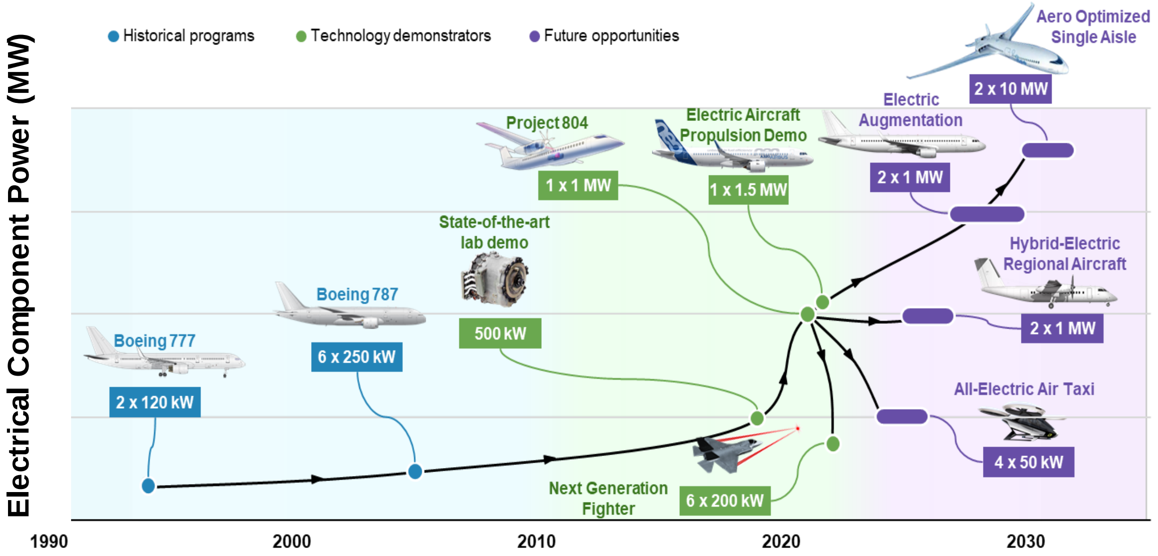
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 50, October 2021.
Invited presentation M3Or1B-03 given at CEC-ICMC 2021, July 19-23, 2021, Virtual.

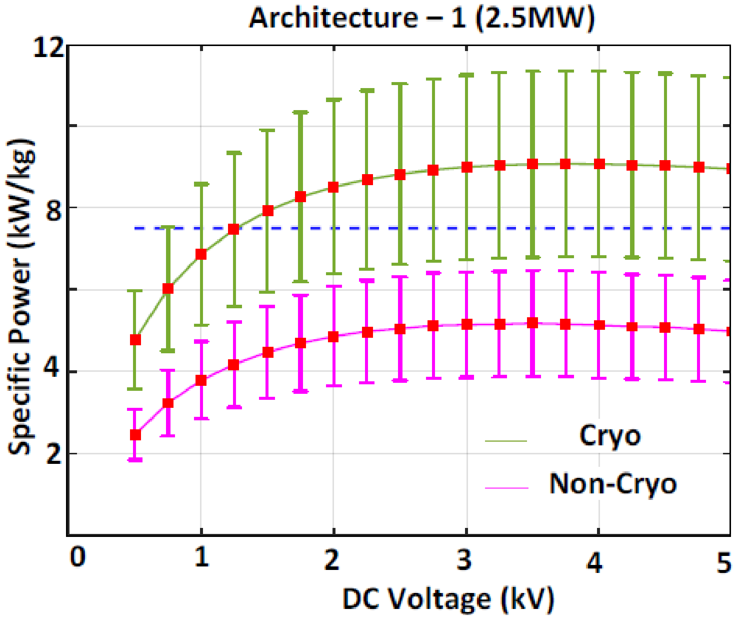
Polymer Matrix Composites for Light-weighting of Cryogenic Electric Propulsion System

Sreenivas Voleti and Parag Kshirsagar
Raytheon Technologies Research Center

Electrification of Propulsion: Cryogenic system

Aerospace Electrification Trends





“Anatomy of a 20 MW Electrified Aircraft: Metrics and Technology Drivers”, AIAA Propulsion, 2020; Kshirsagar et. al.

Challenge:

- Orders of magnitude improvements required in distribution system & component performance
- 3X to 4X improvement in power density required over current State-of-the-Art.
- Superconducting (cryogenic) propulsion system can provide such scale-up in power

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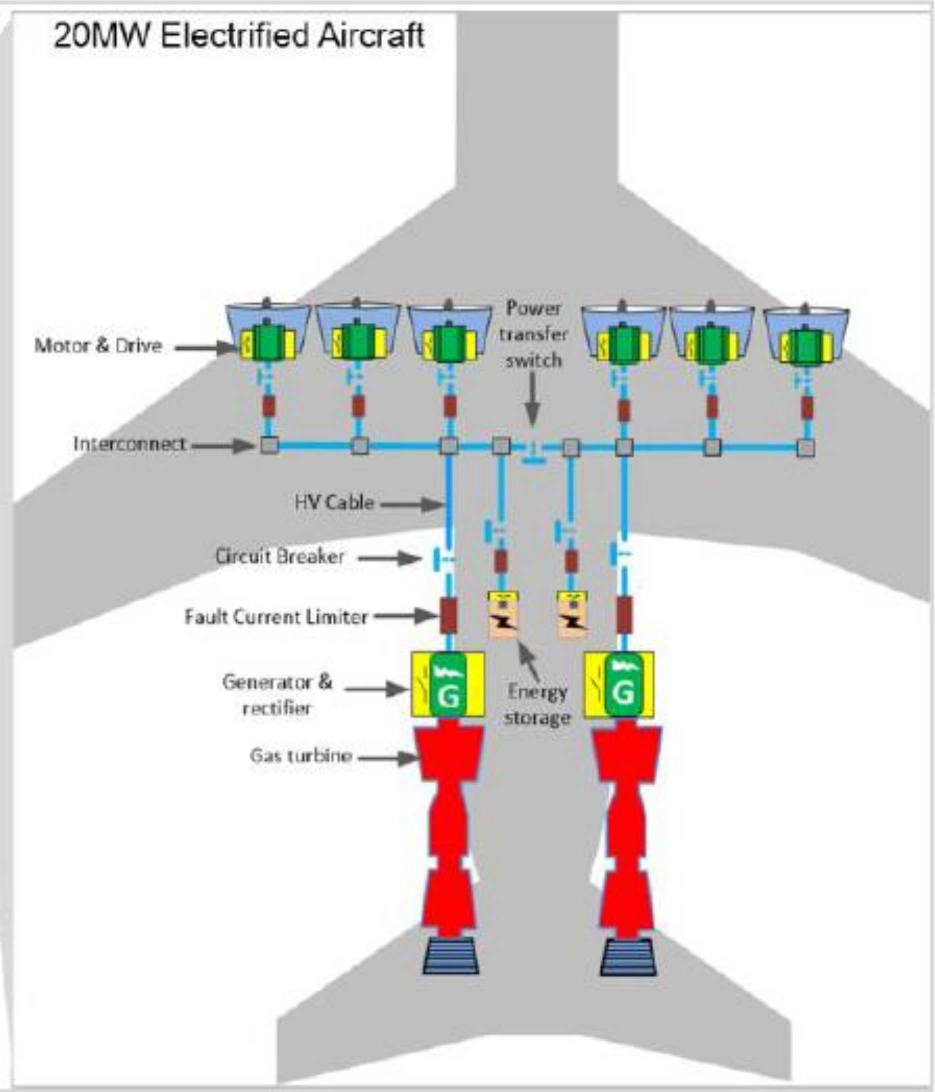
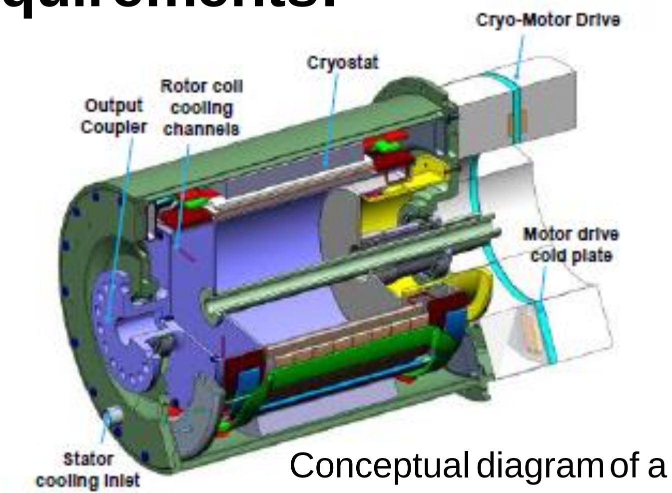
Electric Propulsion Architecture

- 20 MW superconducting propulsion system
- Distributed propulsion with a multi-MW motor
- Turbine driving a generator to produce electricity
- Cryogenic Fuel
- Fully super-conducting including generator, motors, cables (cryostats), fault current limiters, circuit breakers
- Superconducting coils: $MgB_{2,}$ ReBCO

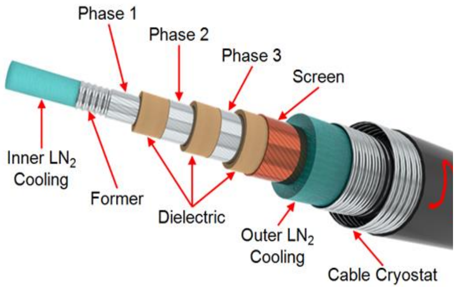


Critical Structural Components and their design requirements:

- Motor, Generator
    - Rotor: rotor case/outer wrap: centrifugal forces and thermal stresses
    - Stator: magnetic forces, eddy currents
    - Torque tube/drive shaft: torsional forces and thermal stresses due to gradient
- Cable cryostat: internal pressure from cryogen
- Superconducting motor: 25% to 40% is structural (e.g. driveshaft, casing, end covers, housing, rotor, stator)
- Cryogen storage tanks: internal pressure and thermal stresses, low/no permeability
- Thermal components
    - Cable cryostat, Cryotank: thermal insulation (need low conductivity ‘K’)
    - Heat exchanger: permit heat flow (high ‘K’ needed)



Conceptual diagram of a 2.5 MW cryo-cooled superconducting motor



Ground-based power cable (Cryogenic) from Nexans

https://www.compositestoday.com/2013/07/nasa-reach-composite-cryogenic-fuel-tank-milestone/

Structural Light-weighting/improving power density

Materials: Fiber reinforced polymer composites, Aluminum and Titanium

- (PMC) Composites have high strength-weight ratios, provide directional reinforcement
- Advantageous where loads are directional (e.g. hoop loads in rotor, pressure tanks)

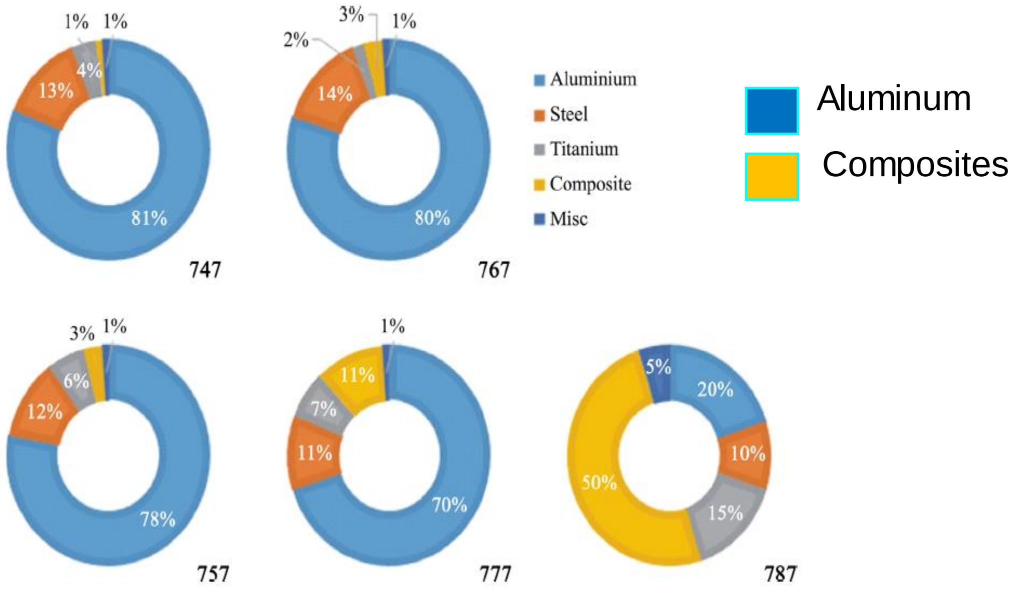
Approximate values for modulus, strength

	stiffness (Modulus E)	yield strength	tensile strength	Density (ρ)	Stiffness /ρ	100*Strength/ρ
Material	MPa	MPa	MPa	kg/m^3		
Steel	200,000	579	1448	7800	25.6	18.6
Aluminum (2024)	85,000	551	758	2700	31.5	28.1
Titanium (Ti-5AL-2.5 Sn)*	115,000	760	790	4200	27.4	18.8
T800-epoxy- UD tape- Cryo	158,000	N/A	2310	1660	95.2	139.2
Quasi-Isotropic-Cryo (IM7-8551)	64,000	N/A	694	1660	38.6	41.8
CFRP-Unidirectional-RT (IM7-8552)	144,000	N/A	2400	1660	86.7	144.6
CFRP-Quasi-Iso-RT (IM7-8552)	57,230	N/A	717	1660	34.5	43.2

Cryogenic performances of T700 and T800 carbon fibre- epoxy laminates, Wei, 2015

Fiber-reinforced polymer Composites in Commercial Aviation:

- **FRP Composites are mature**:
  - Since 4 decades, pace increased significantly in the 90's.
  - Composites form 50% by weight of a Boeing 787
  - Electric aviation will need composites, and other forms of light-weighting, to achieve 3X improvements in power density
- **Challenge for cryogenics community:**
  - To adapt them to aviation cryogenics
  - Changes in material response, thermal stresses from cool-down, thermal gradient, permeability
- **Current cryogenic applications**
  - G10: glass fiber with epoxy (low strength)
  - Cryostats
  - LH2 tanks produced by NASA/Boeing
  - Zylon-fiber composite, pulsed magnet at NHMFL



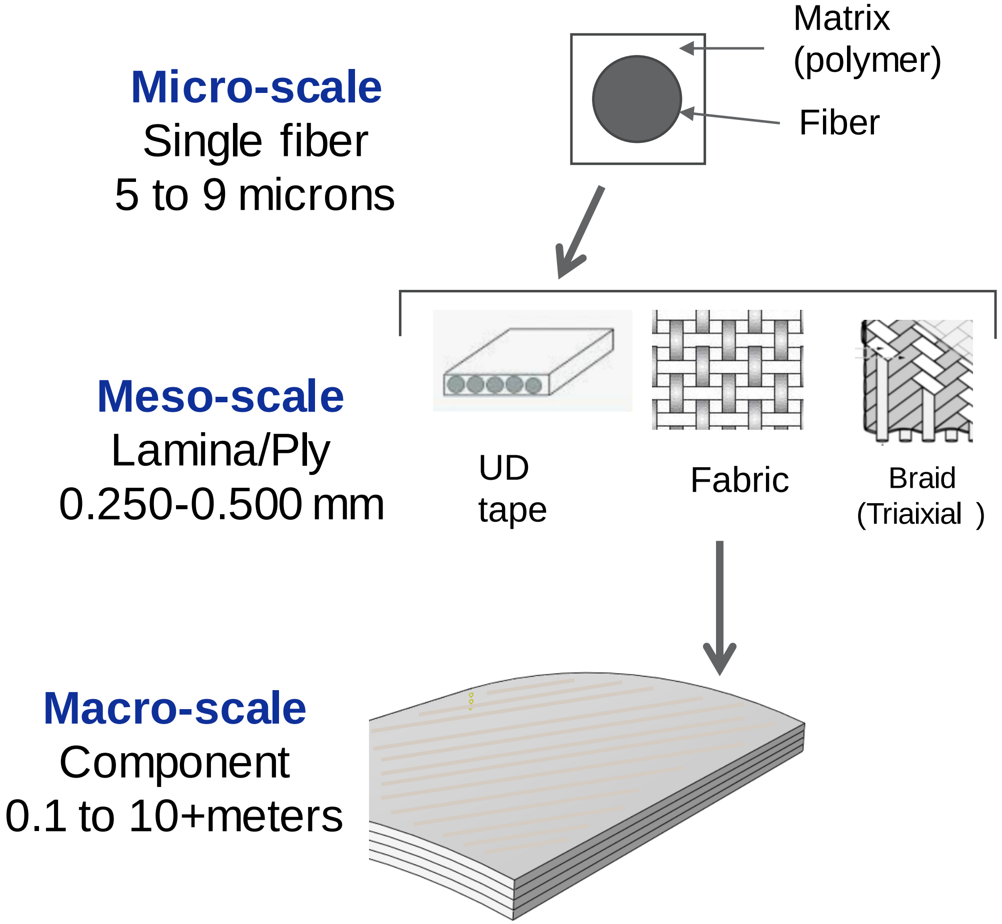
Zhu et. al. Propulsion Power and Research, 2017

5.5m dia.
NASA LH2 tank

Fiber reinforced Composites- Thermo-structural assessment needed at 3 length scales

- Micro-scale (fiber, matrix of resin): ~ 5-9 microns.
- Meso-scale: ply (inter-ply) level; 0.5mm
- Macro-scale (structural component e.g. rotor, tank): centimeters to meters

- Challenges:
  - Different coefficient of thermal expansion between polymer and fiber
  - Polymer property changes during cooldown



Micro-scale
Single fiber
5 to 9 microns

Matrix (polymer)

Fiber

Meso-scale
Lamina/Ply
0.250-0.500 mm

UD tape

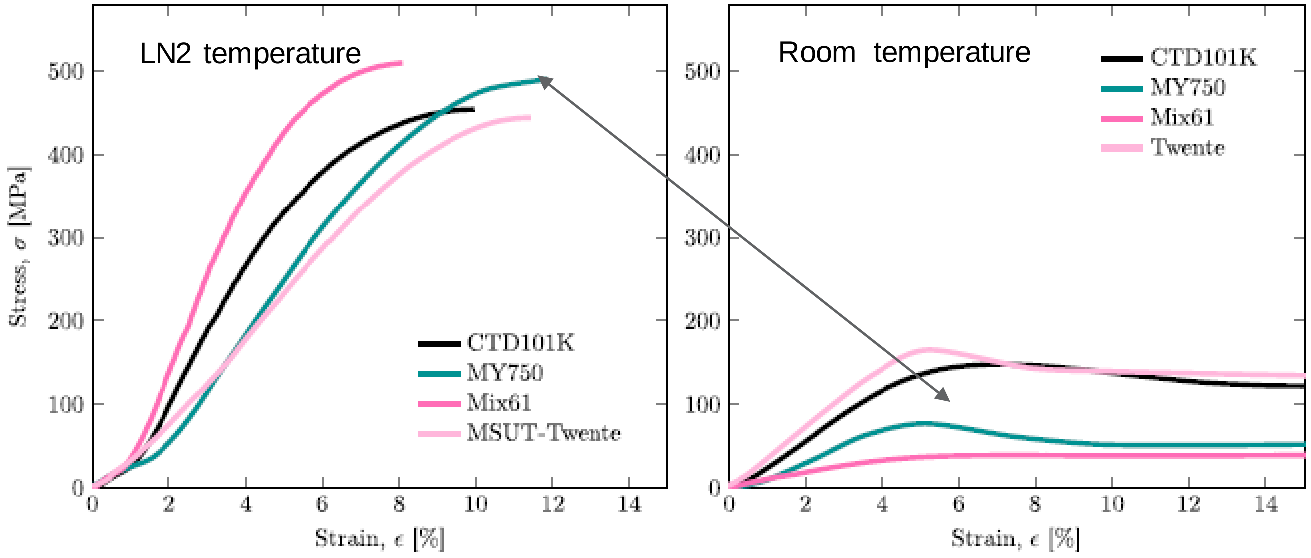
Fabric

Braid (Triaxial)

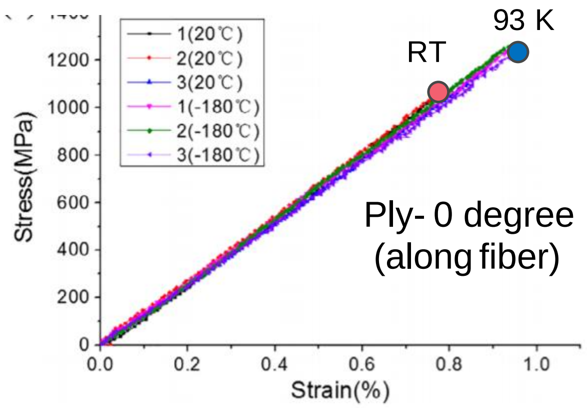
Macro-scale
Component
0.1 to 10+meters

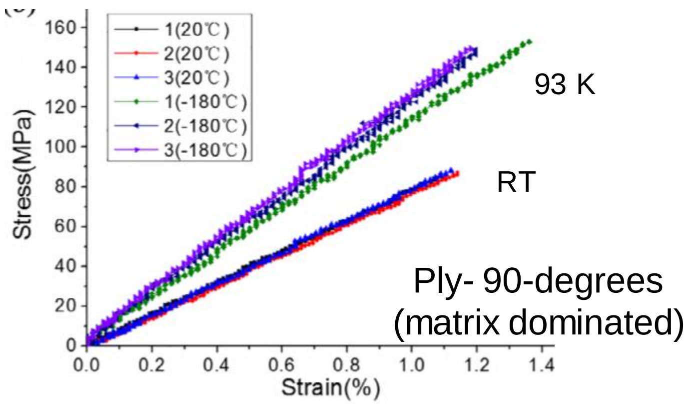
Composite properties at cryogenic temperatures:

- Polymers become stiffer, and less compliant (~ 1.5X modulus, 2X strength)- plots below for effect of low temperature
- Similar response in composites. Data for T700/epoxy UD tape in 0 and 90 degrees (right) show stiffness, strength improve in composite



Brem et. al., Elasticity, plasticity and fracture toughness at ambient, Cryogenics, 2021

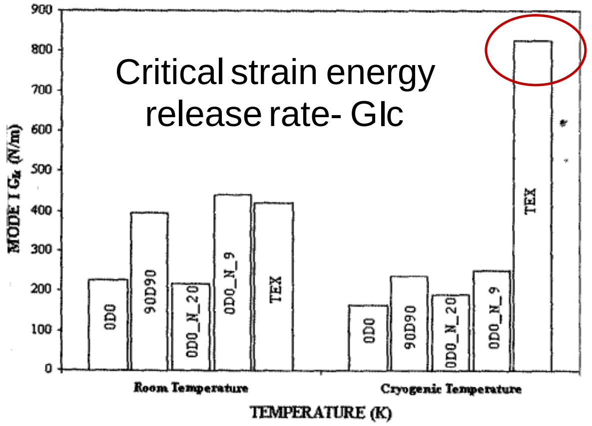




Yang et. al., Prediction on Residual Stresses of Carbon/Epoxy Composite at Cryogenic Temperature; Poly. Comp, 2019

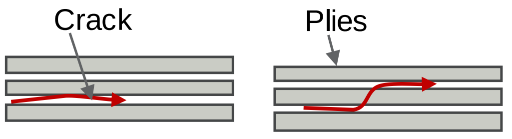
Fracture toughness of composites cryogenic temperatures:

- Fracture toughness (FT): resistance of material to crack growth
  - Depends on polymer, and the ply definition
  - Ply angles at interface of crack- can allow crack to jump across plies rather than propagate between plies
  - Ply architecture: plain weave fabric showed higher toughness than UD tape. Undulating tow architecture may help. Braids have similar undulations.
  - PW glass-epoxy fracture tests showed an increase and then decrease of GIc. Lower temperatures involved fiber-matrix interfacial failure rather than matrix failure



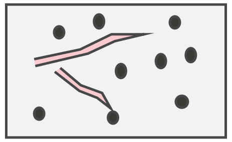
Critical strain energy release rate- GIc

Kalarikkal, Bhavanisankar & Ifju, JEMT 2006



Crack propagates Between plies

Crack jumps Between plies



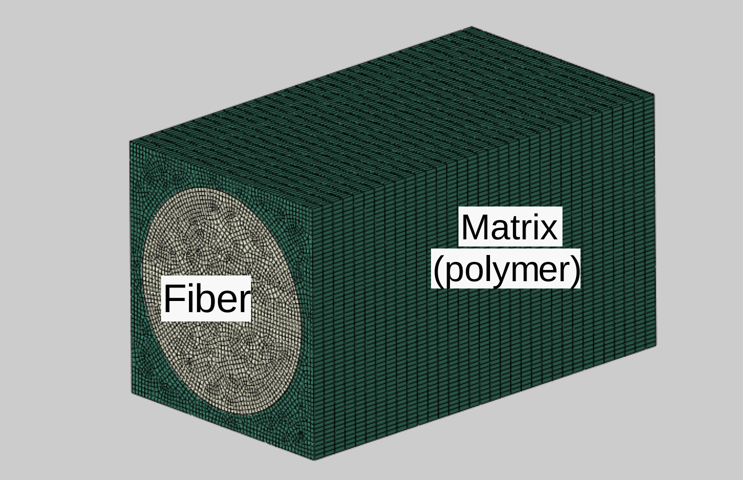
- Additives/inclusions improve FT in some cases
  - Alumina nanoparticles improved toughness in UD CFRPs at 9% conc.
  - Elastomeric particles

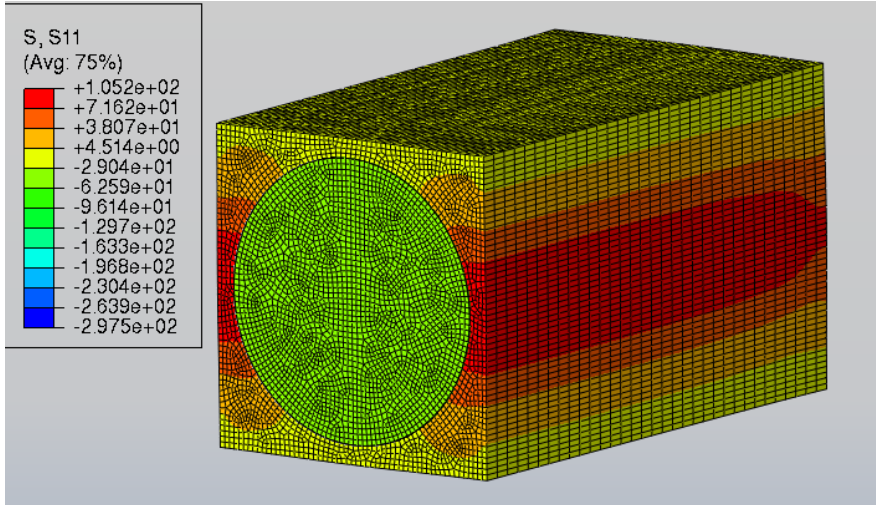
Temp.	MCC method	Area method
R.T.	0.646	0.631
77 K	0.975	0.728
4 K	0.664	0.598

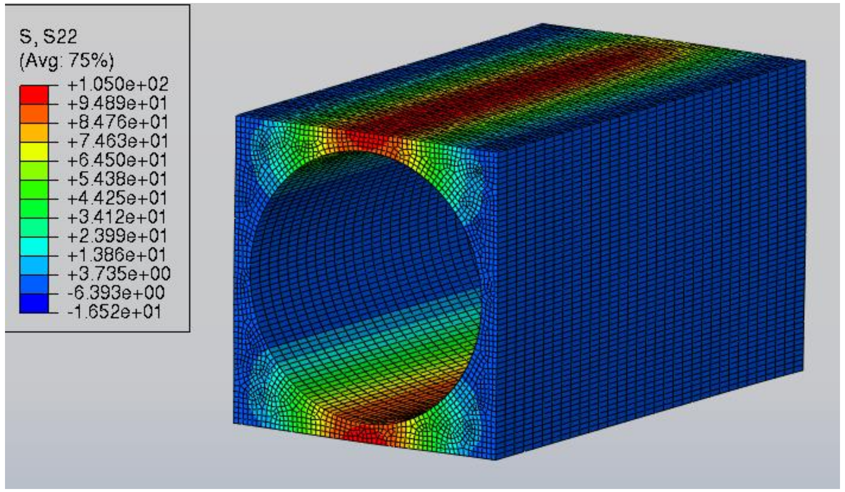
Shindo et. al, JEMT, 2001,

Thermal stresses at individual fiber scale (due to cooling):

- Unit cell model for a single fiber and surrounding matrix (~60% volume fraction):
  - Cooled isothermally from 400K to 20K
  - Carbon fiber & epoxy matrix (977-2)
  - Fiber prevents matrix from shrinking
  - Tensile stresses in matrix (polymer) cause micro-cracks. Failure strength of polymer ~ 100 MPa*
  - Fiber-matrix interface also pre-stressed



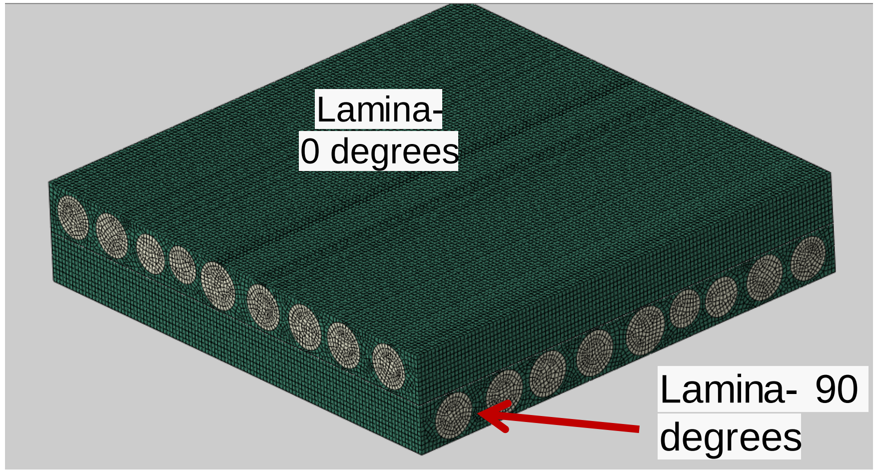


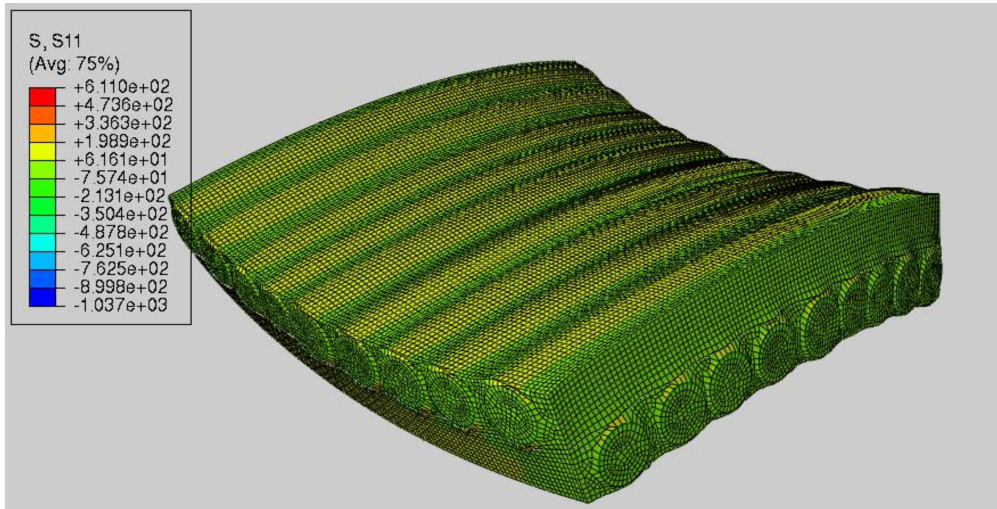


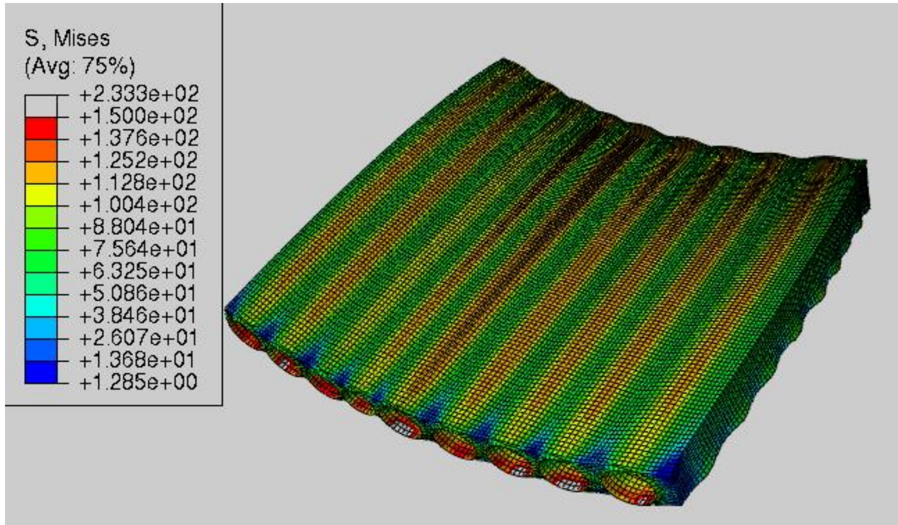
Properties taken from "Choi & Bhavanishankar, Micromechanical Analysis of Composite Laminates at Cryogenic Temperatures", J. Comp. Mat.; 2005

Thermal stresses in laminae due to cooling (meso-scale):

- Two laminae with [0/90] ply angles: worst-case layup for thermal stresses (0.120 mm thick):
  - Fibers prevent contraction along their length. Matrix contracts more.
  - Plies warped out-of-plane in two directions
  - Transverse strength of lamina at cryogenic temperatures: 90 MPa to 120 MPa

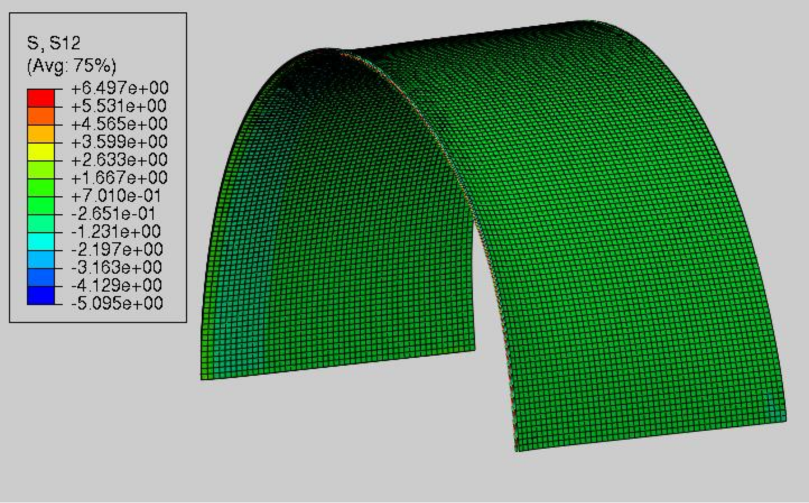


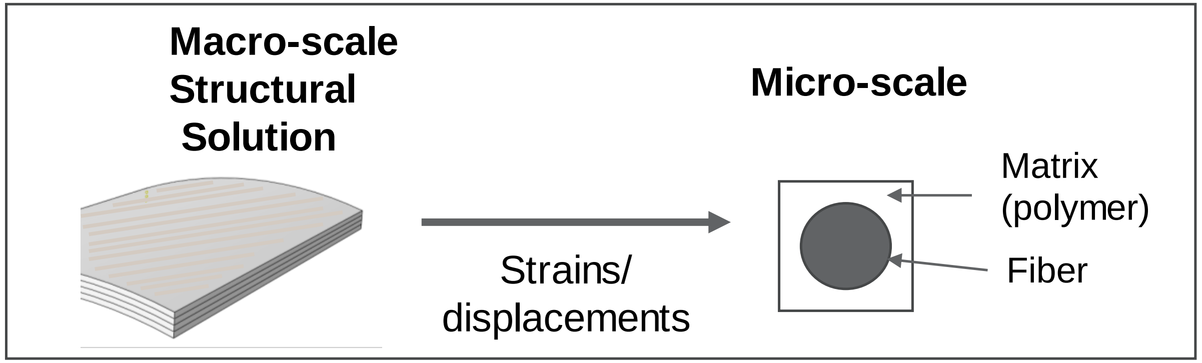




Thermal stresses at macro-scale i.e. component level :

- Rotor over-wrap for holding magnets during high-speed rotation: 0.25m diameter, 0.1 m long
- Carbon-epoxy (IM7/977-2): Layup- [90/45/90/45/90/0/0/0]
- Cooldown from 400K to 20K:
  - Interlaminar stresses at edges due to unequal contraction
  - Distortion function of component geometry, ply layup





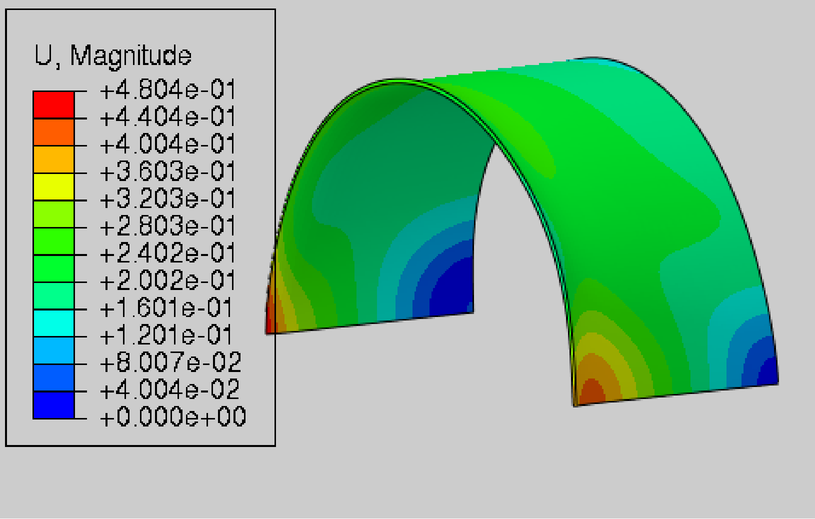
Macro-scale Structural Solution

Micro-scale

Strains/ displacements

Matrix (polymer)

Fiber



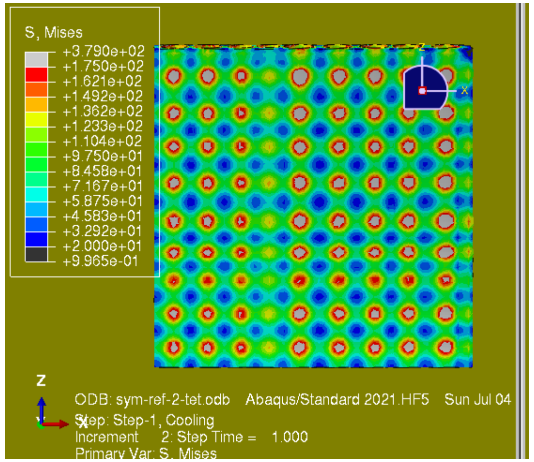
Challenges and Mitigation methods

- Thermal stresses at micro-scale:
  - – Choice of fiber (design)
  - – Higher strength polymers- with fillers (materials)
  - – Interfacial strength (materials)

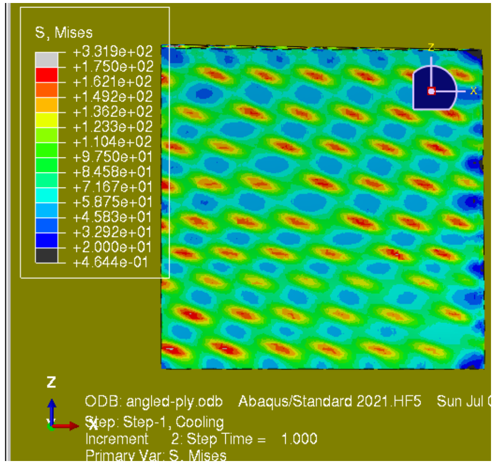
- Thermal Distortion and Failure of component
  - – Optimize Layup, ply architecture (design)
  - – Macro-microscale computational modeling (Mechanics)
  - – Validated ply-level failure theory for cryogenic temp. (Mechanics)

- Material properties at cryogenic temperatures
  - – Stress-strain characterization of PMCs at cryogenic temperatures

- Permeability to cryogens: reduced micro-damage, liners



0-90 laminae interface

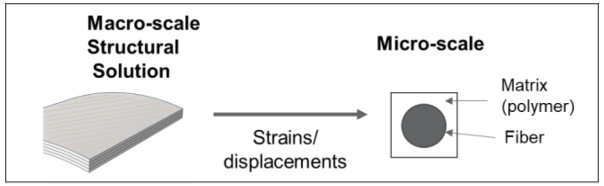


0-45 laminae interface

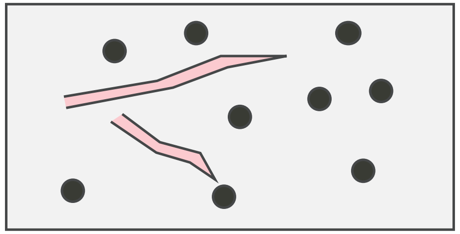
Composites Development for Cryogenic Components: Approach

Composite Architecture Design:
- Optimization of ply layups
- Selection of ply architectures
- Fiber, matrix & interfacial properties

Polymer material development:
- Higher fracture toughness, bond strength
- Inclusions to arrest/deflect crack growth
- Multi-functional properties e.g. thermal conductivity, magnetic properties



Design of light-weight PMC Components for Cryogenic applications



Multi-scale Computational Modeling
- Account for thermo-structural response across length scales
- Failure model for resin at cryogenic temperature
- Ply-level lamina failure model

Testing and material properties database:
- Constitutive response for a combination of polymers, fibers, ply architectures
- Identify failure mechanisms in static and fatigue load at cryogenic temperatures

Summary and Challenges/gaps

Fiber-reinforced and particle-embedded polymer composites have demonstrated their maturity in aerospace. Challenges are in adapting to cryogenics.

- Polymer matrix composites routinely used in commercial aviation structures for light-weighting. Applicable to cryogenic regime.
- Cryogenic applications exist, though not widespread.
- In cryogenic regime, weight reductions of 20%-40% have been reported for tanks

- Challenges in adapting to cryogenics:
  - Materials (polymers):
    - Improvement of polymer capability for toughness, durability
    - Multifunctional polymers (thermally conductive, fillers for magnetic permeability)
  - Material behavior and properties at cryogenic temperatures:
    - Test data for specific systems for static, fatigue and durability
  - Computational modeling and Design:
    - Multi-scale modeling approach needed, design optimization to reduce thermal stresses, failure criteria at cryogenic scale