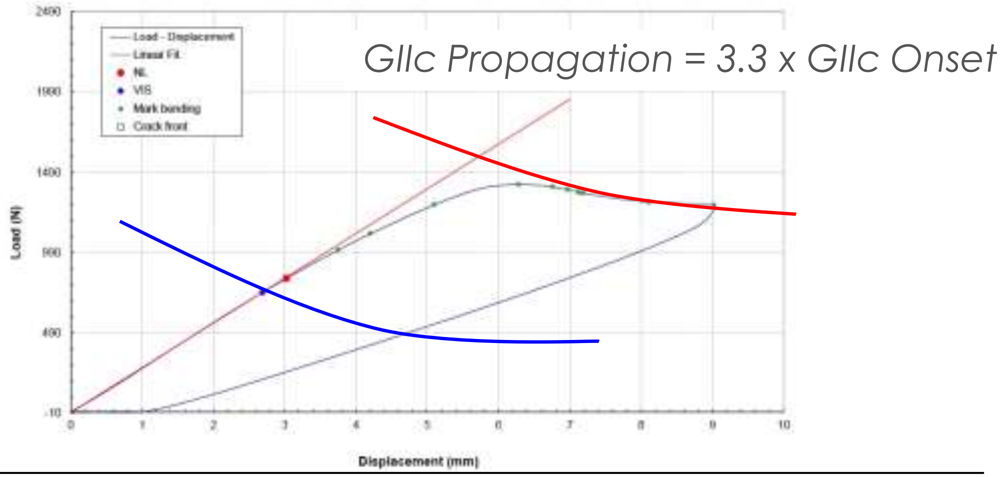
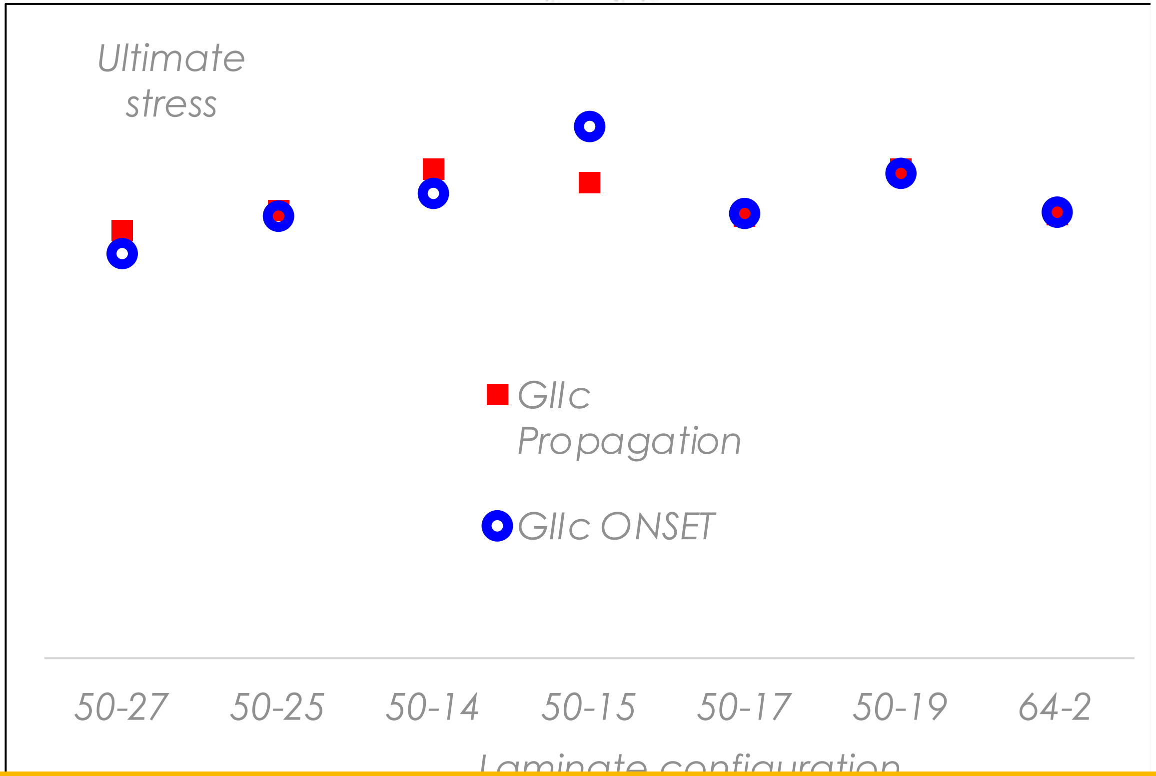
Implications on a filled hole simulation



García-Rodriguez et al.



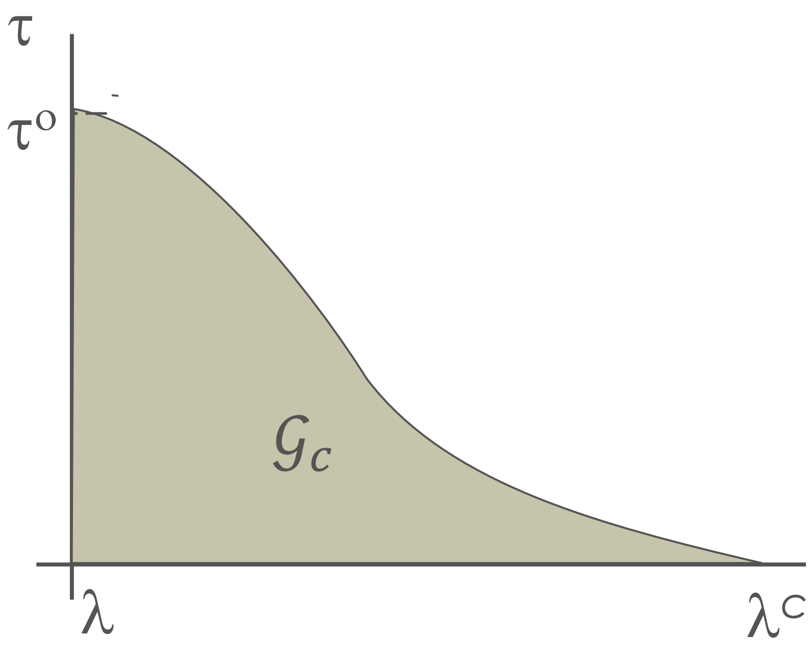


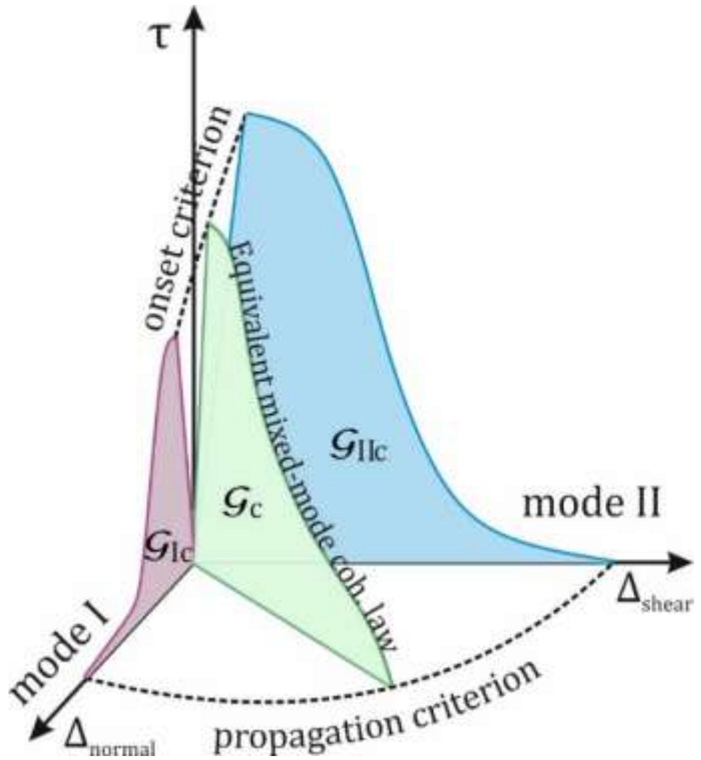
- “Most conservative” option?

Complex scenariors, damage interaction/load redistribution
→ selecting lower input values not necessary means being more conservative

Input properties for my fem model?

Cohesive law!

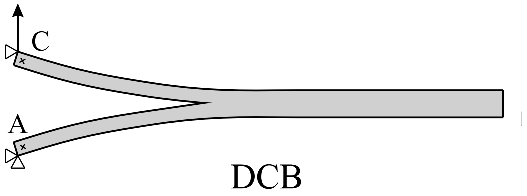


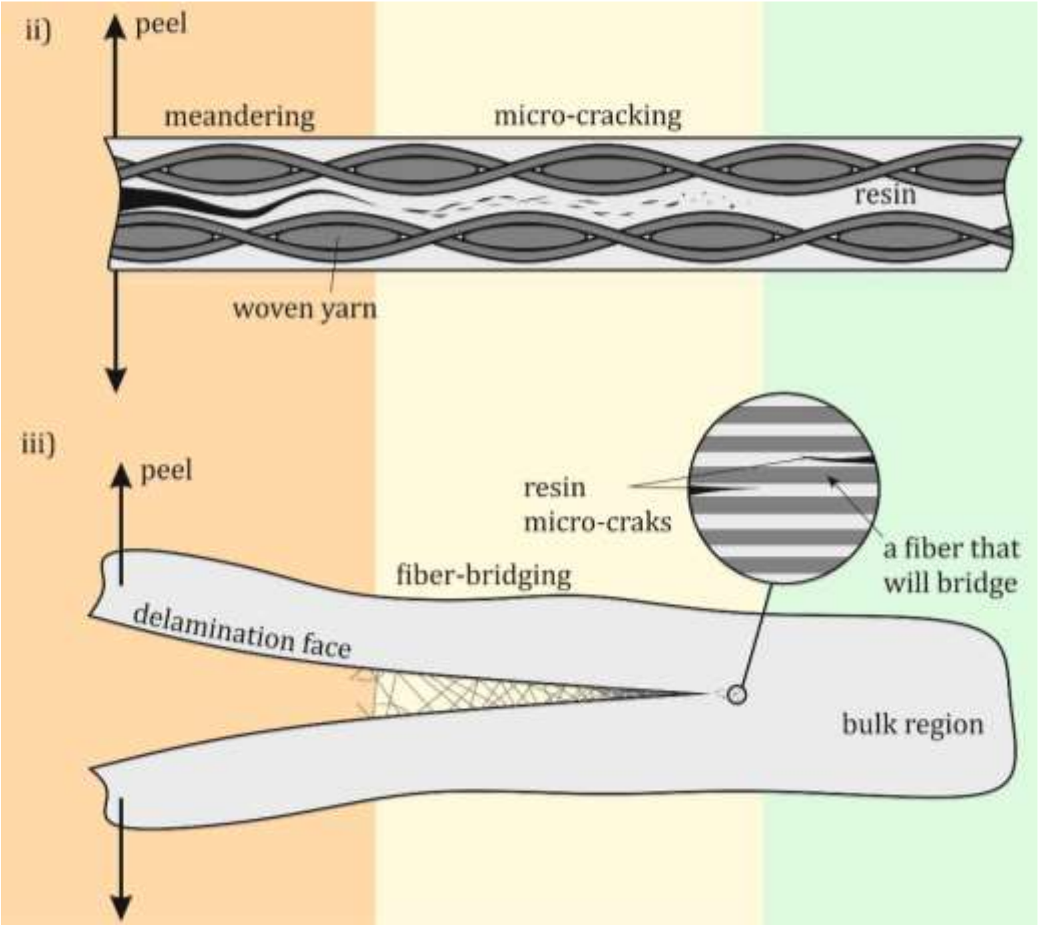


+ CL shape

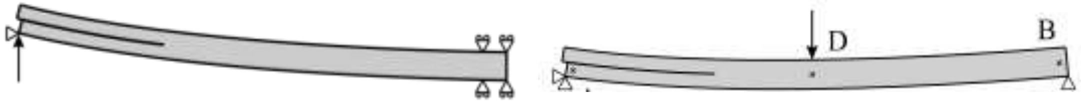
5+1 parameters:
G_{Ic}, G_{IIc}, τ_3, τ_{sh}, η, k

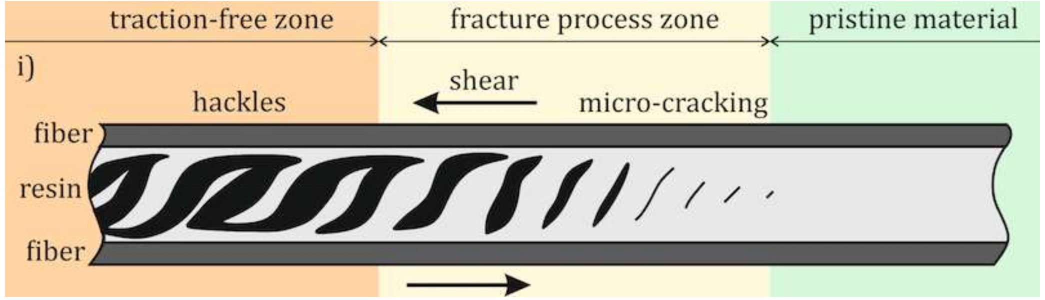
❑ Micromechanical point of view





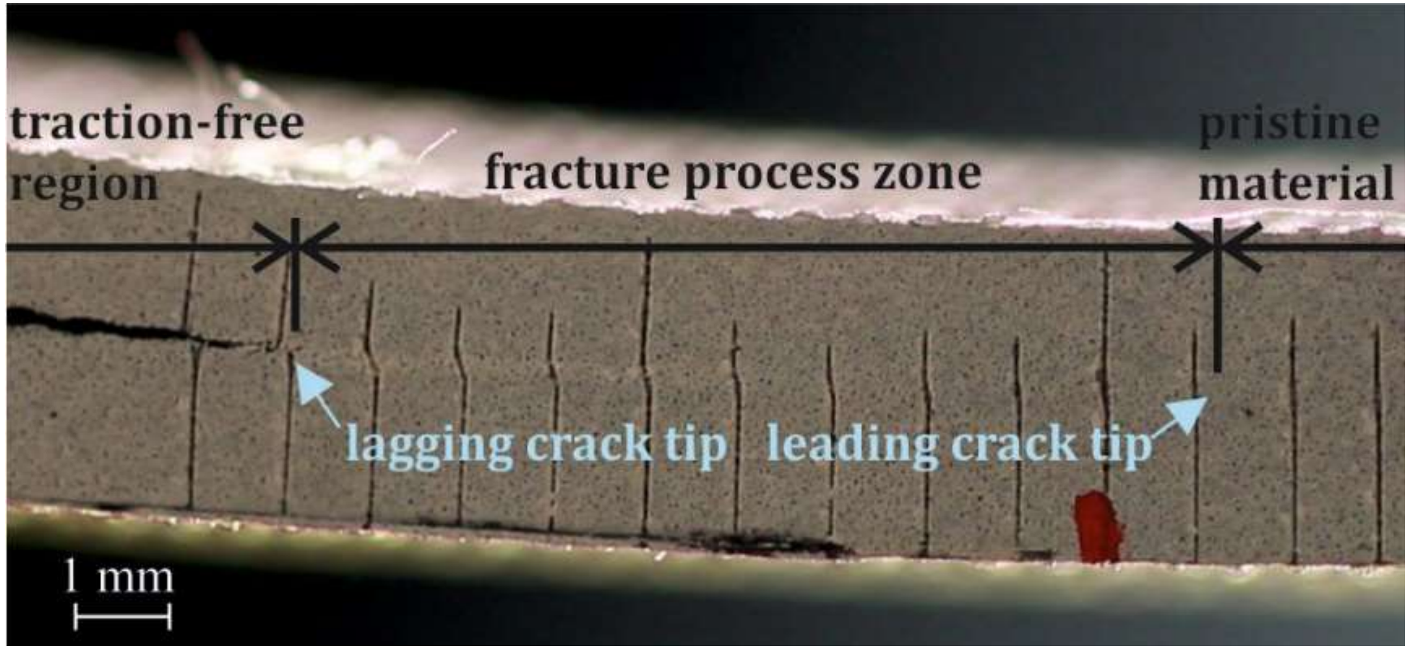
- sequence of different failure events (damage mechanisms) occurring at the microscopic level





❑ Macroscopic (mesoscale) point of view

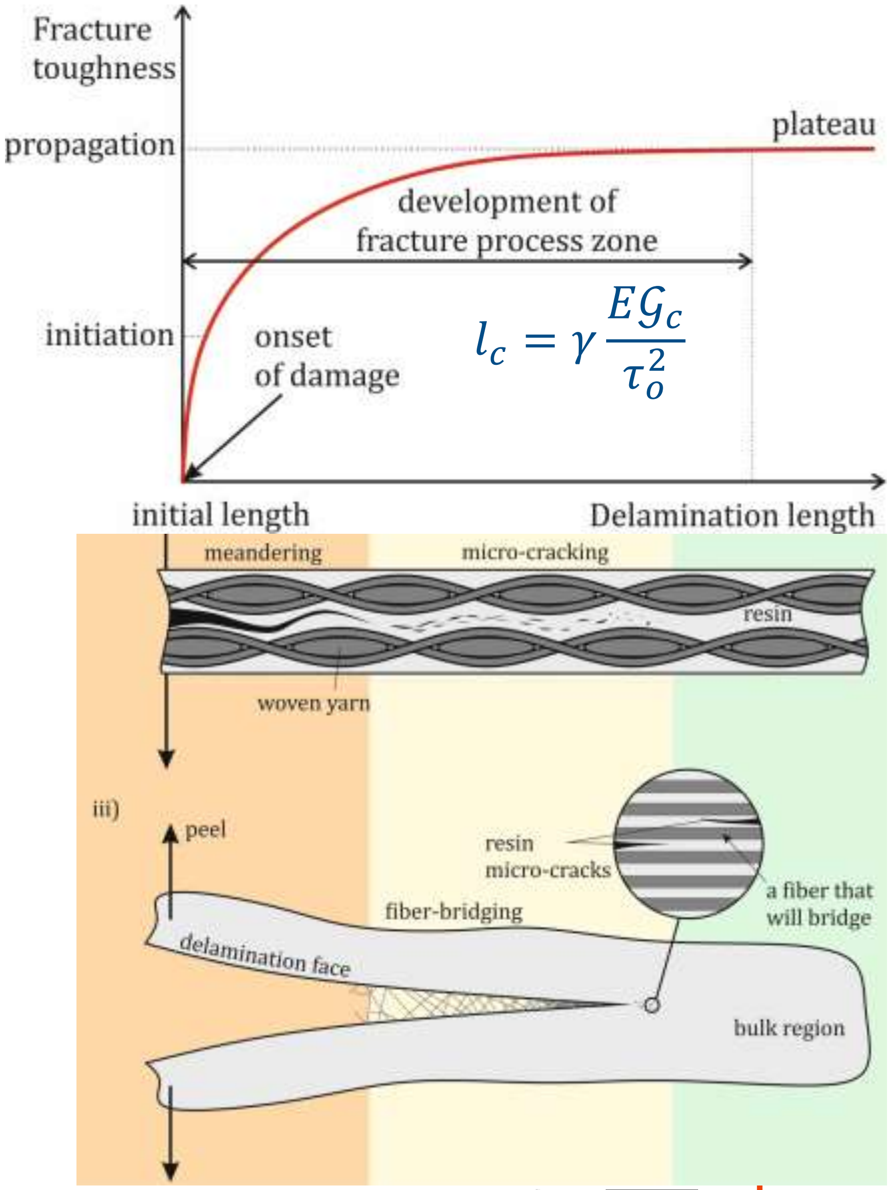
→ all the failure processes occur in a region called a Fracture Process Zone (FPZ)



The FPZ is bound by the “lagging” crack tip, i.e., the limit point where the interface is not able to withstand any traction (stress free region), and the “leading” crack tip, i.e., the limit point where the interface in the pristine material is starting to degrade)

❑ R-Curve

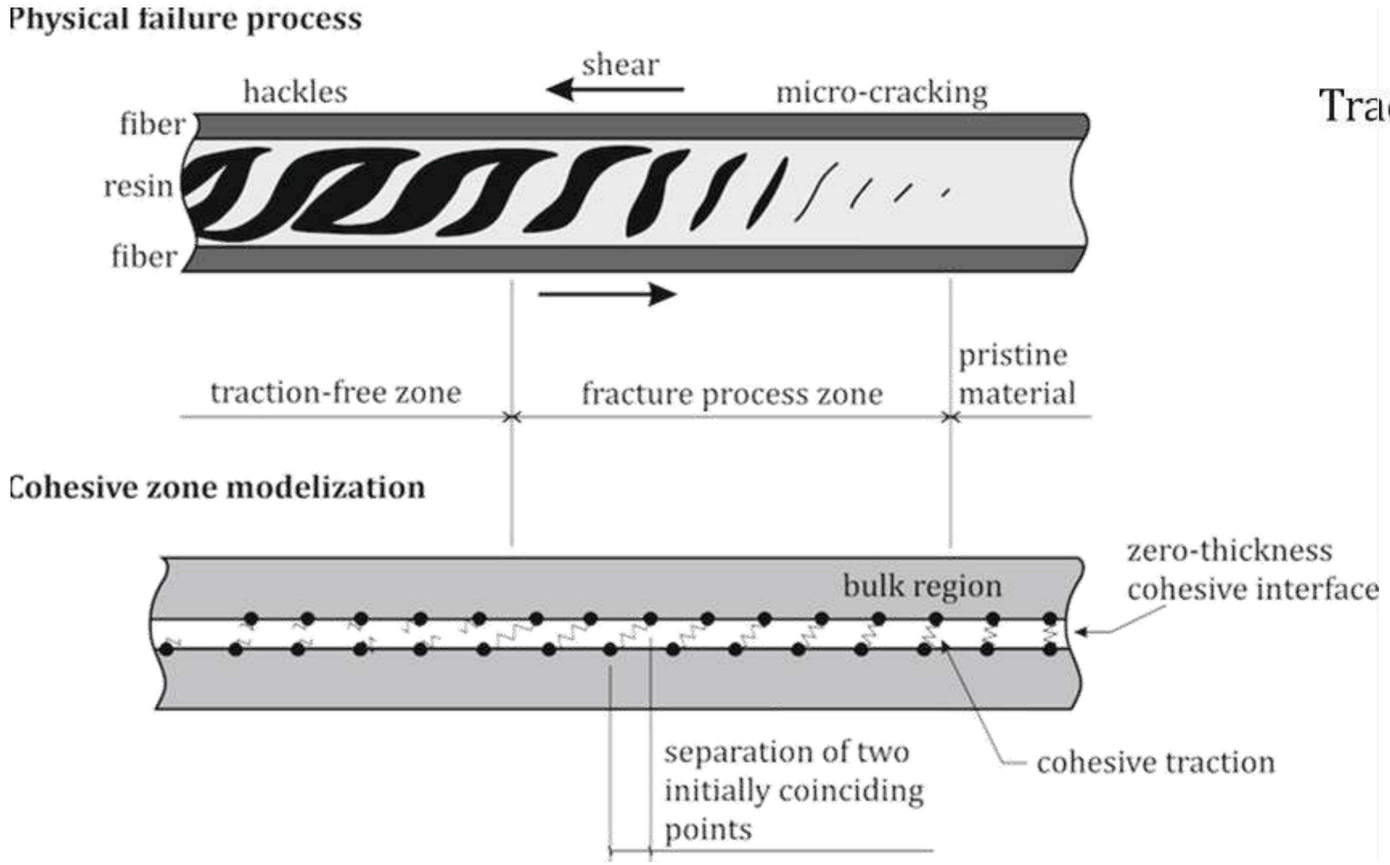
- The combined effect of the various micromechanical damage mechanisms is a fracture toughness that increases as the FPZ develops → R-curve.
- R-curve starts with the onset of early degradation processes (onset of damage) and converges to a plateau value (propagation toughness).
- The more convoluted the microscopic crack path, together with the presence of bridging elements or other blunting mechanisms, the higher the toughness for propagation.
- When the effective toughness reaches the plateau value, the FPZ is completely developed, and the delamination starts to propagate in a self-similar manner.

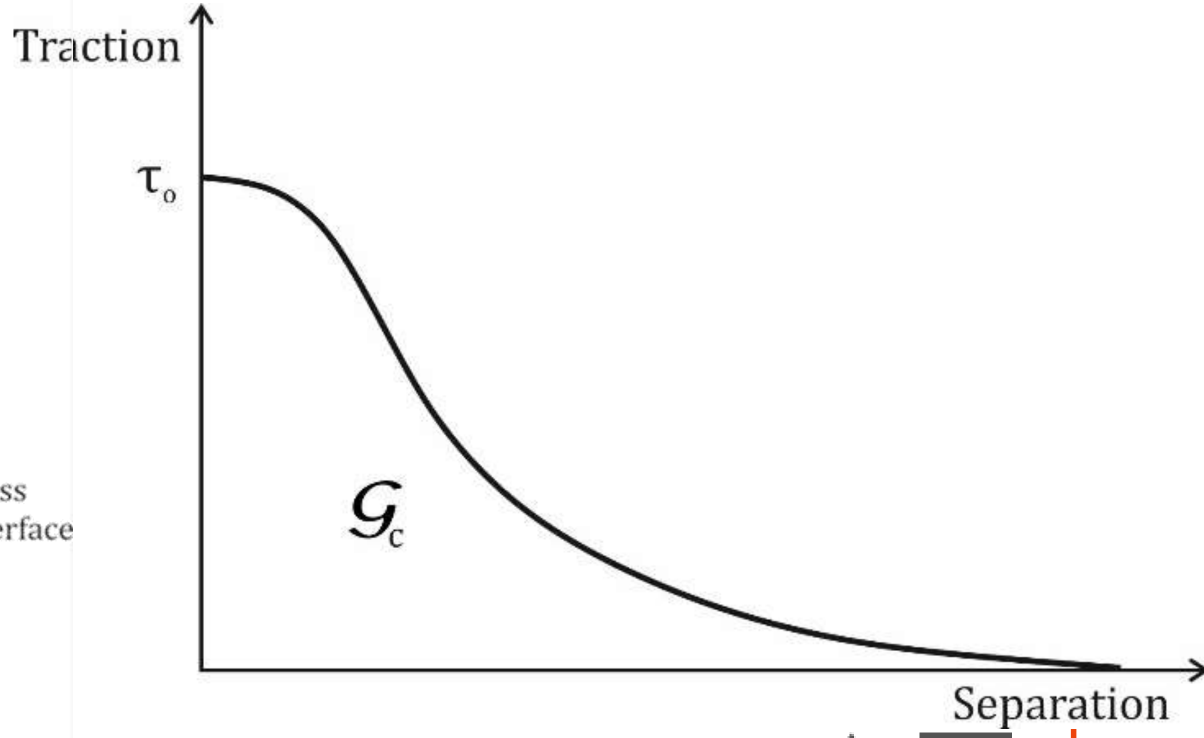


Mechanics of delamination onset and propagation

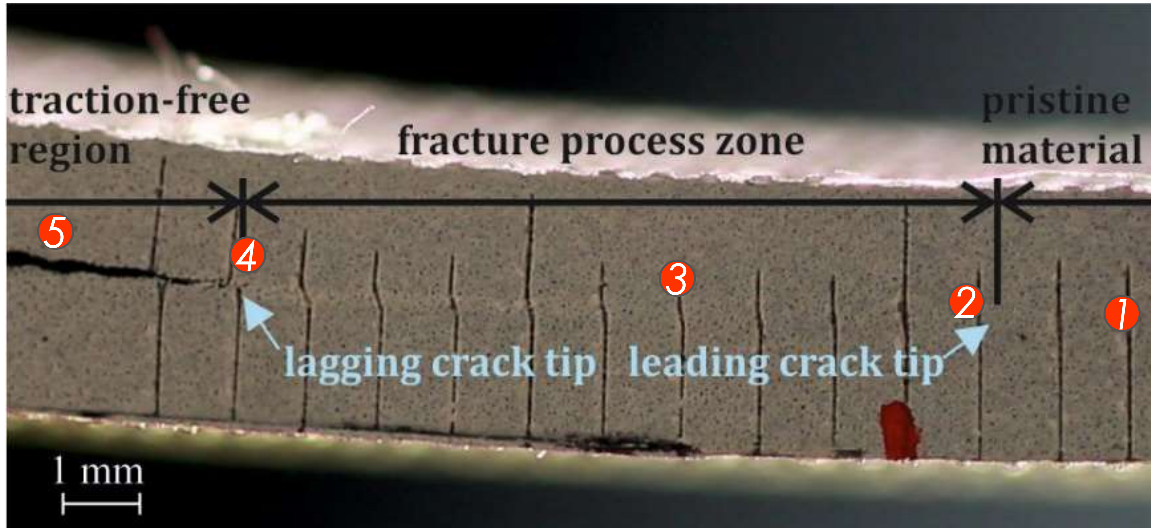
“all the material deformation and degradation of the mechanical properties due to microscopic failure processes can be lumped into a surface”

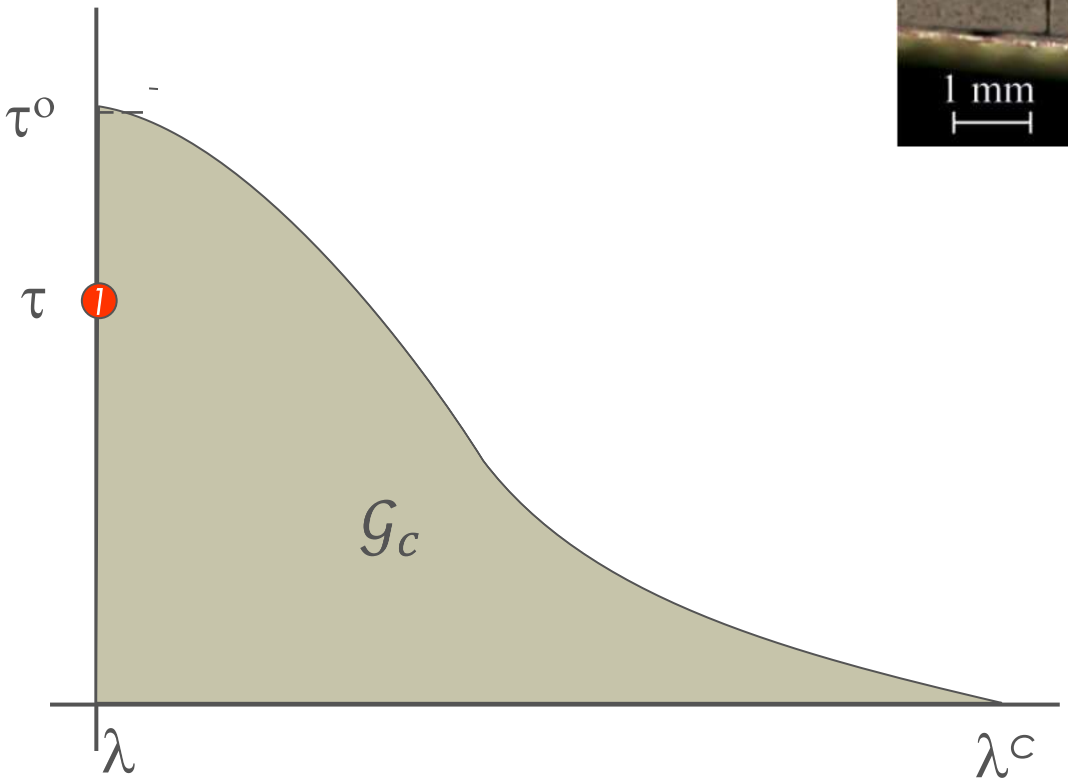
Cohesive zone model approach



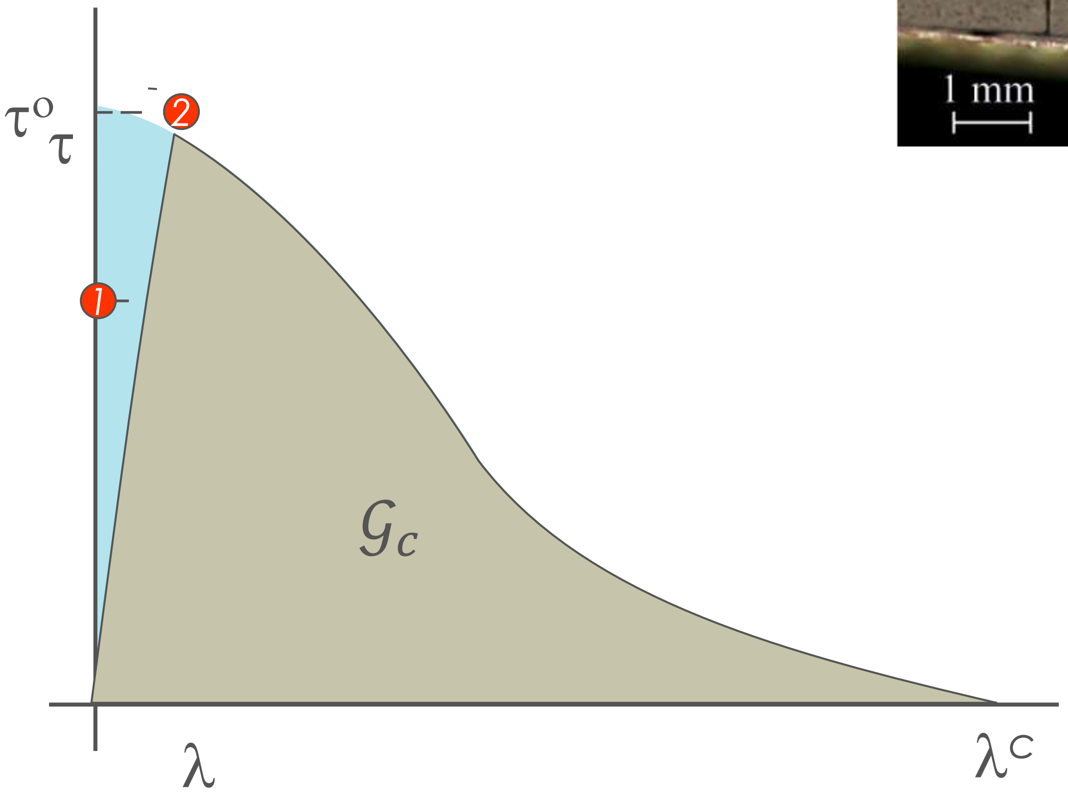


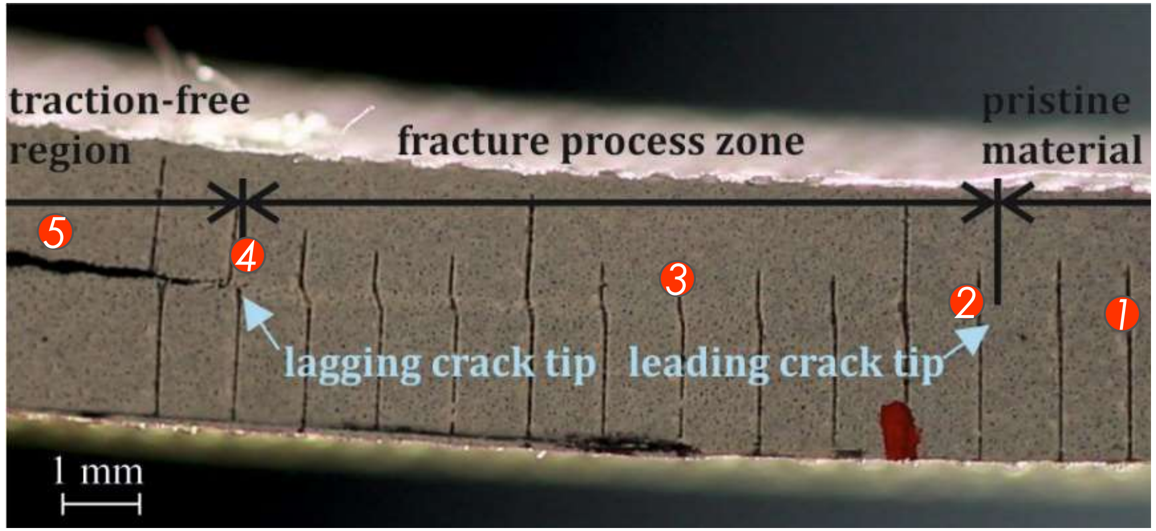
Cohesive zone model approach



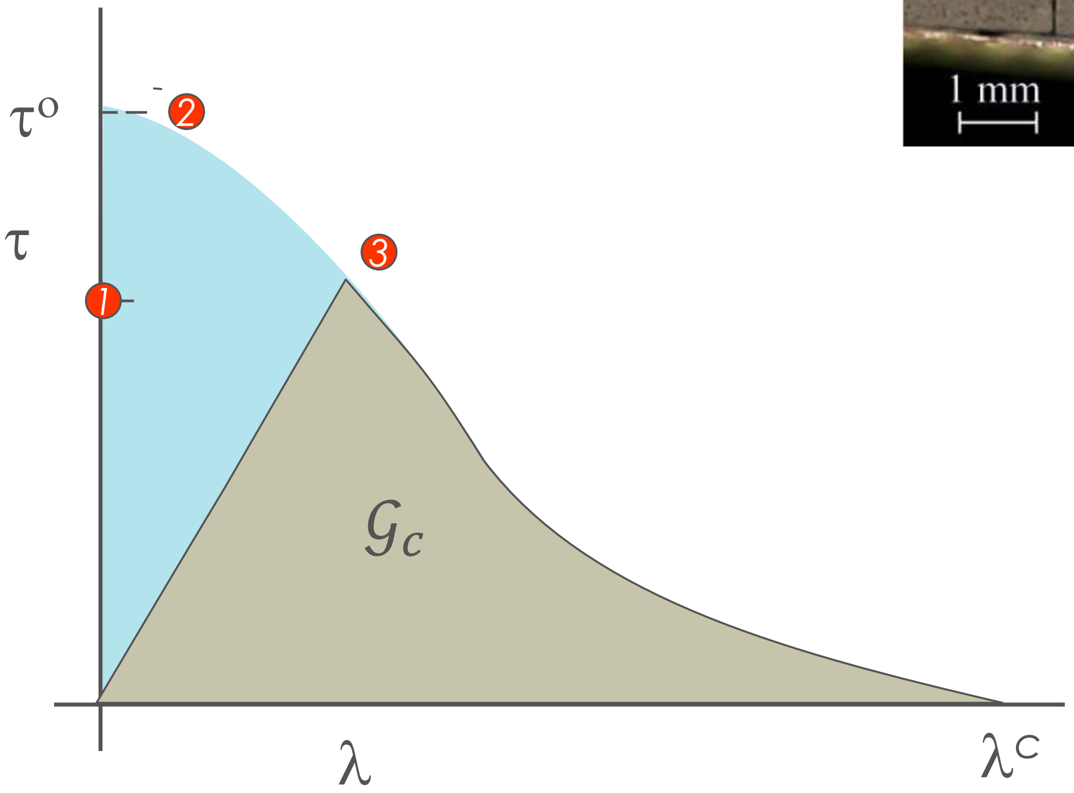


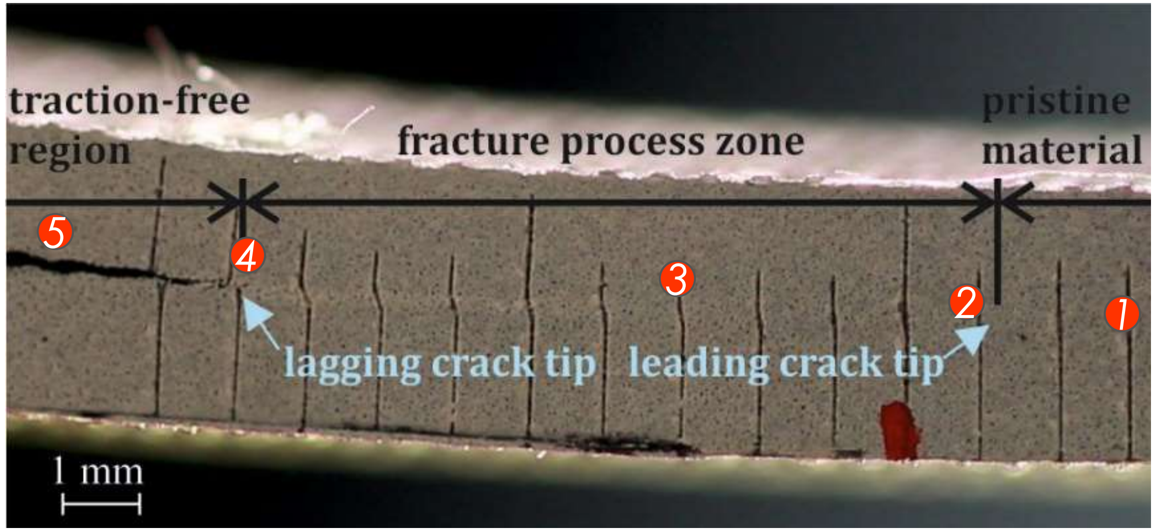
■ *Cohesive zone model approach*





Cohesive zone model approach





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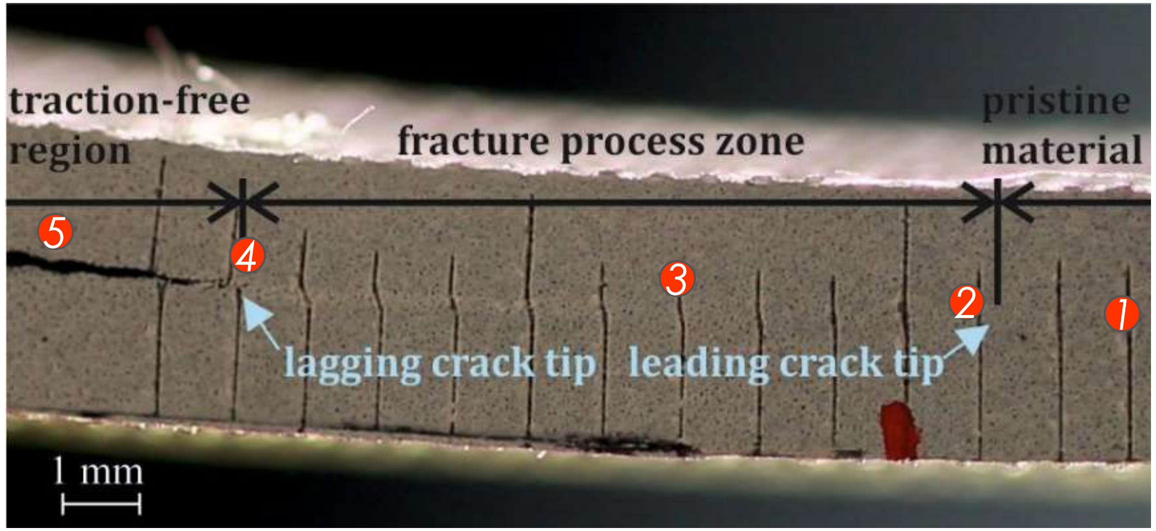
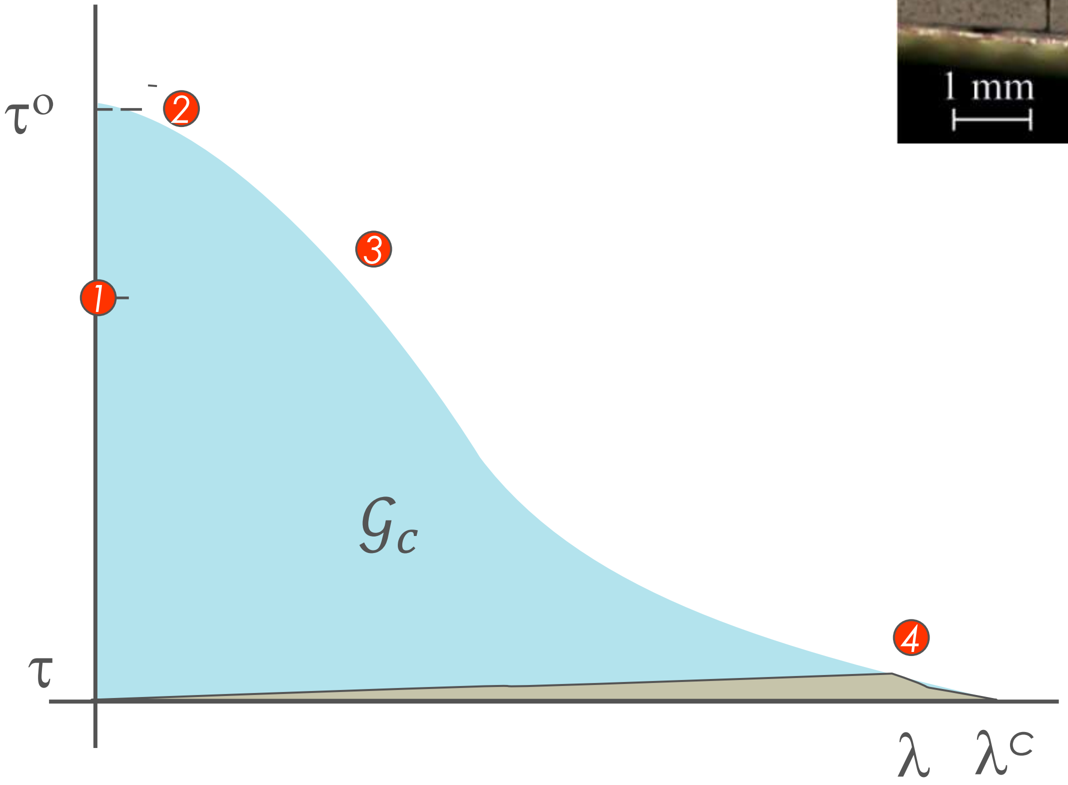
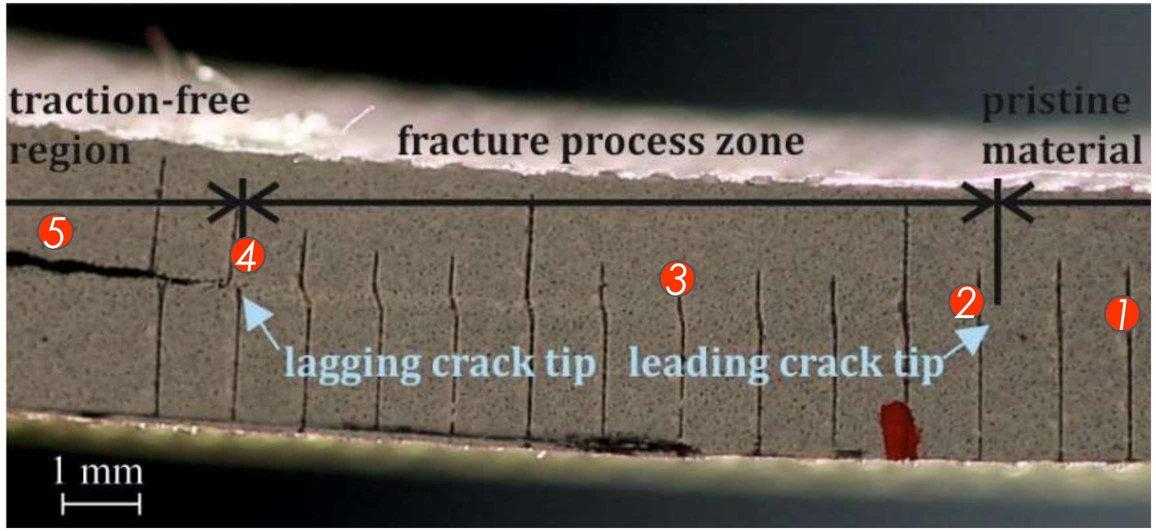
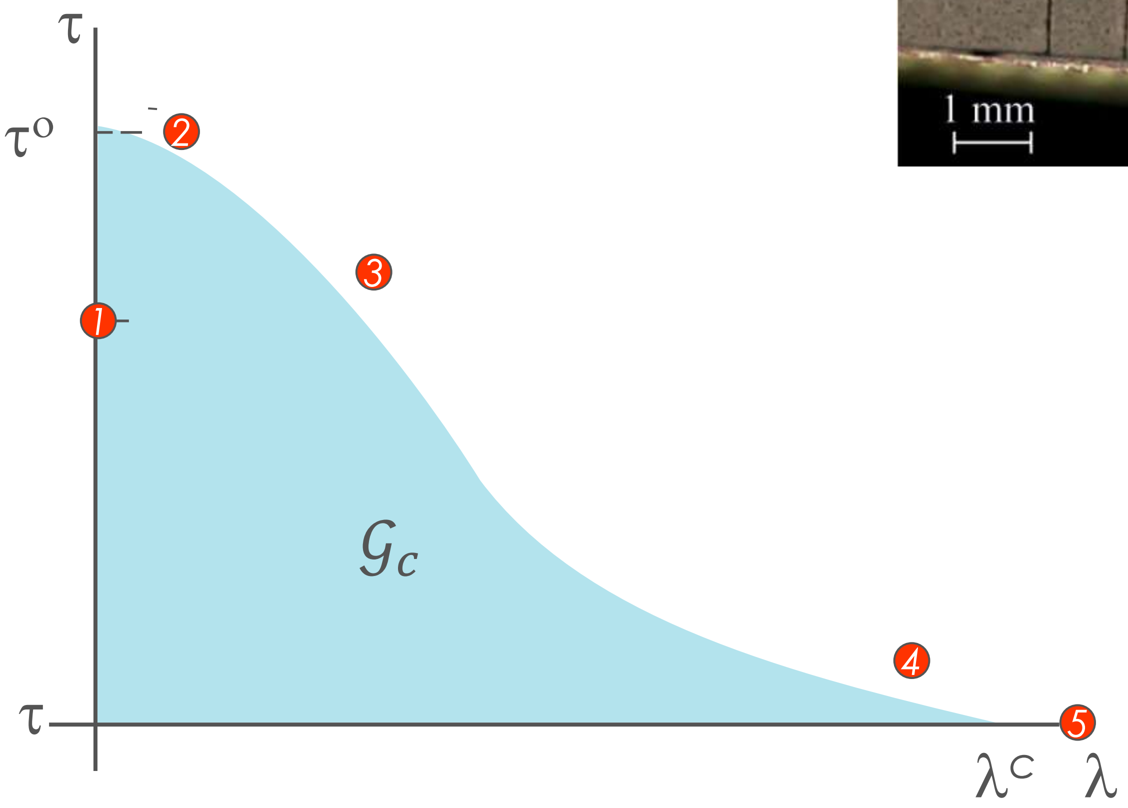


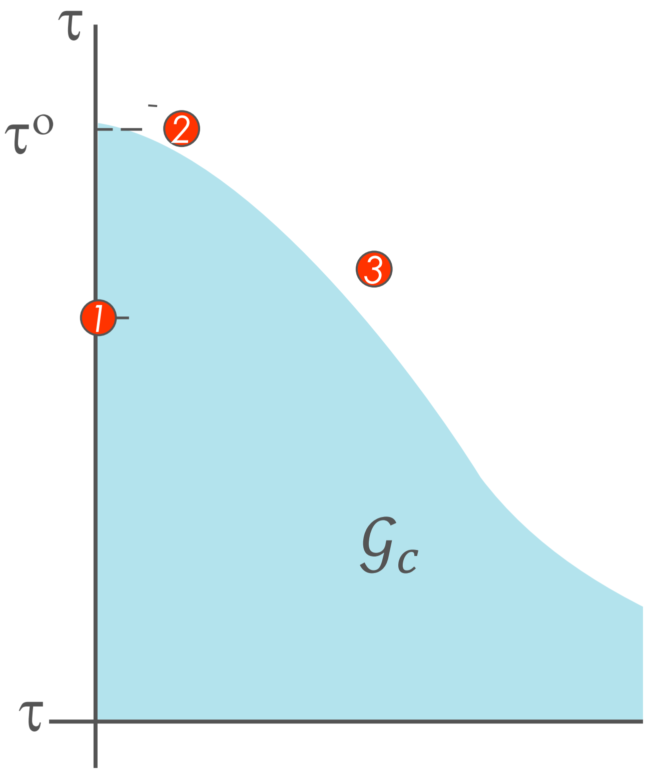


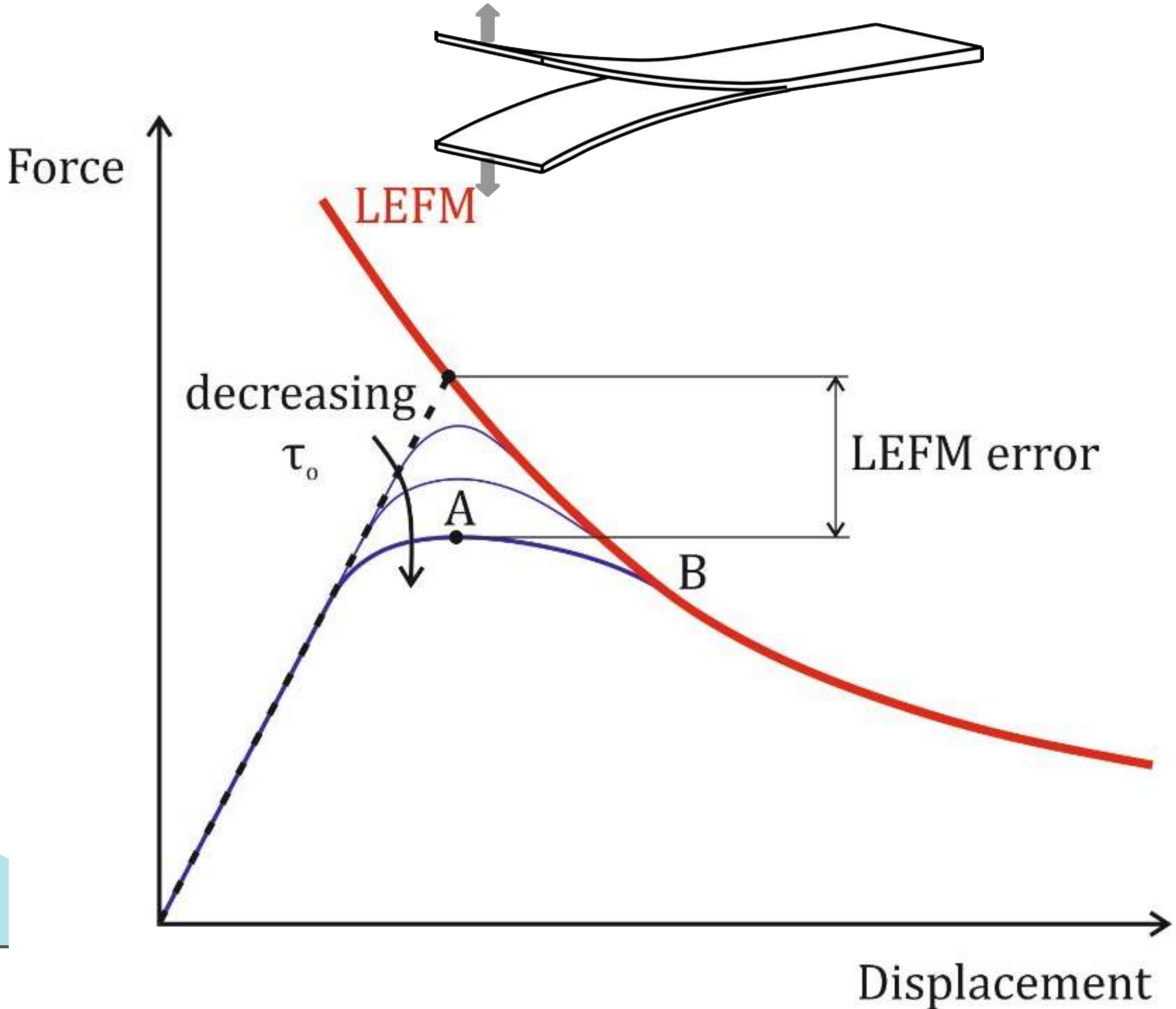
Cohesive zone model approach

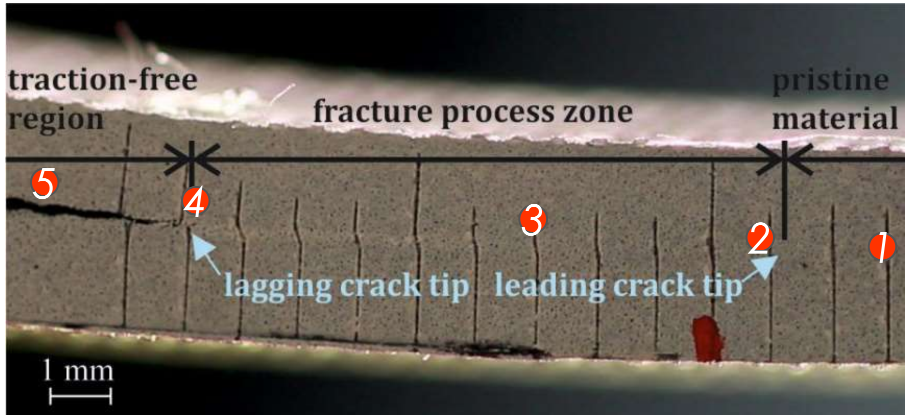


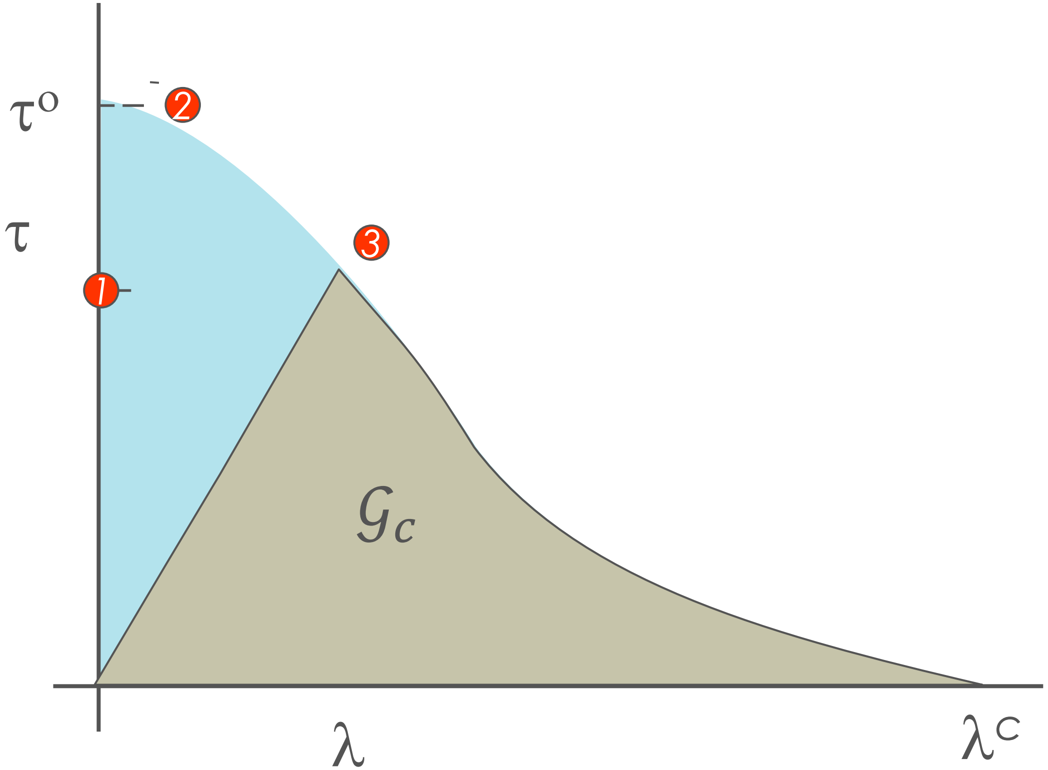


■ *Cohesive zone model approach*

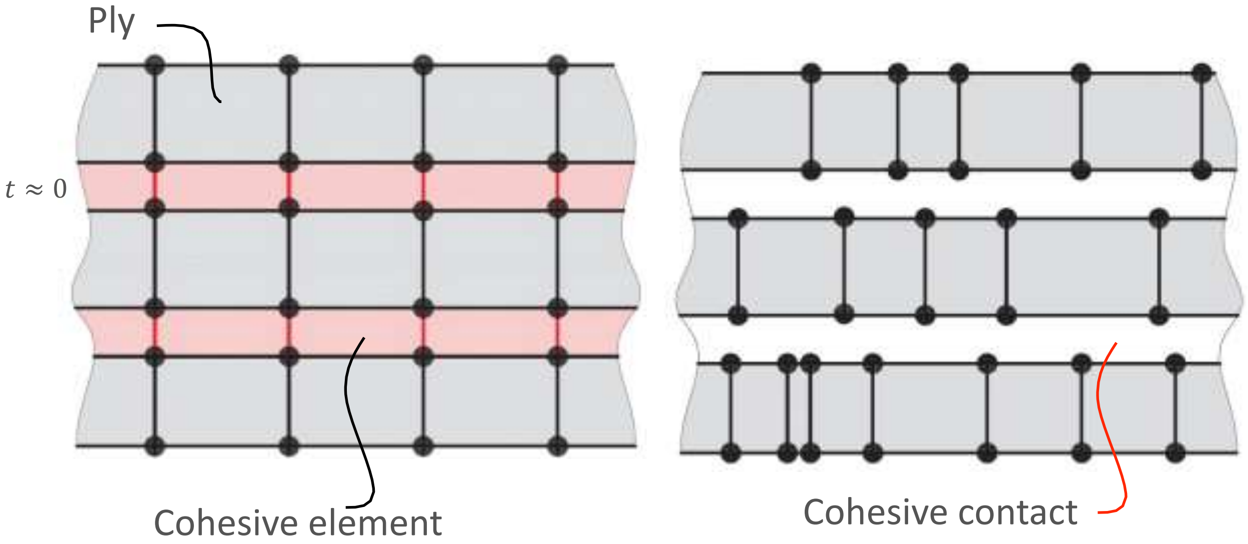


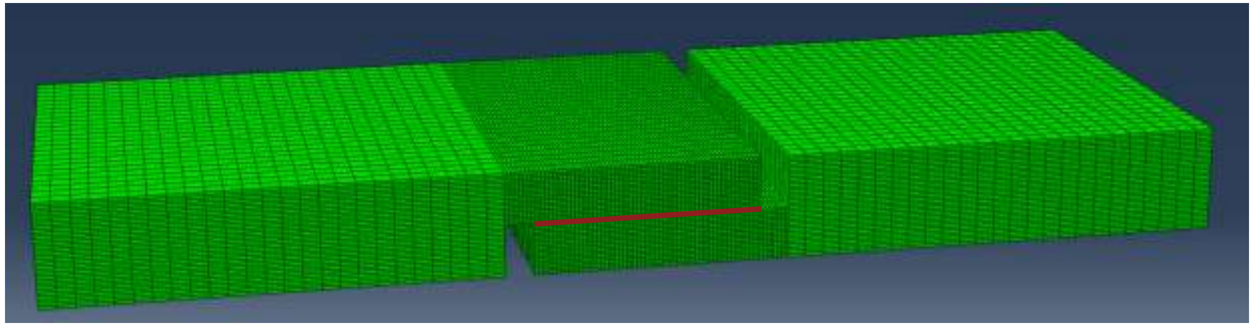






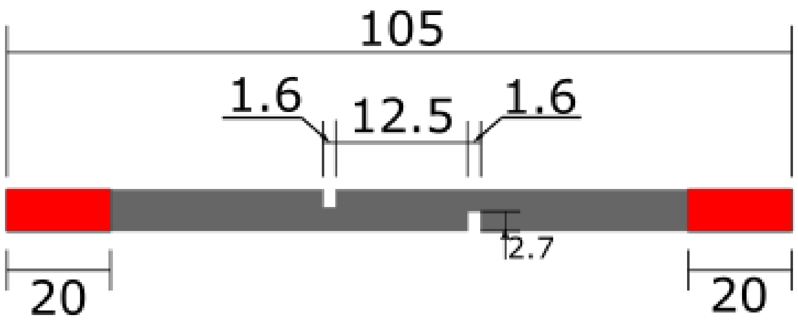
FEM Implementation





Does it work? → Single Lap Shear example

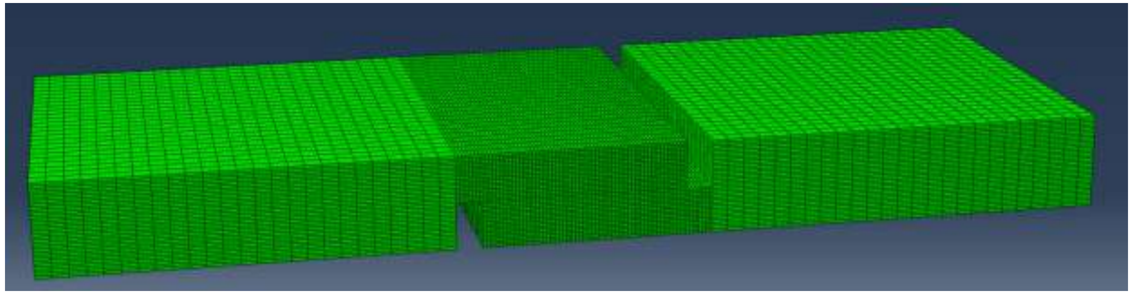
- Dimensions of the specimen



  - Width = 25 mm

- Lay-up
  - 16 plies per arm, [0/45/90/-45]2s
  - Thickness per arm 0.165 x 16 = 2.64 mm (experimentally measured)

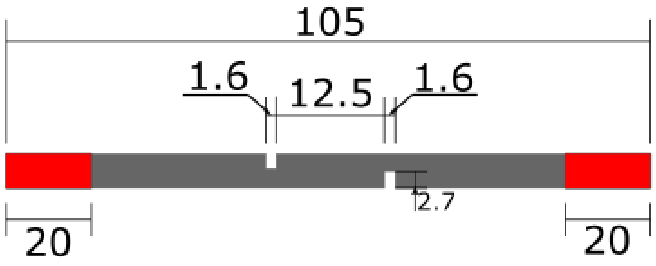
- Numerical Model

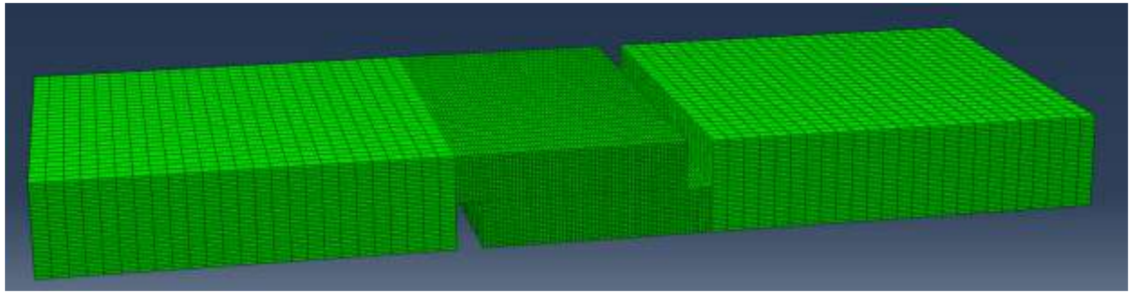


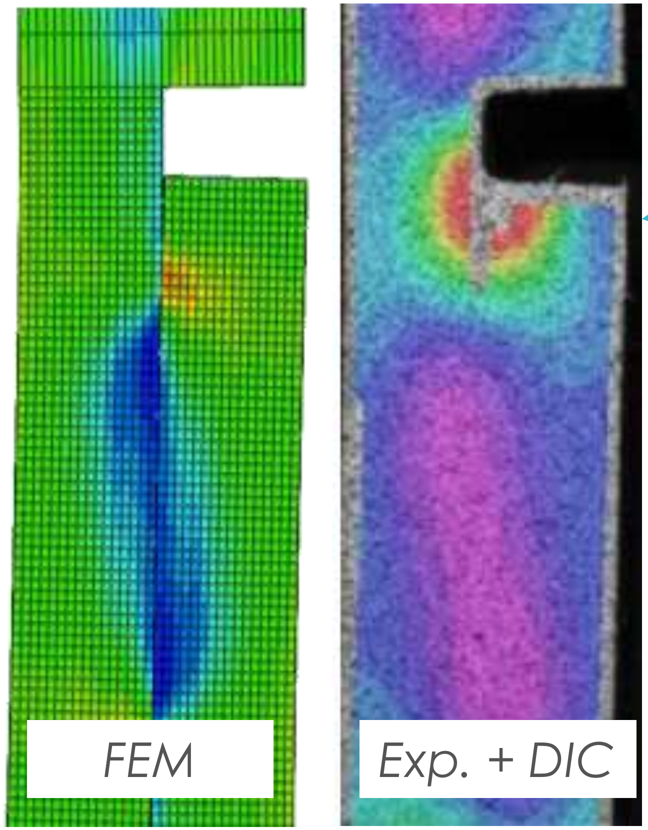
- Solid Elements (plies)
  - 0.2 mm in the fiber direction
  - Thickness = 2 plies per element

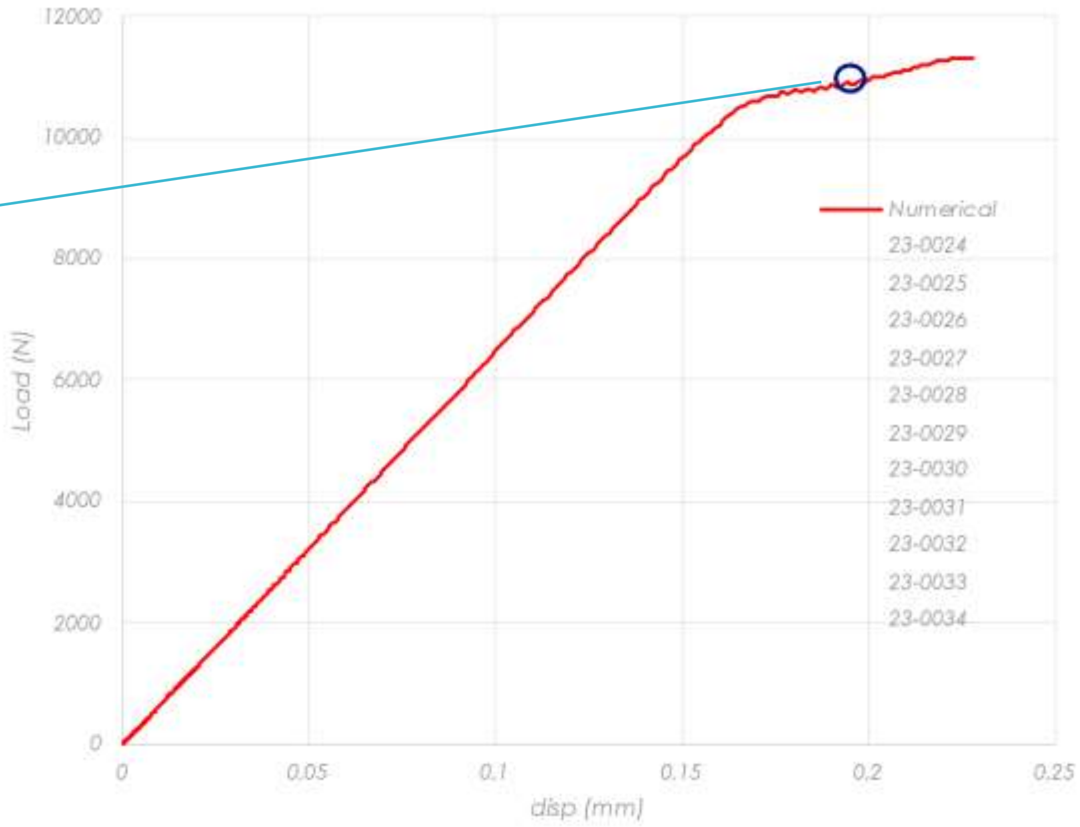
- Cohesive Element size
  - 0.2 mm in the fiber direction
  - VUMAT

Example: Single Lap Shear









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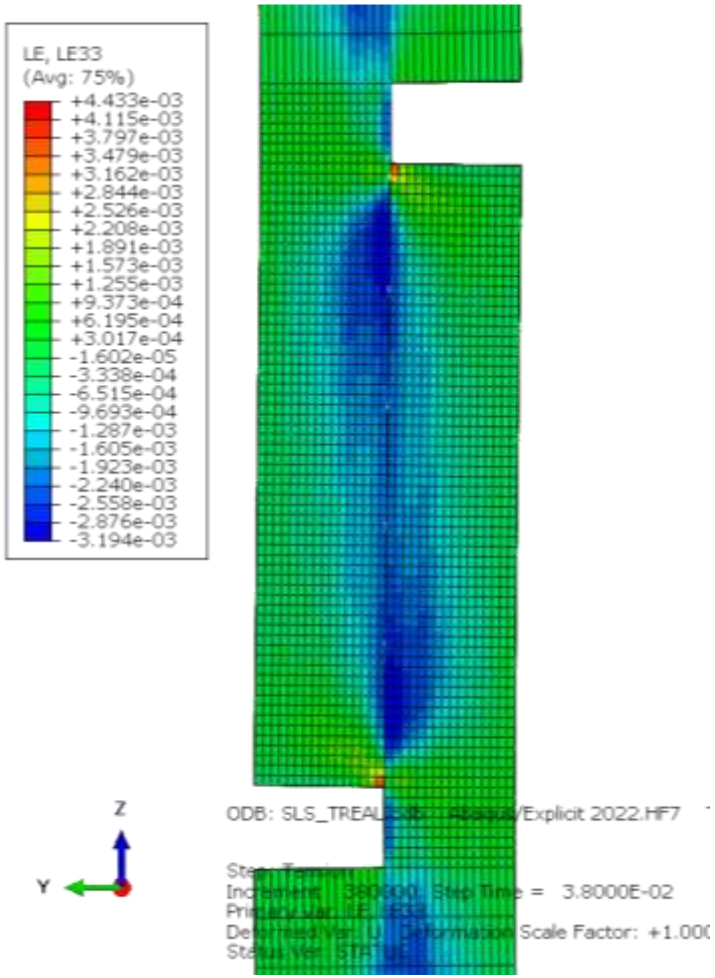
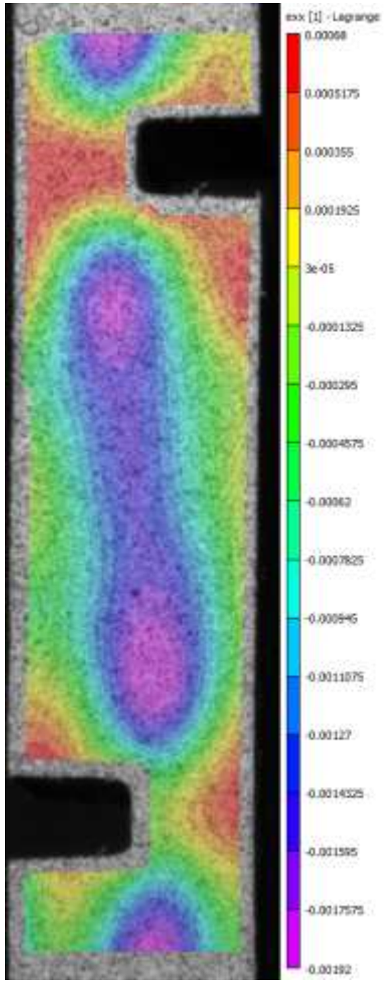
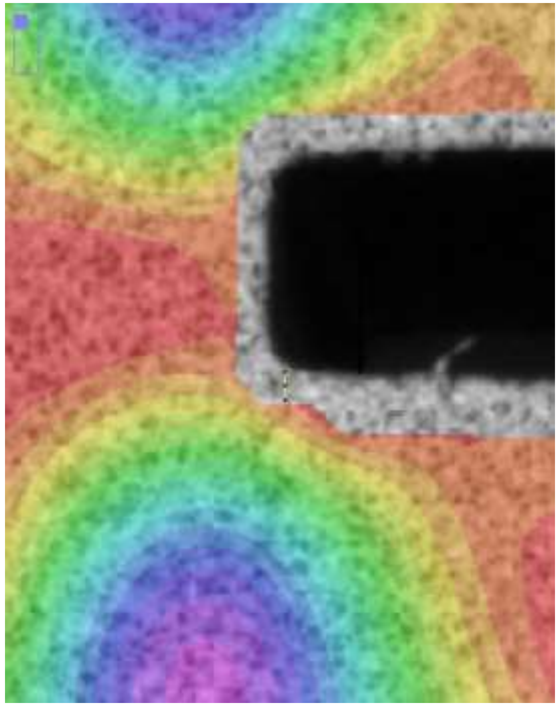


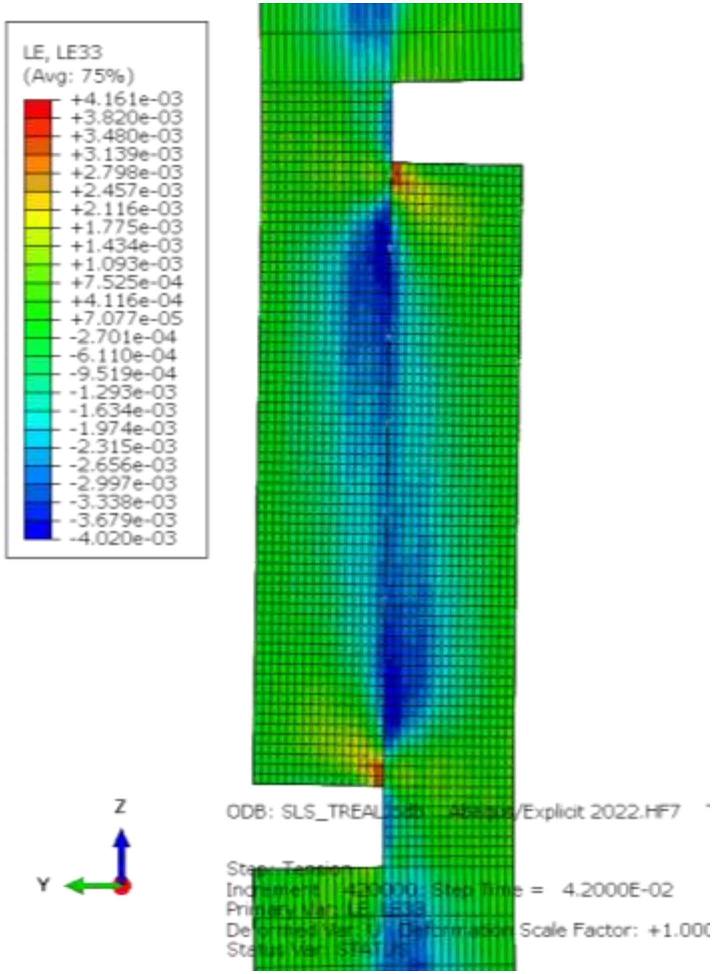
Specimen 23-0032 Picture 113



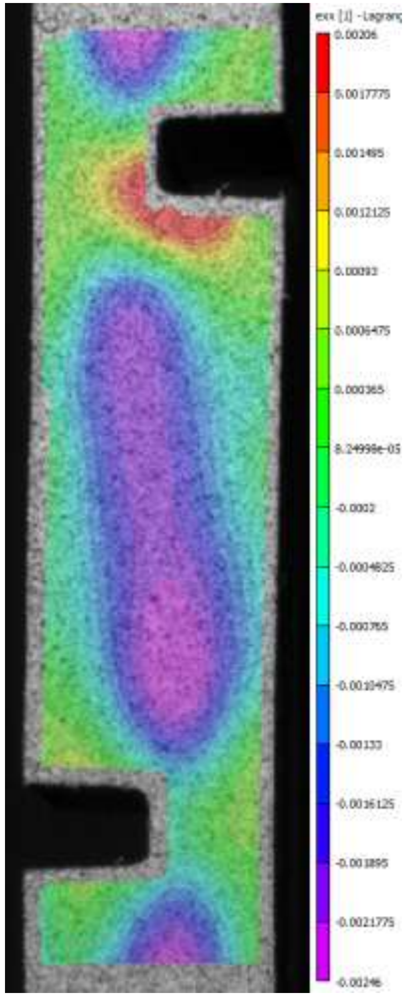
Magnitude	Numerical	23-0026
Load (N)	8149	8150
Displacement (mm)	0.1285	0.1220
Crack grow (mm)	0	0.200



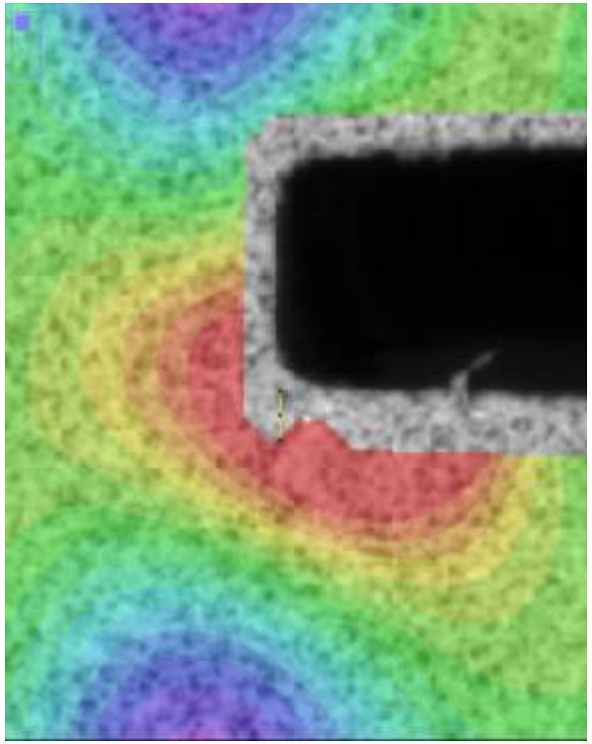
Example: Single Lap Shear



Specimen 23-0032 Picture 150

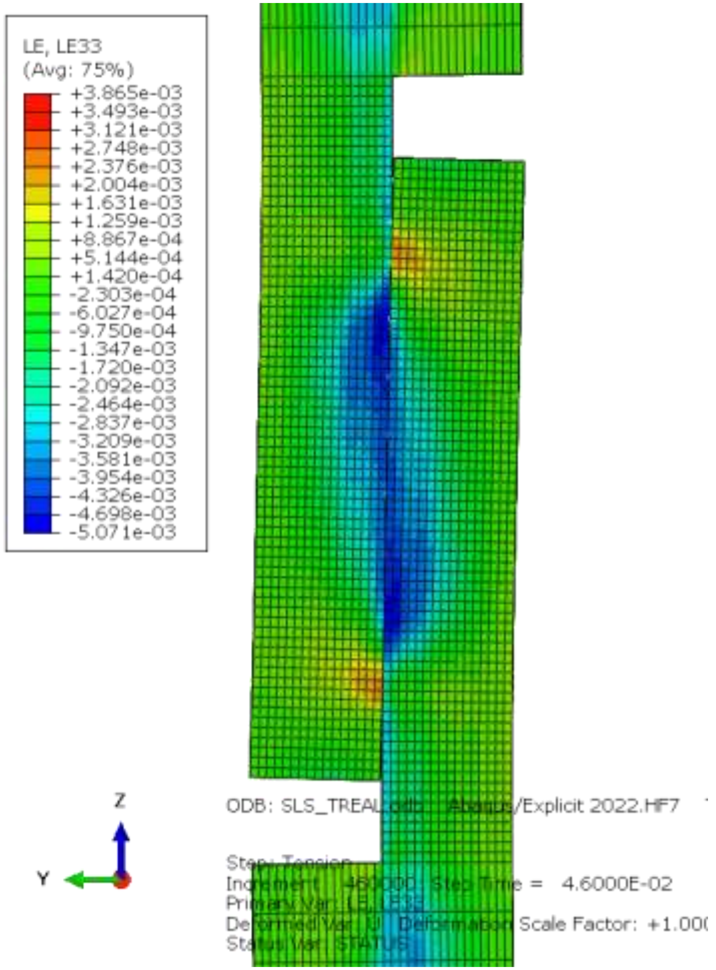


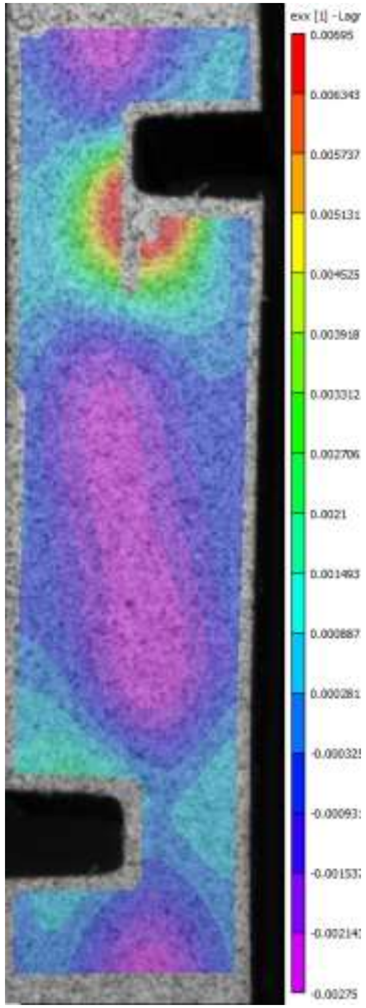
Magnitude	Numerical	23-0026
Load (N)	10046.2	10045.3
Displacement (mm)	0.1541	0.1545
Crack grow (mm)	0	0.36



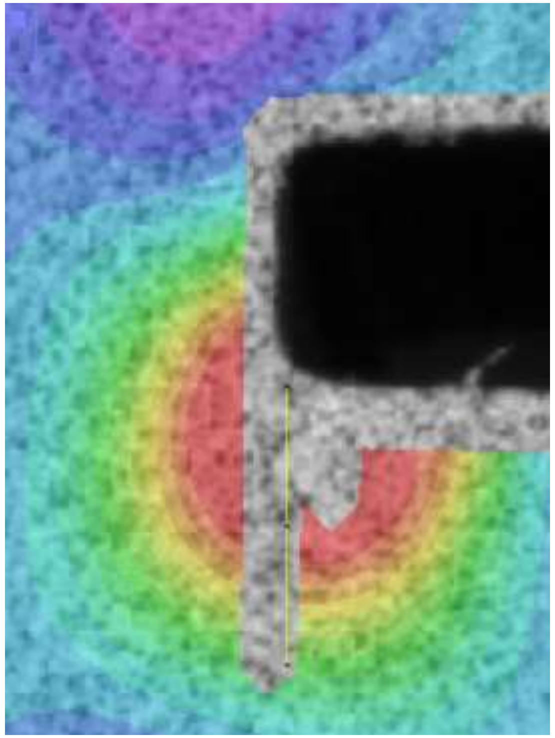
Example: Single Lap Shear

Specimen 23-0032 Picture 174



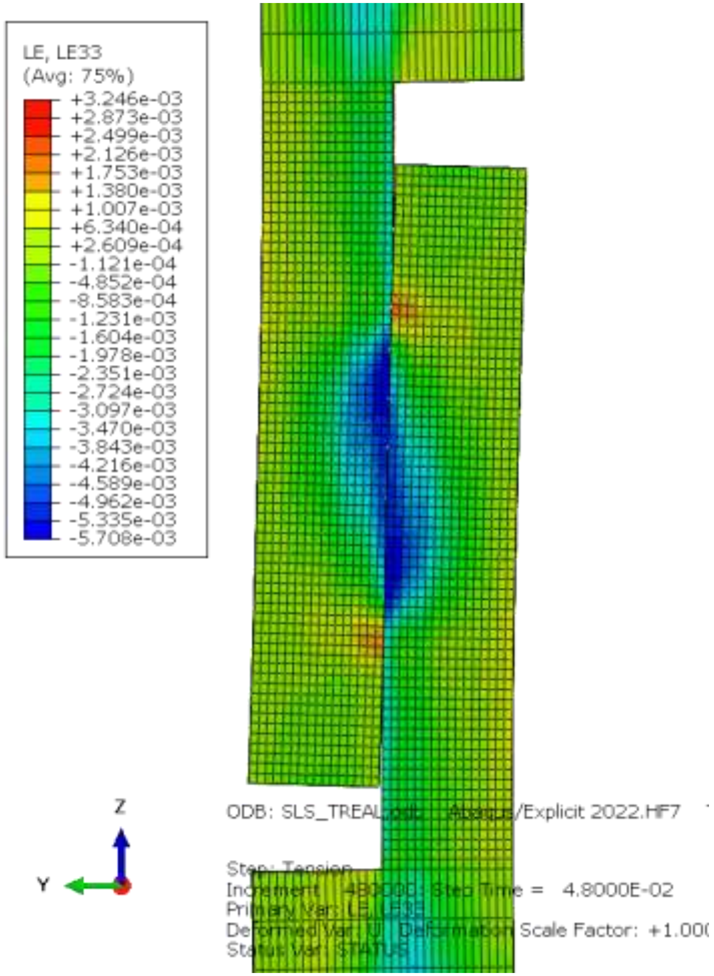


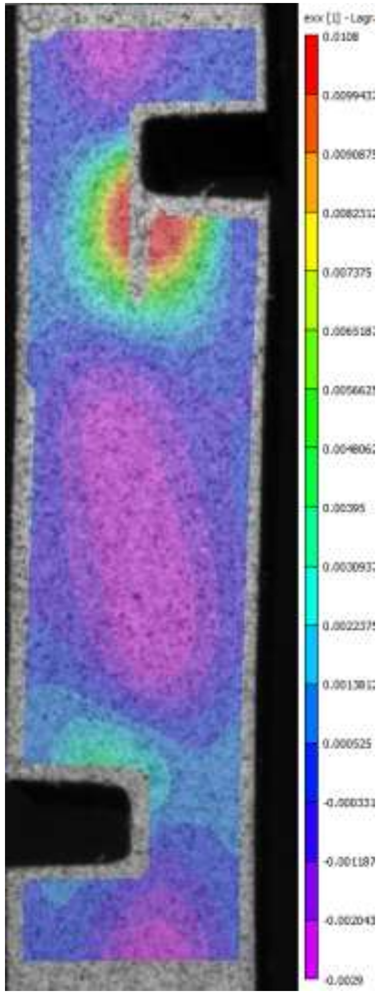
Magnitude	Numerical	23-0026
Load (N)	10892.9	10892.2
Displacement (mm)	0.1951	0.1772
Crack grow (mm)	1.411	1.808



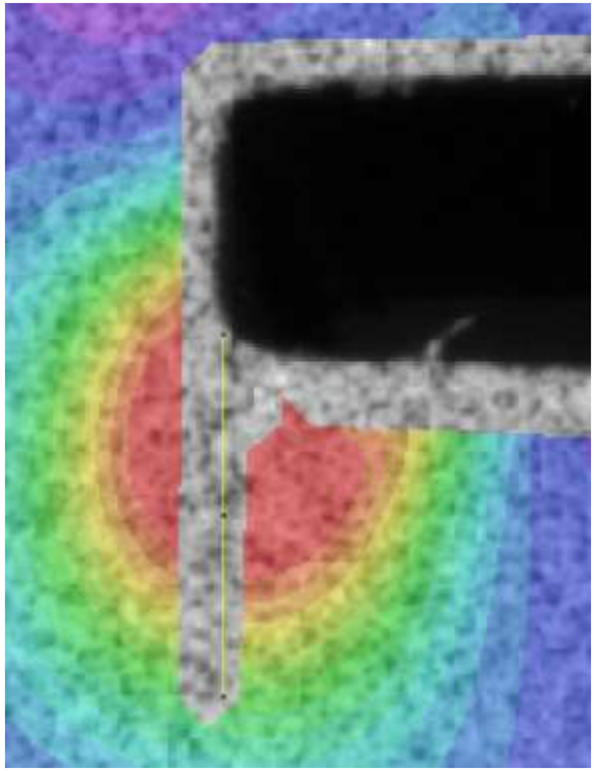
Example: Single Lap Shear

Specimen 23-0032 Picture 186

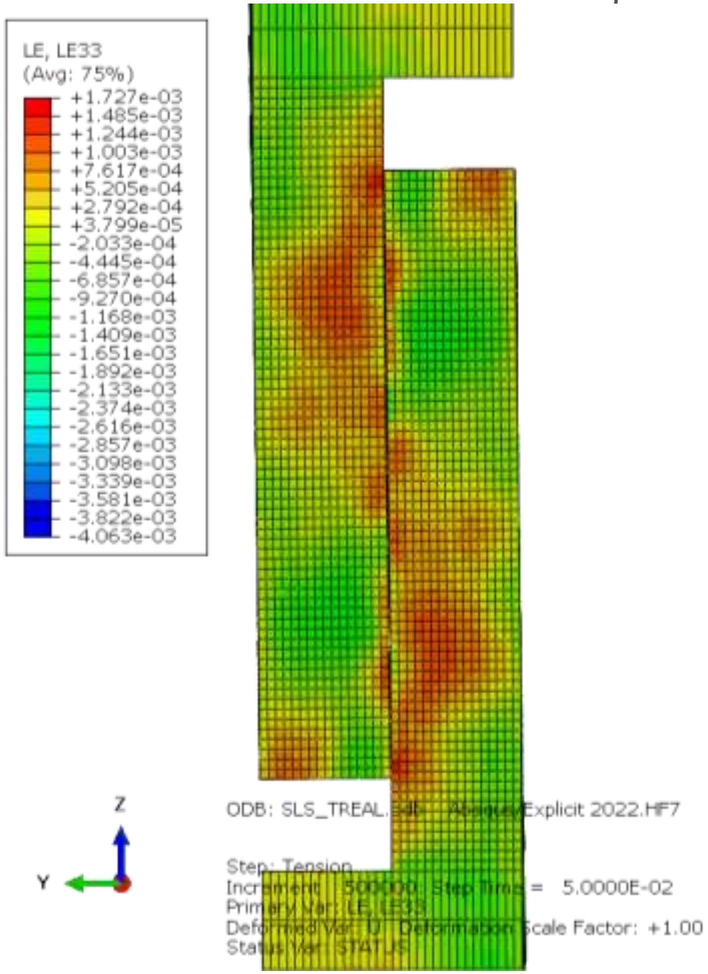




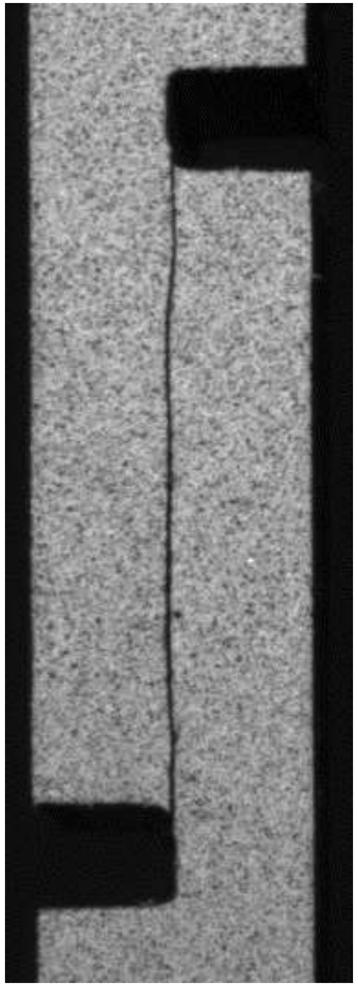
Magnitude	Numerical	23-0026
Load (N)	11164.7	11164.6
Displacement (mm)	0.2132	0.1883
Crack grow (mm)	2.217	2.076



Example: Single Lap Shear

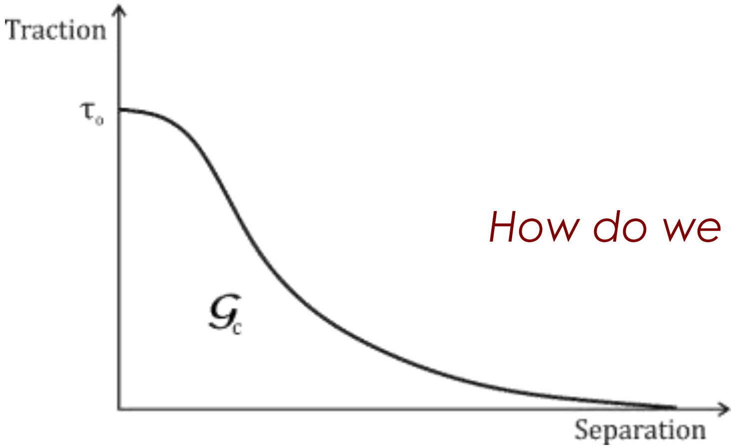


Specimen 23-0032 Picture 203



Magnitude	Numerical	23-0026
Max Load (N)	*11318.1*	*11499*
Displacement (mm)	*0.2269*	*0.2216*
Crack grow (mm)	*Open*	*Open*

Shape of the cohesive law

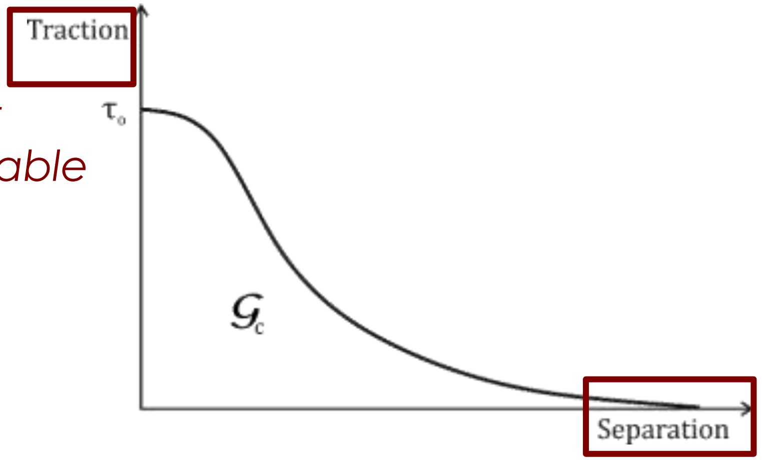


How do we measure it?

- *Direct methods*
- *Inverse methods*

Shape of the cohesive law

- *Direct method*

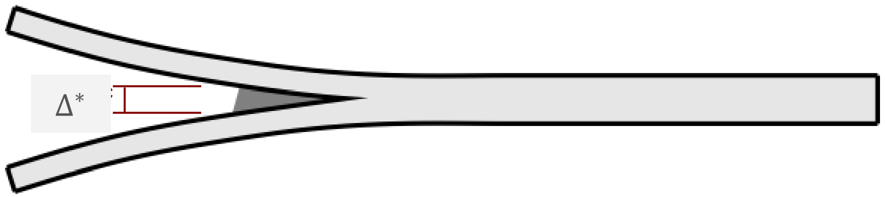


Not measurable

Measurable

Shape of the cohesive law

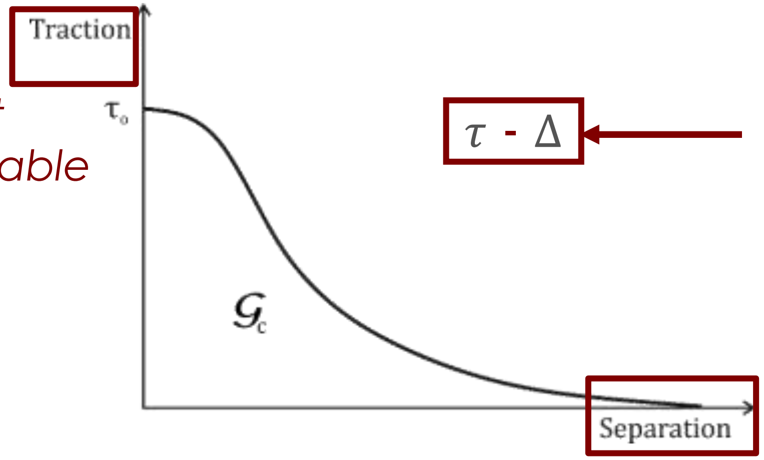
- *Direct method*



$$J = \int_0^{\Delta^*} \tau(\Delta)\, d\Delta$$

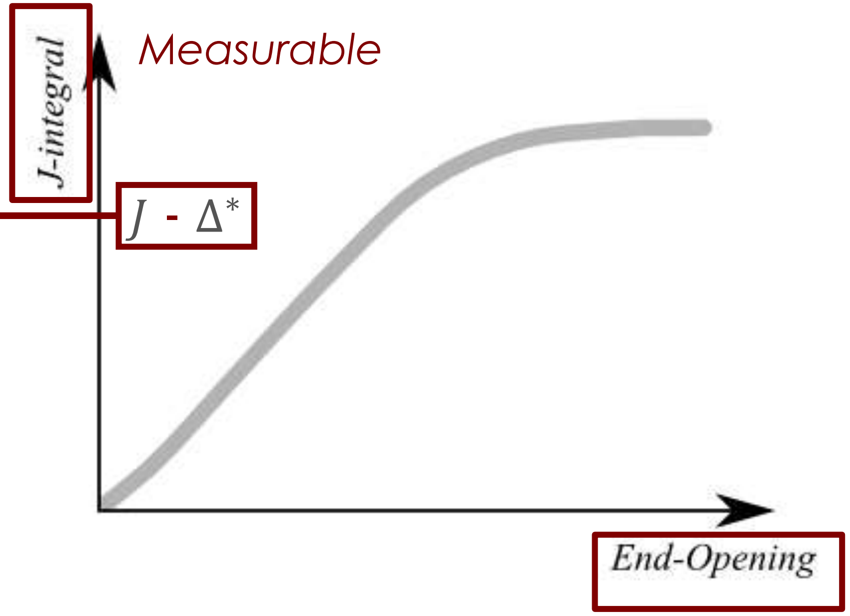
Sørensen and Jacobsen (2003)

Not measurable



Measurable

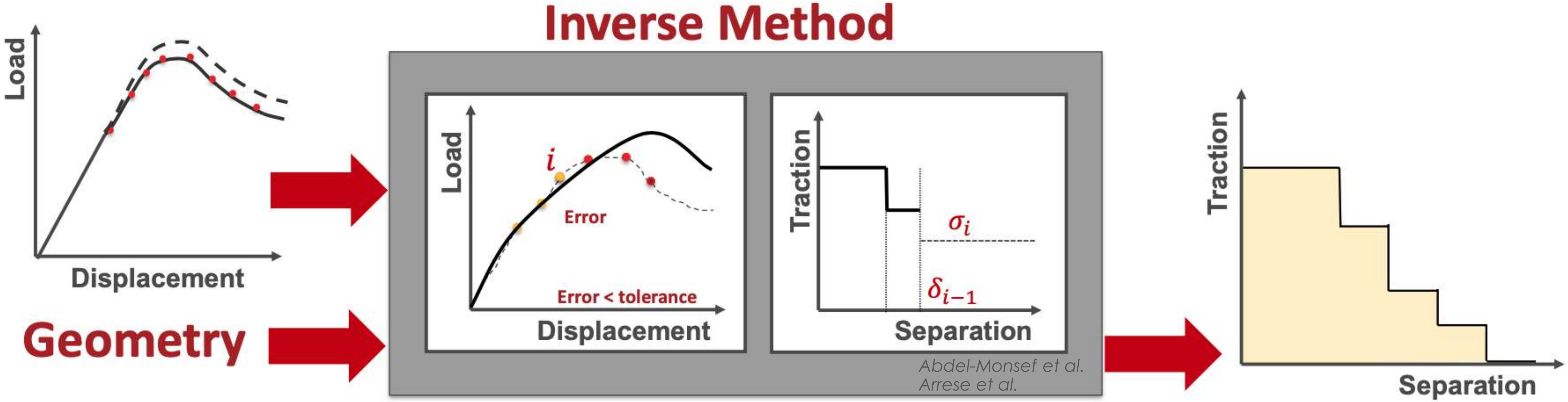
τ - Δ ← $$\tau = \frac{dJ}{d\Delta^*}$$ ← J - Δ^*

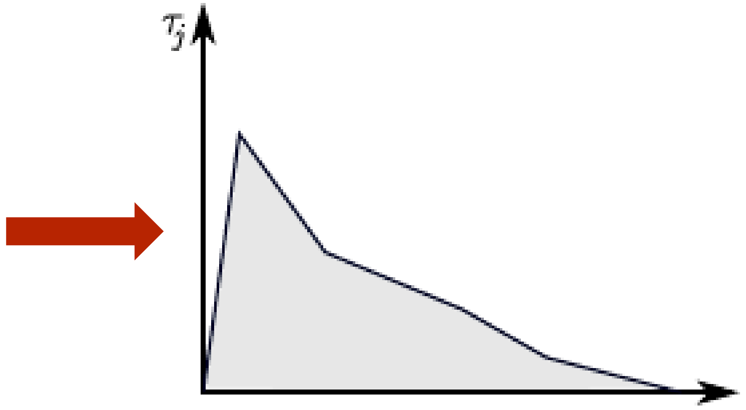


Measurable

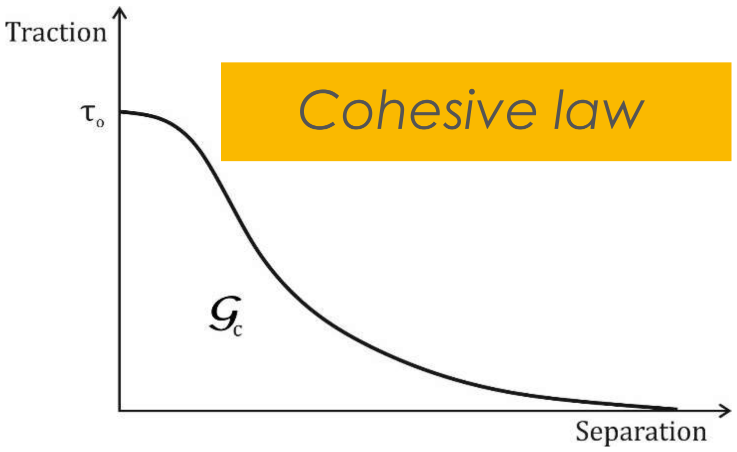
Shape of the cohesive law

Inverse method



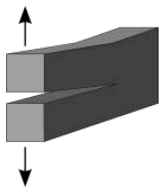


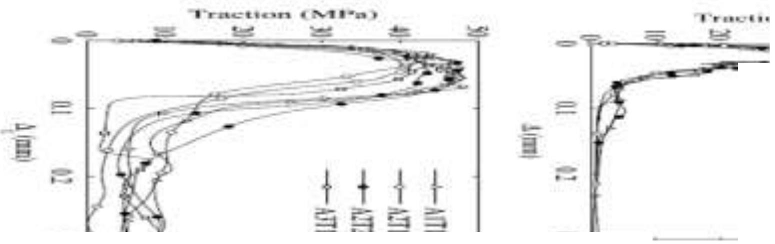
Cohesive law

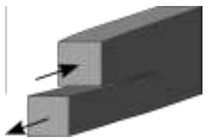


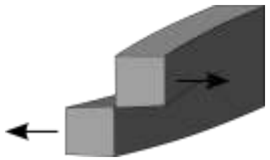
- τ_o
- $\mathcal{G}_c$
- *CL shape*

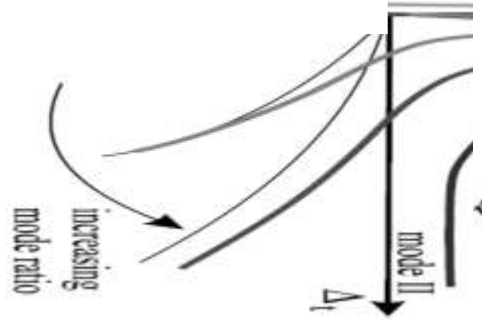
Mode dependent

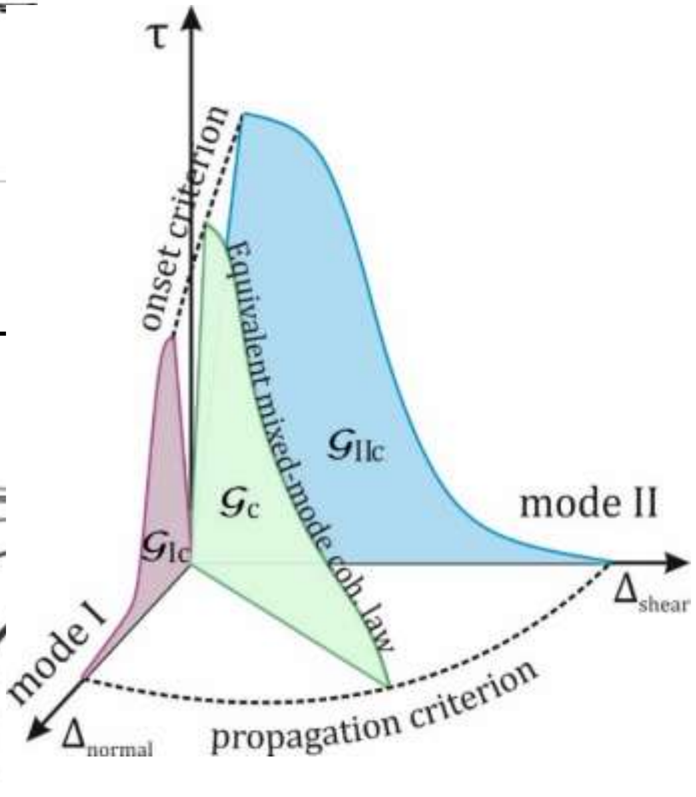












Cohesive law dependence

Two Epoxy adhesives

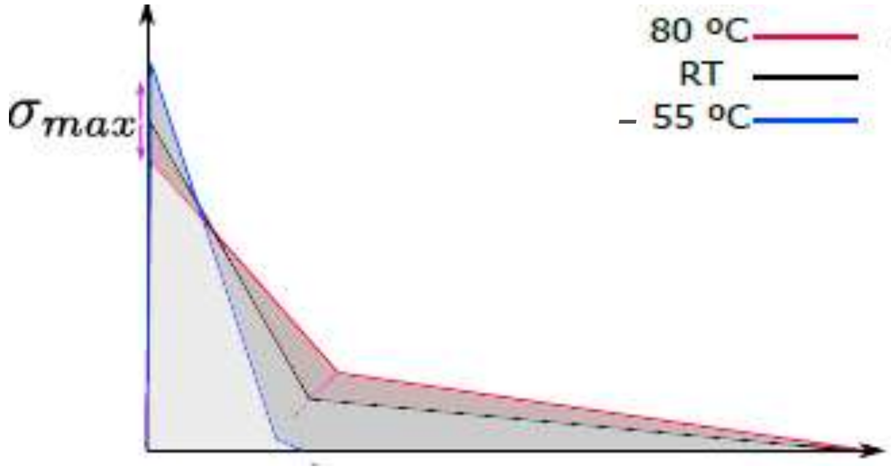
Wet-aged (4 years)/ non-aged

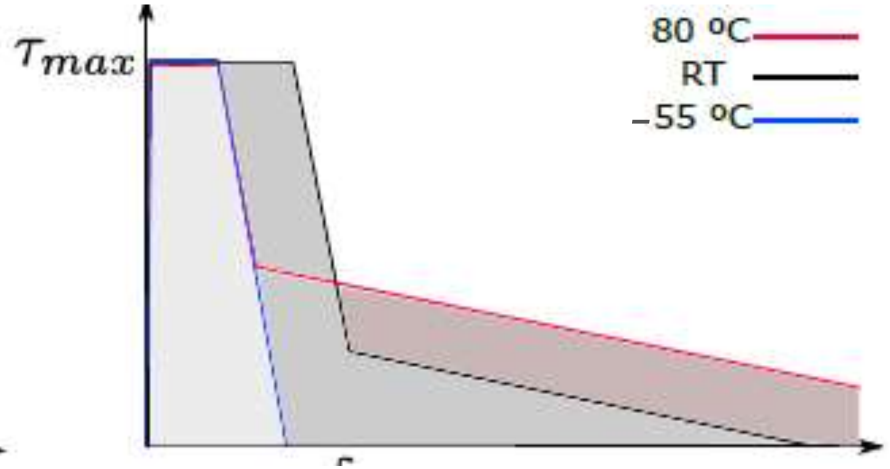
Testing Configuration

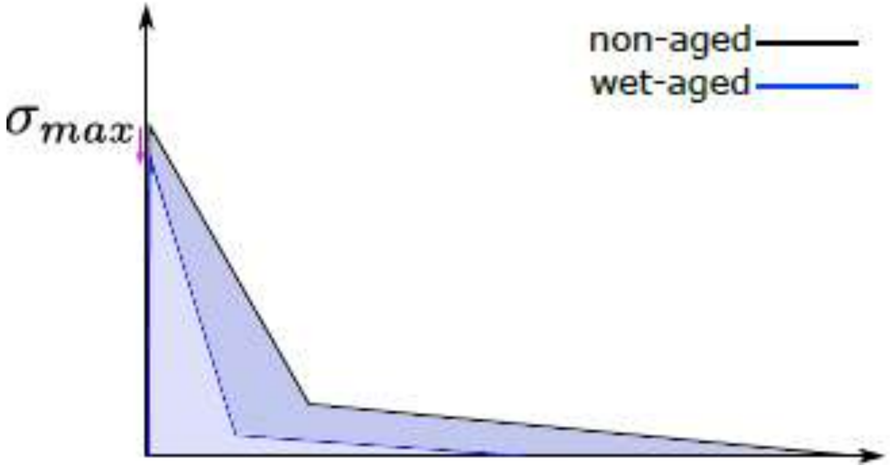
Testing temperature (-55 C, RT , 80 C)

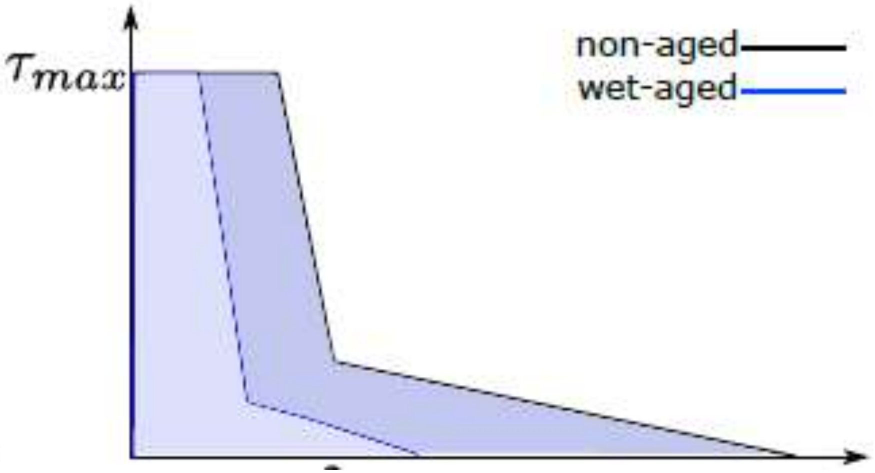
S. Ahmed, PhD thesis (2020)

Cohesive law dependence



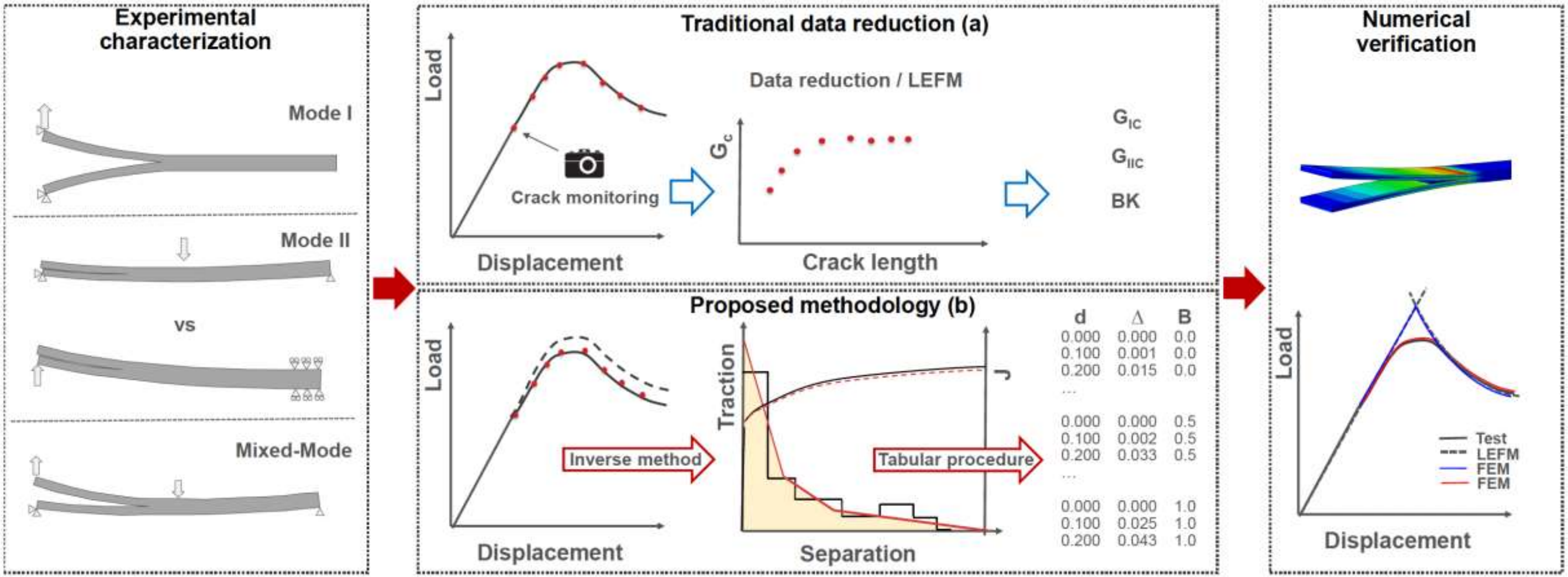






S. Ahmed, PhD thesis (2020)

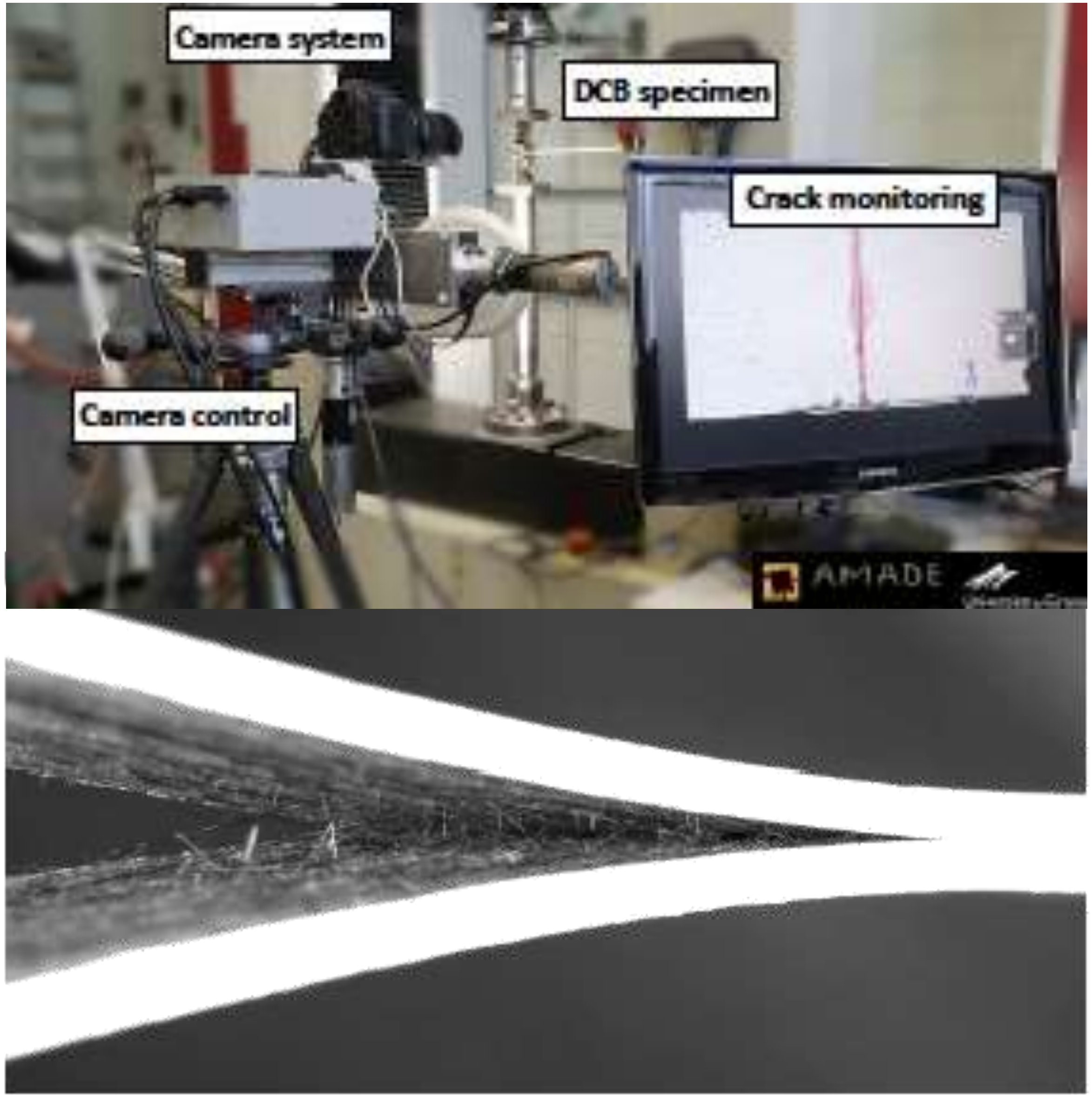
Implementation in FE (Option 1: TABULAR)

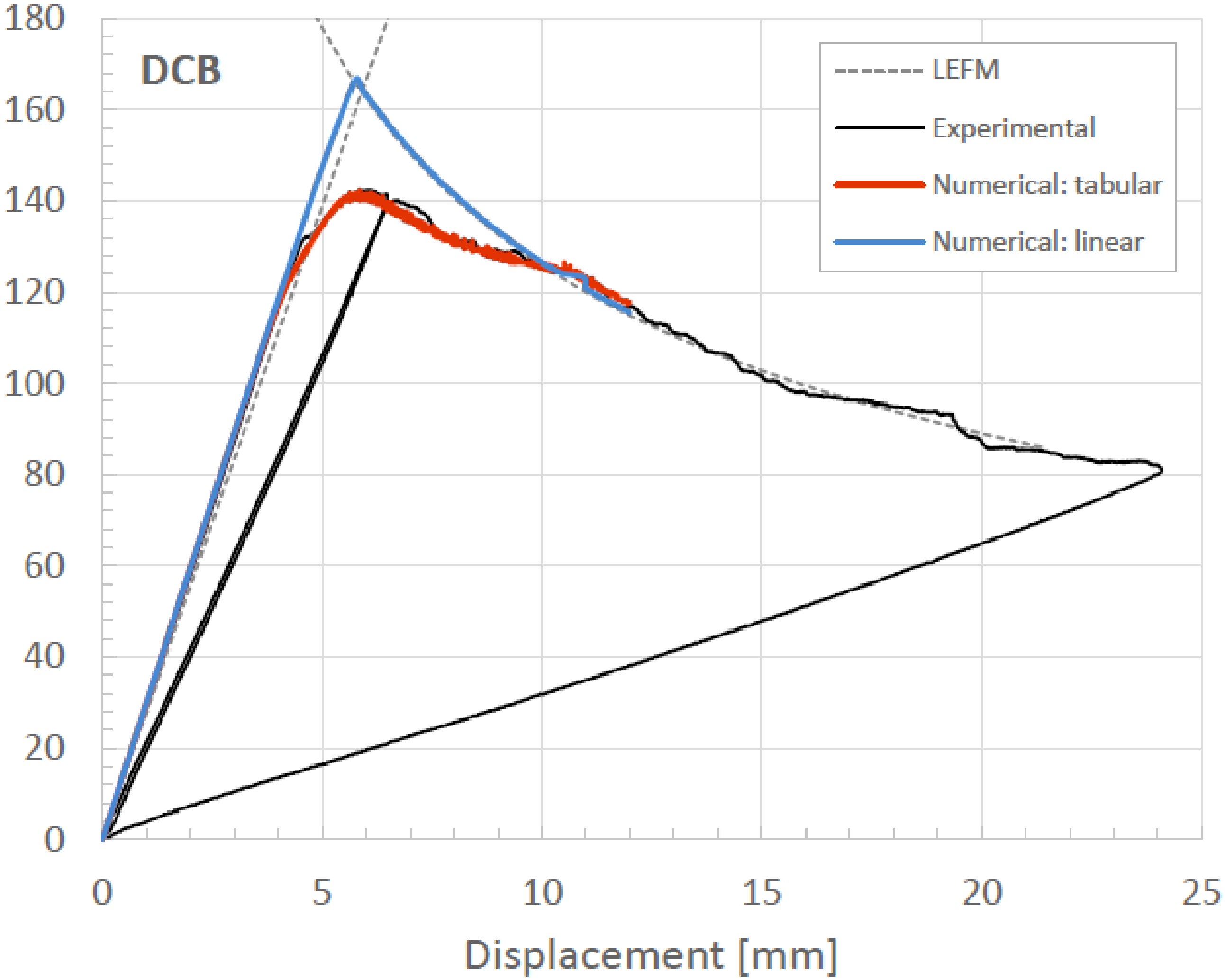


Tijs et al. 2022

Mixed-mode interpolation "managed" by abaqus

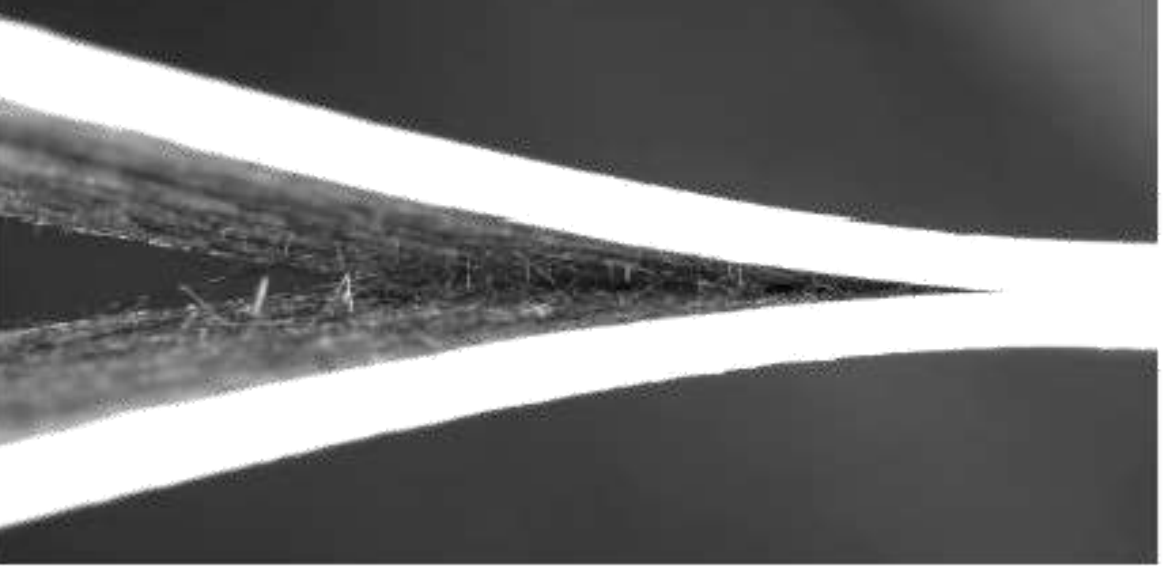
Shape of the cohesive law

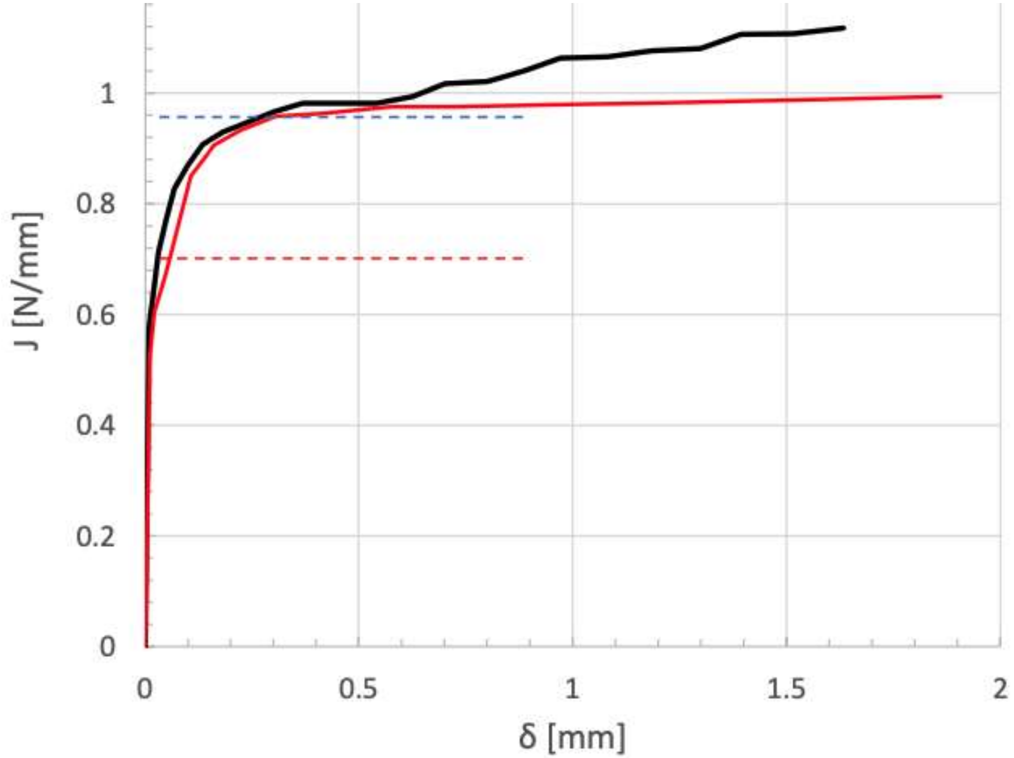


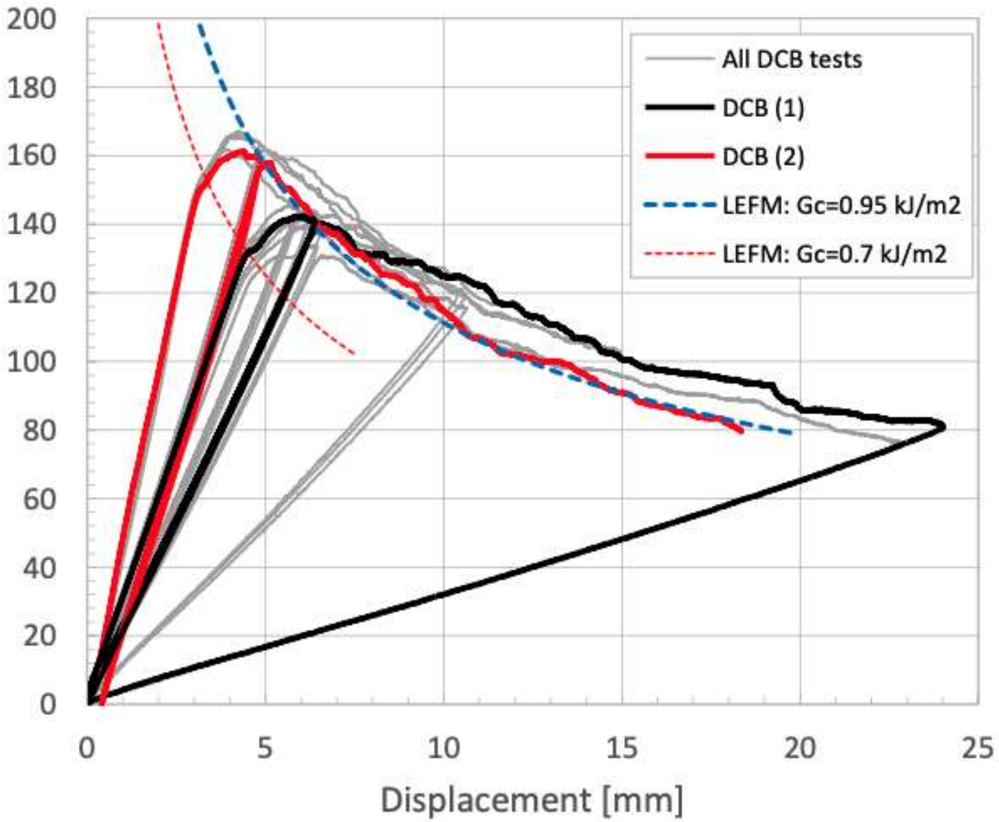


Tijs et al. 2022

UdG

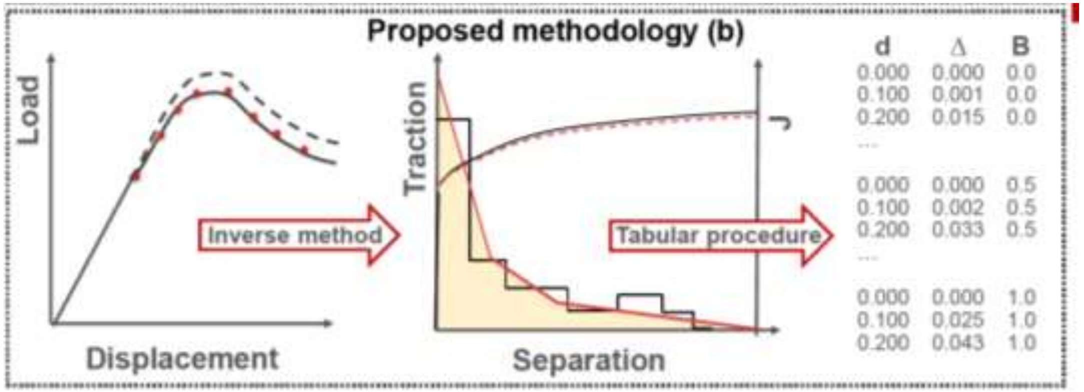




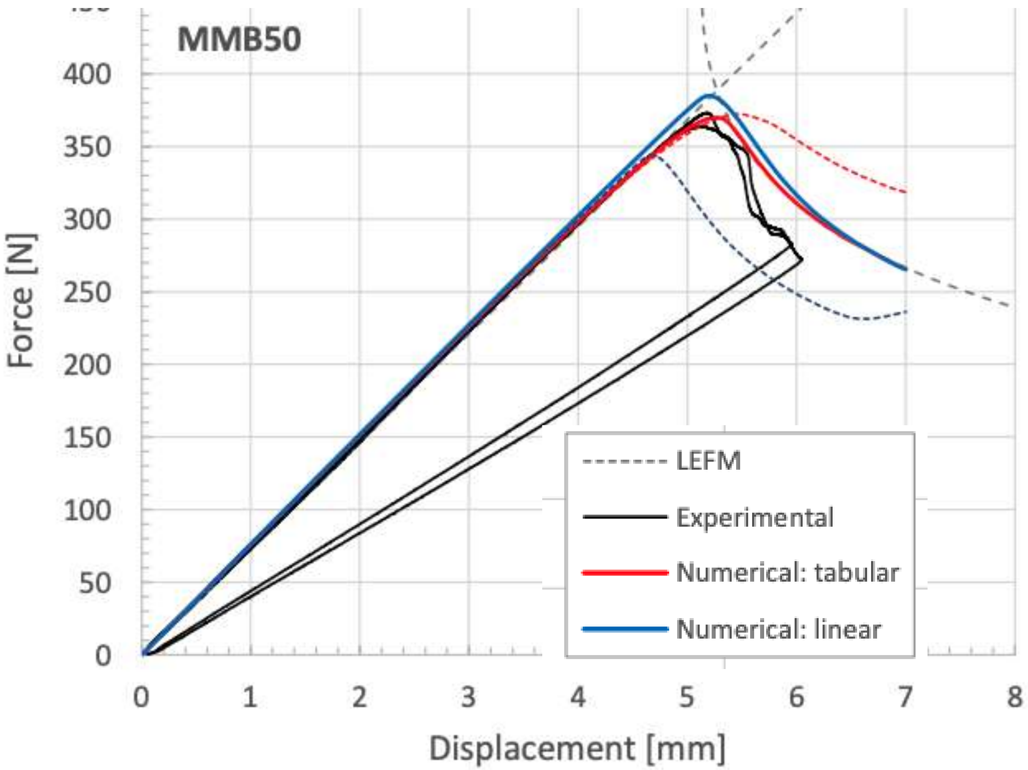


Tijs et al. 2022

Implementation in FE (Option 1: TABULAR)



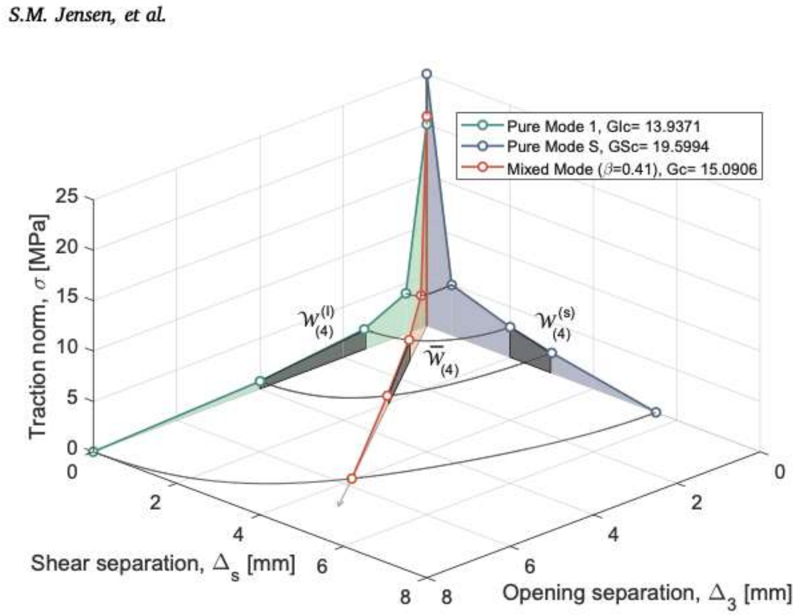
Mixed-mode interpolation "managed by abaqus"



"dotted lines" excluding B=0.1 cohesive law

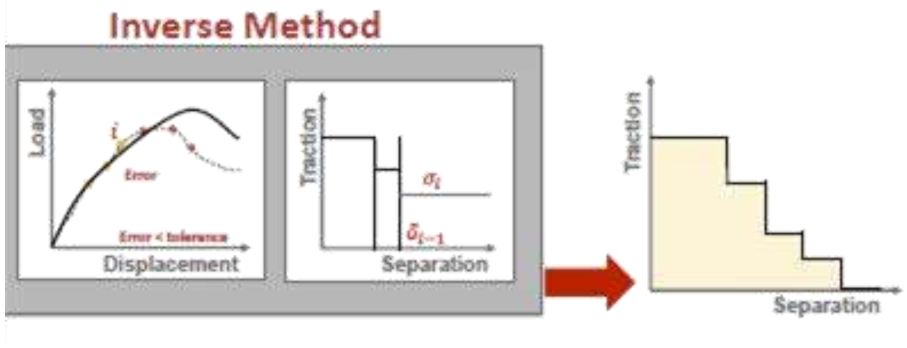
Tijs et al. 2022

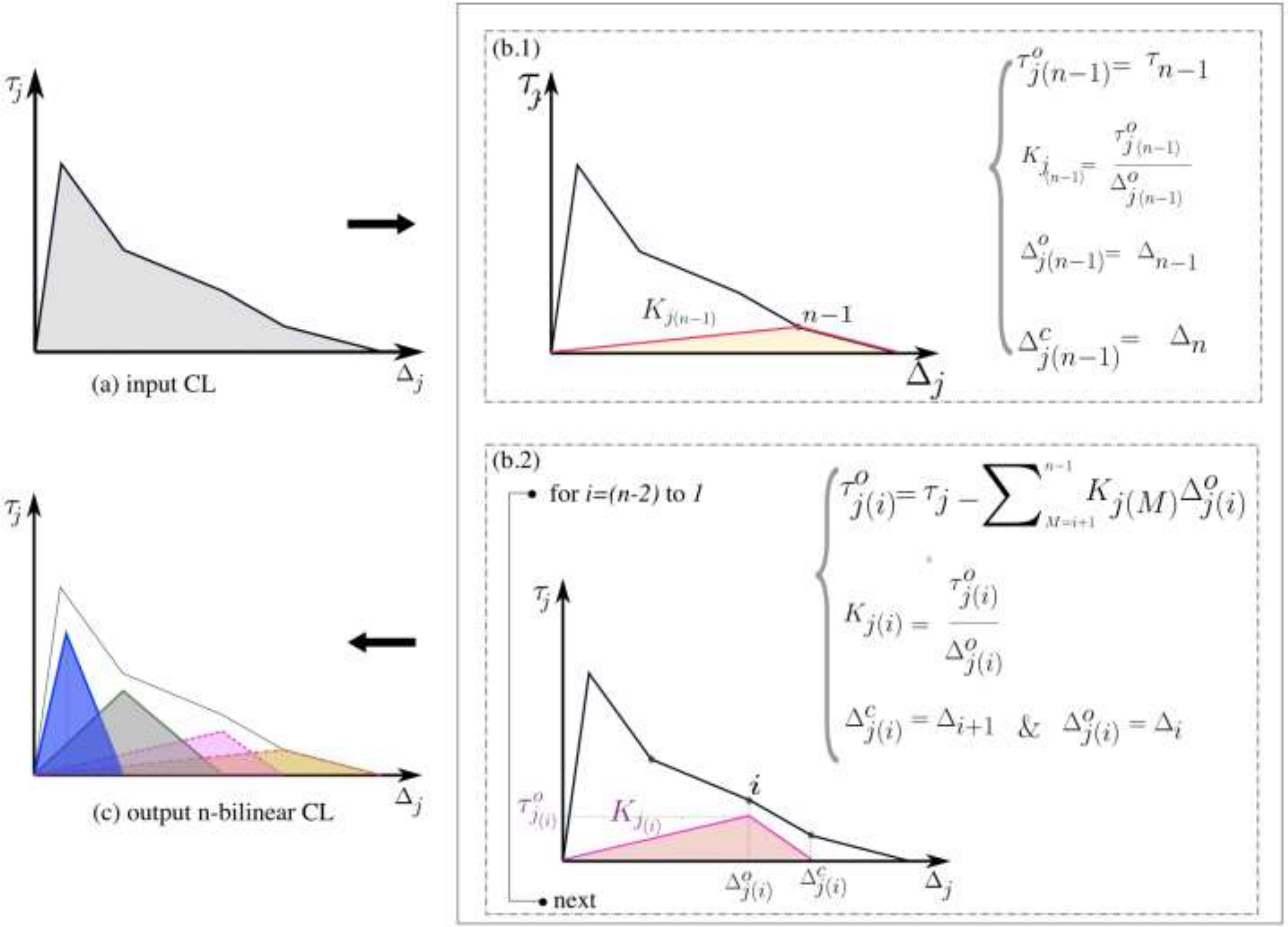
Implementation in FE (Option 2: Superposition)



Jensen et al. 2019

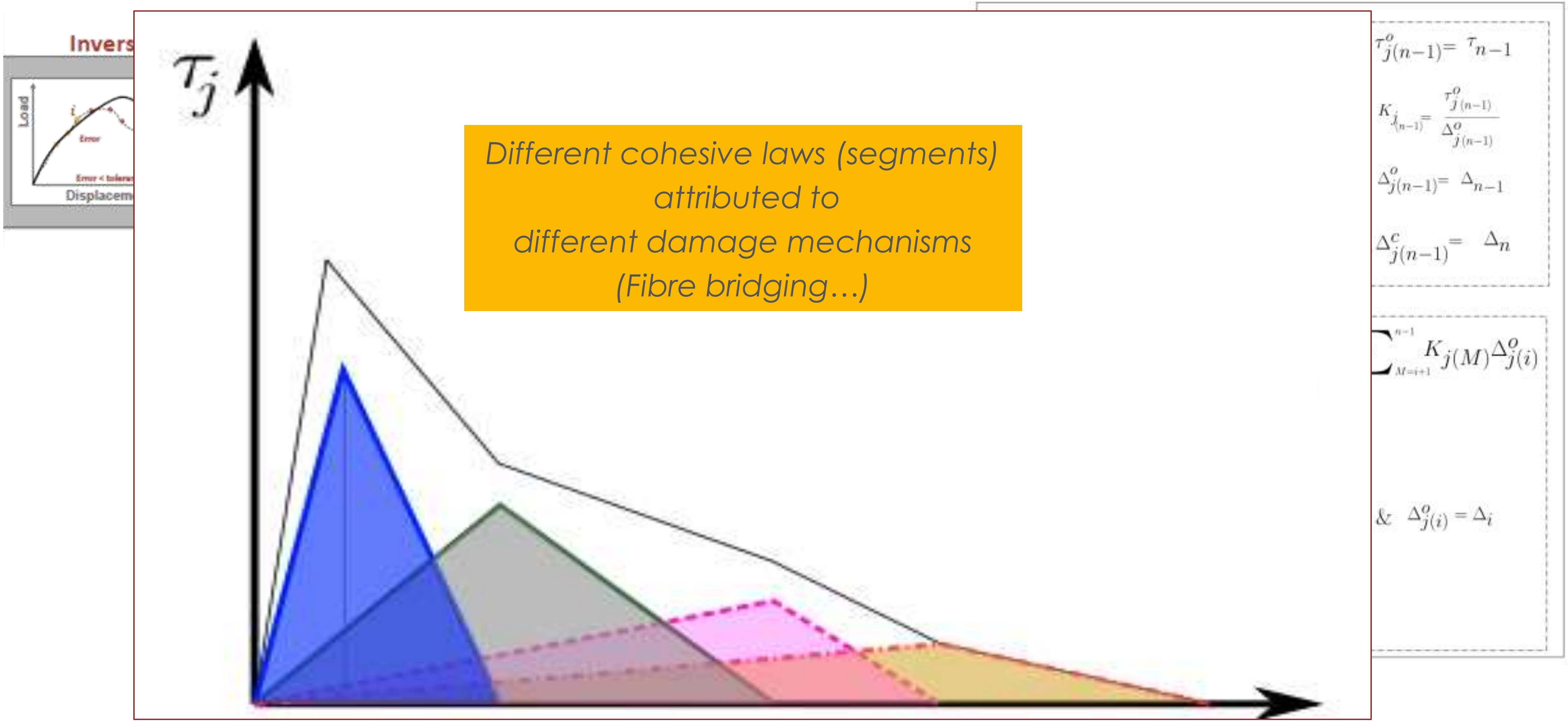
Implementation in FE (Option 2: Superposition)





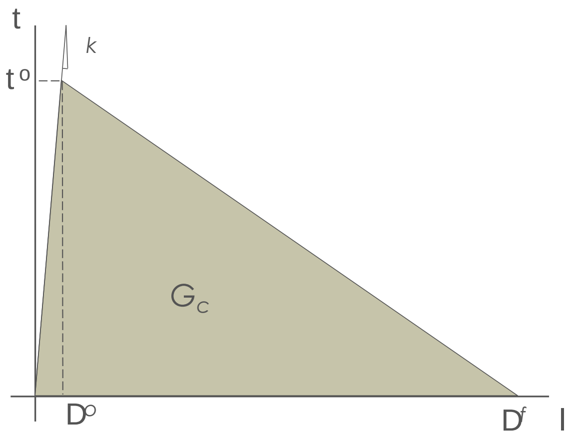
Abdel-Monsef et al. 2023

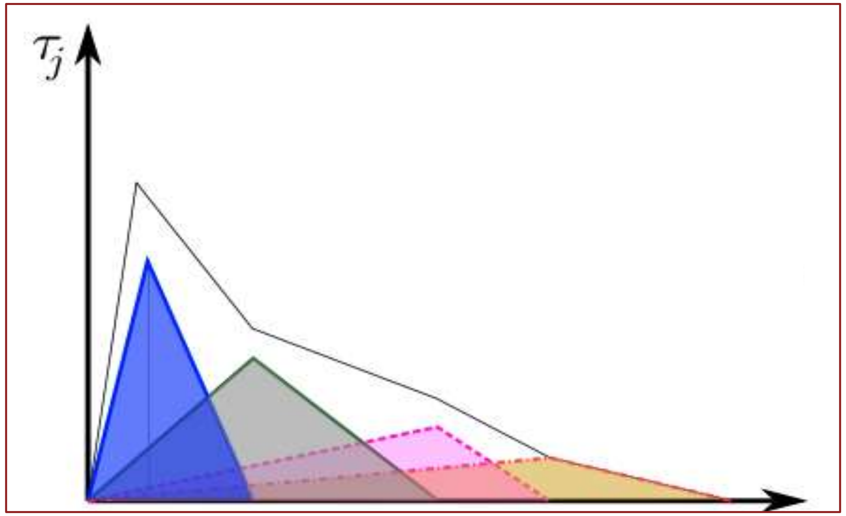
Implementation in FE (Option 2: Superposition)

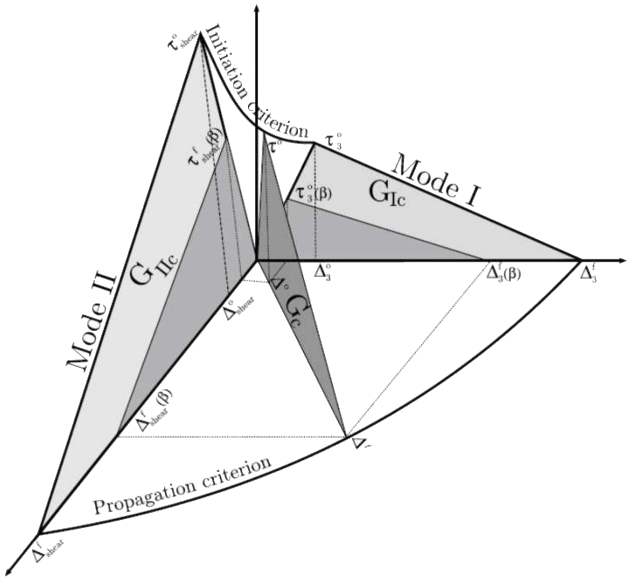


Abdel-Monsef et al. 2023

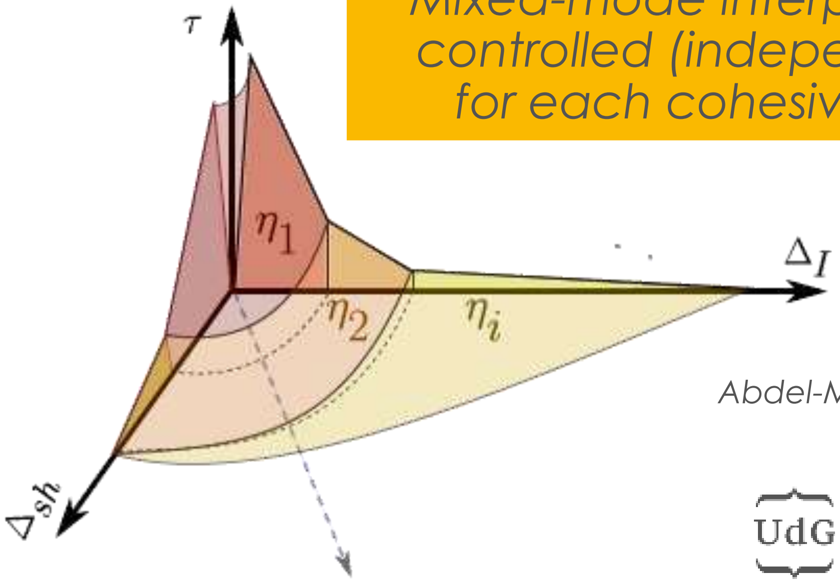
Implementation in FE (Option 2: Superposition)



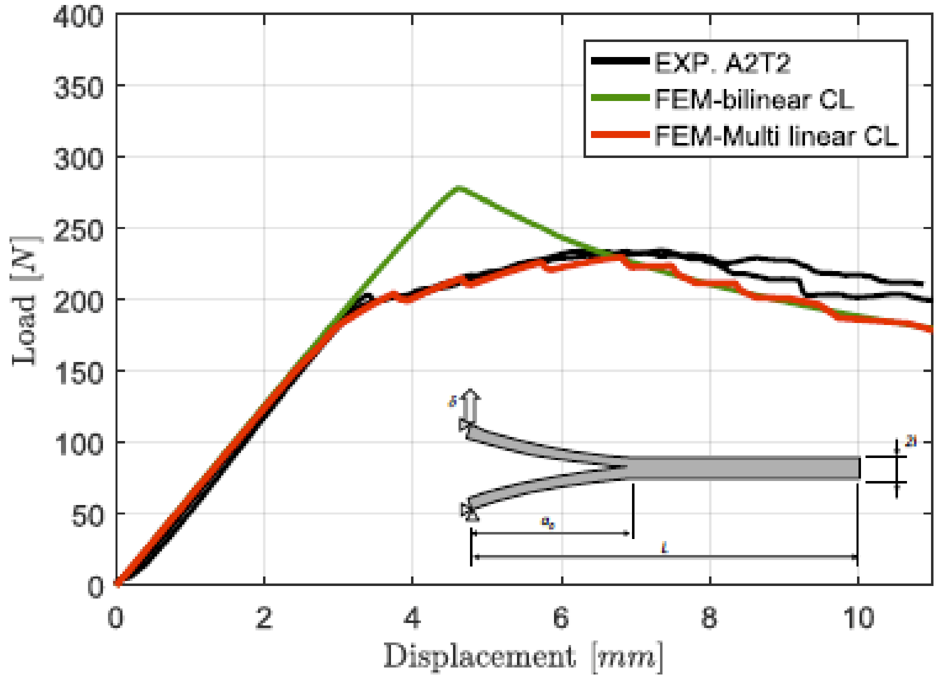




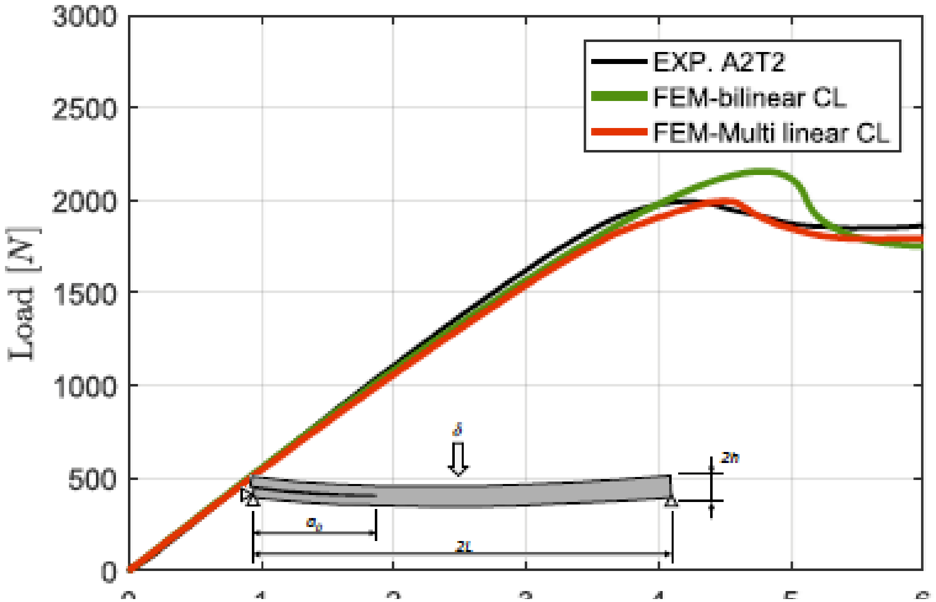
Mixed-mode interpolation controlled (independent) for each cohesive law

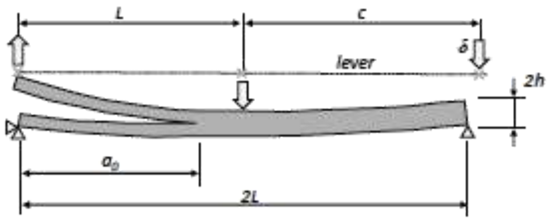


Abdel-Monsef et al. 2023

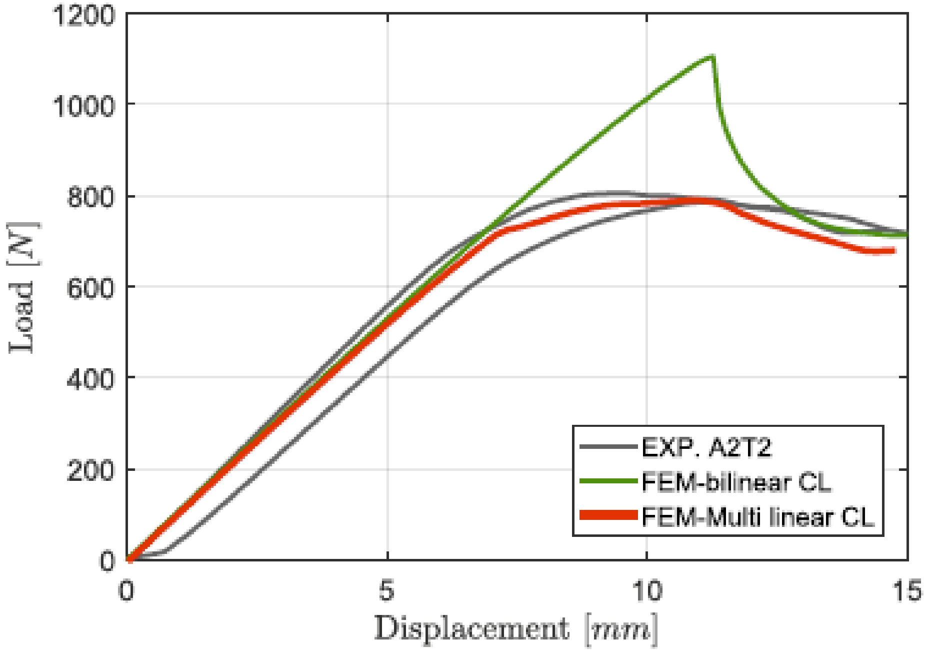


(a) DCB



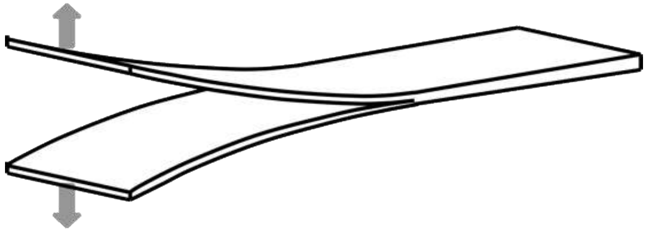


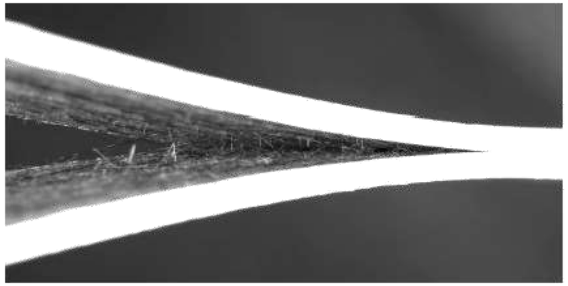
Bonded joint configuration

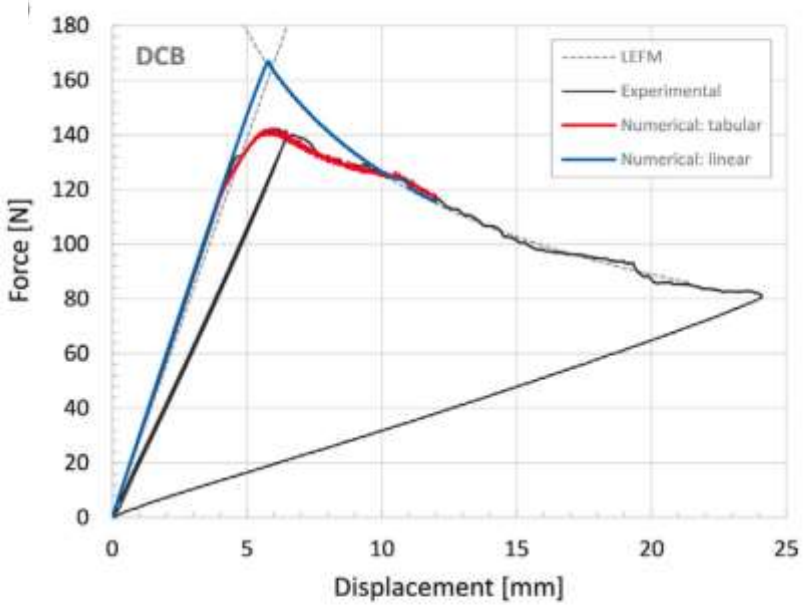


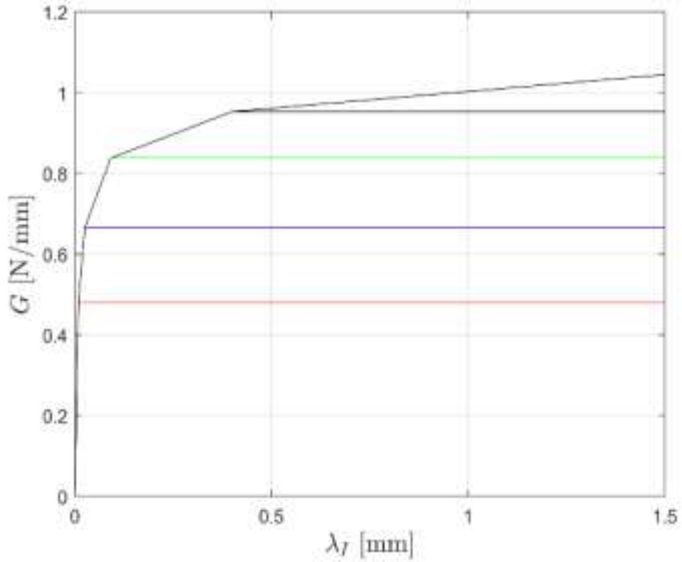
(c) MMB 75%

Static loading

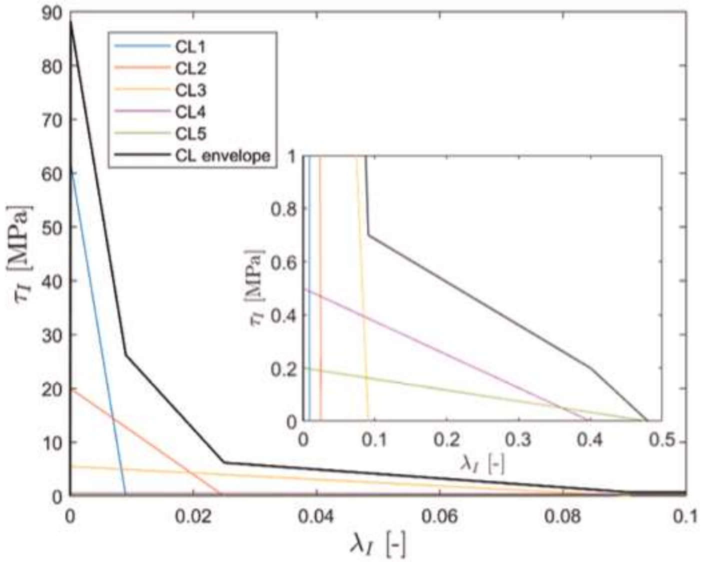






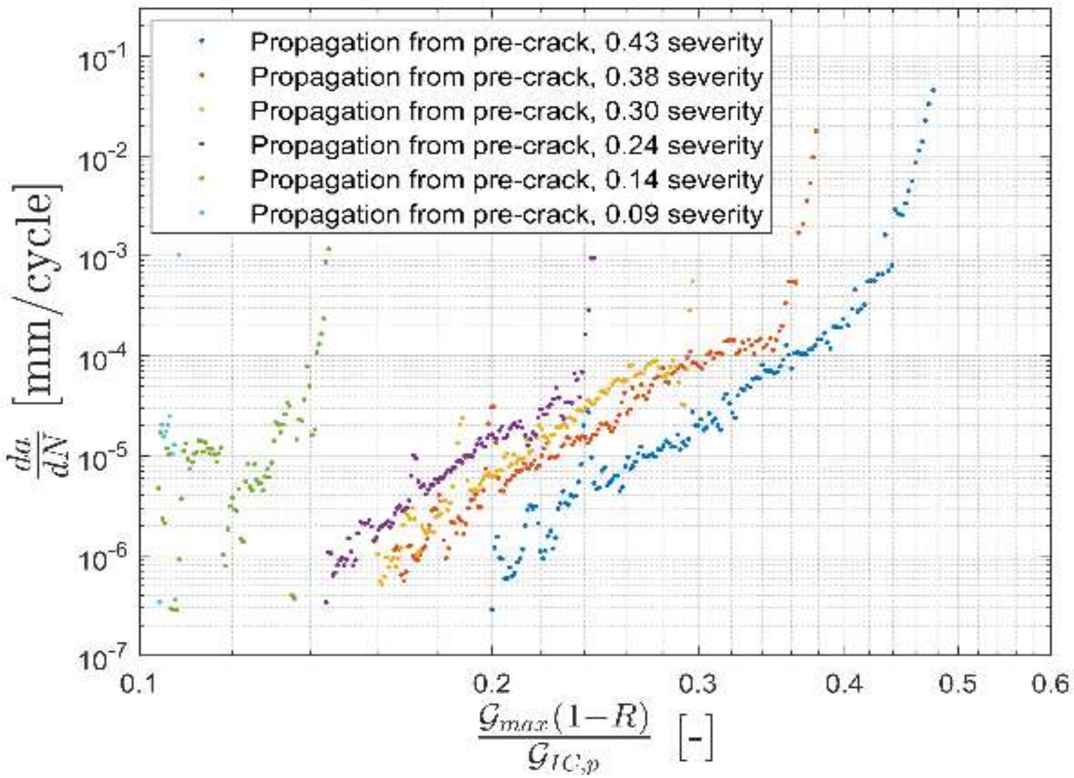


Modelling approach → Superposition of 5 linear (bilinear) cohesive laws



Fatigue response

Experimental crack growth curve

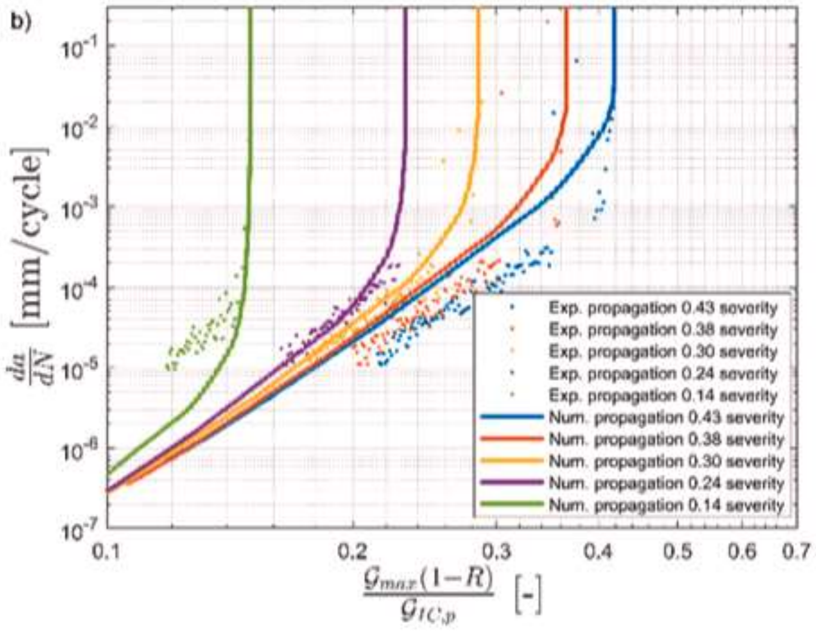


Fatigue simulation

- *Modelling approach*
  - *Superposition of 5 CL (static)*
  - *CL1, CL2 and CL3 undergo static and fatigue degradation*
  - *CL4 and CL5 only static degradation*

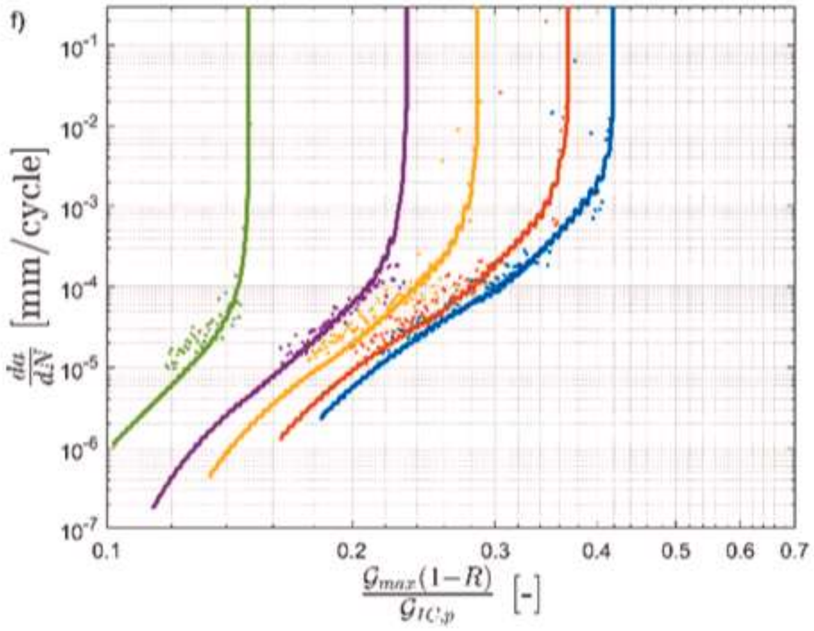
OPTION 1

- *Same fatigue degradation parameters for CL1, CL2 and CL3*



OPTION 2

- *Different degradation parameters for the differents damage mechanisms*

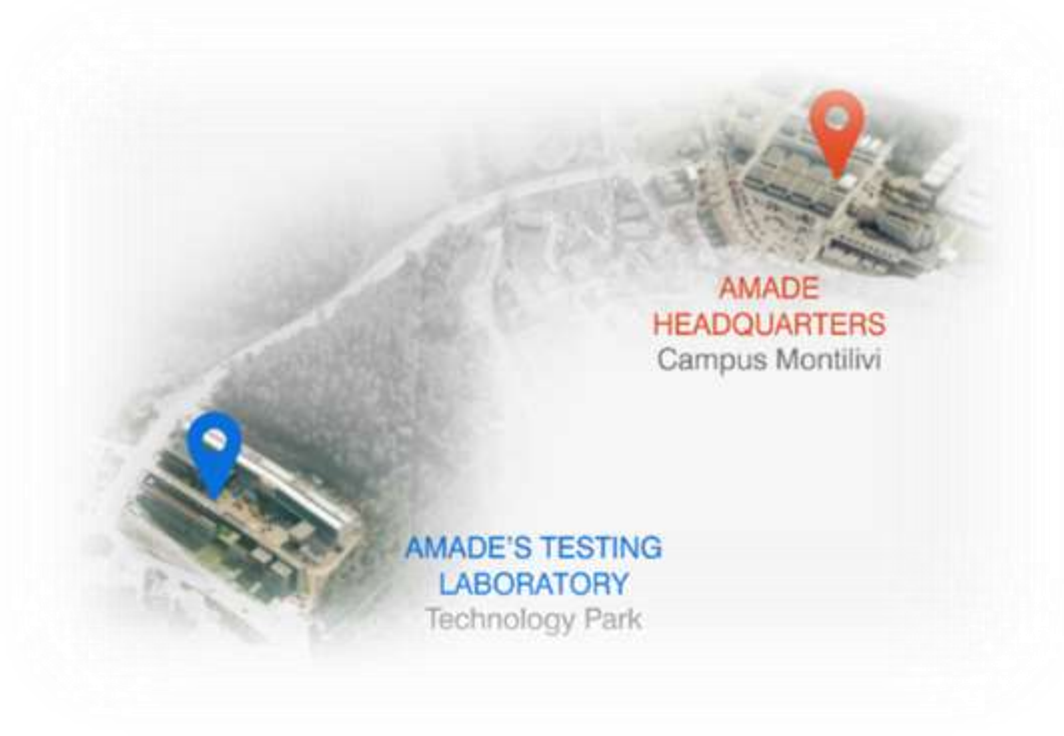


Conclusions

- *Discussed about the mechanics of delamination onset and propagation*
- *"Linked" to the cohesive zone model concept*
- *Cohesive law shape "matters" and how it can be "measured"*
- *Discussed about the implementation using FEM of a general CL shape*
- *Discussed about the intrinsic relation between the shape of the cohesive law and the different damage mechanisms*
- *Discussed about the mixed-mode interpolation*

Keynote speakers selection by the conference committee (Sept. 2022)

- *there are many researchers who use cohesive elements and never ask questions*
- *there is another (smaller) group that considers all this as nonphysical and rejects the method in spite of its applicability and practical usefullness*
- *there is a third group that HAS to use cohesive elements, but they want answers based on physics. (I hope we all belong to this group...)*



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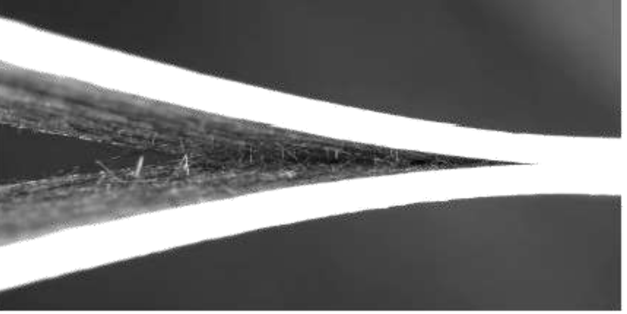
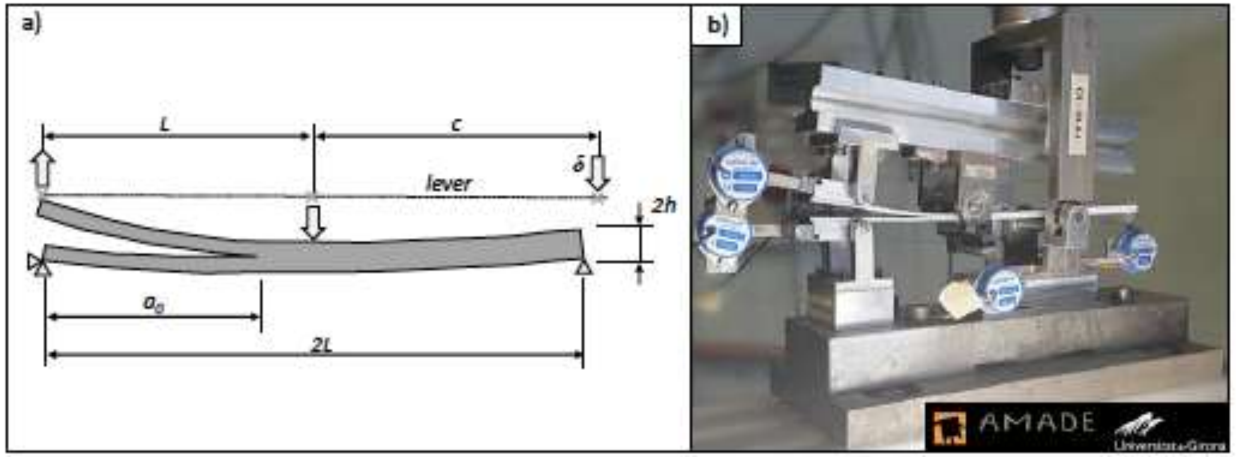
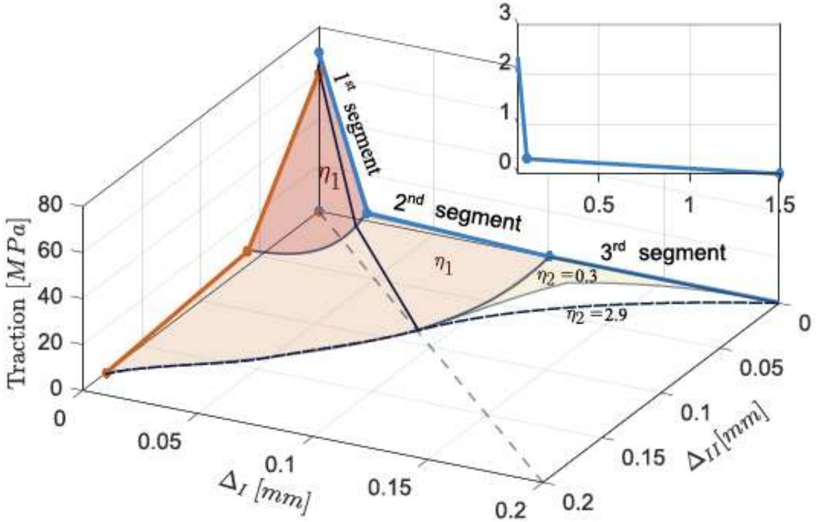
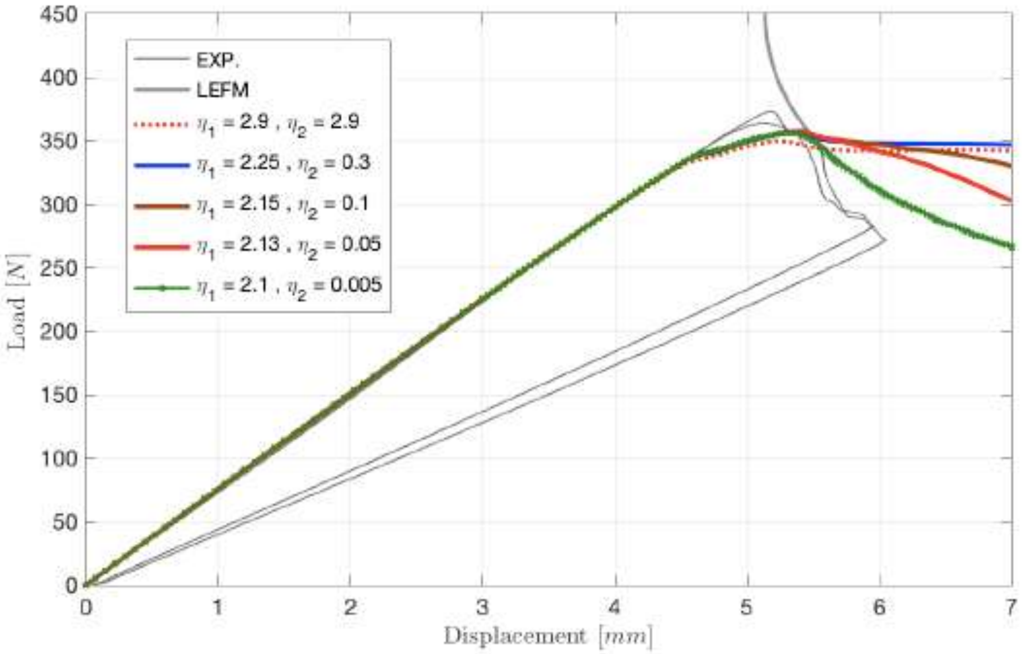



a)
L
c
δ
lever
2h
a0
2L
b)
AMADE
Universitat de Girona

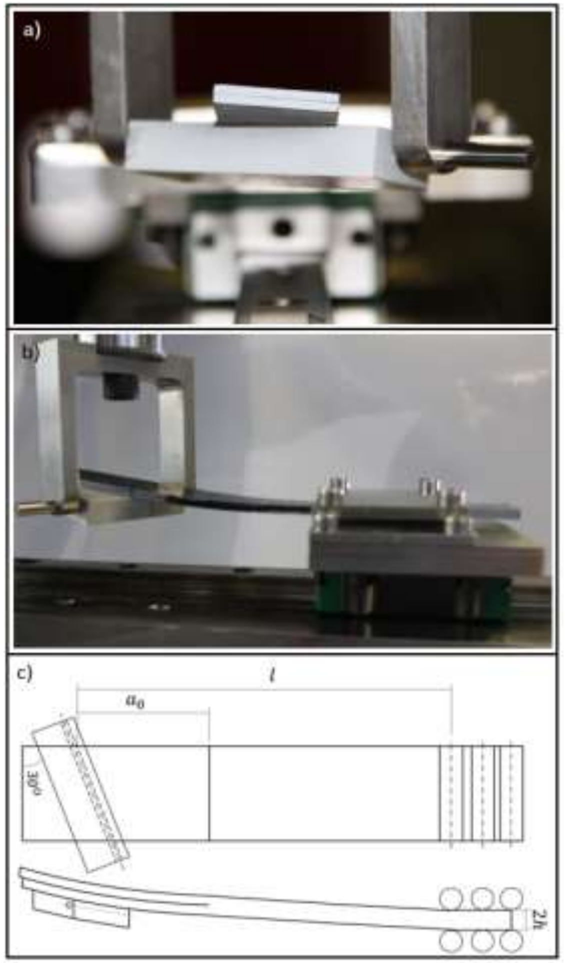

1st segment
2nd segment
3rd segment
η1
η2 = 0.3
η2 = 2.9
Traction [MPa]
ΔI [mm]
ΔII [mm]


EXP.
LEFM
η1 = 2.9 , η2 = 2.9
η1 = 2.25 , η2 = 0.3
η1 = 2.15 , η2 = 0.1
η1 = 2.13 , η2 = 0.05
η1 = 2.1 , η2 = 0.005
Load [N]
Displacement [mm]

UdG

Fatigue simulation

Challenging test case

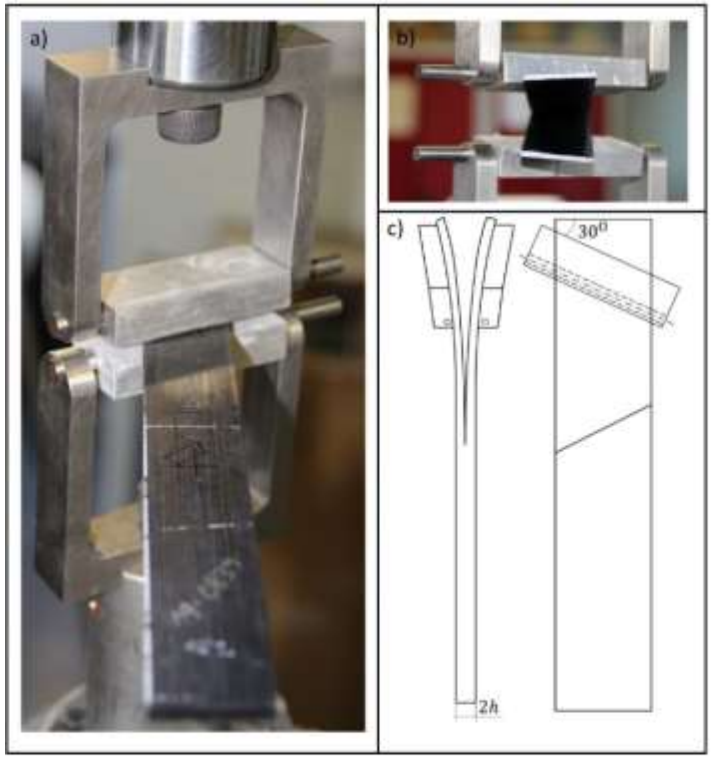


Loading conditions of Hybrid benchmark test that can be considered as equivalent as in service loading:

Step	Loading mode	Loading angle	Maximum displacement, δ_{max} [mm]	Number of cycles
0	Mode I	+ 0º	-	-
1	Shear mode	+ 30º	7	12 000
2	Mode I	− 30º	5	30 000
3	Mode I	− 30º	10	-
4	Mode I	− 30º	10	400 000

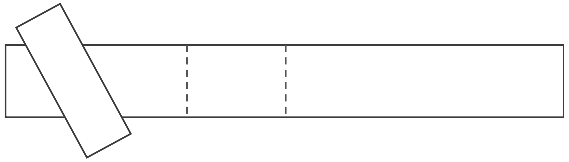
Fatigue simulation

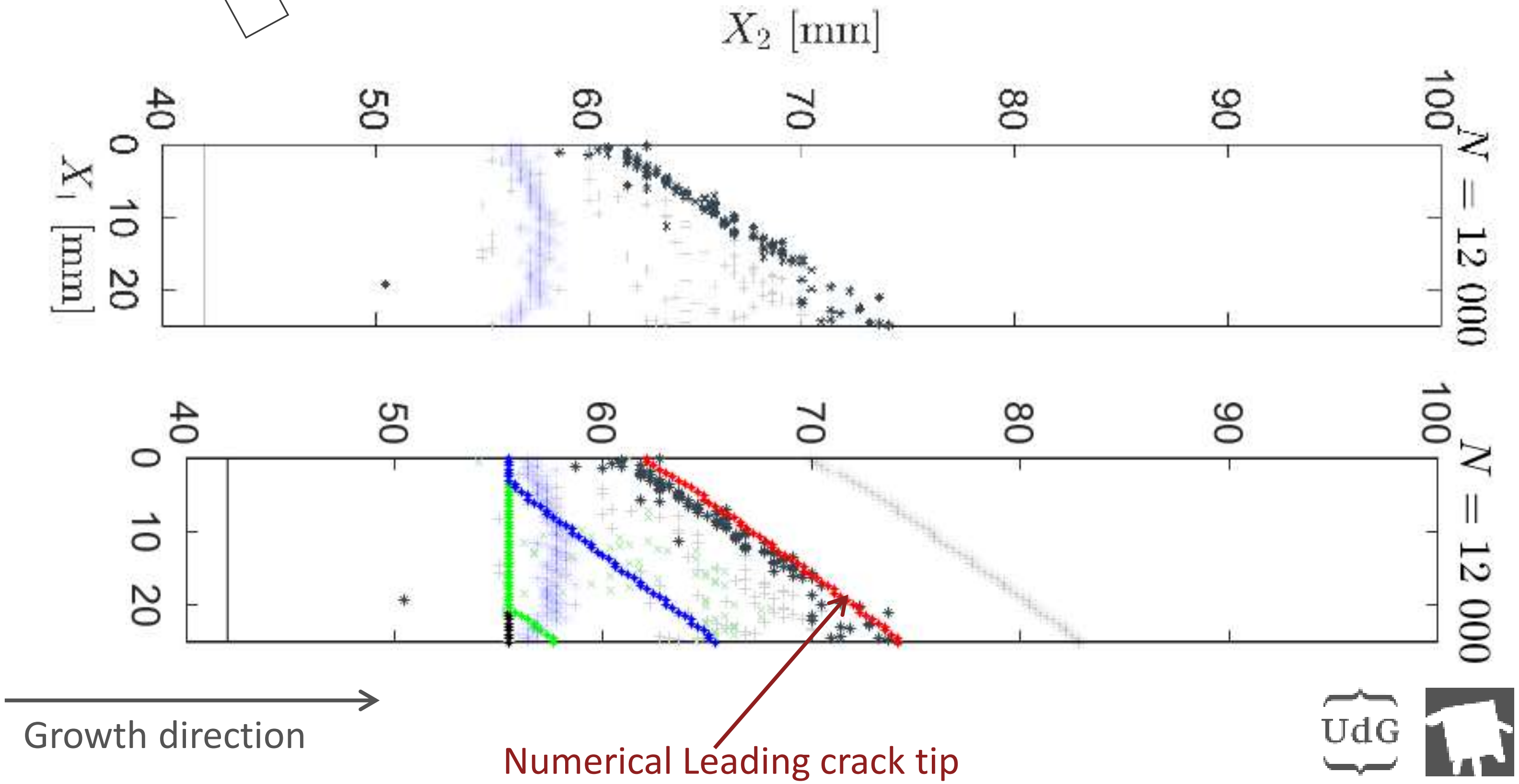
- *Challenging test case*



Loading conditions of Hybrid benchmark test that can be considered as equivalent as in service loading:

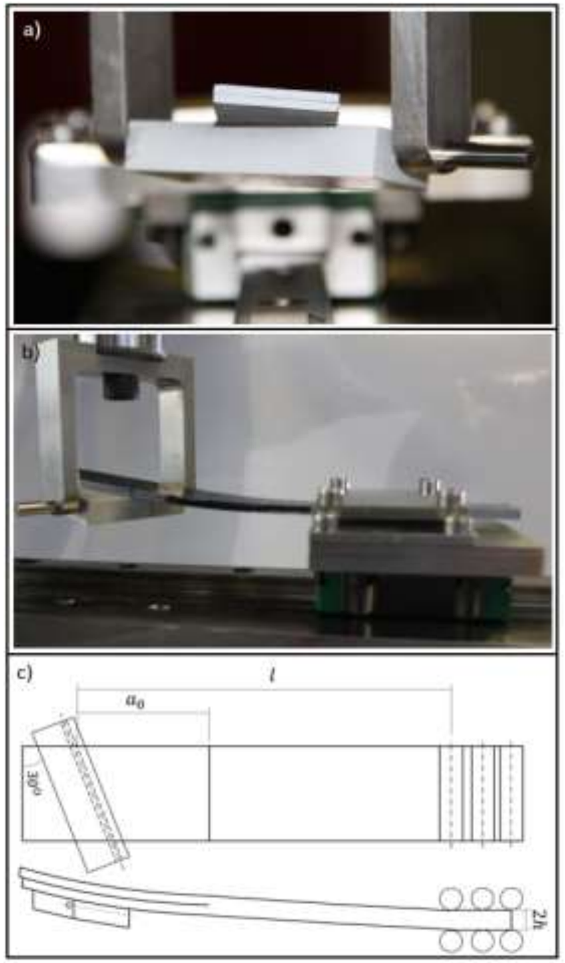
Step	Loading mode	Loading angle	Maximum displacement, δ_{max} [mm]	Number of cycles
0	Mode I	$+0^{o}$	-	-
1	Shear mode	$+30^{o}$	7	12 000
2	Mode I	-30^{o}	5	30 000
3	Mode I	-30^{o}	10	-
4	Mode I	-30^{o}	10	400 000





Fatigue simulation

- *Challenging test case*



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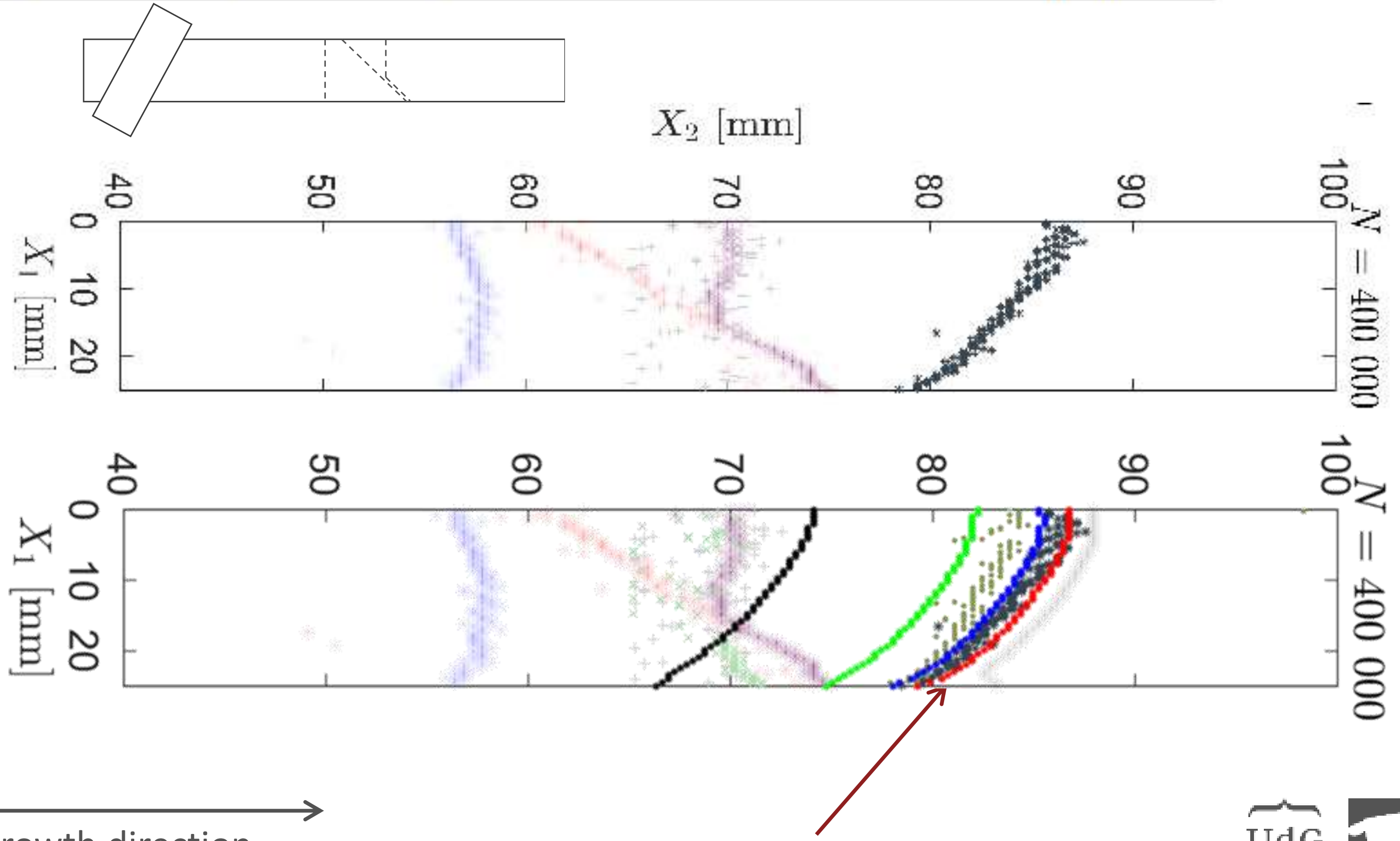

Conclusions