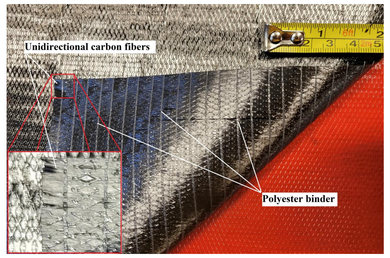
Modeling of Damage and Residual Load-Bearing Capacity of Non-Crimp Fabric Composites

M. Kazemian, Ph.D. Candidate
A. Cherniaev, Ph.D. P.Eng., Assoc. Prof.
Department of Mechanical, Automotive and Materials Engineering, University of Windsor, Ontario, Canada

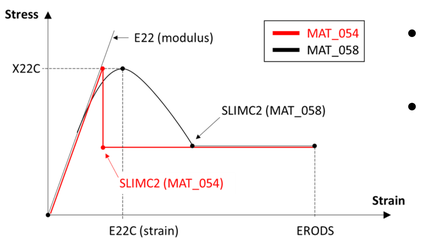
University of Windsor

Background

Material: Unidirectional Non-Crimp Carbon Fabrics (NCF).
Advantage: combination of high mechanical properties and excellent manufacturability.
Applications: load-bearing aerospace structures, automotive parts, and wind energy components.



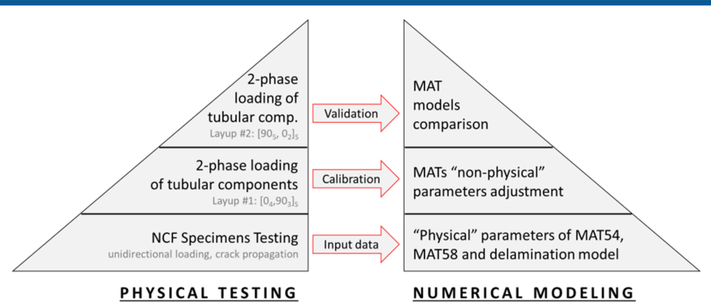
Structure: multiple straight and parallel yarn bands joined by polyester stitching (binder).
Problem: in-service damage can be a cause for severe reduction in load-carrying capacity of NCF composites.
Numerical modeling can provide cost-efficient solution for accessing damage and post-impact (residual) load-carrying capacity of NCF parts, as well as accelerated decision making.
Goal of this study: Evaluate the applicability of the commonly used composite material model available in LS-DYNA (MAT54) for predicting damage and residual load bearing capacity in structural elements made of NCF.



MAT54:

- strength criterion-based model.
- multiple non-physical parameters governing post-failure behavior of the material.

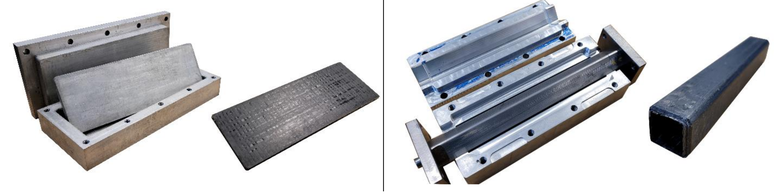
Methodology



Manufacturing

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

Flat panels | Tubular components



Manufacturing: PLC oven at 132 °C (4 °C/min ramp rate, holding for 4 hours). Pressure: mold closing screws.

Experimental work

Material characterization

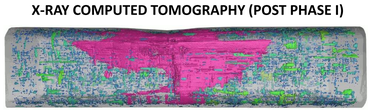
Property	Units	Value	Method
Longitudinal Young's modulus, E_1	MPa	149018	ASTM D 3039
Transverse Young's modulus, E_2	MPa	6071	
Major in-plane Poisson's ratio, ν_{12}	-	0.32	
In-plane shear modulus, G_{12}	MPa	4217	10° off-axis
Longitudinal tensile strength, X_t	MPa	2060	ASTM D 3039
Longitudinal compressive strength*, X_c	MPa	814	Modified ASTM D695
Transverse tensile strength, Y_t	MPa	29.1	ASTM D 3039
alcTransverse compressive strength*, Y_c	MPa	121	Modified ASTM D695
In-plane shear strength, S_L	MPa	44.5	10° off-axis
Longitudinal tensile strain-at-failure, ε_{1f}	%	1.37	ASTM D 3039
Transverse tensile strain-at-failure, ε_{2f}	%	0.40	ASTM D 3039
In-plane shear strain-at-failure, γ_{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

Component testing

Damaging the specimen using a cylindrical indenter

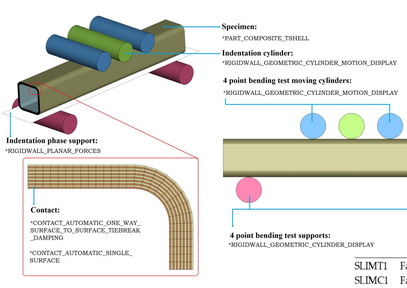
Measuring the residual load-bearing capacity using 4-point bending test

X-RAY COMPUTED TOMOGRAPHY (POST PHASE I)

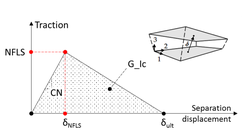


Numerical model

LS-DYNA MODEL FOR PHASE I & PHASE II LOADING



DELAMINATION MODEL (OPTION 9 TIEBREAK)



Property	Unit	Value
NFLS	MPa	75.00
SFLS	MPa	43.30
G_Ic	kJ/m^2	0.66
G_IIc	kJ/m^2	2.77
CN	MPa/mm	200,000
CT2CN	-	0.37

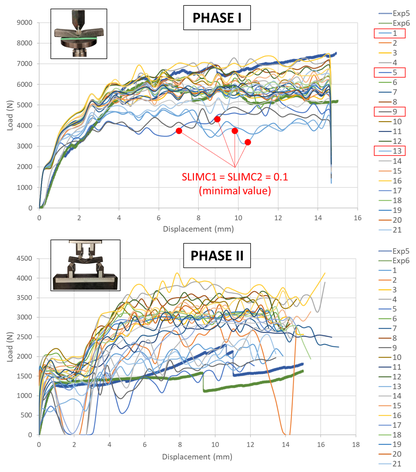
NON-PHYSICAL PARAMETERS OF MAT54

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

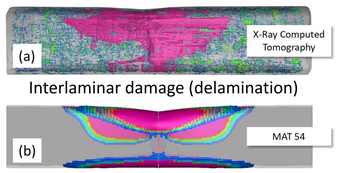
Results

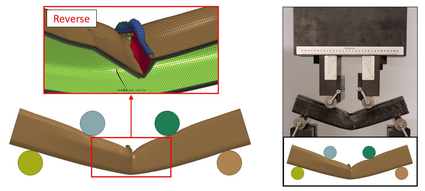
Multiple non-physical parameters combinations were studied

	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



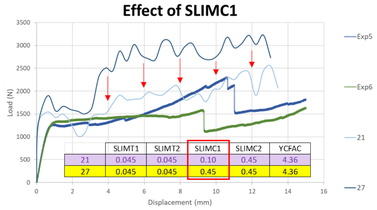
- Phase I: only few outliers
- Phase II: only few accurate predictions (e.g., case 21 below)





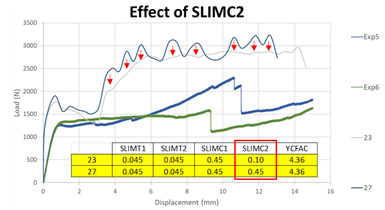
Sensitivity study evaluated the effect of individual non-physical parameters of MAT54 on Phase II modeling results:

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 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

Conclusions

- Reasonably accurate predictions of load-bearing capacity of damaged NCF parts can be achieved using MAT54 but require identification of its non-physical parameters.
- For compression-dominated loading, SLIMC1 appears to be the most influencing non-physical parameter.