Load Bearing Capacity Prediction of Non-Crimp Fabric Composites Using MAT54 and MAT58 Constitutive Models

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16th LS-DYNA Forum 2022, Bamberg, Germany

Agenda

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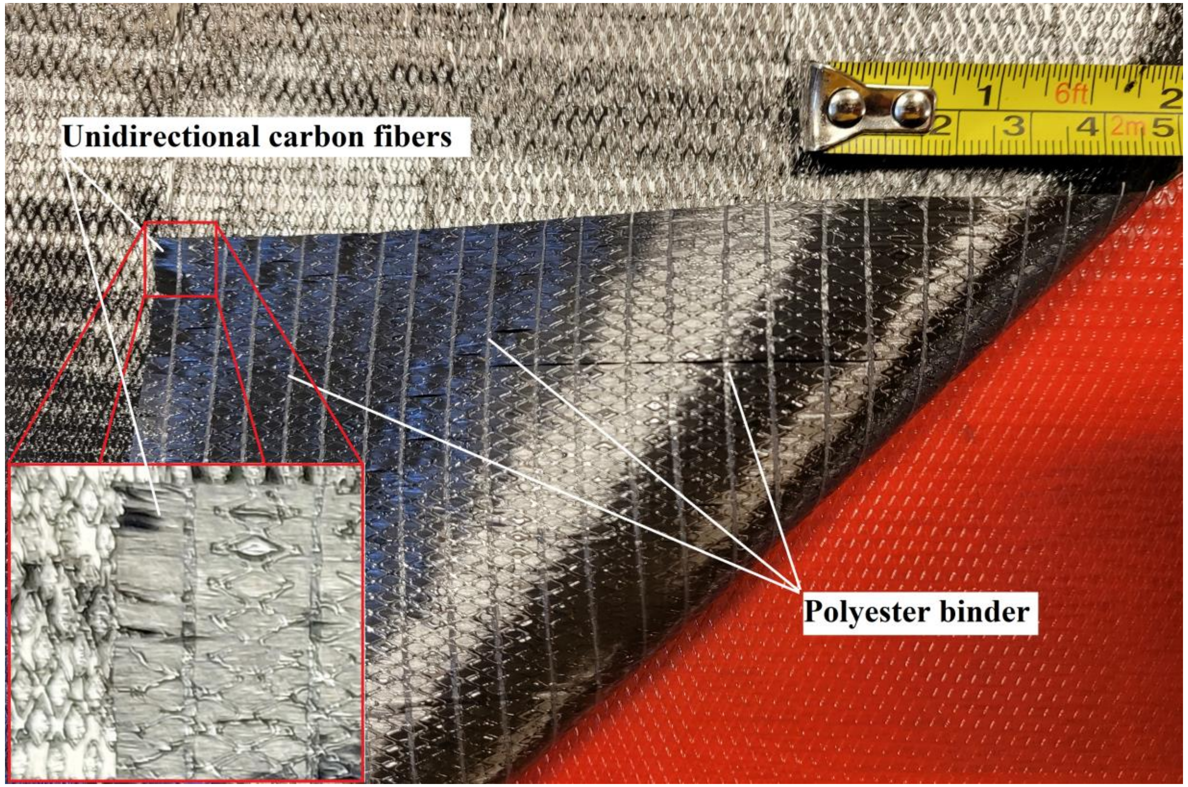
III. Material Models
IV. Methodology
V. Manufacturing
VI. Material Characterization
VII. Component Testing
VIII. Numerical Model
IX. Results
X. Conclusions

Material: Unidirectional Non-Crimp Carbon Fabric

- **Advantage**: combination of high mechanical properties and excellent manufacturability.
- **Applications**: load-bearing aerospace structures, automotive components, and wind energy applications.
- **Structure**: multiple straight and parallel yarn bands joined by polyester stitching (binder)
- **Problem**: as in conventional UD tape- and woven fabric-based materials, in-service damage (tool dropping, unintended impact) can be a cause for severe reduction in load-carrying capacity of NCF composites



Research Objective

Ways of assessing damage and post-impact (residual) load-bearing capacity of NCF parts:

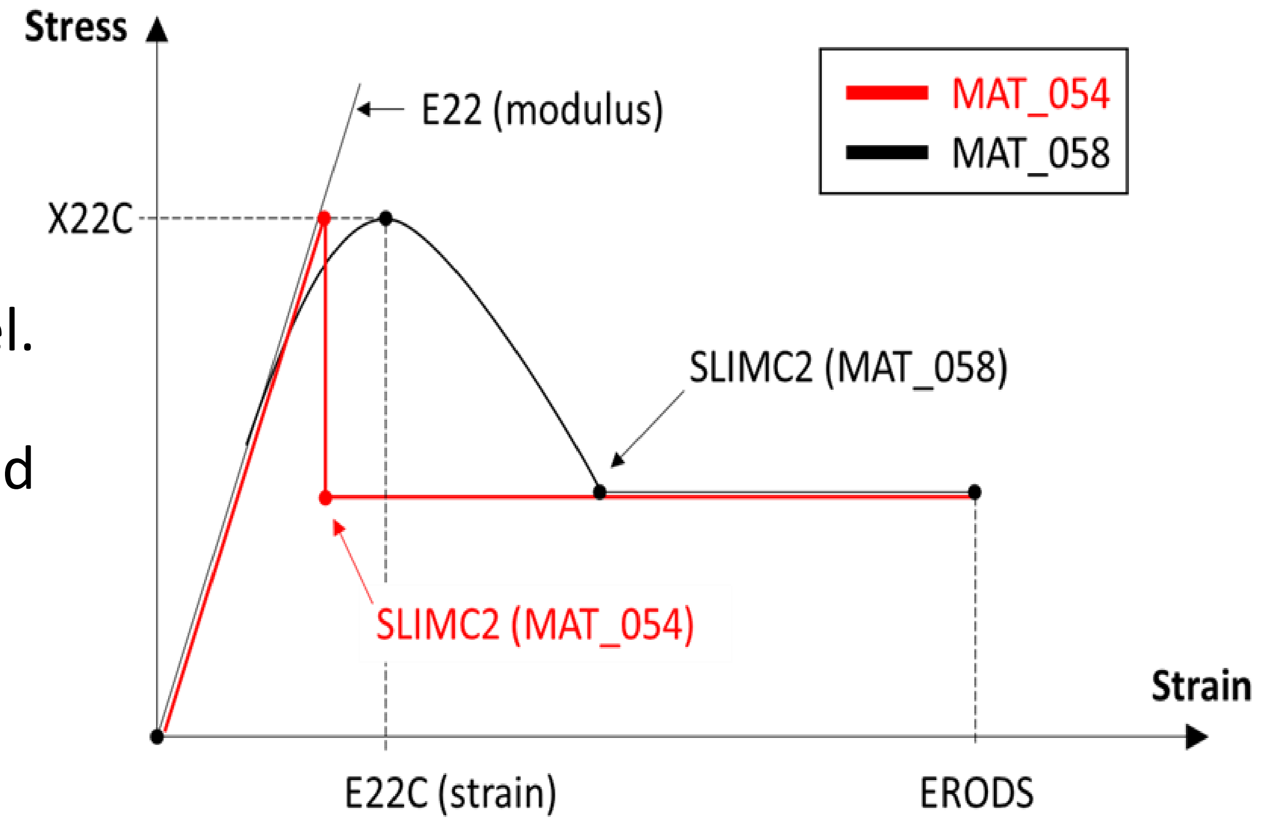
- **Experimental destructive and non-destructive methods** (in combination). Disadvantage: requires considerable financial and time investments.
- **Numerical modeling**.
  Potential: significant cost savings and accelerated decision making.
  Challenge: no established process for non-crimp fabrics (NCF).

Goal of this study:

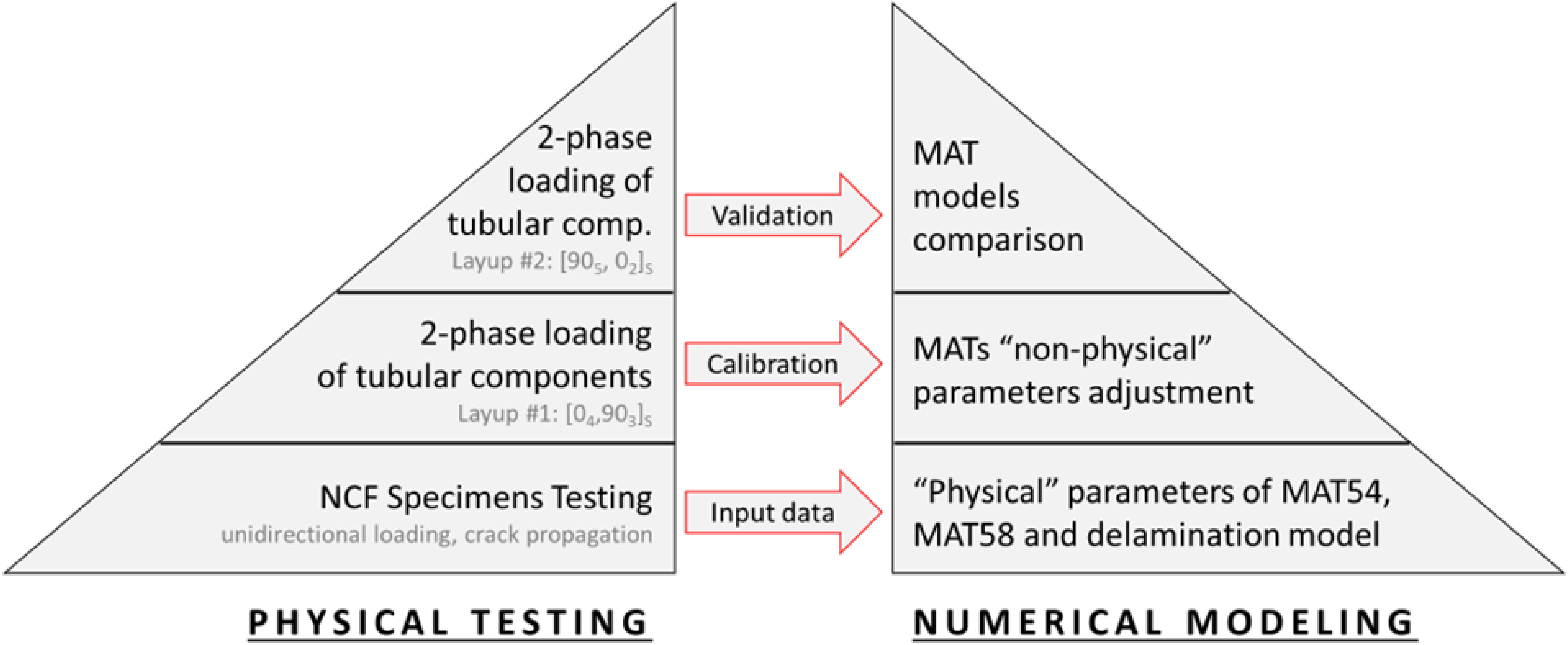
- Evaluate the applicability of the commonly used composite material models available in LS-DYNA for predicting **damage** and **residual load bearing capacity** in structural elements made of NCF.

Material Models: MAT54 and MAT58

- 25+ years history, well-known to and commonly used by industry
- **MAT54**: strength criterion-based model (Chang–Chang model)
- **MAT58**: damage mechanics-based model. Accounts for both pre- and post-peak softening of composite plies. UD tape and woven fabric formulations available.
- **Features** (both models): multiple non-physical parameters governing post-failure behavior of the material.

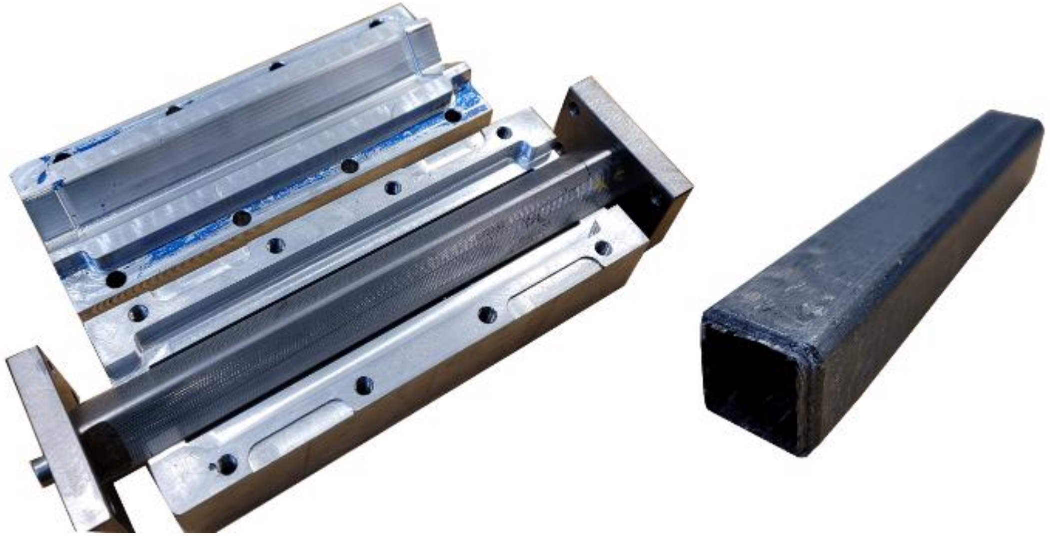


Methodology



Manufacturing

- **Material**: 12K UD intermediate modulus (IM) non-crimp carbon fabric pre-impregnated with epoxy resin. Areal density – 140 g/m^2, resin content – 38±3%.

Flat panels	Tubular components
	

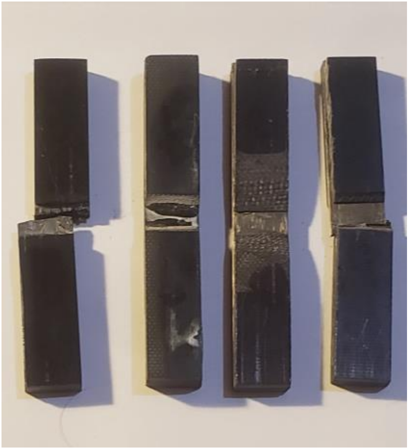
- **Manufacturing**: curing in a PLC oven. Temperature – 132 $^\circ$C (4 °C/min ramp rate, holding for 4 hours). Pressure – torque on the mold closing screws.

Material Characterization

Property	Units	Value	Method
Longitudinal Young's modulus, $\mathbf{E_1}$	MPa	149018	ASTM D 3039
Transverse Young's modulus, $\mathbf{E_2}$	MPa	6071	
Major in-plane Poisson's ratio, $\boldsymbol{\nu_{12}}$	-	0.32	
In-plane shear modulus, $\mathbf{G_{12}}$	MPa	4217	10° off-axis
Longitudinal tensile strength, $\mathbf{X_t}$	MPa	2060	ASTM D 3039
Longitudinal compressive strength*, $\boldsymbol{X_c}$	MPa	814	Modified ASTM D695
Transverse tensile strength, $\mathbf{Y_t}$	MPa	29.1	ASTM D 3039
alcTransverse compressive strength*, $\mathbf{Y_c}$	MPa	121	Modified ASTM D695
In-plane shear strength, $\mathbf{S_L}$	MPa	44.5	10° off-axis
Longitudinal tensile strain-at-failure, $\boldsymbol{\varepsilon_{1f}}$	%	1.37	ASTM D 3039
Transverse tensile strain-at-failure, $\boldsymbol{\varepsilon_{2f}}$	%	0.40	ASTM D 3039
In-plane shear strain-at-failure, $\gamma_{\mathbf{12f}}$	%	1.71	10° off-axis
Longitudinal compressive strain-at-failure, ε_{1f}	%	0.55	Modified ASTM D695
Transverse compressive strain-at-failure, ε_{2f}	%	1.99	Modified ASTM D695
Mode I strain energy release rate, G_{Ic}	kJ/m^2	0.66	ASTM 5528b
Mode II strain energy release rate, G_{IIc}	kJ/m^2	2.77	ENF bending

Longitudinal (along fibers) compression strength

- UD tape-based composite – 1200 - 1500 MPa
- UD NCF-based composite (ASTM 695) – 814 MPa


Possible reasons:

- crimp still present due to stitching
- waviness of fiber bundles (tows) in-plane

Component Testing

PHASE I

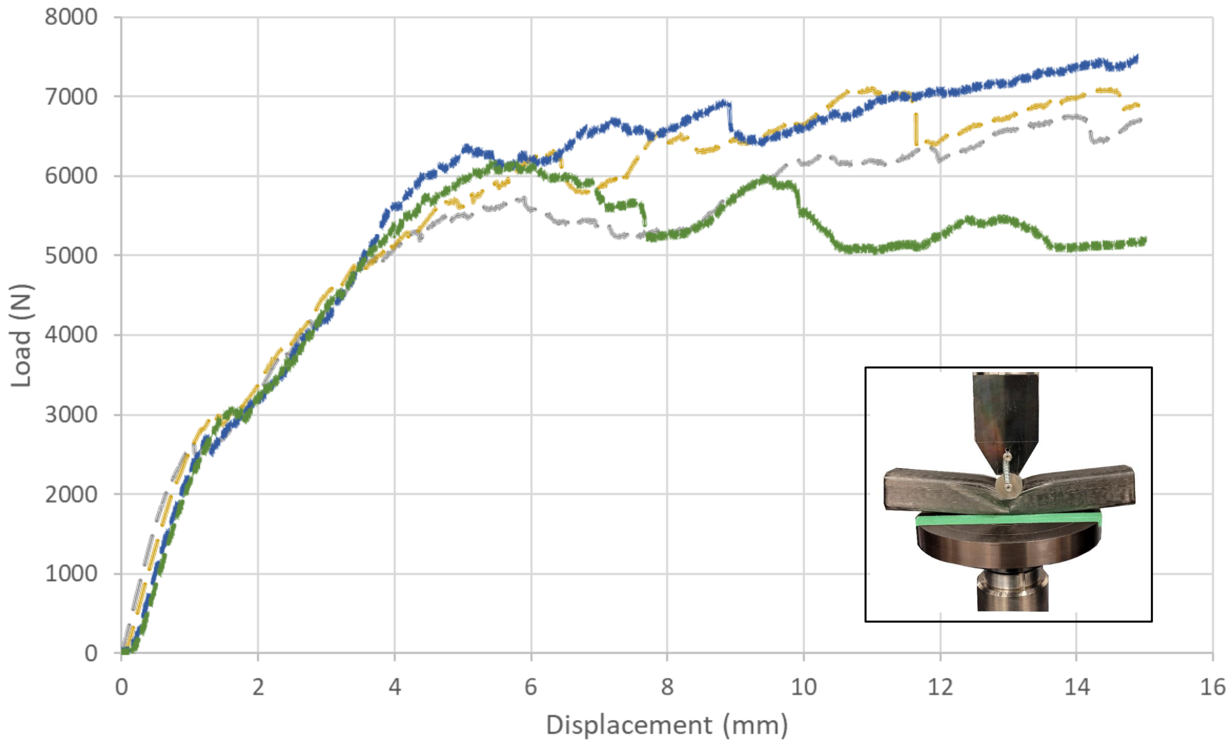
Damaging the specimen using a cylindrical indenter

PHASE II

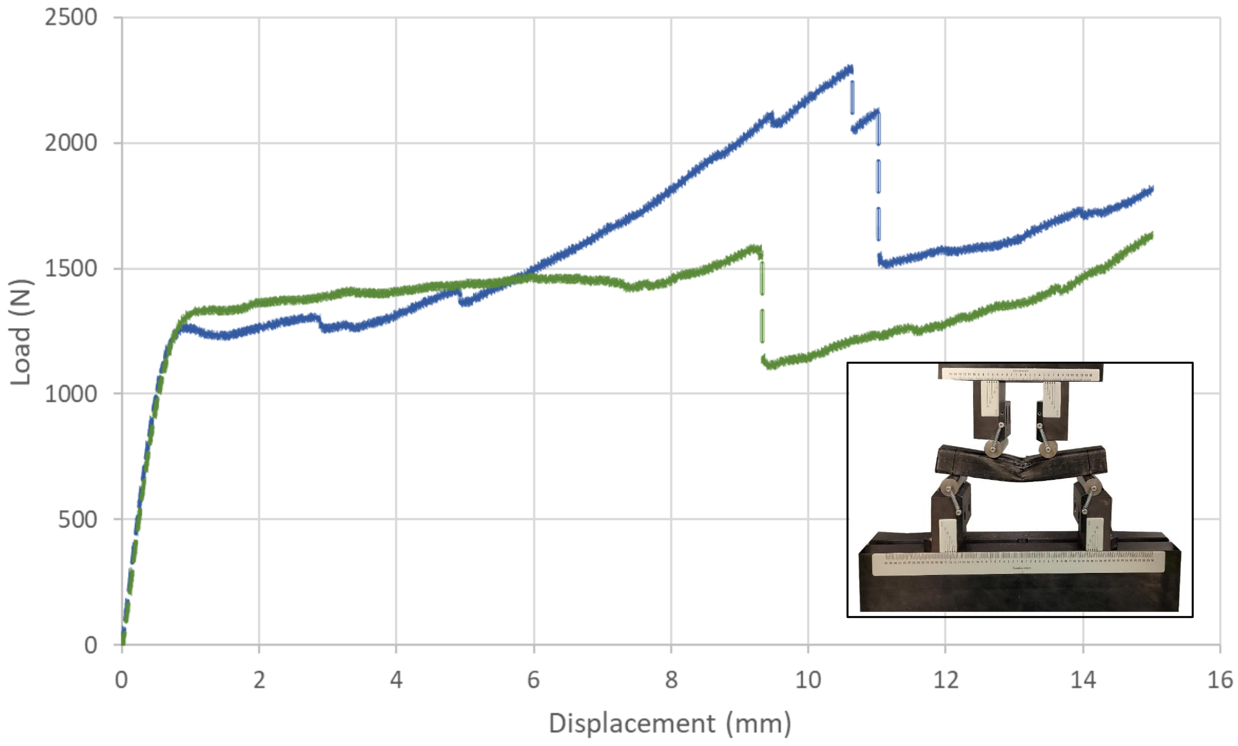
Measuring the residual load-bearing capacity using 4-point bending test

Component Testing

PHASE I



PHASE II



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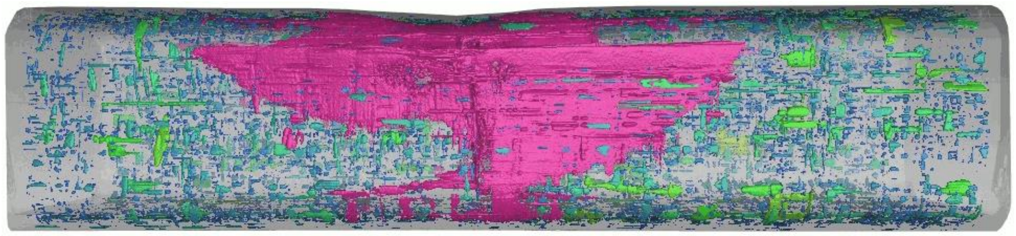
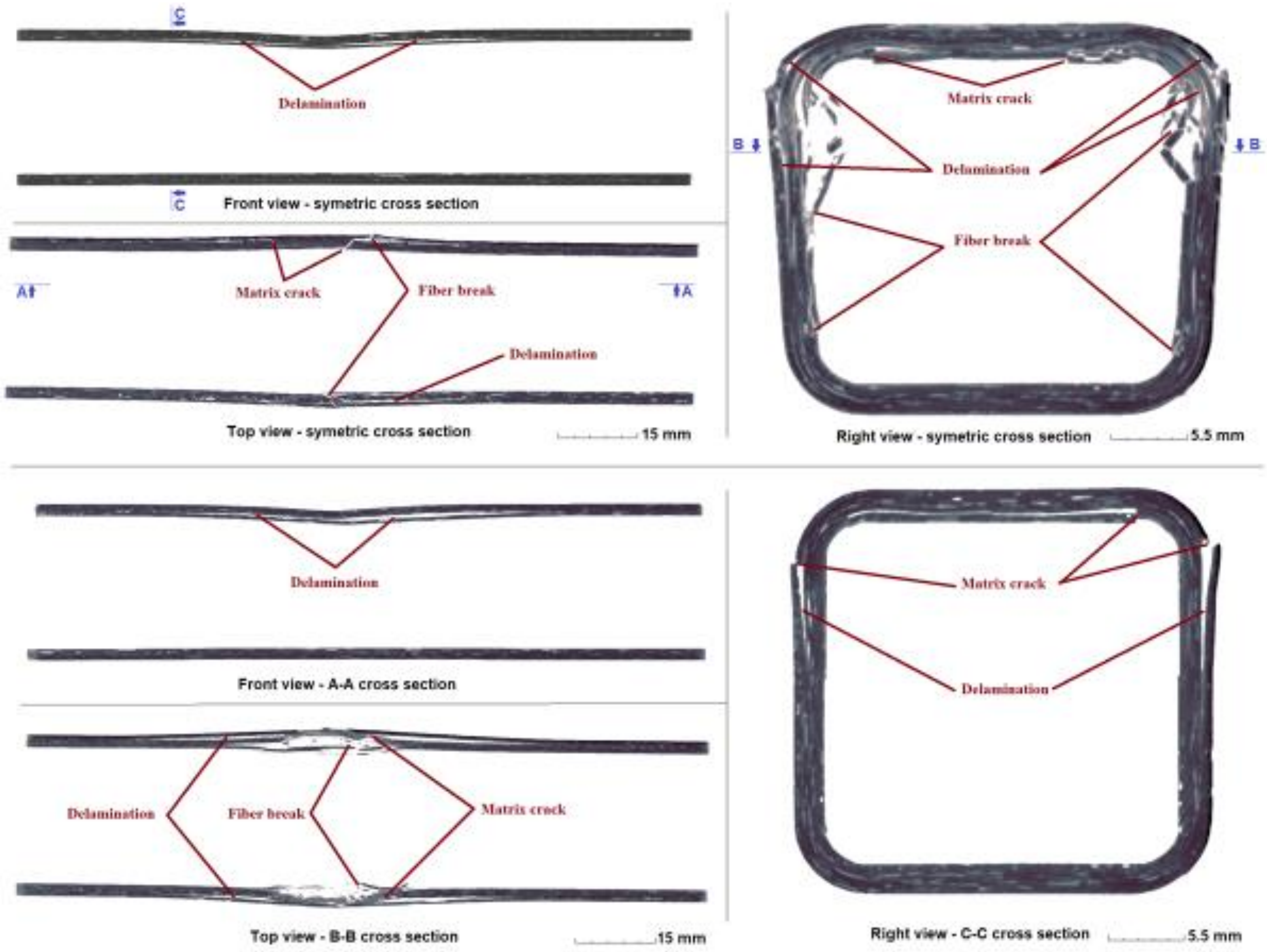
Component Testing: NDE (CT-Scan)

- **Method**: X-ray computed tomography
- **Object** : a 100 mm central segment of the damaged (post phase I) tube with $[0_4, 90_3]_S$ layup
- **Goal**: measure of the extent of induced damage in phase I and assist with verification of numerical models





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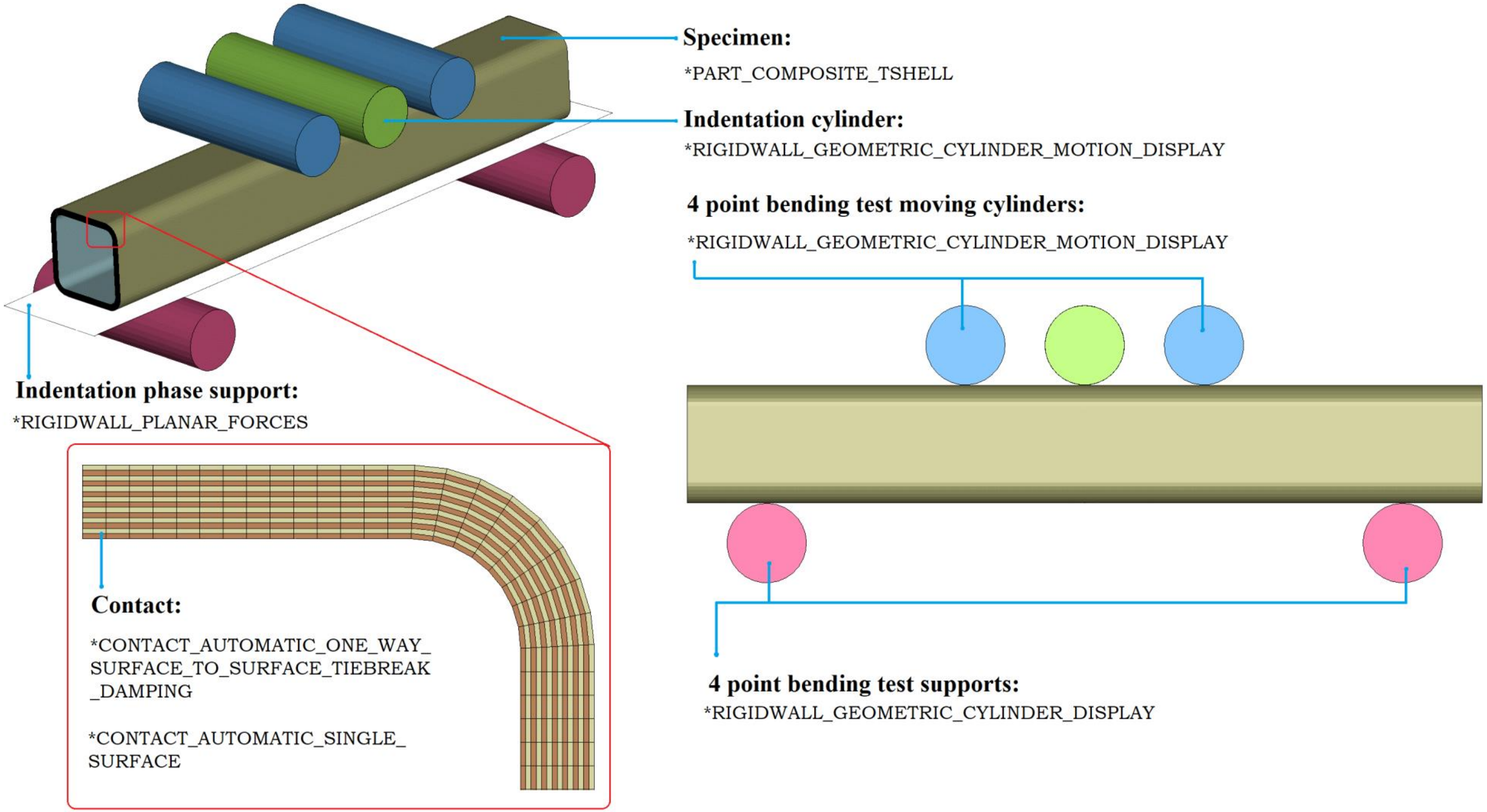
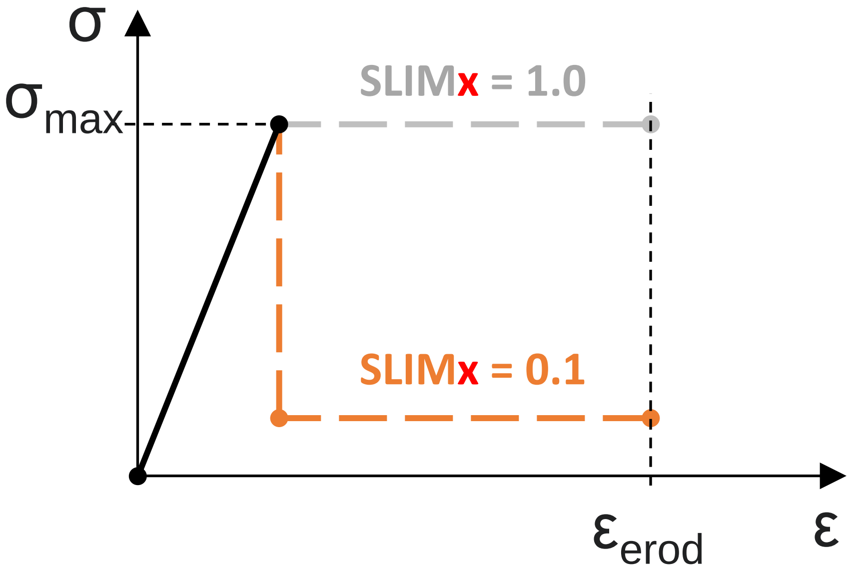
Numerical Model



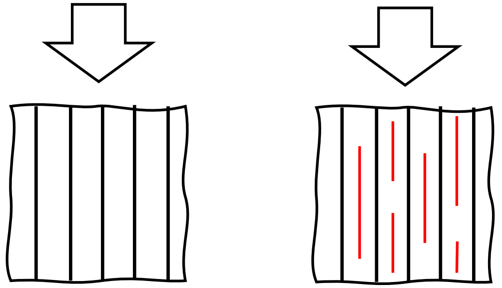
Numerical Model: Non-Physical Parameters of MAT54 & 58

SLIMT1	Factor to determine the minimum stress limit after stress maximum (fiber tension).
SLIMC1	Factor to determine the minimum stress limit after stress maximum (fiber tension).
SLIMT2	Factor to determine the minimum stress limit after stress maximum (matrix tension).
SLIMC2	Factor to determine the minimum stress limit after stress maximum (matrix compression).
SLIMS	Factor to determine the minimum stress limit after stress maximum (shear).
YCFAC	Reduction factor for compressive fiber strength Xc after matrix compressive failure



SLIMC = [0.1; 1.0], SLIMT = [0.01; 0.100]

YCFAC: influence of matrix cracking on longitudinal compressive strength (Xc)



No matrix cracks   Matrix cracks

$$X_c > X'_c$$

$$X'_c = \text{YCFAC} \times Y_c$$

$$\text{YCFAC}_{max} = X_c / Y_c = 6.72$$

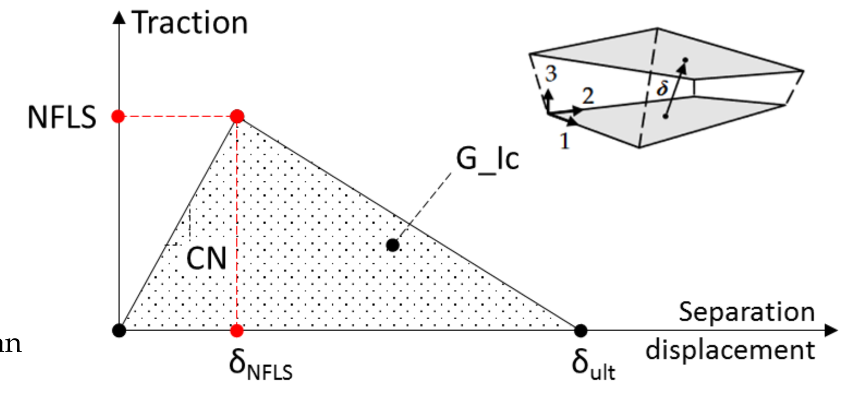
$$\text{YCFAC}_{min} = 2.00 \text{ (default)}$$

*YCFAC – MAT54 only

Numerical Model: Delamination Model Parameters

- **Delamination model**: ...SURFACE_TO_SURFACE_TIEBREAK contact with OPTION 9 – equivalent to using zero-thickness cohesive zone elements and is based on the fracture model with bilinear traction-separation law, mixed-mode delamination criterion, and damage formulation (same as *MAT138)

Property	Unit	Value	Rationale
NFLS	MPa	75.00	The ultimate strength of bulk epoxy resin multiplied by a scaling factor of 0.95 to account for the mesh dependency (recommended for meshes with element sizes of 0.7 mm).
SFLS	MPa	43.30	Assumed as SFLS = NFLS$\sqrt{3}$ (von Mises criterion)
G_Ic	kJ/m^2	0.66	Measured experimentally
G_IIc	kJ/m^2	2.77	Measured experimentally
CN	MPa/mm	200,000	CN = E_{epoxy}/δ_{RRR}, where E_{epoxy} is the Young's modulus of epoxy matrix (~3650 MPa) and δ_{RRR} is the thickness of the interlaminar resin-rich region (typically within 0.01 and 0.10 mm). Thus, the lower and upper bounds for CN correspond to 36,500 MPa/mm and 365,000 MPa/mm, accordingly. This averages to 200,000 MPa/mm as an estimate for the CN parameter.
CT2CN	-	0.37	CT2CN = CT/CN = G_{epoxy}/E_{epoxy} = 1/2 × (1 + ν_{epoxy}), where G_{epoxy} and ν_{epoxy} are the shear modulus and the Poisson's ratio (~0.35) of epoxy resin, correspondingly.



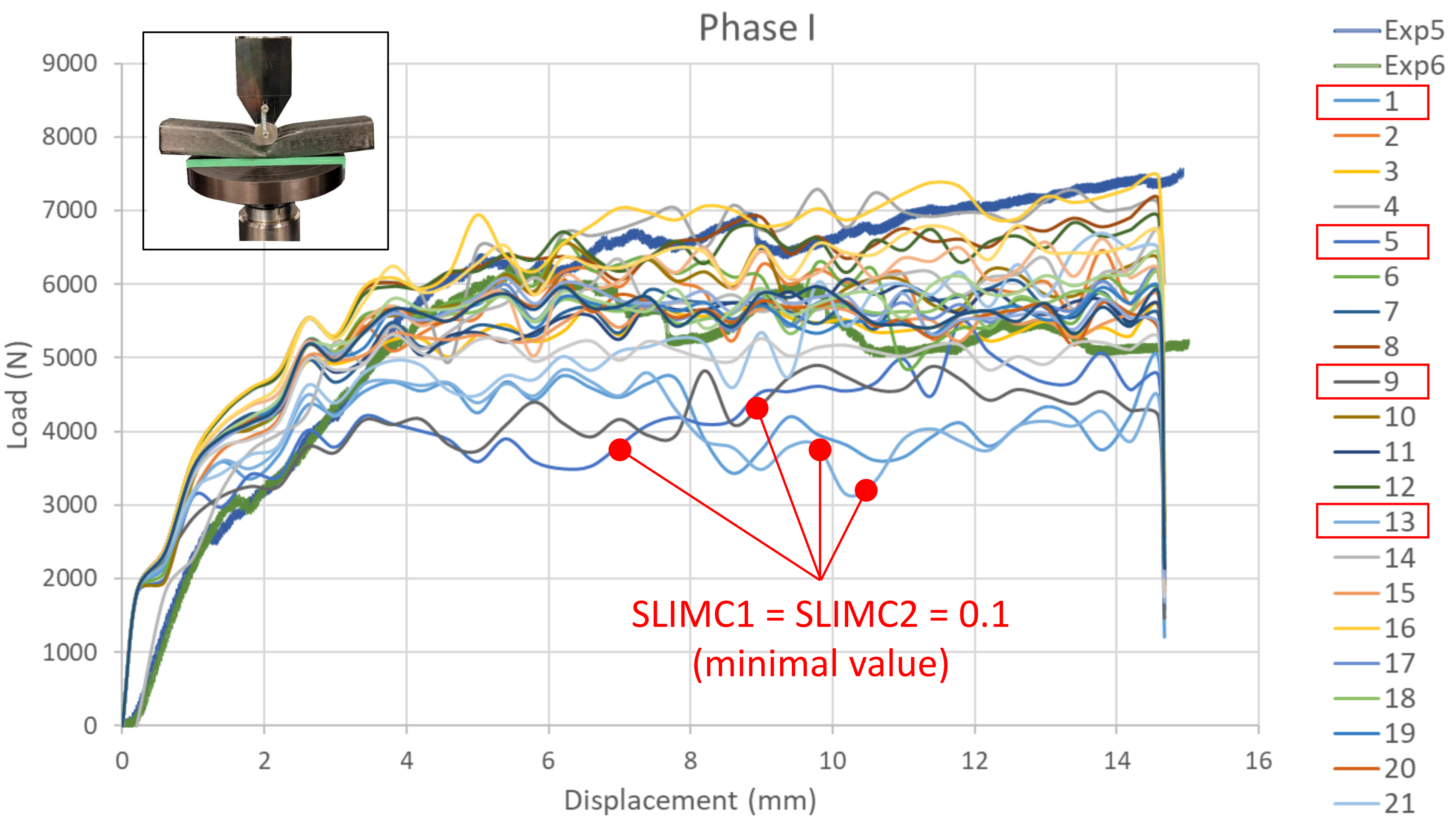
Results

	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
1	0.01	0.01	0.1	0.1	6.72
2	0.01	0.01	0.1	1	2
3	0.01	0.01	1	0.1	2
4	0.01	0.01	1	1	6.72
5	0.01	0.1	0.1	0.1	2
6	0.01	0.1	0.1	1	6.72
7	0.01	0.1	1	0.1	6.72
8	0.01	0.1	1	1	2
9	0.1	0.01	0.1	0.1	2
10	0.1	0.01	0.1	1	6.72
11	0.1	0.01	1	0.1	6.72
12	0.1	0.01	1	1	2
13	0.1	0.1	0.1	0.1	6.72
14	0.1	0.1	0.1	1	2
15	0.1	0.1	1	0.1	2
16	0.1	0.1	1	1	6.72
17	0.01	0.045	0.45	0.45	4.36
18	0.1	0.045	0.45	0.45	4.36
19	0.045	0.01	0.45	0.45	4.36
20	0.045	0.1	0.45	0.45	4.36
21	0.045	0.045	0.1	0.45	4.36
22	0.045	0.045	1	0.45	4.36
23	0.045	0.045	0.45	0.1	4.36
24	0.045	0.045	0.45	1	4.36
25	0.045	0.045	0.45	0.45	2
26	0.045	0.045	0.45	0.45	6.72
27	0.045	0.045	0.45	0.45	4.36

- **Parameters matrix**: design of experiments (DOE) "Central composite design" plan
- **Number of simulations**: 27
- **Output**: force-displacement diagrams for phases I and II

	Min	Median	Max
SLIMT	0.010	0.045	0.100
SLIMC	0.100	0.450	1.000
YCFAC	2.000	4.360	6.720

Results: Phase I (All Simulations)



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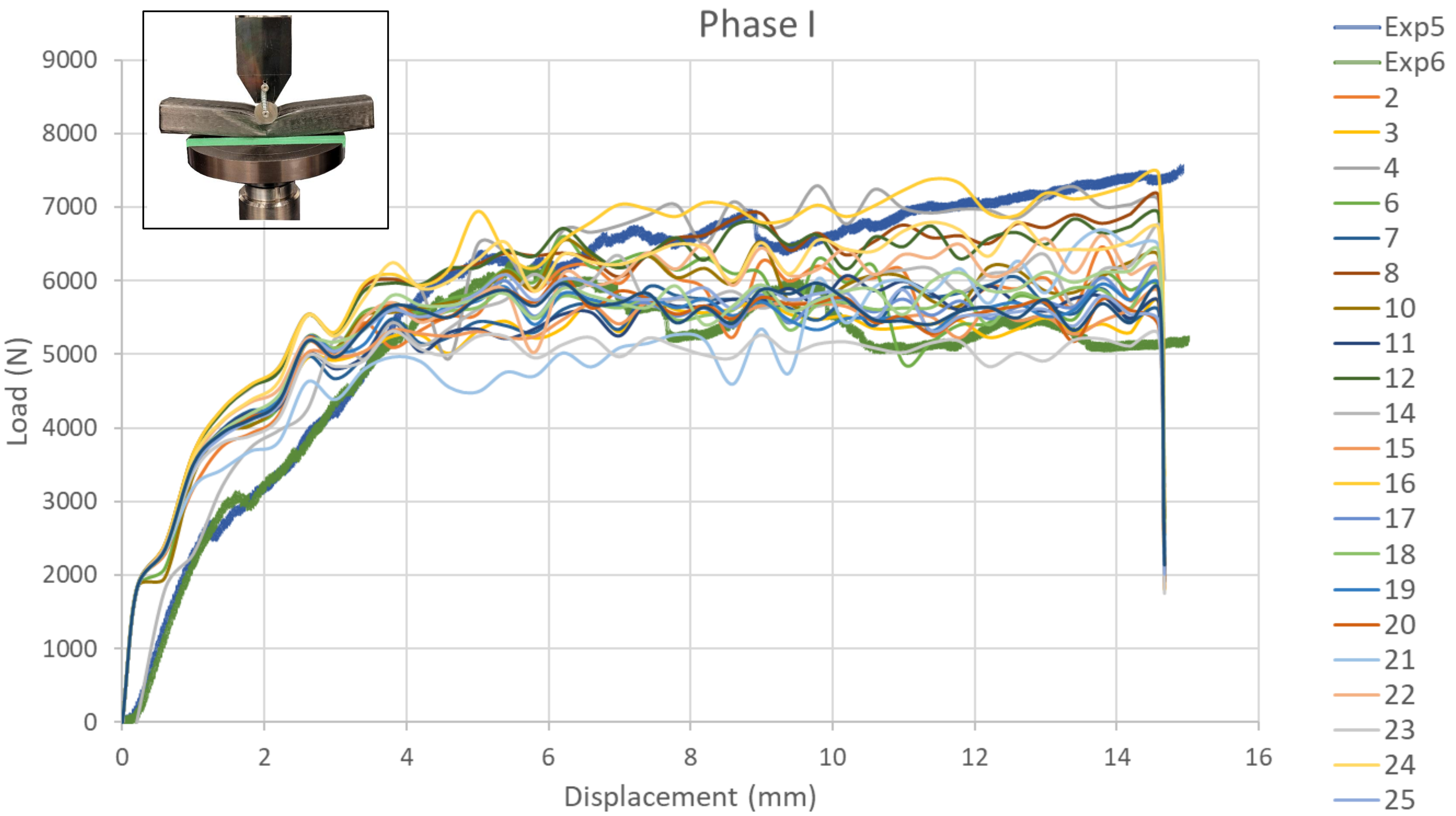
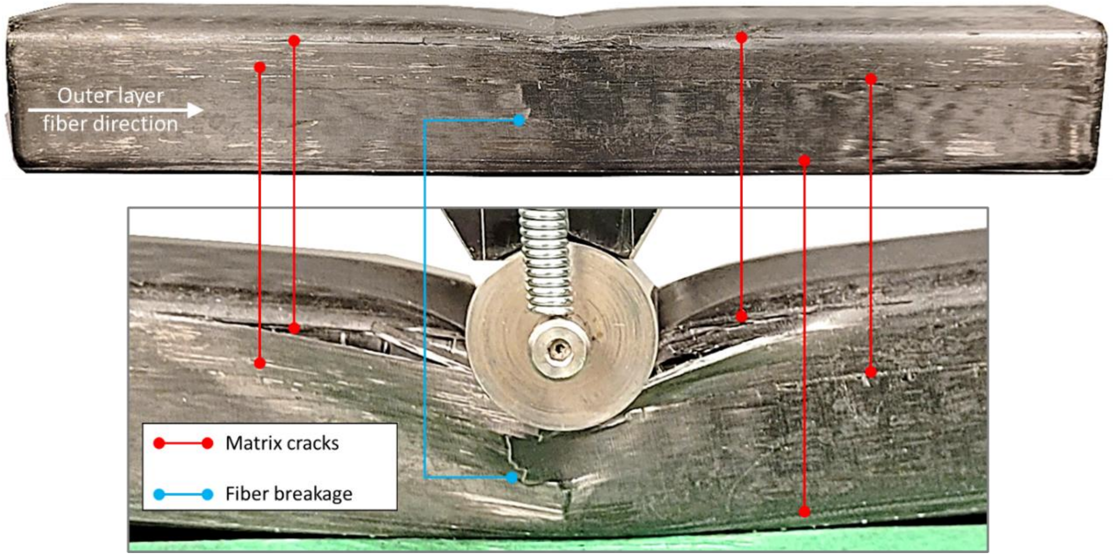
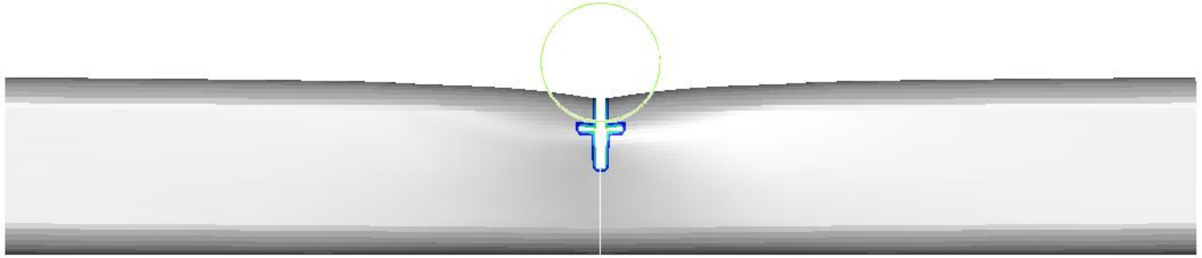
Results: Phase I (Outliers Removed)



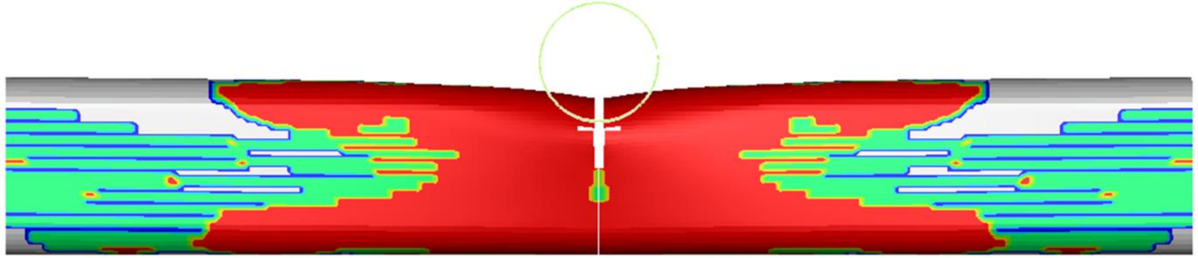
Results: Phase I – Outer Layer (“Visual”) Damage



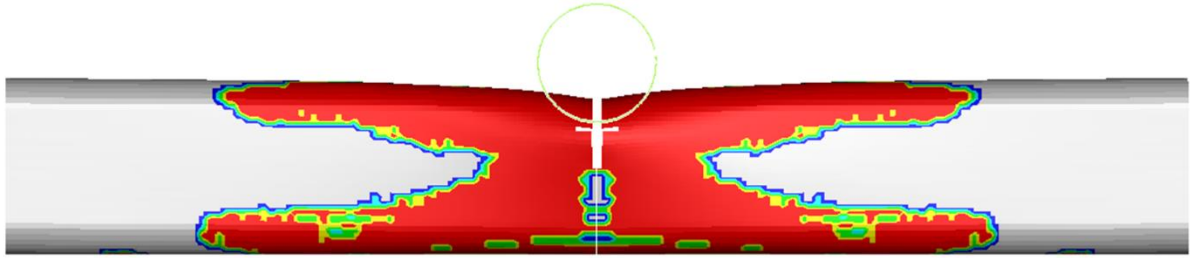
Visual damage — experiment



Longitudinal (fiber) tensile & compressive failure (MAT54 HV1&2)

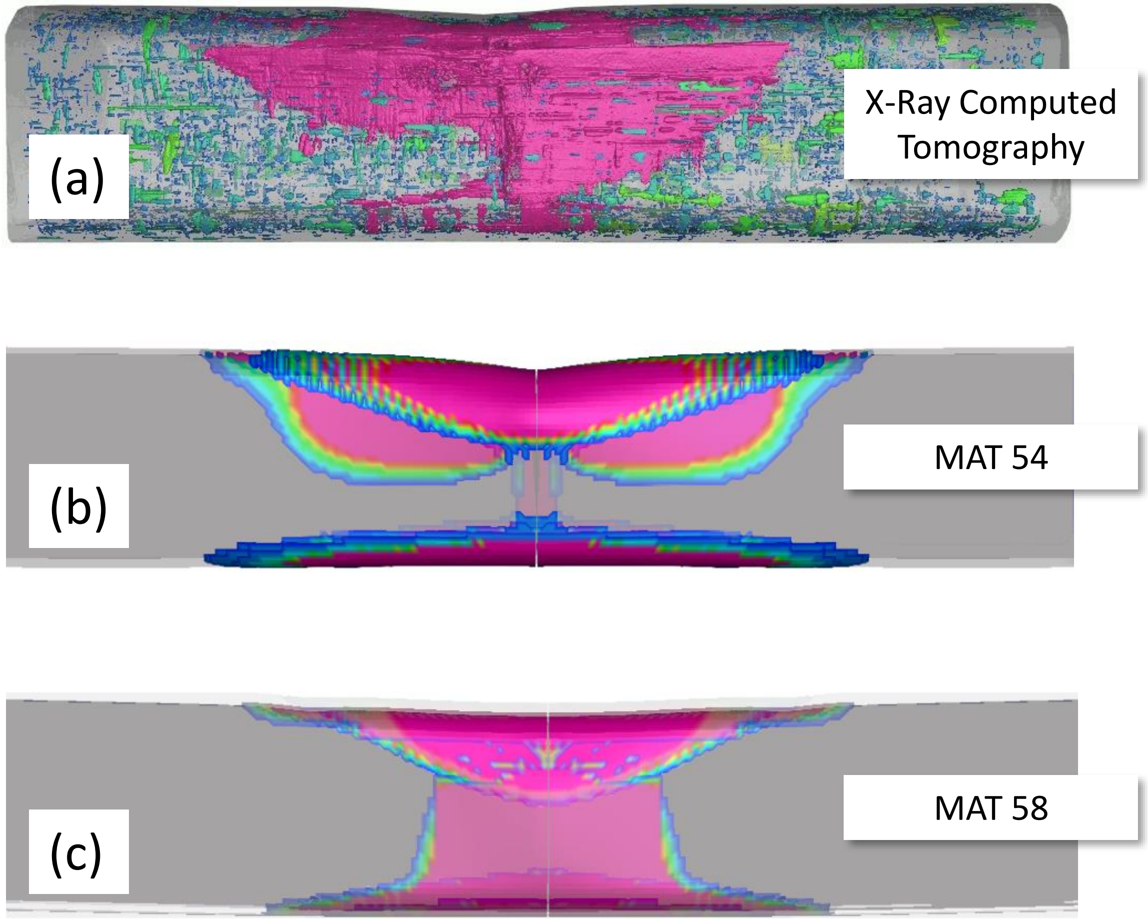


Transverse (matrix) tensile failure (MAT54 HV3)



Transverse (matrix) compressive failure (MAT54 HV4)

Results: Phase I – Interlaminar Damage (Delamination)

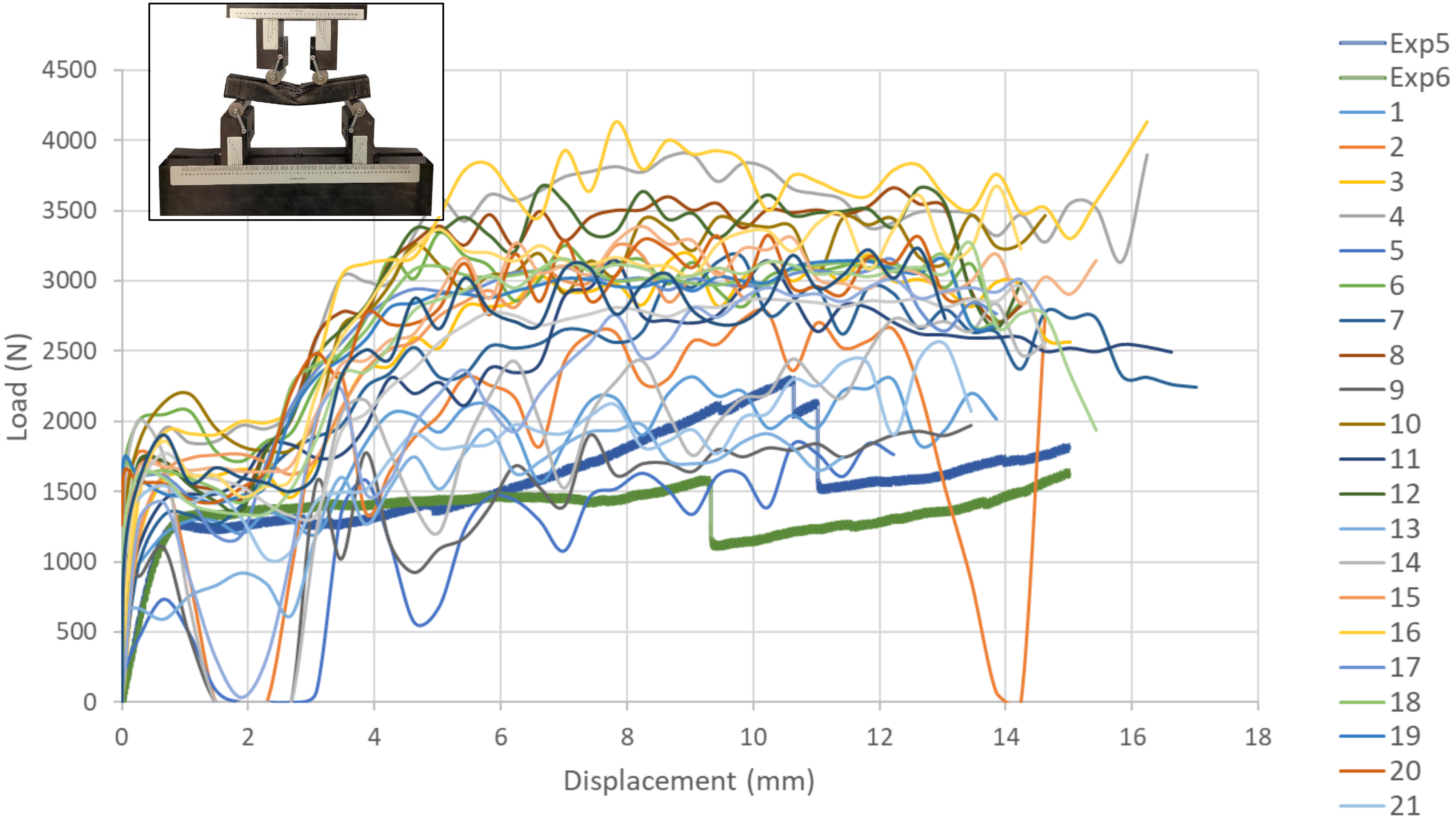


- X-ray computed tomography was processed using the **Porosity Analysis** module of myVGL software to visualize the region of the tube affected by delamination. The “Equivalent diameter” feature of the module was used, which indicates the diameter of a sphere that has the same volume as the detected defect in the material.

- In modeling, delamination was visualized as **contact gap** between stacked TSHELL elements connected using *CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK (OPTION 9). In total there are 13 ply interfaces in each model on which delamination (contact gap) can be displayed. To make the modeling results comparable with the X-ray output, the contact gap images from ply interfaces were **made half-transparent and placed on top of each other**.

Delamination area: 26.6% of image (a), 26.9% of (b), and 25.8% of (c)

Results: Phase II (All Simulations)



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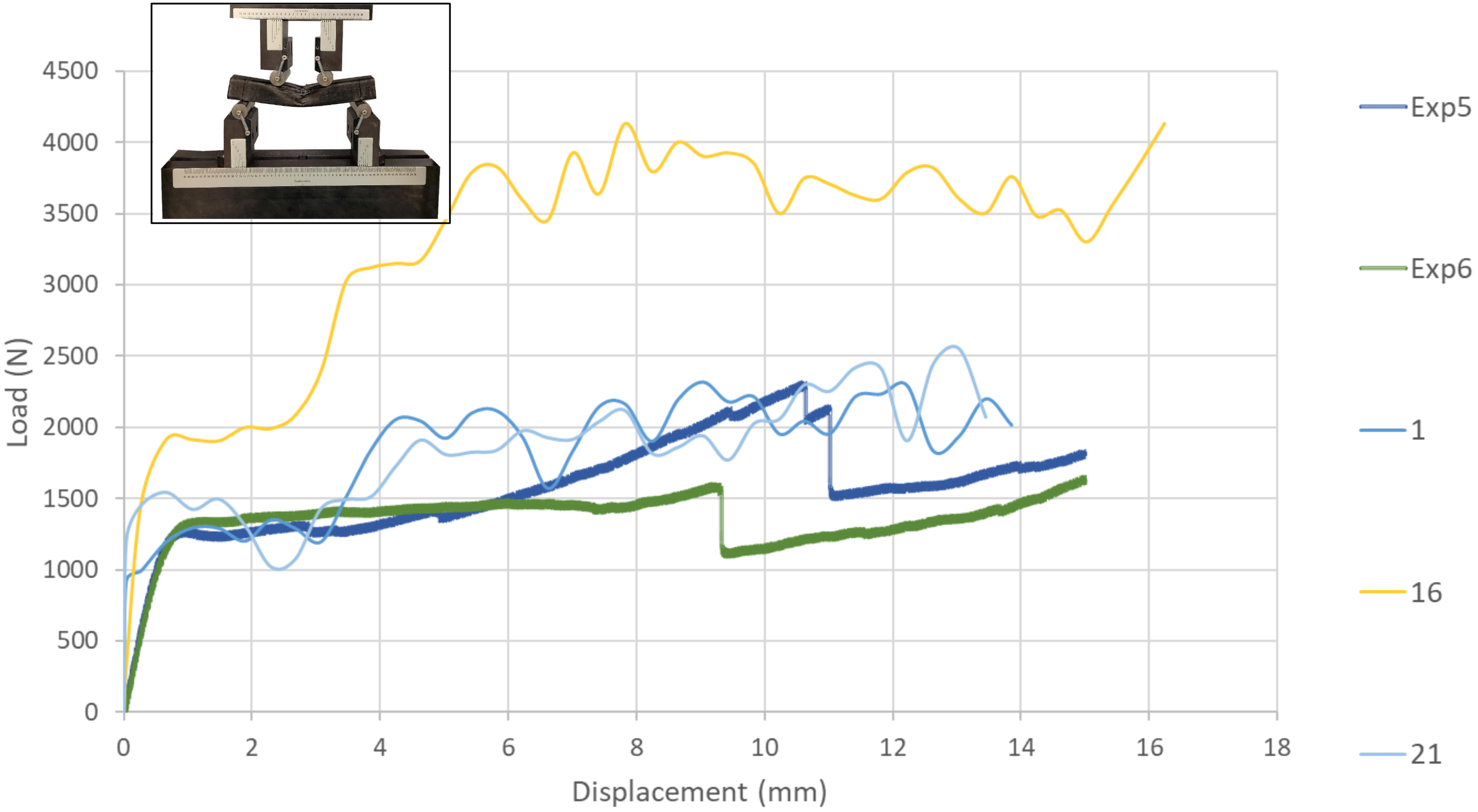
Results: Phase II (All Simulations)



	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
1	0.010	0.010	0.10	0.10	6.72
21	0.045	0.045	0.10	**0.45**	4.36

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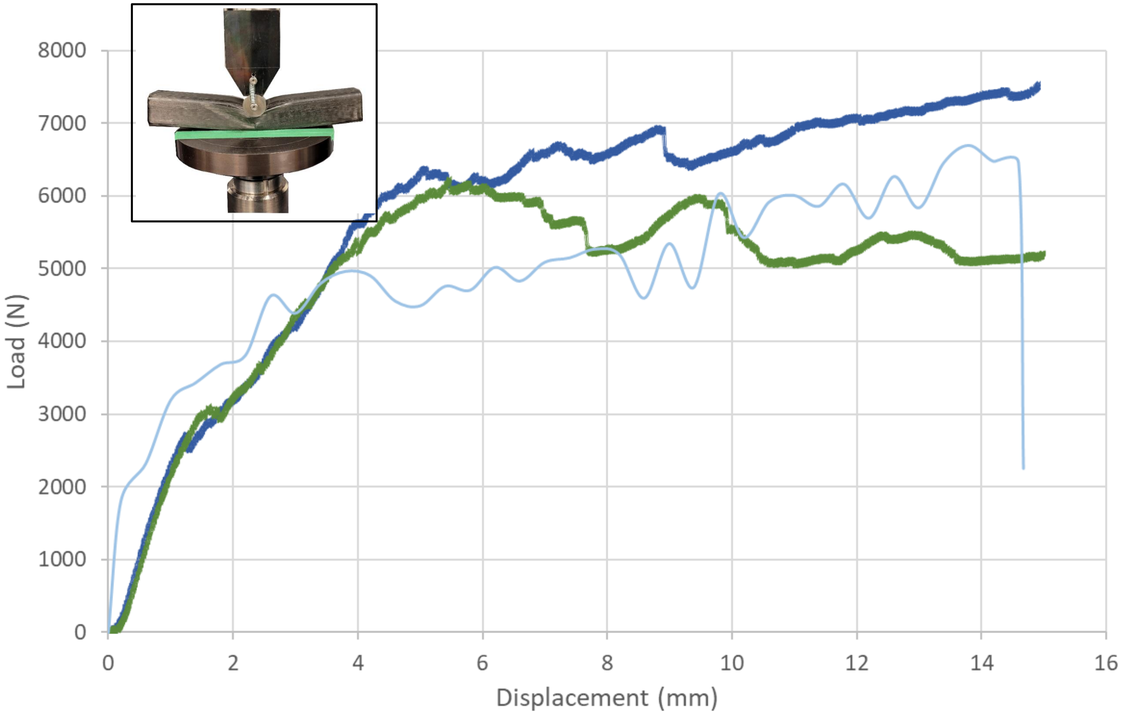
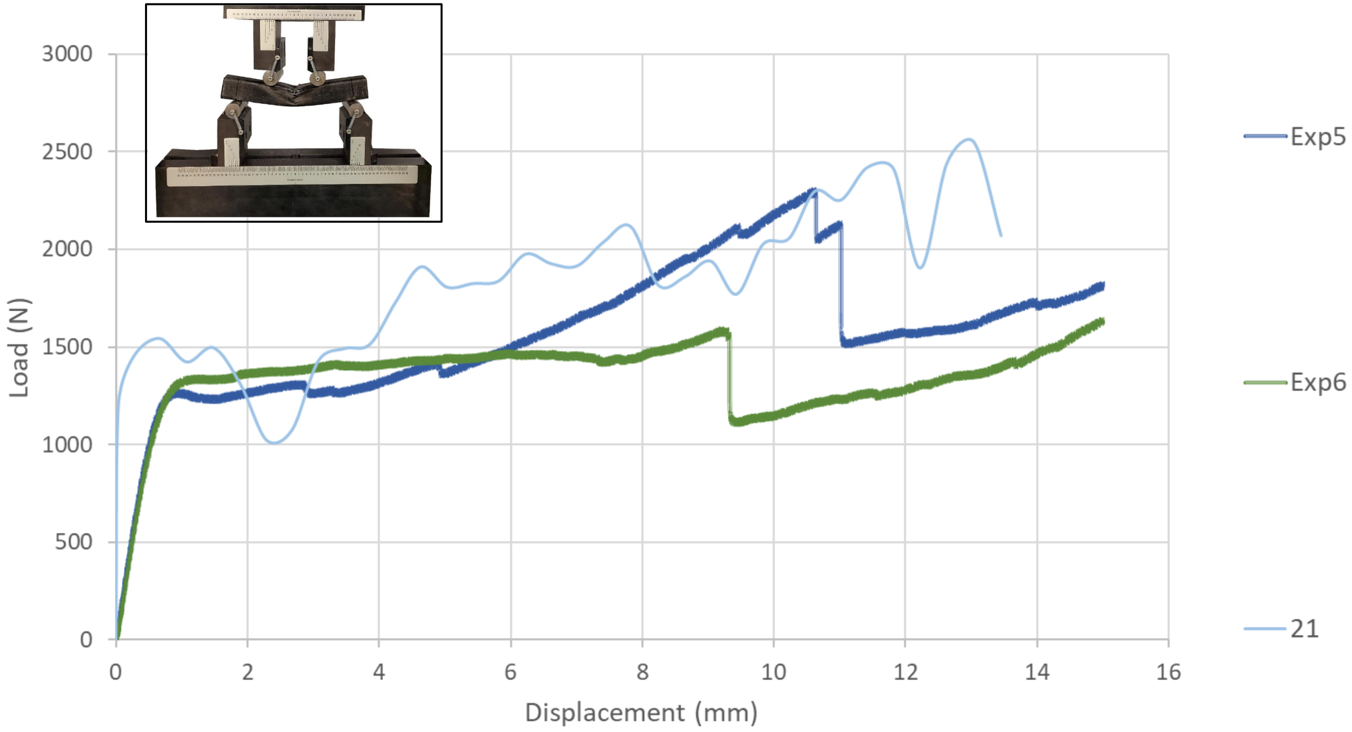
Results: Phase I & Phase II (case #21)

PHASE I

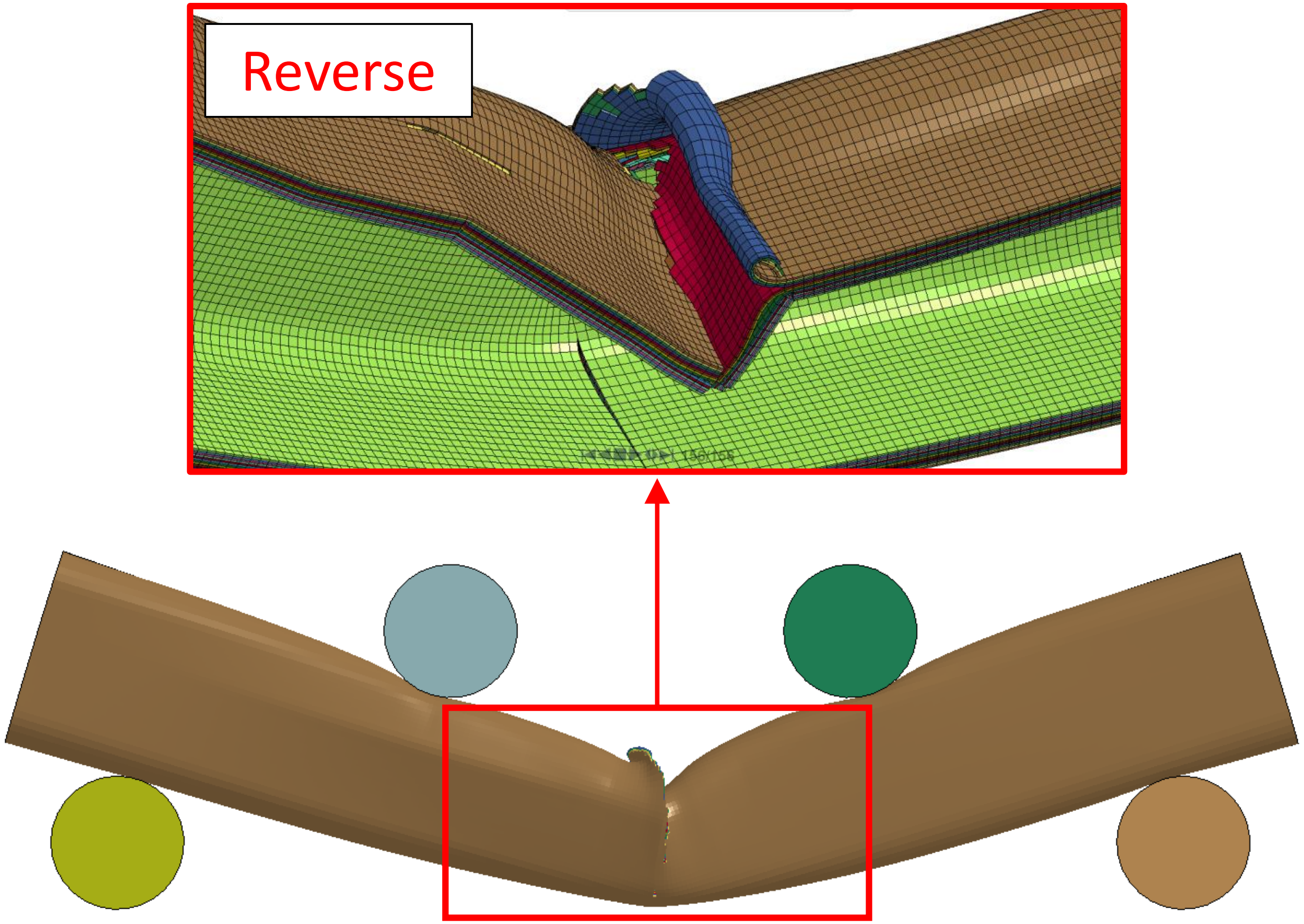


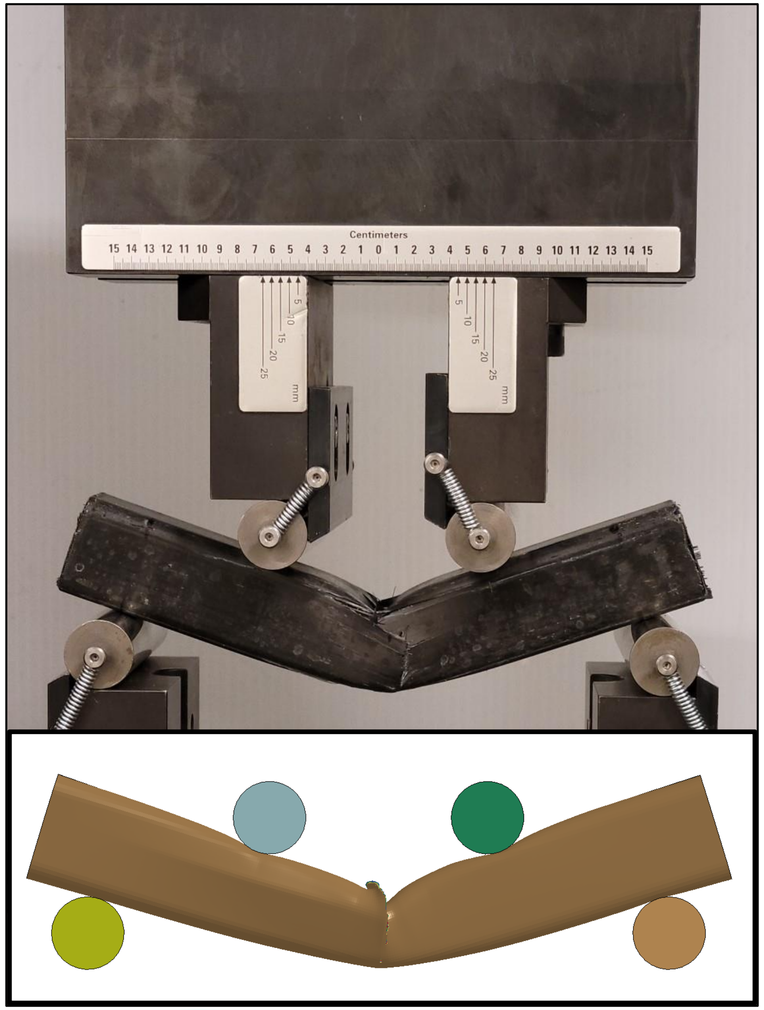
PHASE II



	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
21	0.045	0.045	0.10	0.45	4.36

Results: Phase II (case #21)

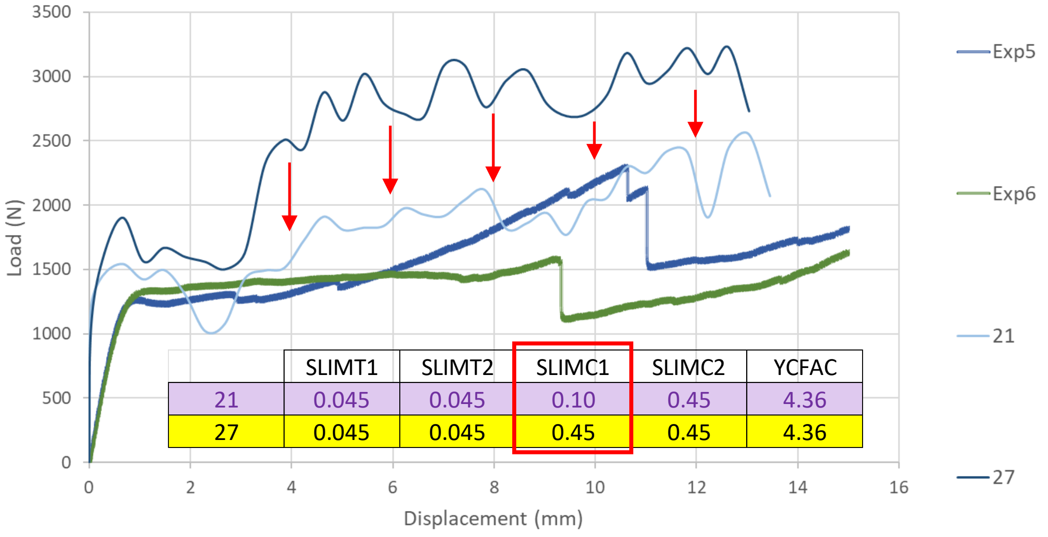




	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
21	0.045	0.045	0.10	0.45	4.36

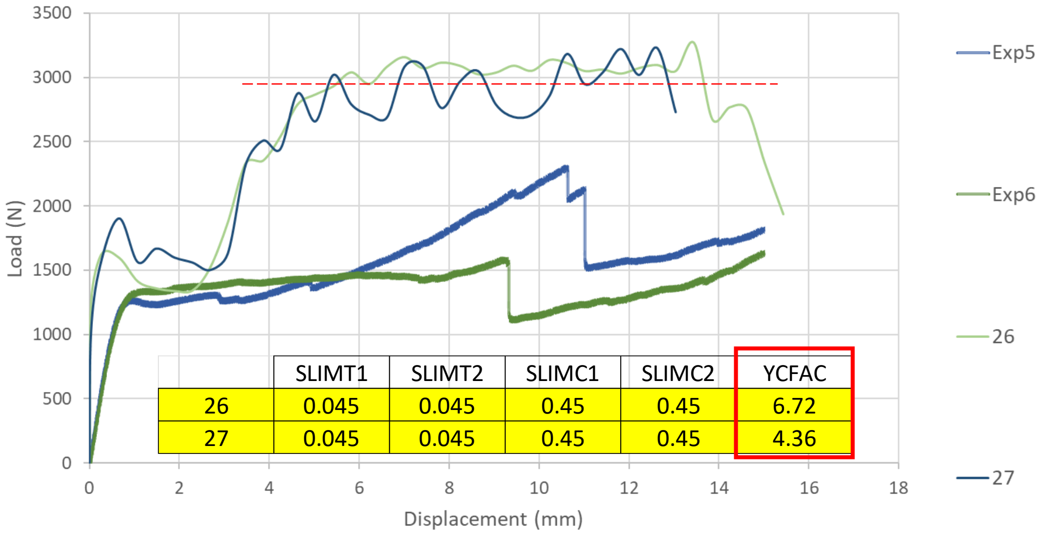
Results: Sensitivity Analysis

Effect of SLIMC1



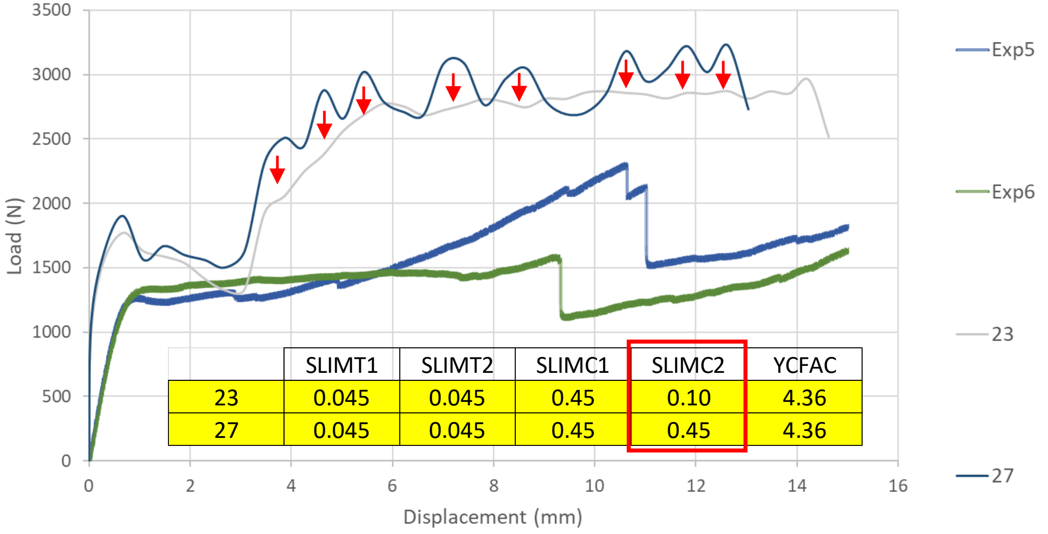
	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
21	0.045	0.045	0.10	0.45	4.36
27	0.045	0.045	0.45	0.45	4.36

Effect of YCFAC



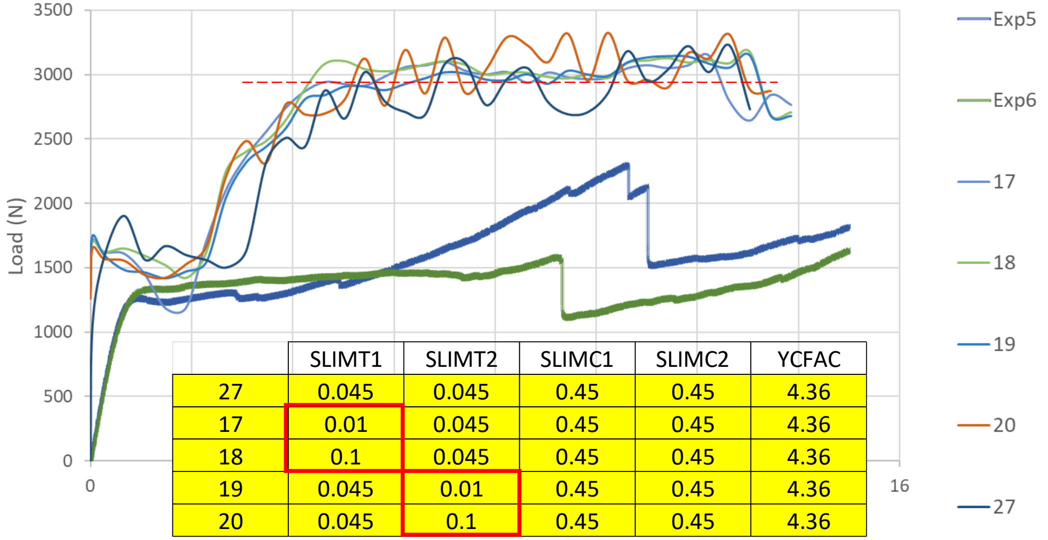
	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
26	0.045	0.045	0.45	0.45	6.72
27	0.045	0.045	0.45	0.45	4.36

Effect of SLIMC2



	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
23	0.045	0.045	0.45	0.10	4.36
27	0.045	0.045	0.45	0.45	4.36

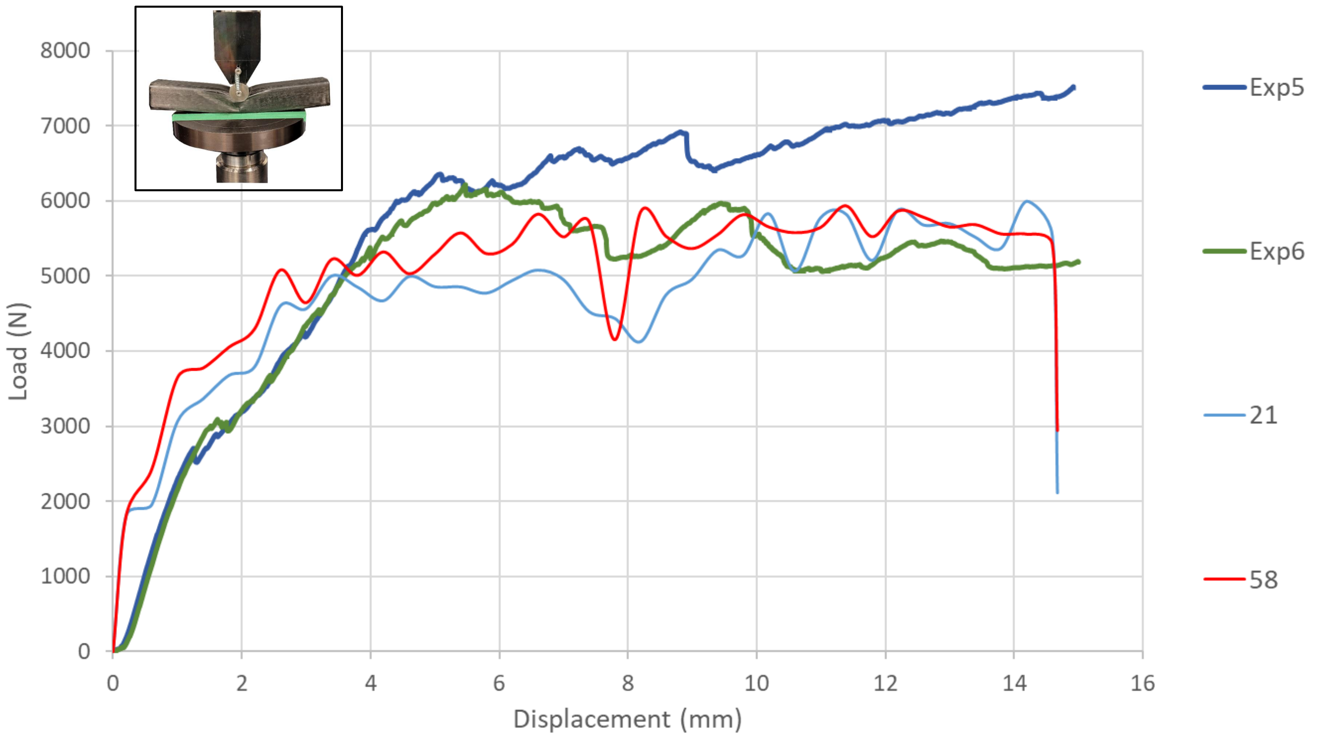
Effect of SLIMTx



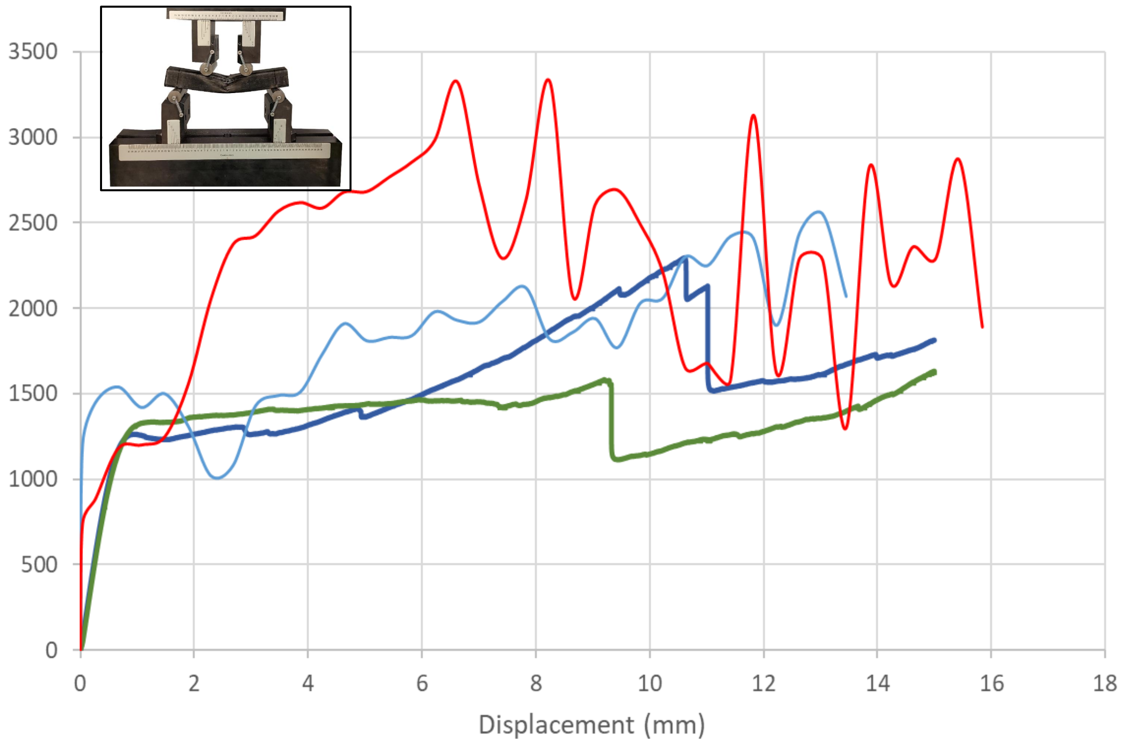
	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
27	0.045	0.045	0.45	0.45	4.36
17	0.01	0.045	0.45	0.45	4.36
18	0.1	0.045	0.45	0.45	4.36
19	0.045	0.01	0.45	0.45	4.36
20	0.045	0.1	0.45	0.45	4.36

Results: MAT54 vs. MAT58

PHASE I



PHASE II



	SLIMT1	SLIMT2	SLIMC1	SLIMC2	YCFAC
21	0.045	0.045	0.10	0.45	4.36
58	0.045	0.045	0.1	0.45	N/A

Conclusions and Future Work:

- It is possible to achieve good predictions of residual load-carrying capacity of damaged NCF parts using MAT54 constitutive model (MAT58 – to be studied), however identification of the non-physical parameters (SLIM, YCFAC) is required.
- For compression-dominated loading, SLIMC1 appears to be a parameter influencing the most the predictions of the residual load-carrying capacity.
- Future work will include
  (a) building the response surface using generated DOE matrix and searching for the "optimal" values of non-physical parameters;
  (b) verification for different layup(s) and loading conditions (damaged zone in tension);
  (c) extending this study to MAT58.