MANUFACTURING, MODELING, AND CHARACTERIZING THERMOPLASTIC COMPOSITES FOR MILITARY VEHICLE APPLICATIONS

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Why Structural Thermoplastics?

- Defense and automotive industries seek lightweight material solutions.
  - Increases in mobility and fuel economy [1]
  - Frees design weight for additional up-kitting
- Thermoplastic composites have many benefits:
  - Low material density
  - High specific stiffness and strength
  - High energy absorption

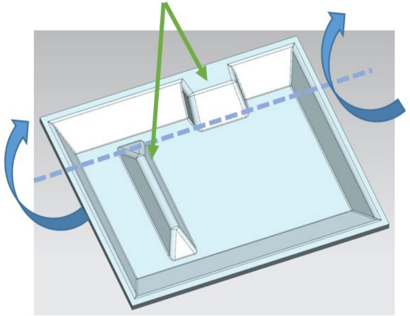
[1] R. J. Hart and R. J. Gerth. "The Influence of Ground Combat Vehicle Weight on Automotive Performance, Terrain Traversability, Combat Effectiveness, and Operational Energy," in Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), Novi, 2018.

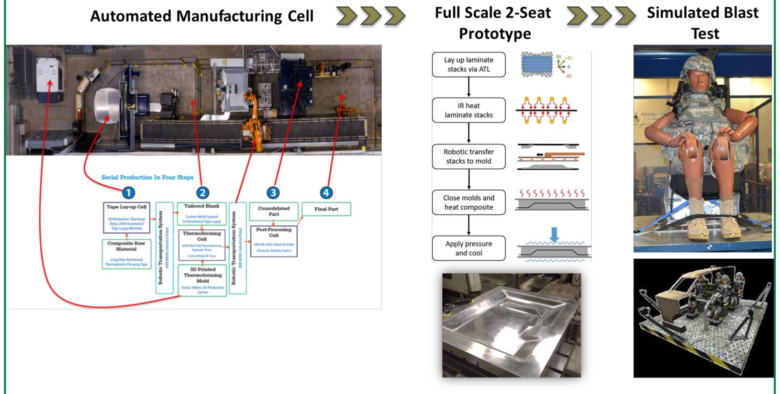
Examples of Thermoplastic Utilization

- Structural thermoplastic composites have been recently used to make a lightweight tactical cargo shell that was 35% lighter than aluminum [1].
- Combat vehicle crew floor was 56% lighter than a baseline aluminum design [2].

Finished 100% composite part 36% weight savings over original aluminum part.
53” long x 24” tall x 16” wide

Overlapping Geometric Stiffeners Reduce Bending Due To Natural Hinge Effect



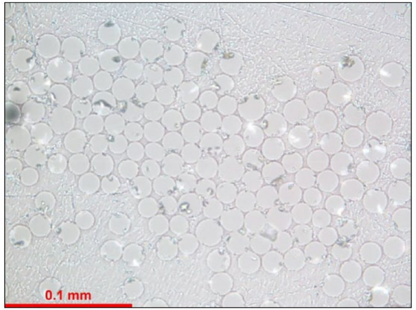


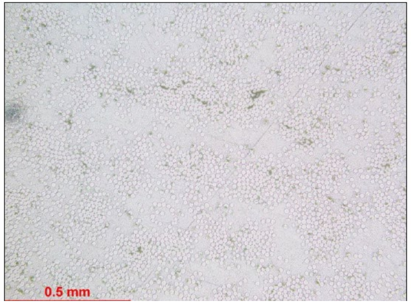
[1] D. Erb, B. Dwyer, J. Roy, W. Yori, R. Lopez-Anido, A. Q. Smail and R. J. Hart. "Utilizing Additive Manufacturing to Enable Low-Cost, Rapid Forming of High Temperature Lightweight Ground Vehicle Structures," in Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), Novi, 2021.

[2] R. J. Hart, B. Dwyer, A. Q. Smail, A. Chishti, D. Erb, and R. Lopez-Anido. "Lightweight Composite Crew Floor for Ground Combat," in Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), Novi, 2021.

Getting to That Point.....

- Thermoplastics can be extremely complex
  - Manufacturing specific properties!
    - Processing temperatures (heating and cooling)
      - Defines crystallinity within a material
    - Consolidation pressures
      - Has some influence on crystallinity
    - Dwell time
  - Manufacturing defects
    - Fiber wash
      - Resin/fiber-rich areas



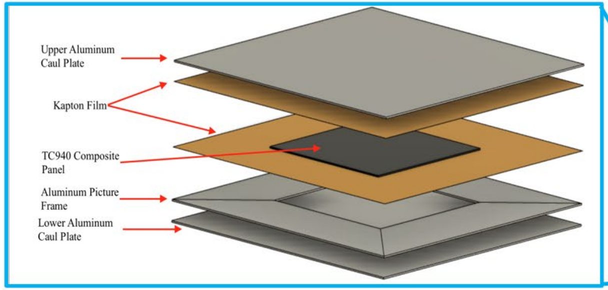


Methods for Designing Around These Issues
Case Study

- Manufacturing, Characterization, and Modeling of PET/GF
  - Good candidate for a manufactured, specific composite
    - PET can be semi-crystalline or amorphous
    - Unidirectional
  - Manufacturing
    - Hot press consolidation
  - Characterization
    - Tension, compression, shear, interlaminar
  - Modeling
    - LS-DYNA

Image courtesy of BASF

Manufacturing

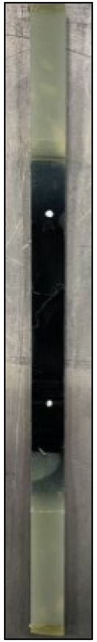


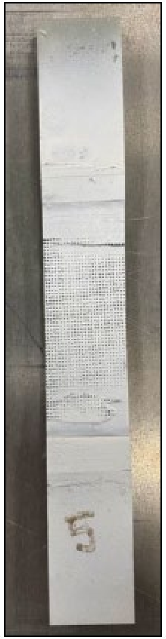
Manufacturing Schedule:

1. Preload at 35-ton force, (0.83 MPa),
2. Heat to 510 °F (maintain 35-ton force),
3. Dwell at 510 °F for 15 min (maintain 35-ton force), and
4. Cool to 70 °F at a rate of 59 °F/min (maintain 35-ton force until room temperature).

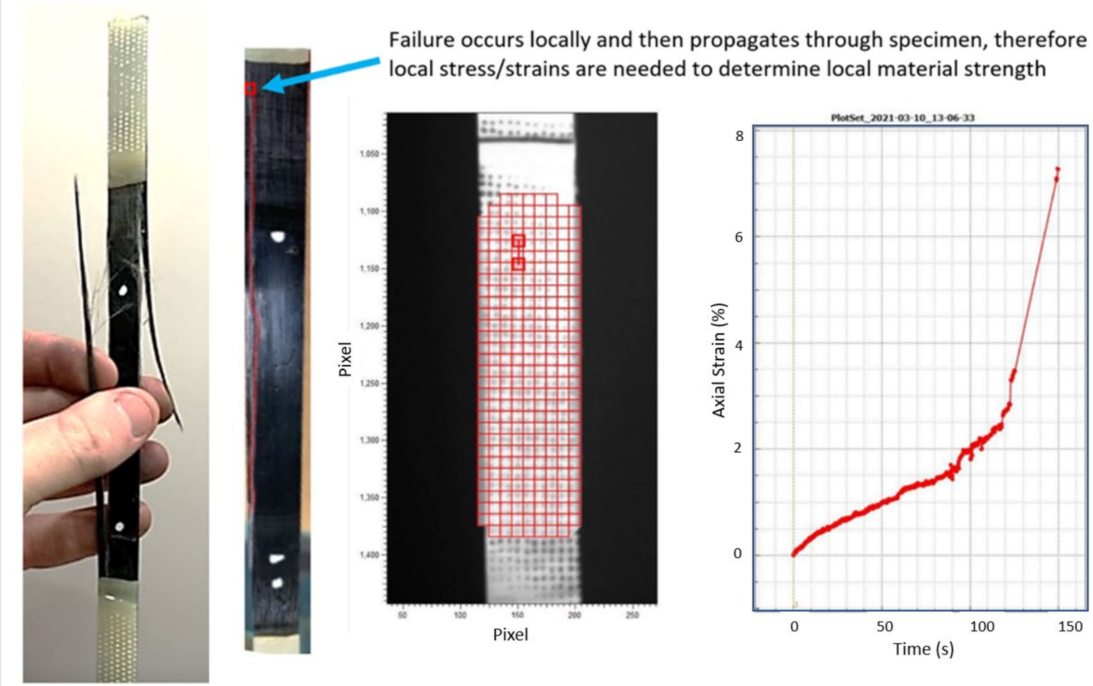
Characterization Difficulties

- Tension
  - Premature failure
    - DIC Implementation to obtain local failure strains to calculate stress
    - Tab design (angle of tabs, tab material, adhesive, adhesive thickness, etc.)
- Compression
  - Pristine axisymmetric specimens
    - Cylindrically lathed specimens



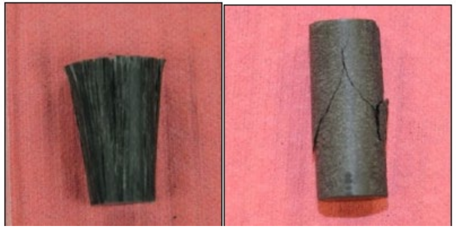


Characterization Difficulties



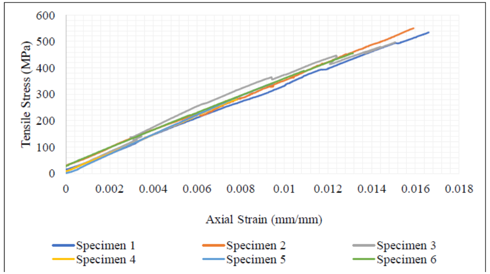
<u>Tension</u>: Fiber drift carries fibers off axis, causing premature failure.

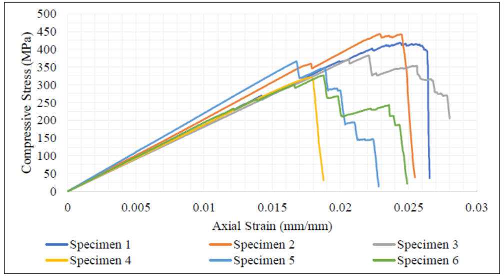
<u>Compression</u>: Flatness and parallelism of top and bottom surfaces are critical so that specimen does not crush before catastrophic failure occurs.

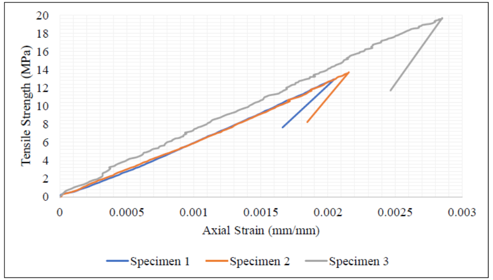


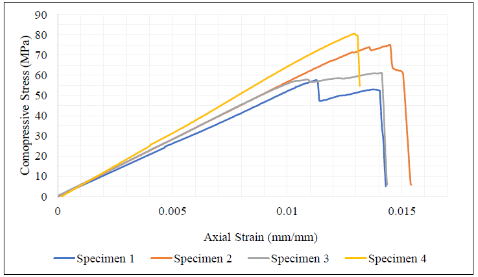
Characterization Results

Property	Manufacturer*	Exp.	Diff.
T-90 Mod	7.05GPa	6.53GPa	7.4%
T-0 Mod	32GPa	35.3GPa	10.3%
$S_{12/13}$ Mod	2.82GPa	2.32Gpa	17.7%
S_{23} Mod	2.58GPa	2.12GPa	17.8%
T-0 Strength	960MPa	960MPa**	N/A
T-90 Strength	68.4MPa	15.4MPa	77.5%
C-90 Strength	54.2MPa	68.2MPa	25.8%
C-0 Strength	329MPa	378MPa	14.9%









*Most manufacturer-supplied properties were based on theory and not validated experimentally.
**DIC

Model Implementation

- MAT_054 Damage Model
  - Ability to capture wide variety of failure aspects
    - Fiber-buckling or fracture
      - Chang-Chang Failure Criterion
    - Matrix-crushing or fracture
      - Chang-Chang Failure Criterion
    - Delamination
      - Utilizing obtained normal and shear characterization data

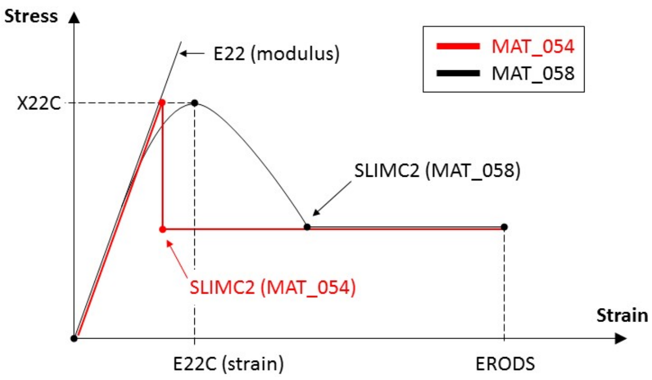


Image courtesy of Livermore Software Technology Corporation

$$\left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 > 1$$

Model Implementation

- MAT_054 Damage Model
  - Complete material card for structural & dynamic failure analysis

MID	RO	EA*	EB*	(EC)	PRBA	PRCA	PRCB
	0.00189	3.53e4	6530	6530	0.0185		.5
GAB*	GBC	GCA	(KF)	AOPT	2WAY	TI	
2320	2122	2320					
XP	YP	ZP	A1	A2	A3	MANGLE	
						0.0	
V1	V2	V3	D1	D2	D3	DFAILM	DFAILS
					0	0	0
TFAIL	ALPH	SOFT	FBRT	YCFAC	DFAILT	DFAILC	EFS
1e-7	0	.57	0	2	0	0	.55
XC**	XT**	YC**	YT**	SC**	CRIT	BETA	
378	960	68.2	15.4	70	54.0	0	

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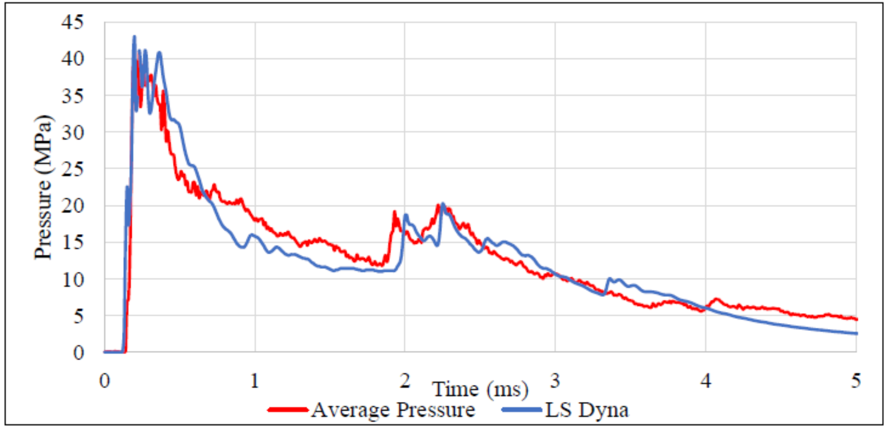
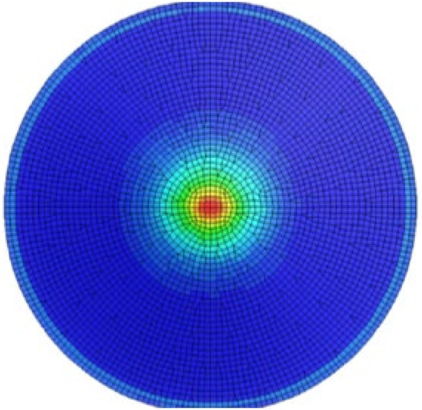
MAT054 Parameter	Description	Notes
EA*	Young's Modulus - longitudinal direction	Determined from 0^0 tensile test
EB*	Young's Modulus - transverse direction	Determined from 90^0 tensile test
PRBA	Poisson's Ratio ba	Determined from 0^0 tensile test
GAB*	Shear Modulus ab	Determined from in-plane shear test
EFS	Effective Failure Strain	Includes Elastic and Plastic Strain
XC**	Longitudinal Compressive Strength	Determined from 0^0 compression test
XT**	Longitudinal Tensile Strength	Determined from 0^0 tensile test
YC**	Transverse Compressive Strength	Determined from 90^0 compression test
YT**	Transverse Tensile Strength	Determined from 90^0 tensile test
SC**	Shear strength (in-plane)	Determined from in-plane shear test

These properties have been identified as critical structural properties that must be obtained through materials testing to produce realistic material response.

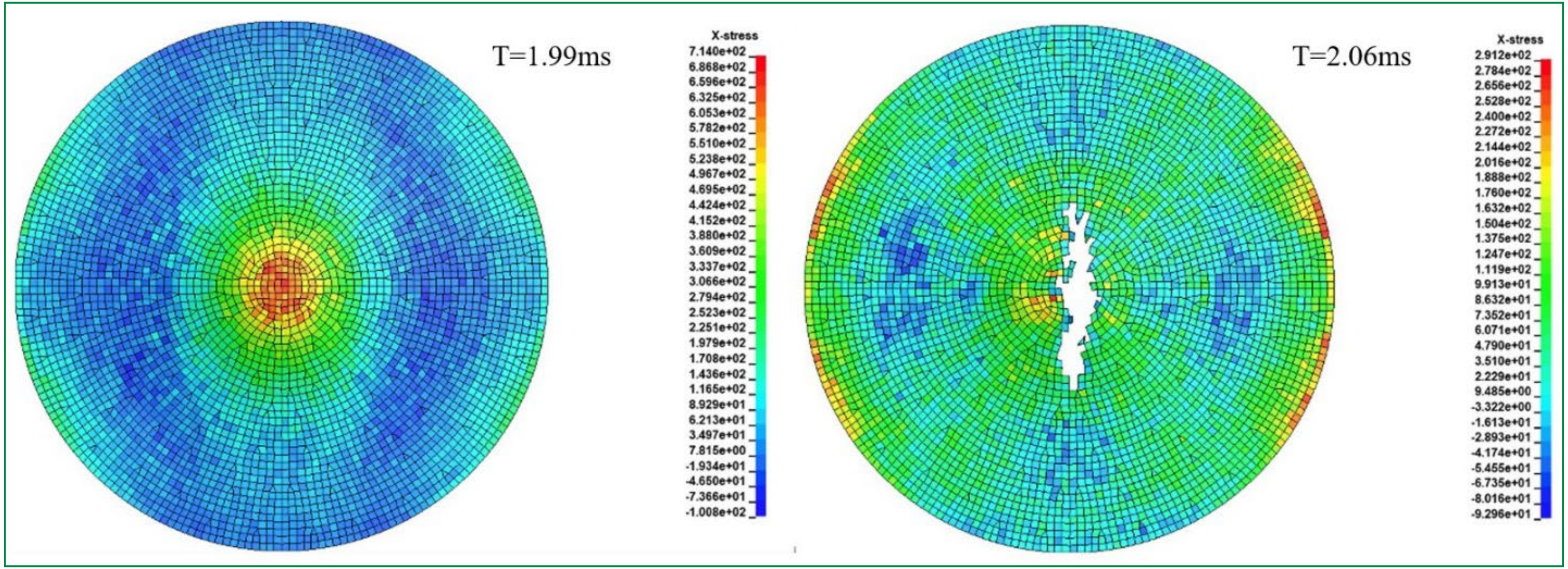
Case Study: Application of Ideal Blast Wave

- Applied the material characterization results/LS-DYNA material card to simulate response to an ideal blast wave





Model Results: Case Study



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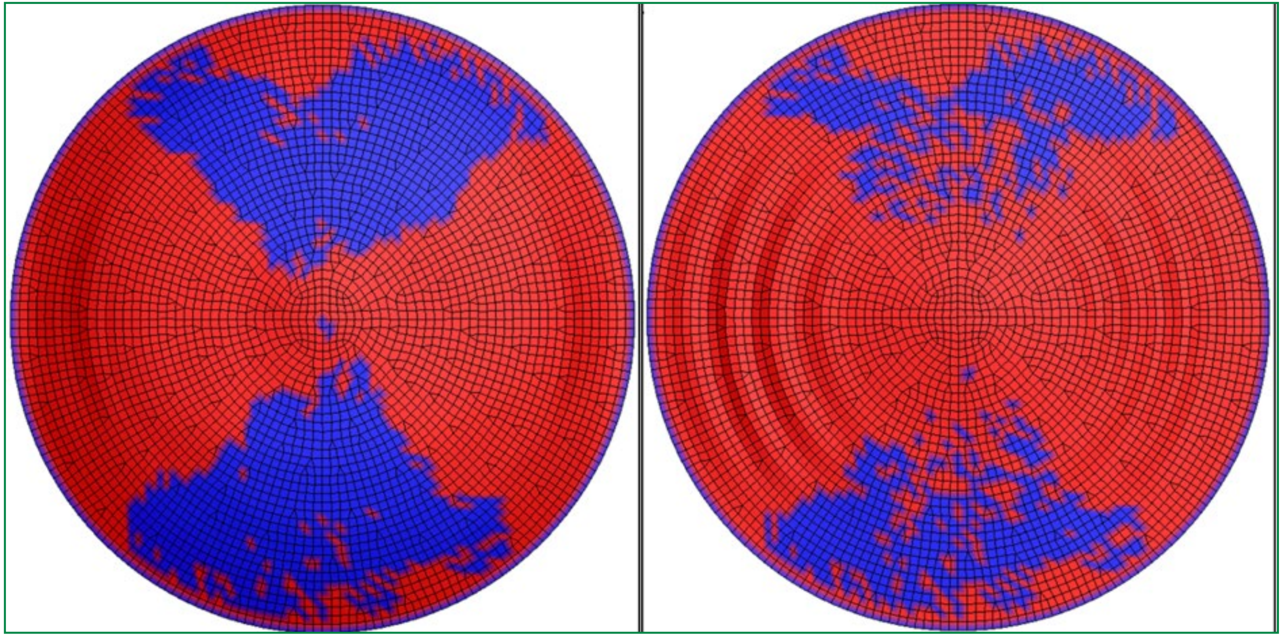
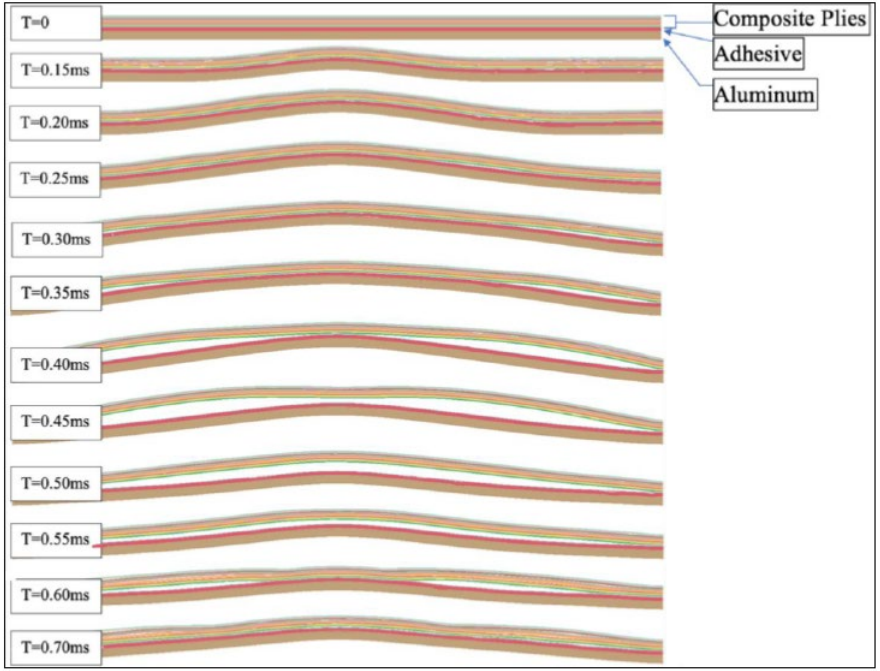


(red indicates delamination - blue indicates tied nodal constraint)

Model Results: Case Study



Conclusions

- Thermoplastics demand manufacturing specific characterizations.
  - Captures resin/fiber-rich areas
  - Reflects crystallinity within material
  - Fiber drift
- Accurate experimental characterization of material properties AND failure modes is critical to accurately model dynamic and failure response.