MULTIFUNCTIONAL FIBERGLASS-REINFORCED COMPOSITES WITH LASER INDUCED GRAPHENE

Boyang Chen[a], Adam Childress[a], Jalal Nasser[a], LoriAnne Groo[a], Henry A. Sodano*[abc]

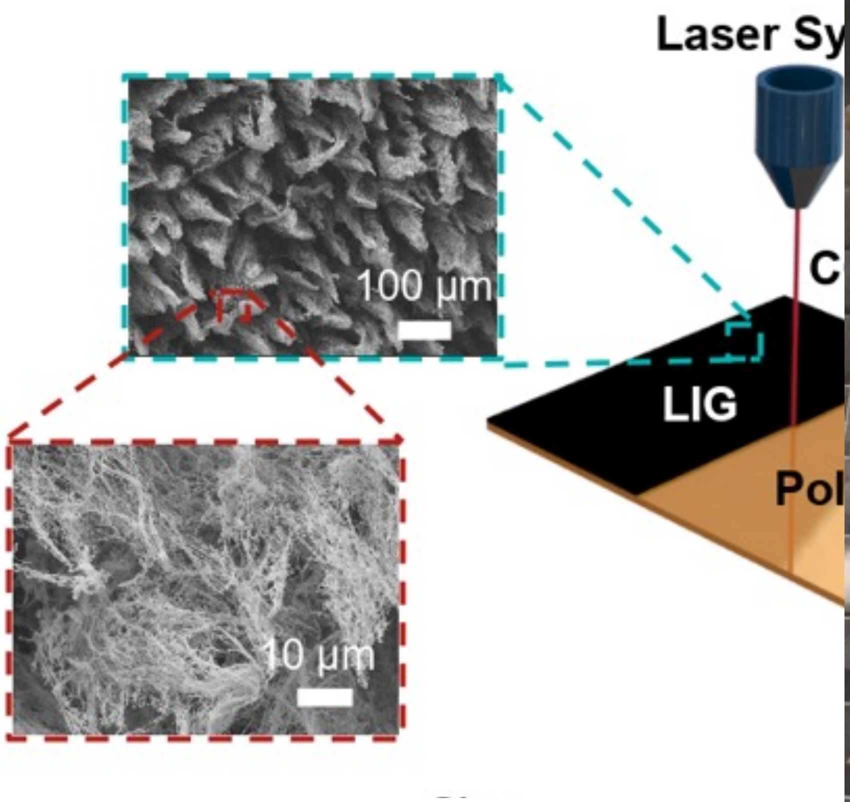
[a] Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan USA 48109,

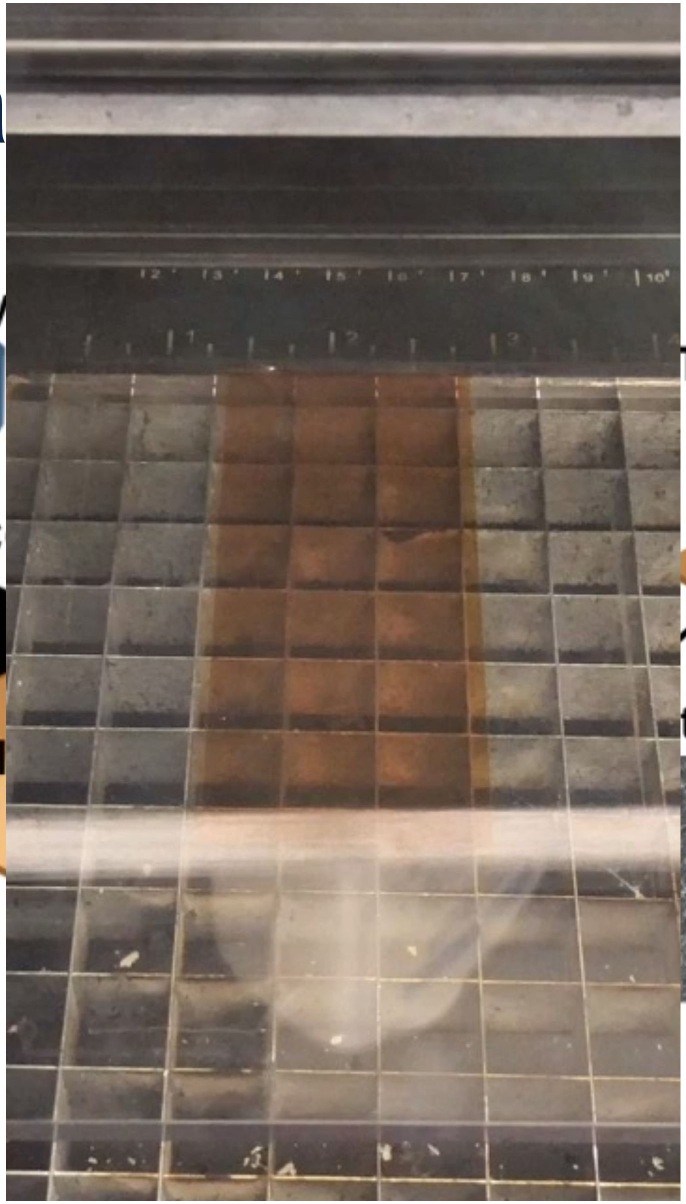
[b] Department of Material Science and Engineering, University of Michigan, Ann Arbor, Michigan USA 48109,

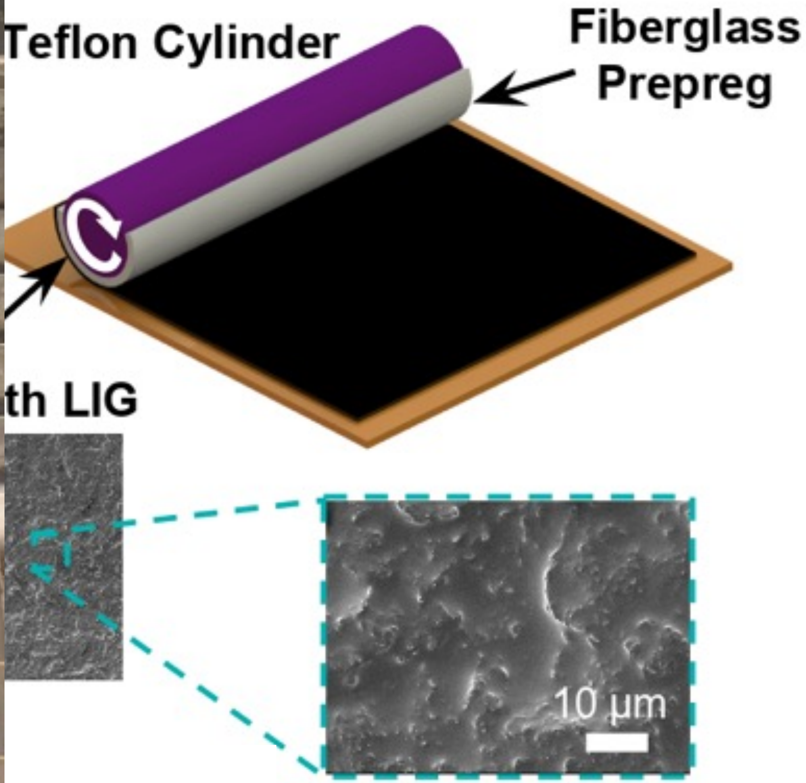
[c] Macromolecular Science and Engineering, University of Michigan, Ann Arbor, Michigan USA 48109

UNIVERSITY OF MICHIGAN

Laser Induced Gra

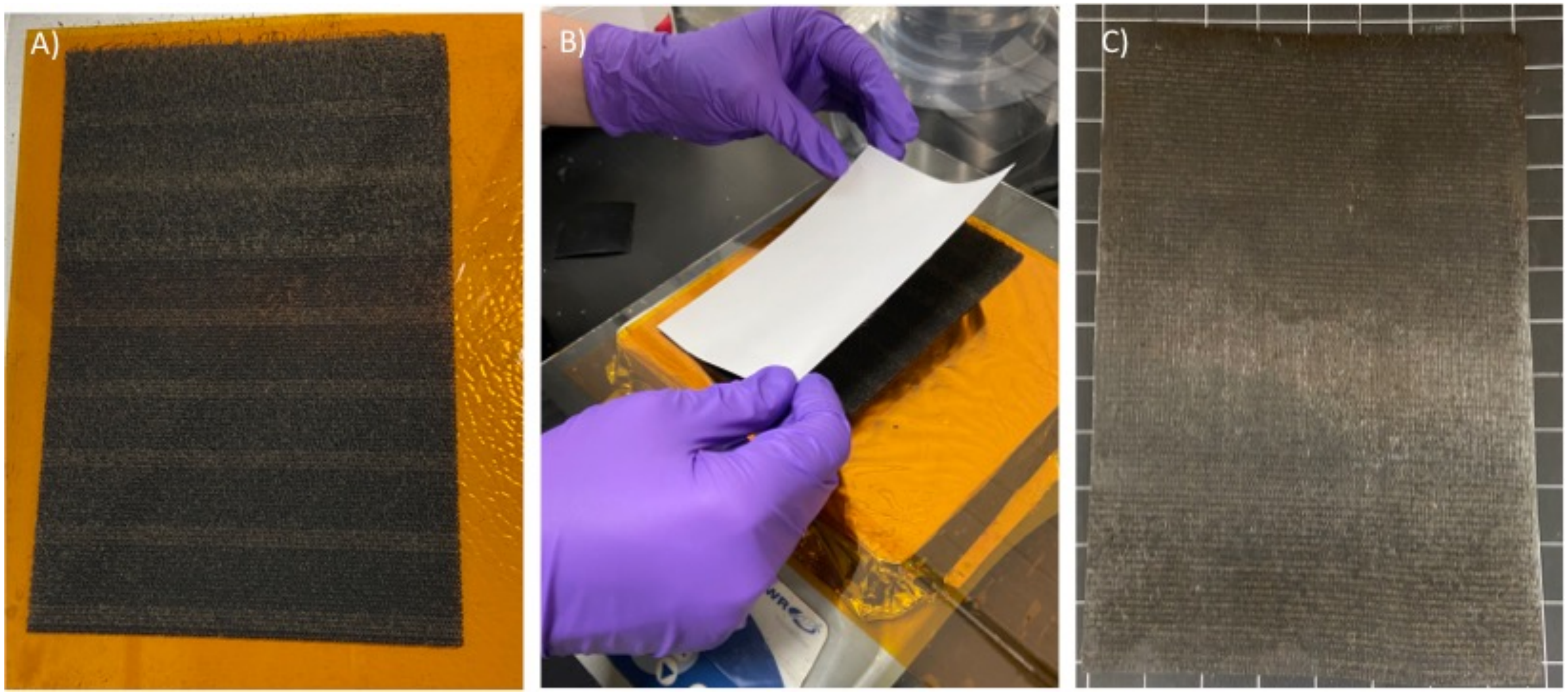






LIG Preparation and Transfer

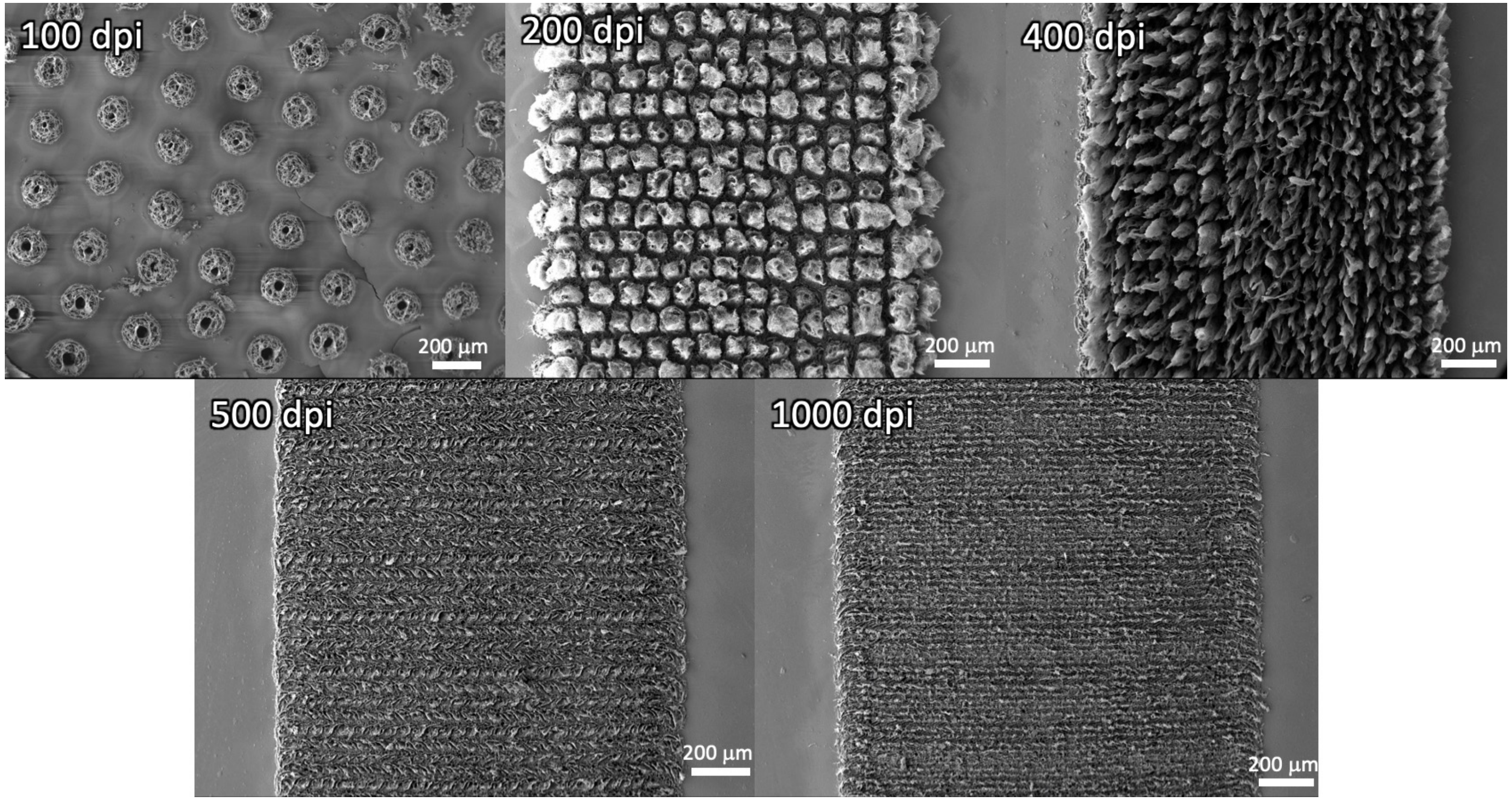
- LIG formed on polyimide (Kapton) films, then heated and brought into contact with prepreg which is then peeled from the polyimide surface with an LIG coating



UNIVERSITY OF MICHIGAN

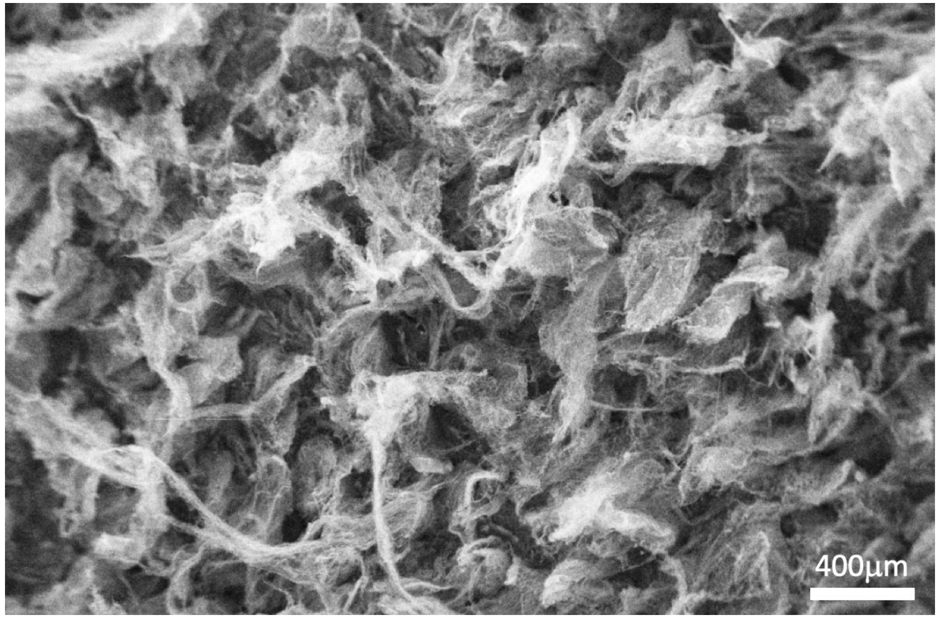
Laser Induced Graphene Process Optimization

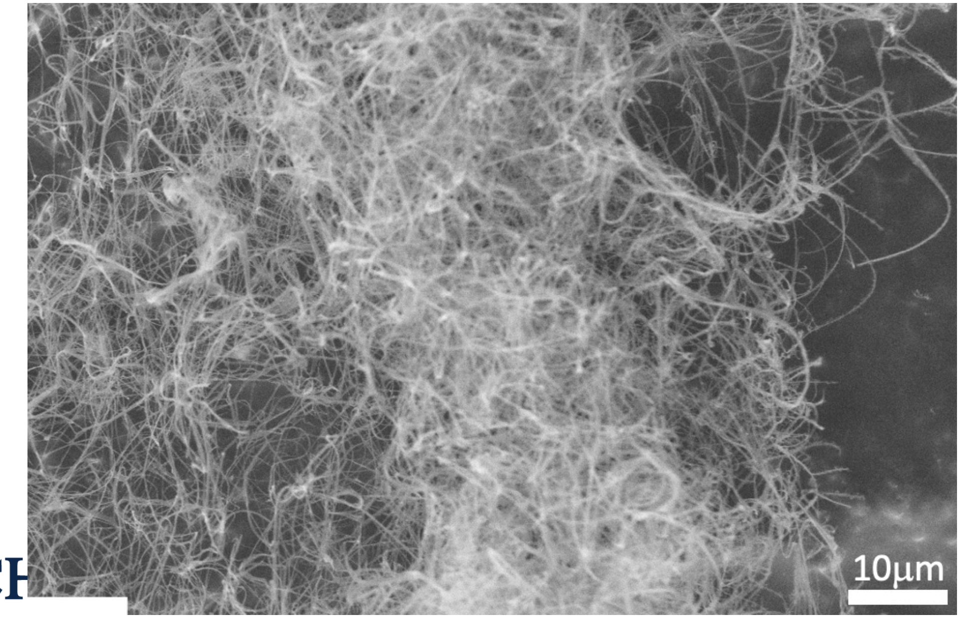
- The LIG morphology is significantly altered by the laser pulse density and energy



LIG Microstructure

- LIG process leads to the formation of a carbon nanofiber structure
- We have found that a low pulse density and high power produces a fibrous array
- High aspect ratio fibers are desirable for reinforcement of the polymer and the enhancement of electrical conductivity
- Chemical analysis shows similar structure to graphene although not single layer graphene

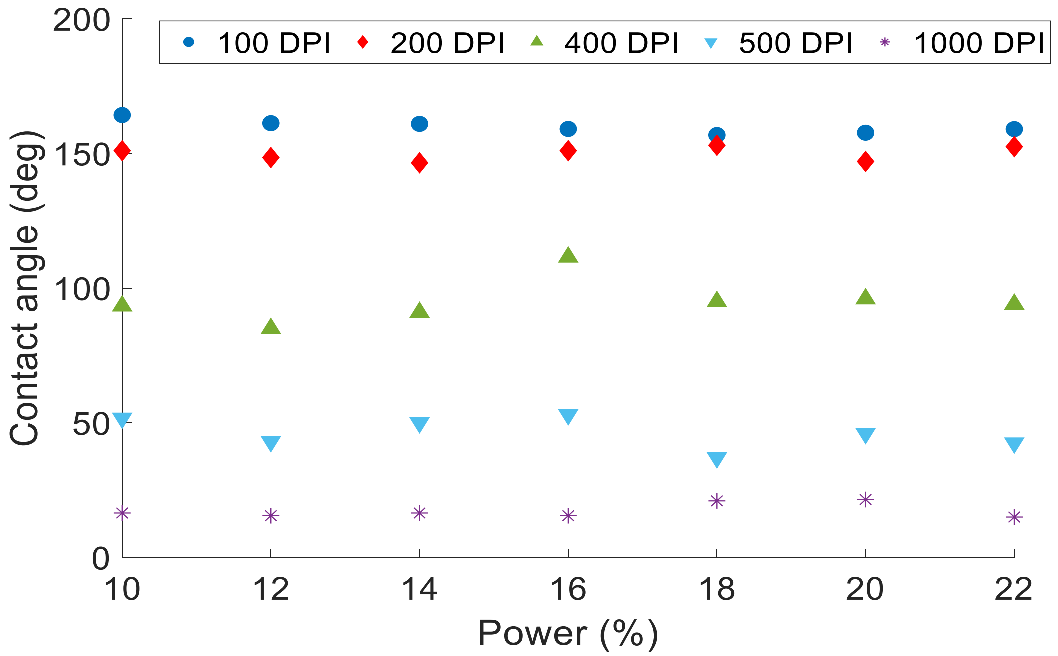


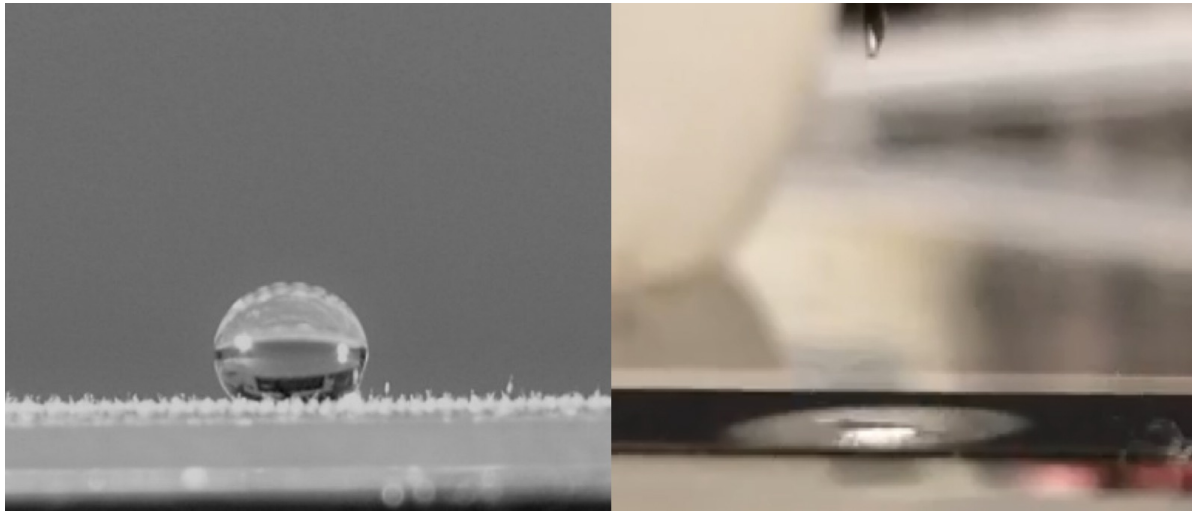


UNIVERSITY OF MICH

LIG Surface Properties

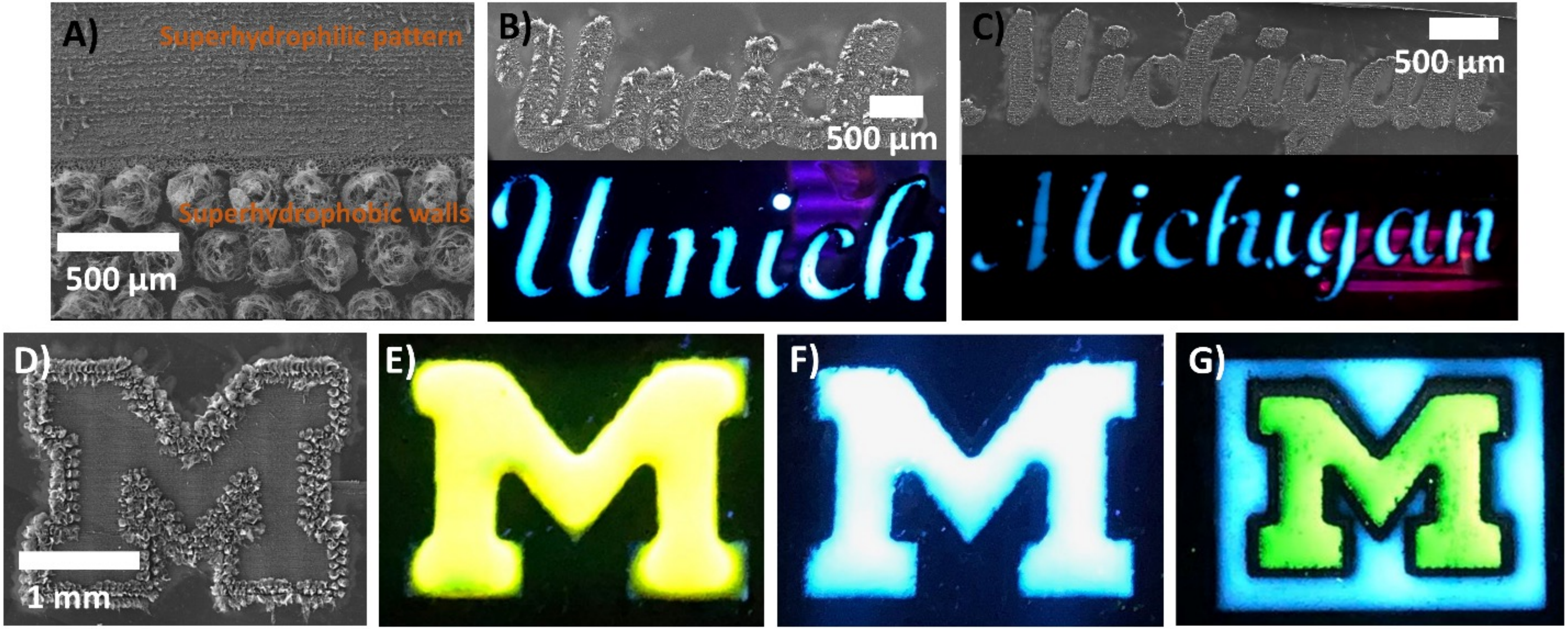
- We have shown that the LIG process leads to significant change in the wettability of the surface
- Morphology can produce super hydrophobic or super hydrophilic surfaces
- It may be possible to use this process to create self-cleaning surfaces
- The process can also be used to direct flow through super hydrophilic pathways with super hydrophobic borders





UNIVERSITY OF MICHIGAN

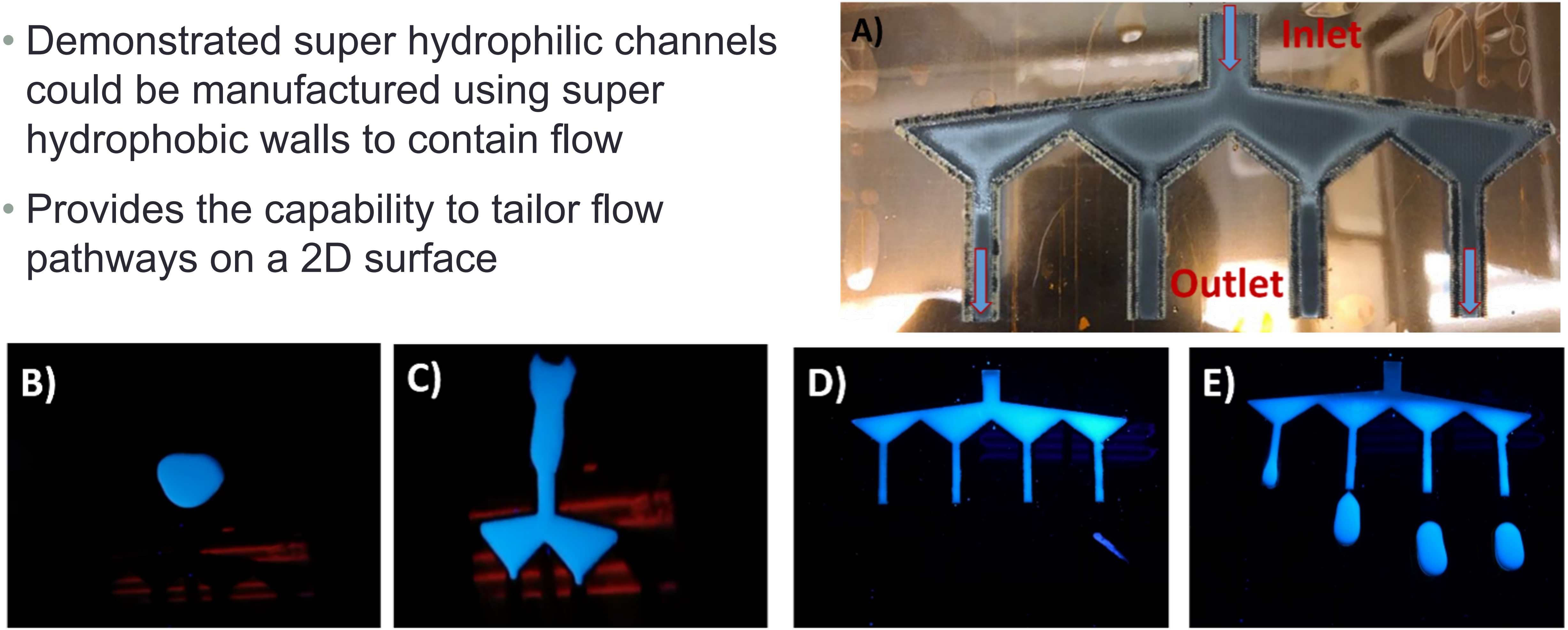
Fluidic Patterning



UNIVERSITY OF MICHIGAN

2D Microfluid Channels

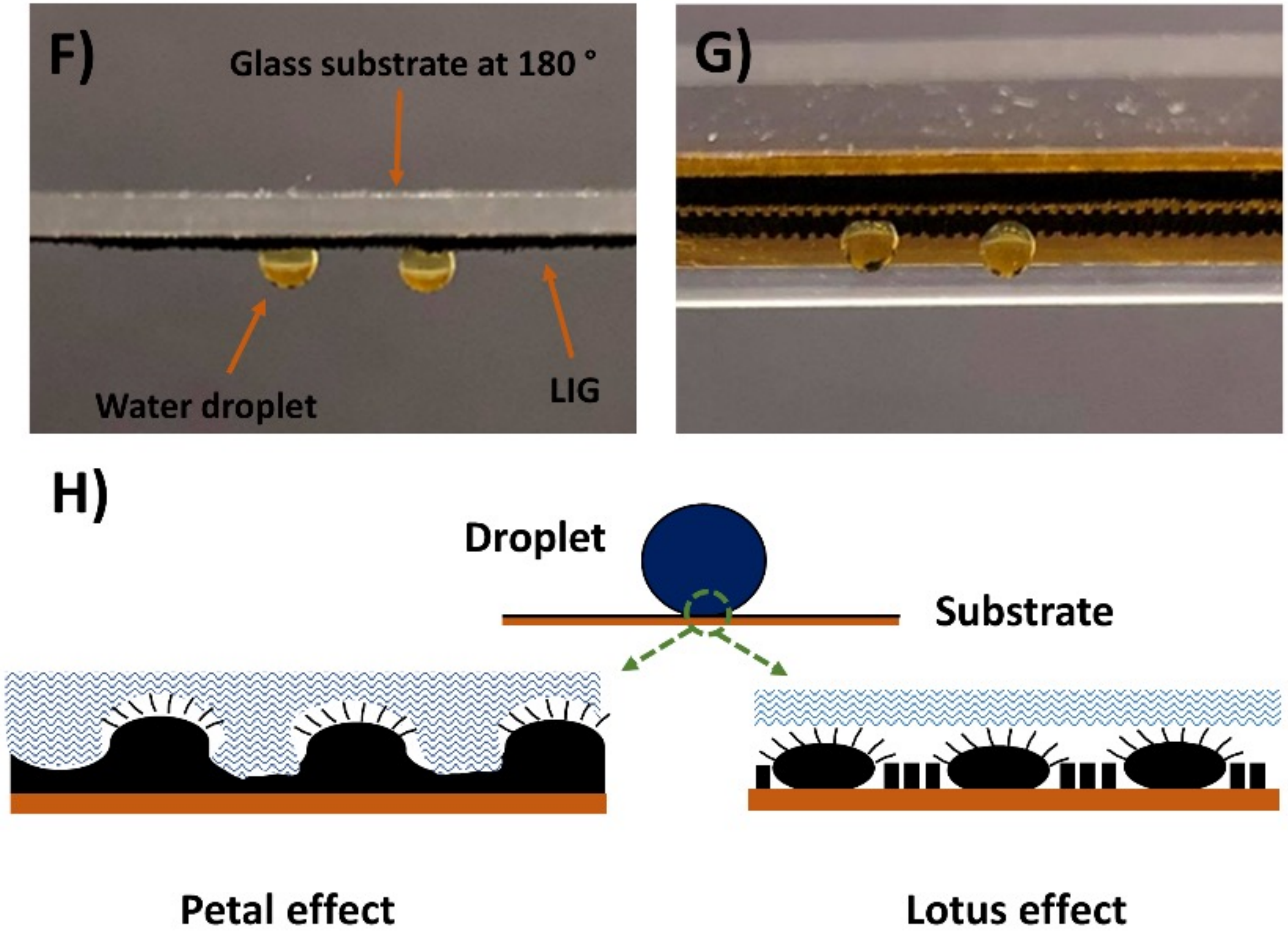
- Demonstrated super hydrophilic channels could be manufactured using super hydrophobic walls to contain flow
- Provides the capability to tailor flow pathways on a 2D surface



UNIVERSITY OF MICHIGAN

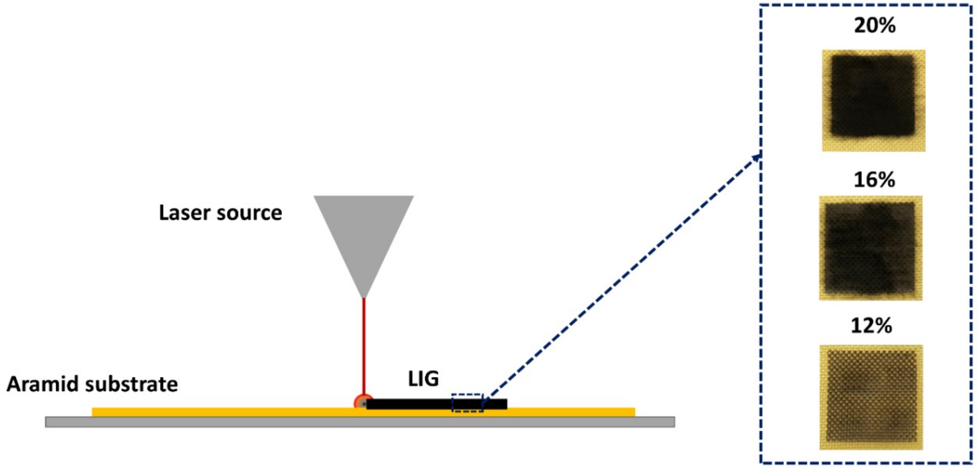
Parahydrophobic Surfaces

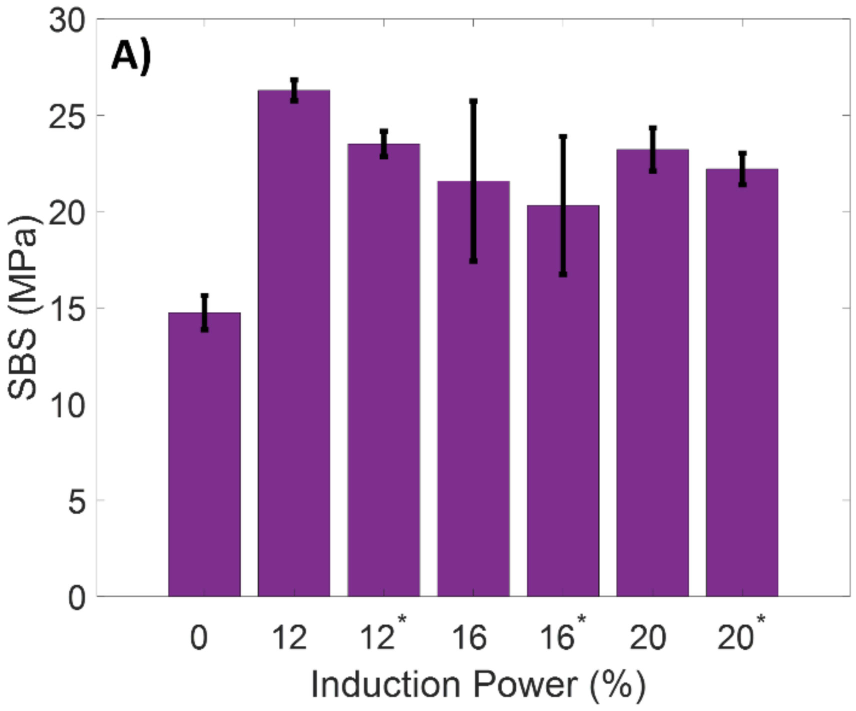
- Hydrophobic LIG surfaces exhibit parahydrophobic behavior
- Parahydrophobic behavior shows high contact angles with strong adhesion
- Water droplet is in a Cassie impregnating wetting state on the LIG surfaces
- Liquid able to penetrate between larger microstructures, yet not between smaller ones, avoiding the formation of air pockets underneath the liquid

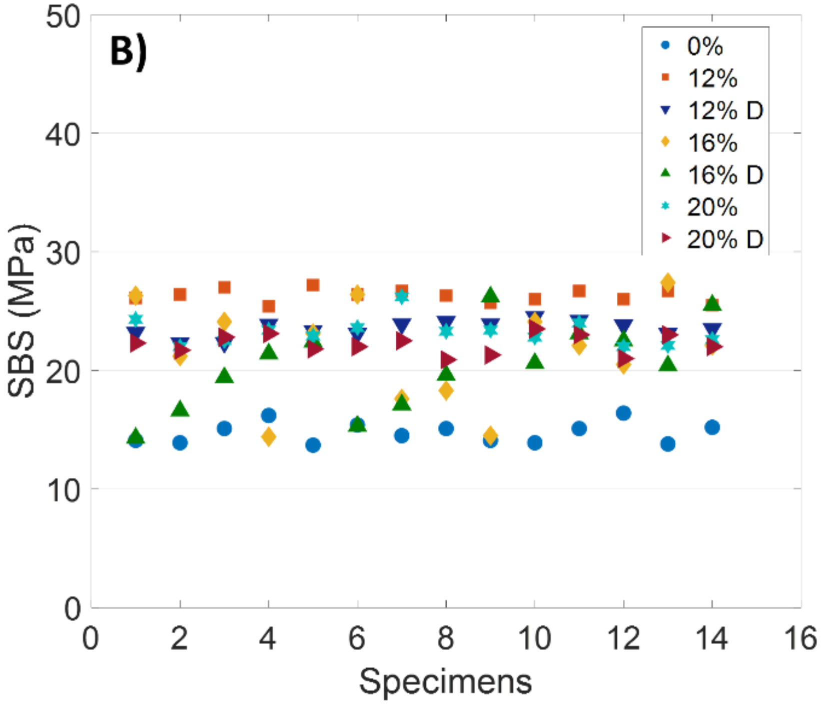


LIG on Kevlar

- Most thermosets require a transfer process for the LIG
- LIG can be formed directly on the surface of Kevlar
- The formation of graphene on the Kevlar surface improves short beam strength
- Can be used to provide embedded sensing



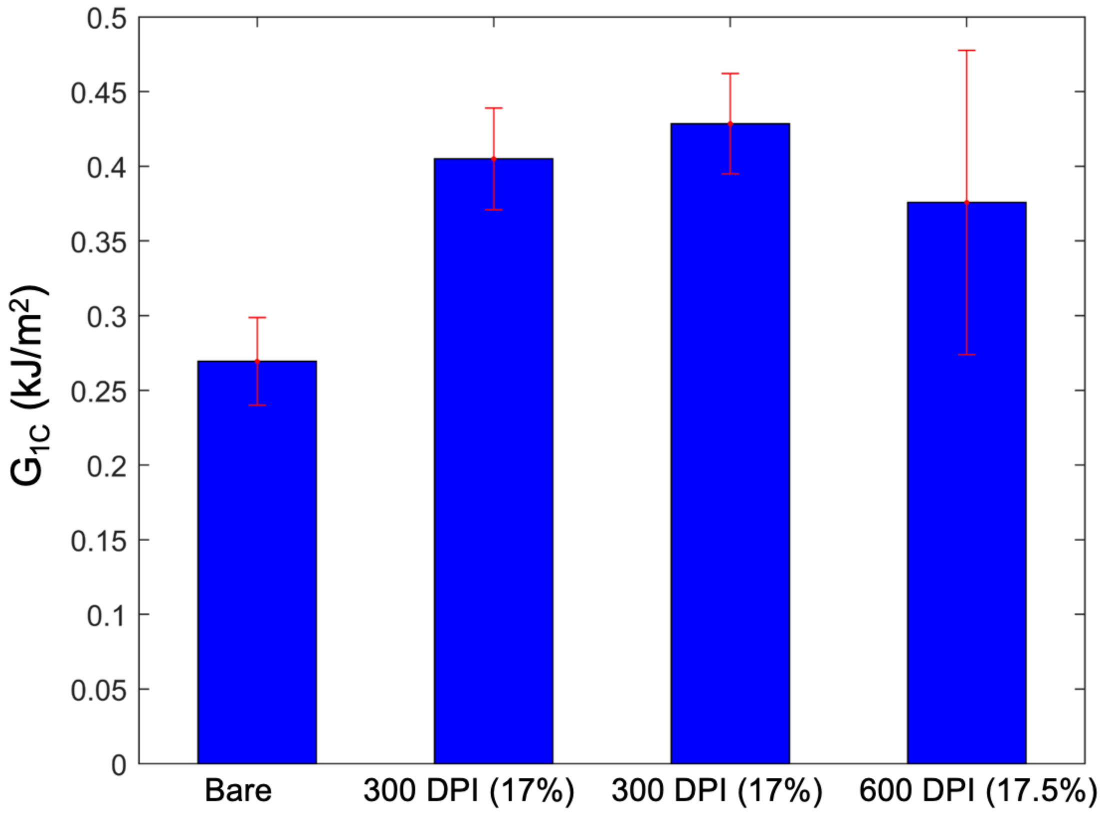




UNIVERSITY OF MICHIGAN

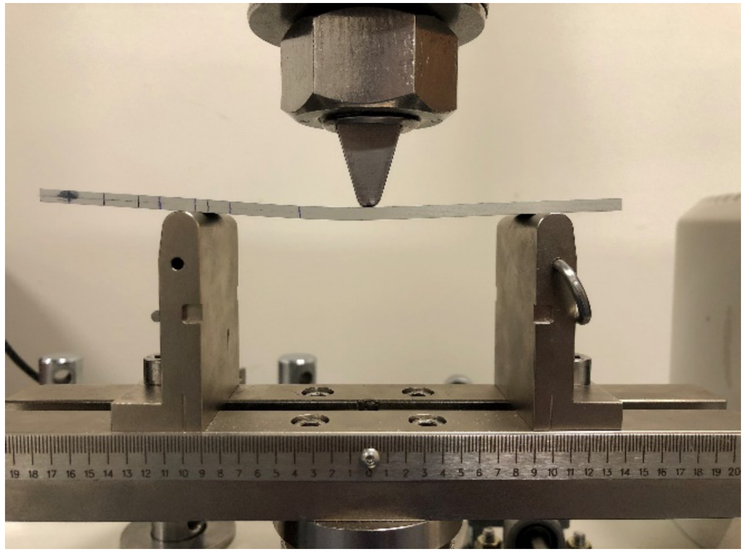
Mode I Fracture Toughness

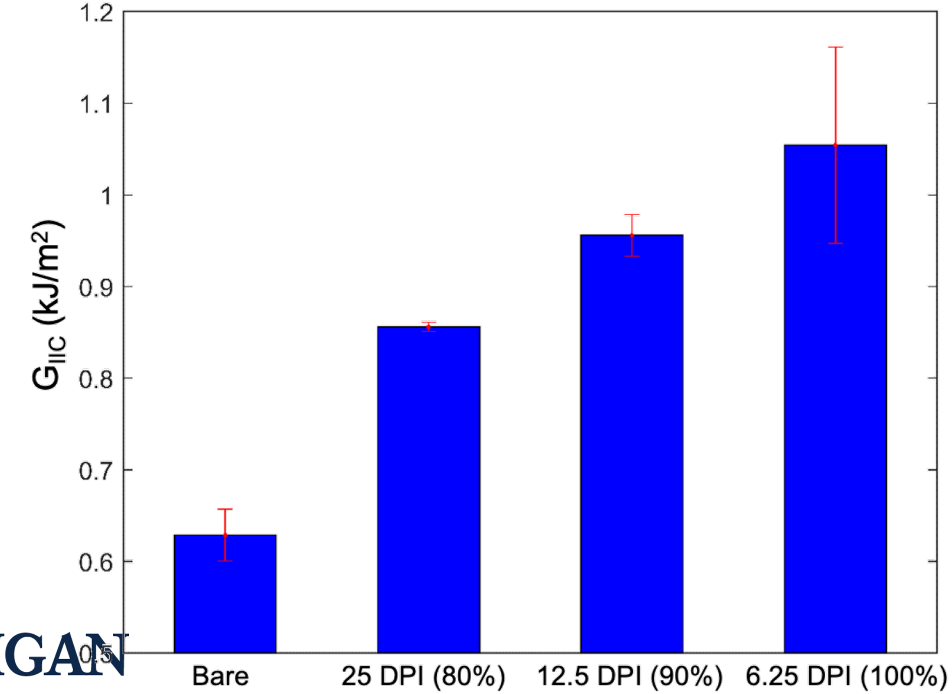
- Mode I toughness at crack initiation measured following a 5 mm stable precrack
- G_{IC} value showed a maximum increase of 59% over the neat prepreg
- With LIG the G_{IC} shows an increasing trend with crack length indicating toughening mechanism
- Possible microcracking or crack bridging
- High DPI used in our Mode I testing



Mode II Fracture Toughness

- Mode II fracture toughness was evaluated with LIG reinforcement in accordance ASTM D7905
- Mode II specimens were precracked prior to measurement of the G_{IIC}
- G_{IIC} value had a maximum increase of 68% over the neat prepreg
- Mode II testing was performed with low DPI LIG
- Lower DPIs can increase print speed
- Preliminary results show that the proposed graphene arrays can significantly outperform CNTs
- Conductivity of graphene provides a range of potential embedded functions

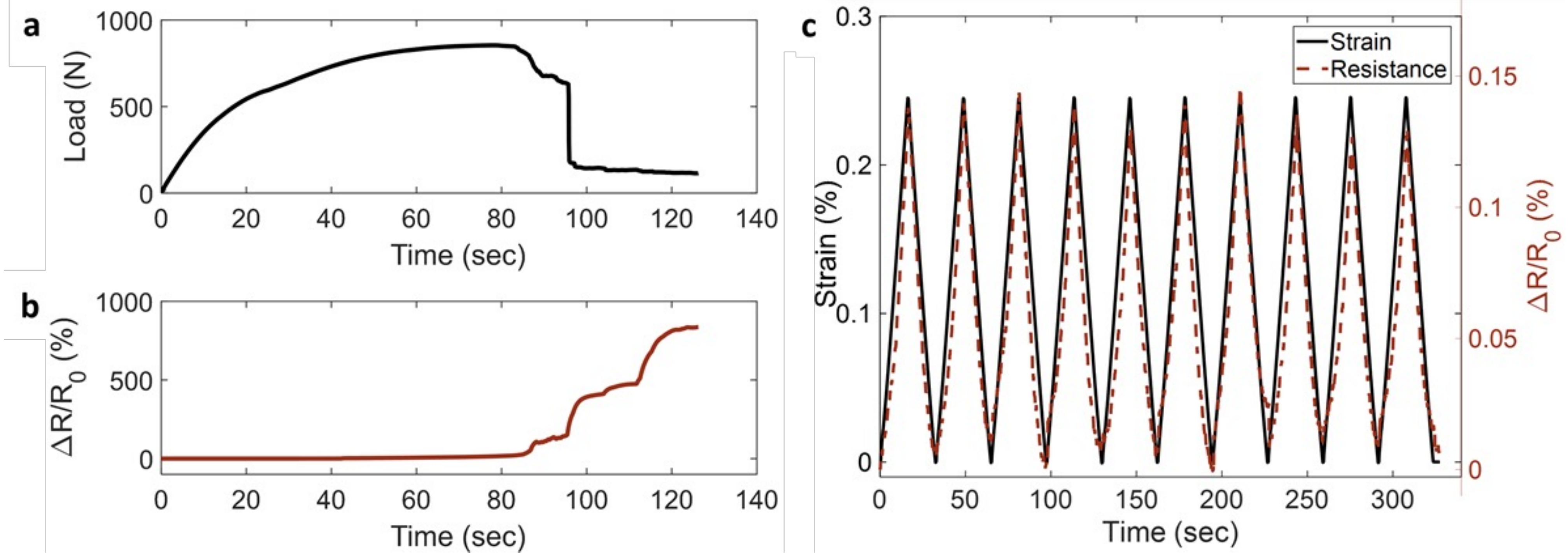




UNIVERSITY OF MICHIGAN

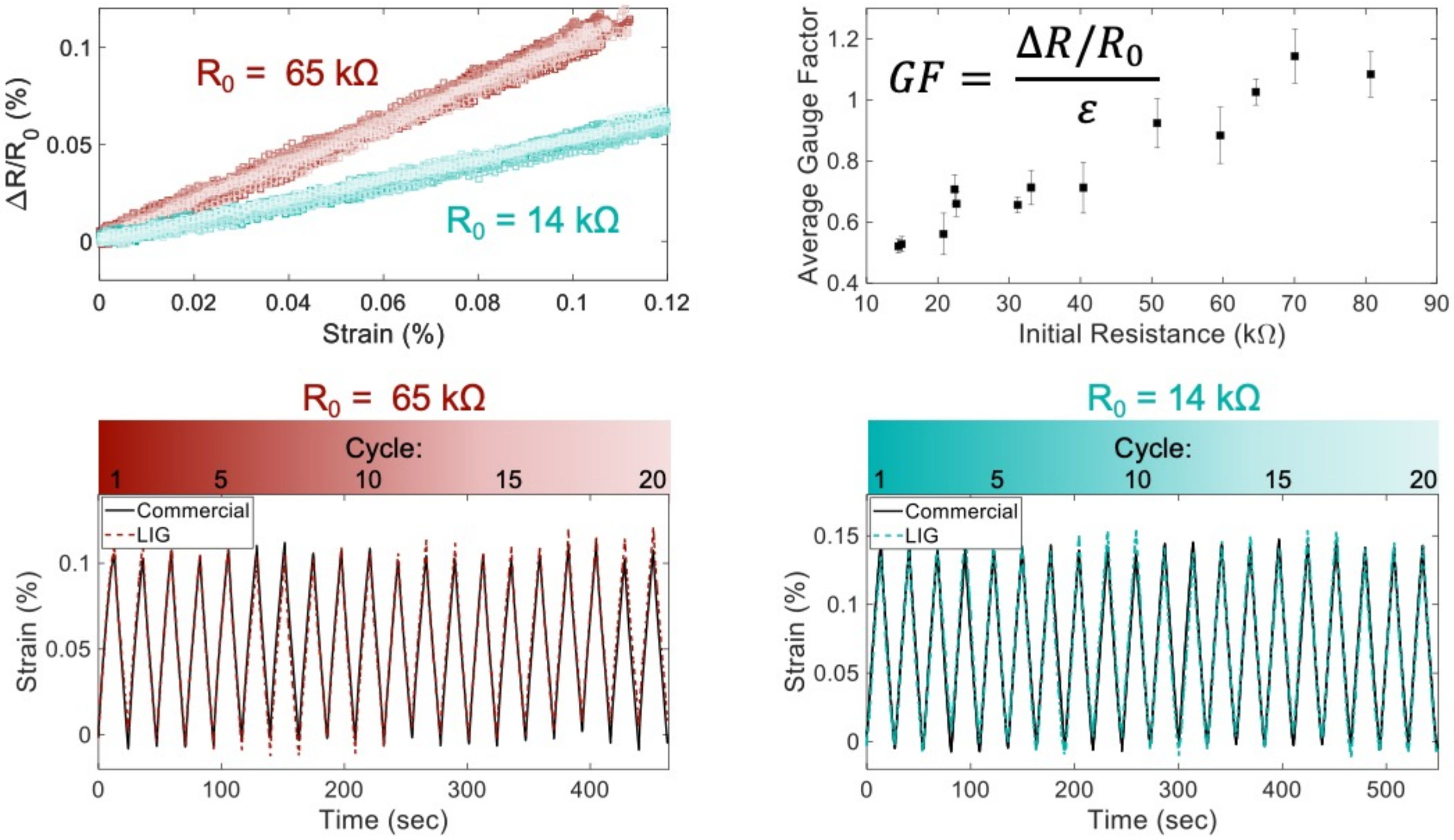
Multifunctionality: Strain Sensing

- Cyclic loading matches the strain measured by commercial strain gauge
- Cyclic loading shows repeatable measurements
- Results demonstrate LIG can be used to produce an accurate strain gauge



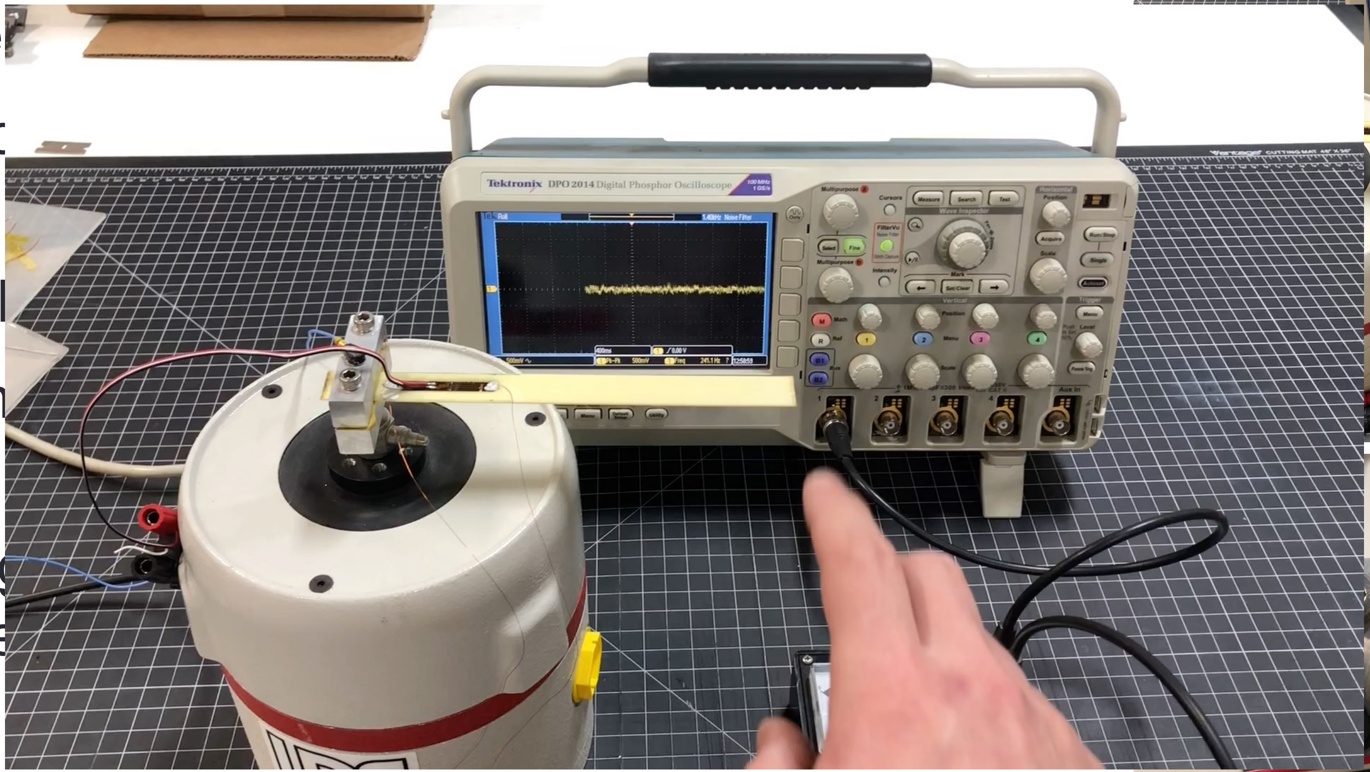
Strain Gauge Sensitivity

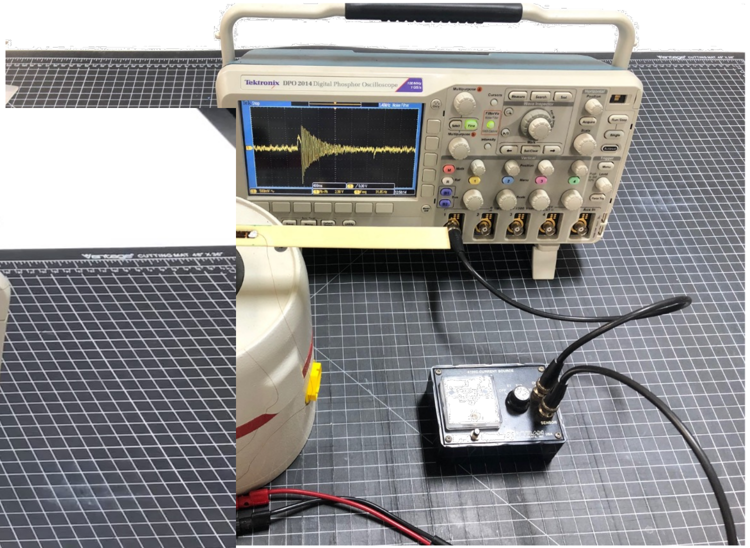
- Gauge factor increases with initial resistance of the strain gauge
- Our work over the course of the Phase I has improved the repeatability of the printing process
- Cyclic loading matches commercial strain gauge and given a known gauge factor

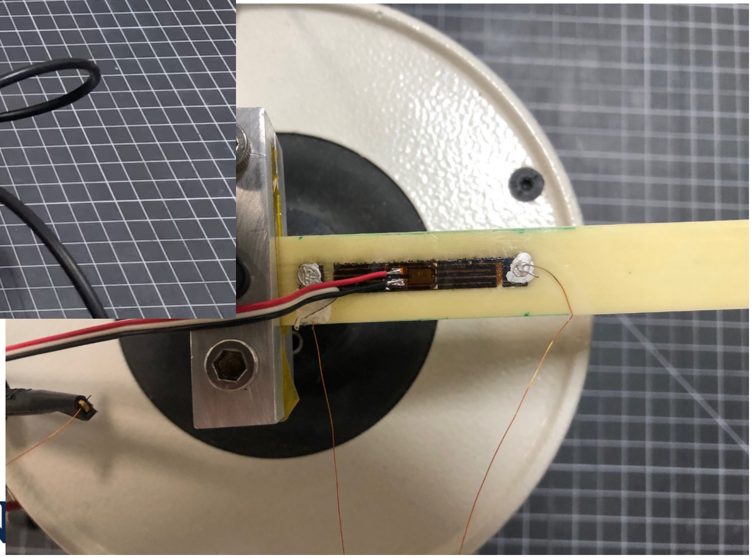


Multifunctionality: Strain Sensing

- Strain gauge made
- Constant current sc
  measured
- Wires attached to tl
- Dynamic measuren
  shaker
- Commercial strain
  to validate measure
- Accelerometer and
  signal



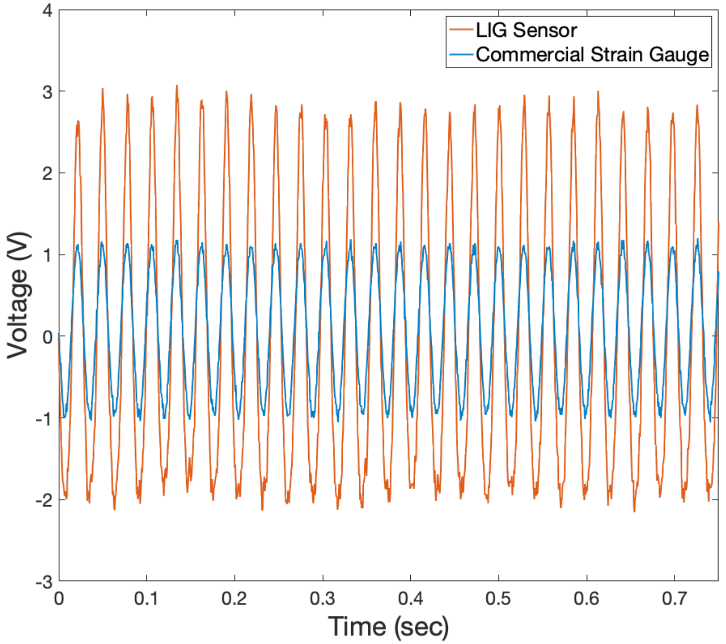


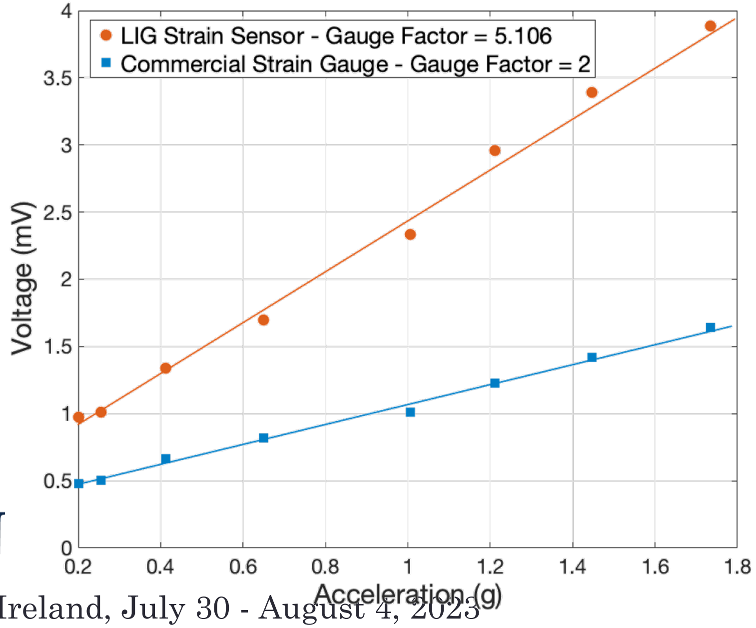


UNIVERSITY OF MICHIGAN

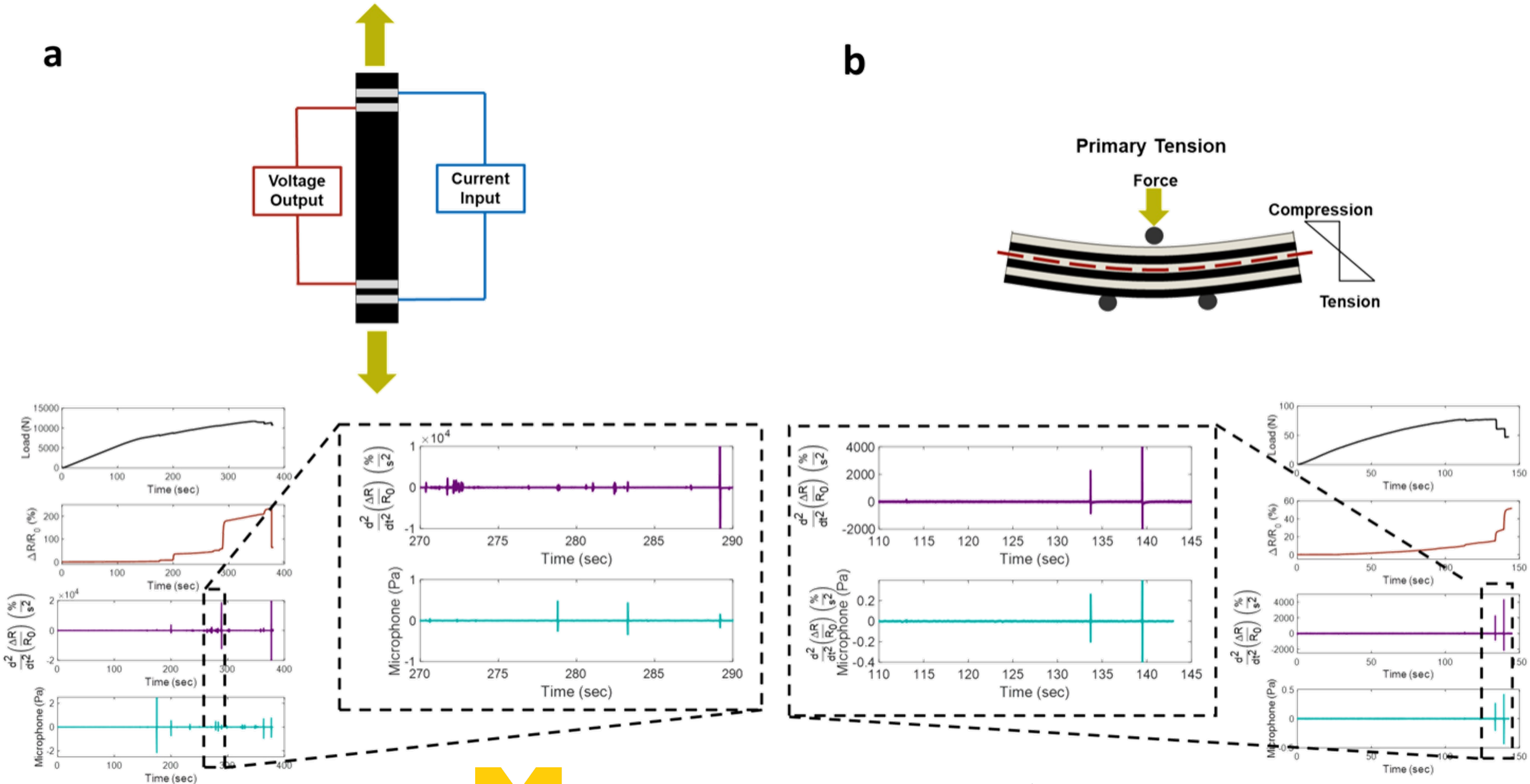
Multifunctionality: Strain Sensing

- Time domain measurements of the voltage output under excitation
- Commercial strain gauge had a gauge factor of 2.0
- LIG sensor had a gauge factor 2.5 times greater than the commercial strain gauge
- Response amplitude under increasing excitation shows a linear tread
- Results shown the LIG approach can clearly function as a sensor

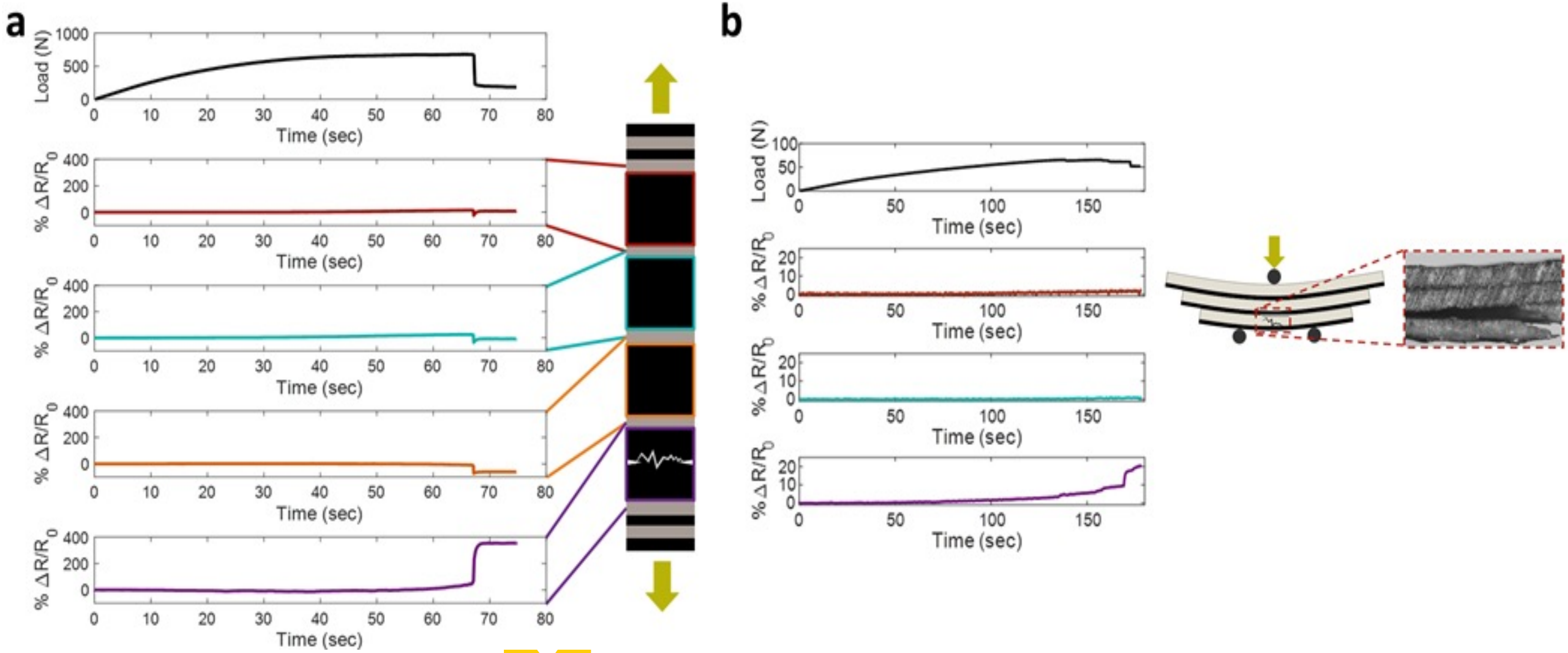




UNIVERSITY OF MICHIGAN


a
Voltage Output
Current Input
Time (sec)
Microphone (Pa)
b
Primary Tension
Force
Compression
Tension
Time (sec)

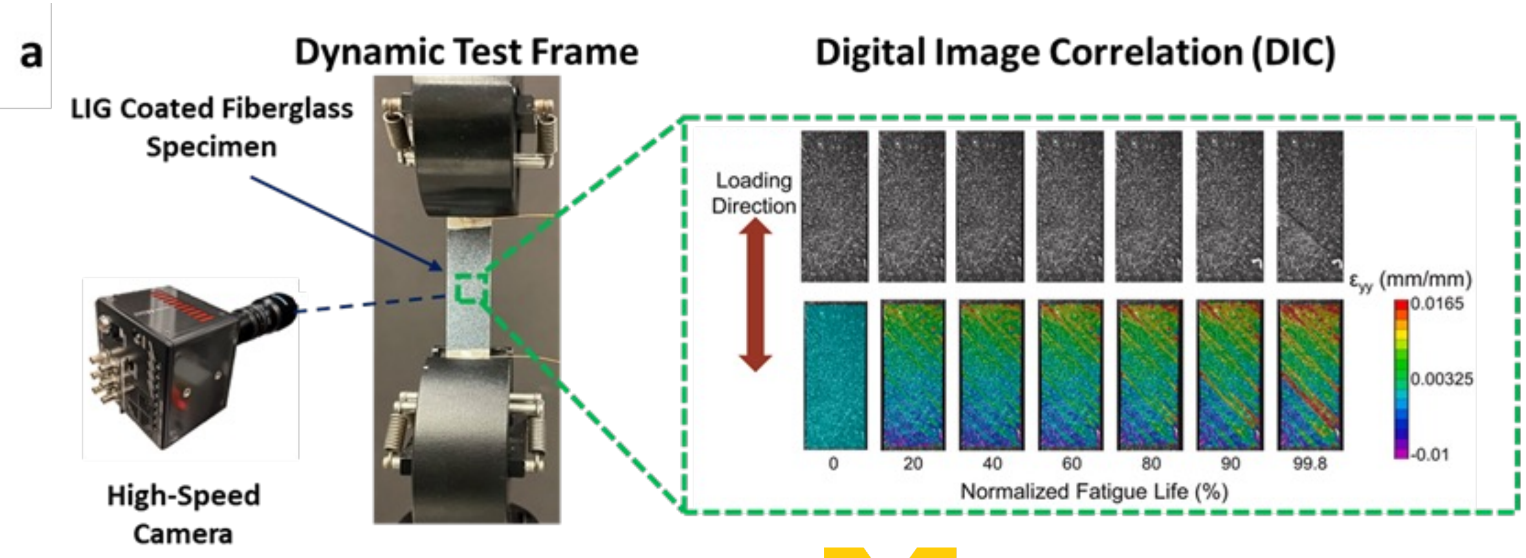
Damage Localization

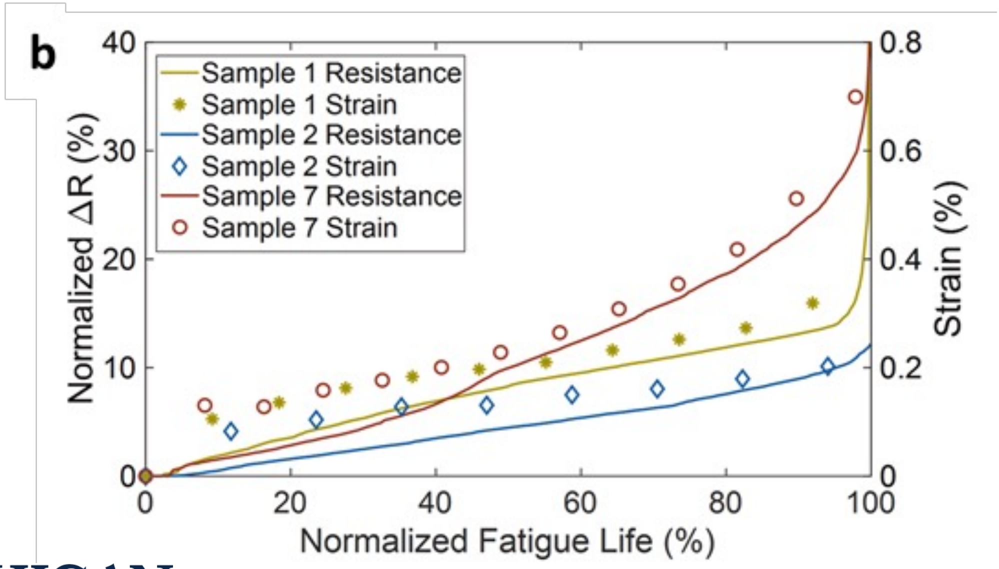


UNIVERSITY OF MICHIGAN

Characterization of Fatigue Loading

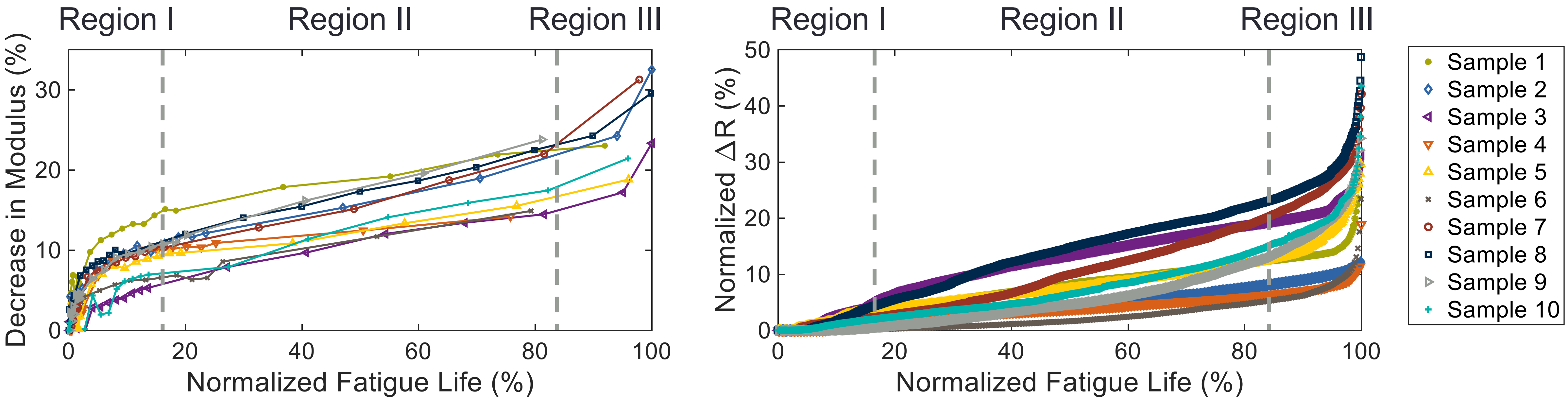
- Performed fatigue loading of ±45° specimens with LIG coating applied to the composite
- Used DIC to track the formation of damage int eh composite which can be correlated to resistance changes
- As damage accumulates in the composite the resistance of the specimen changes
- We can extract features from the data to try to predict the remaining life span





UNIVERSITY OF MICHIGAN

Characterization of Fatigue Loading



Region I: dominant form of damage is matrix cracking especially within off-axis plies

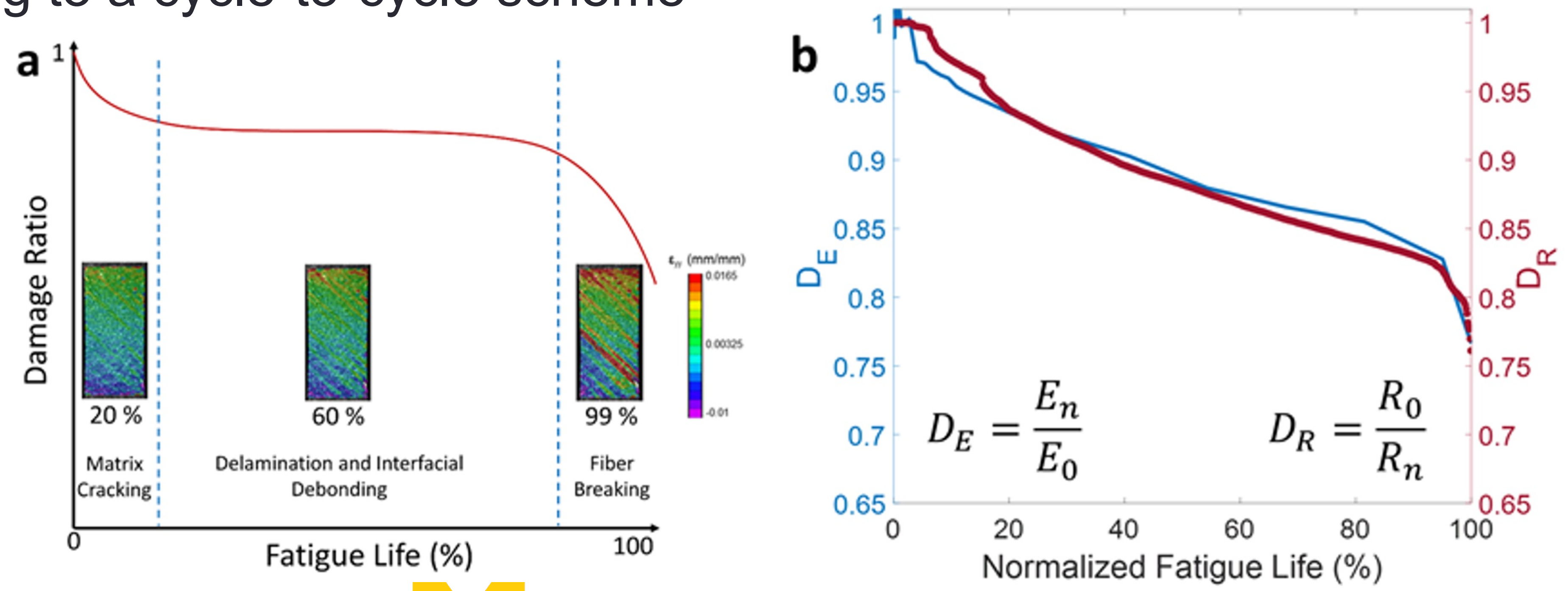
Region II: matrix cracking propagates and delamination with some fiber fracture occurs

Region III: severe damage initiation and propagation predominantly occurring as delamination and fiber fracture

UNIVERSITY OF MICHIGAN

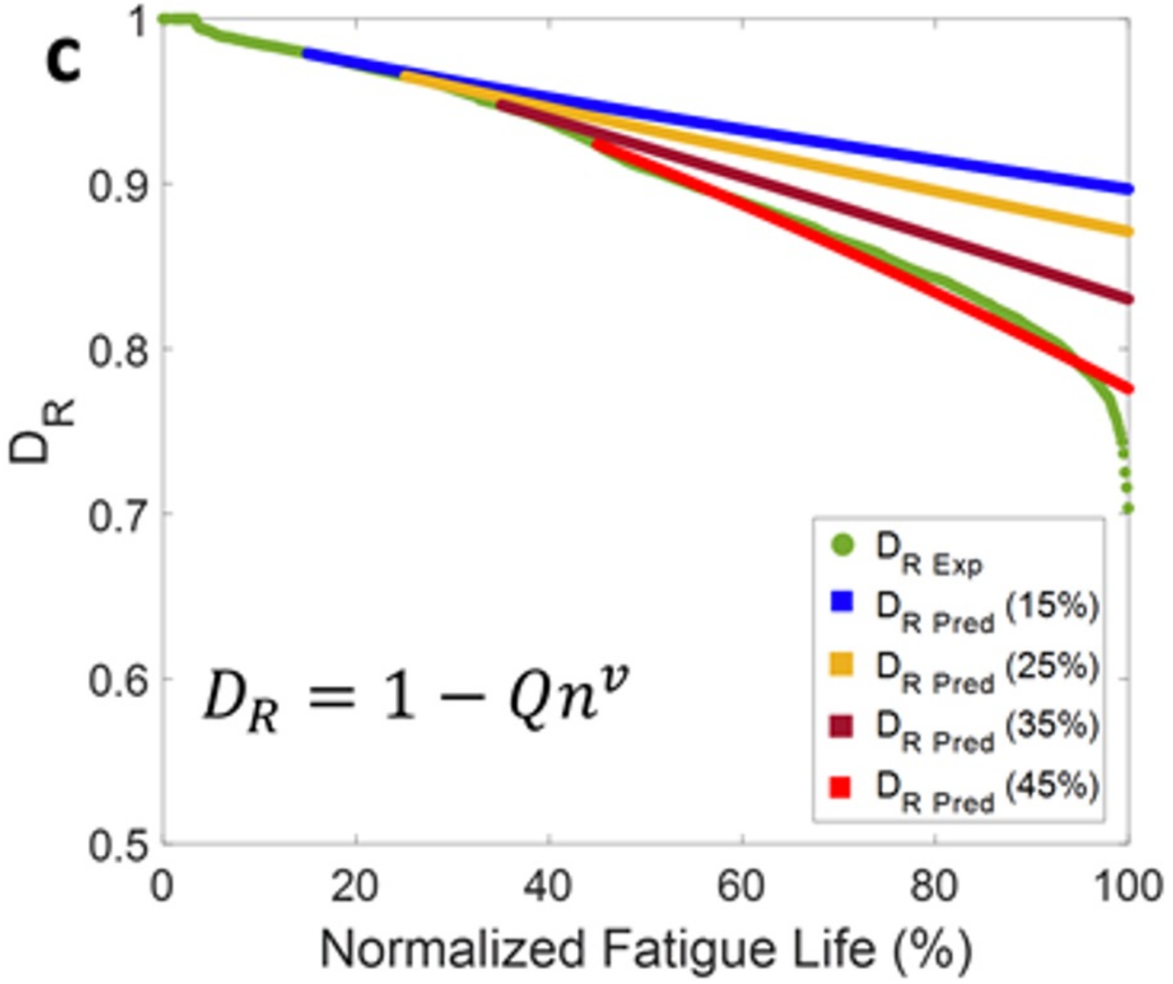
Fatigue Life Prediction

- Both elastic stiffness (D_E) and electrical resistance damage parameters (D_R) display comparable trends throughout the fatigue life
- Can use D_R to describe and predict the future damage state of fiberglass composited according to a cycle-to-cycle scheme



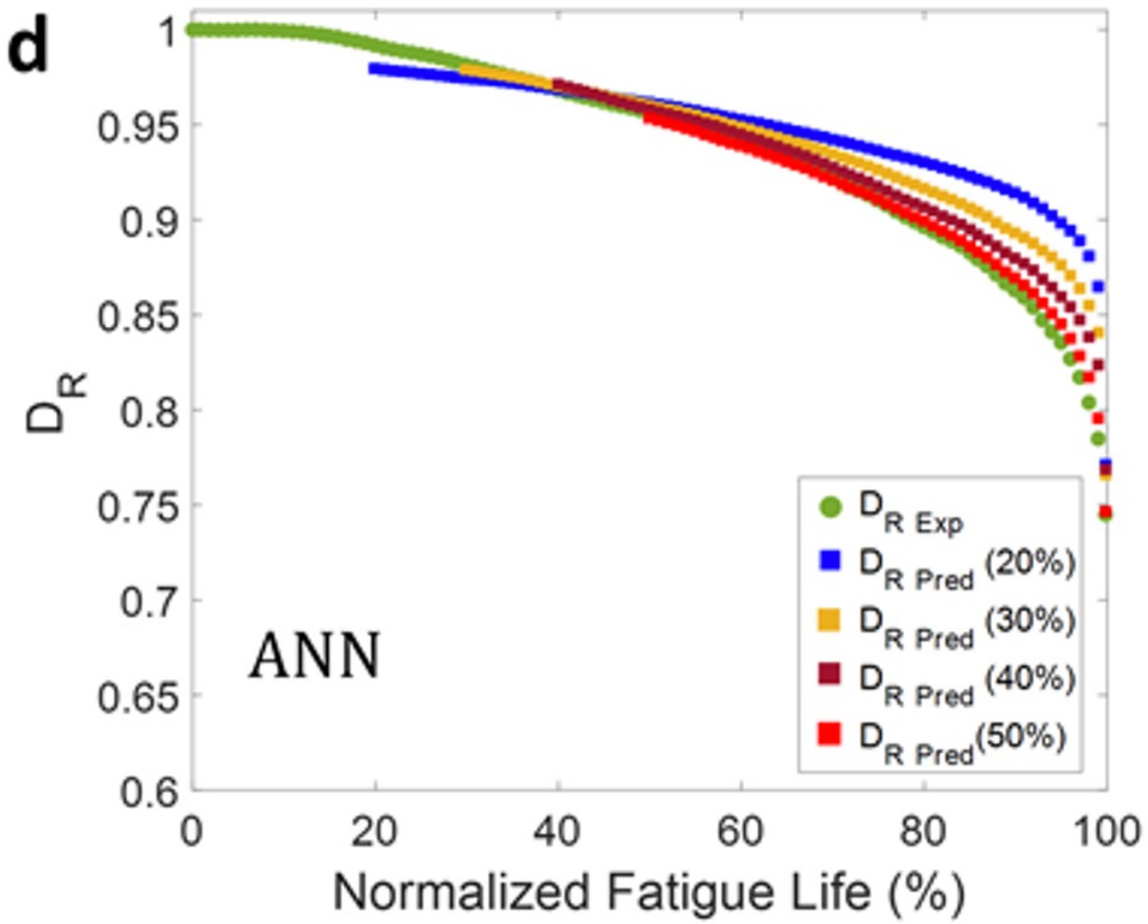
Fatigue Life Prediction

- A power function can be used to capture the piezoresistive response
- Phenomenological model is found capable of accurately forecasting future damage state in fiberglass composites based on a linear regression
  - where Q and v are material constants which can be determined using a least-square fitting, and n is the number of cycles
- Model is unable to capturing the final and highly non-linear damage phase



Fatigue Life Prediction

- Recurrent neural networks (RNNs) are suitable for continuously predicting fatigue damage progression and service life in the cycle domain
- RNN trained four different times using 10 different fiberglass specimens by supplying 20%, 30%, 40%, and 50% of the initial D_R measurements
- R^2 and RMSE corresponding for both training and testing cases when using more than 30% of the initial D_R measurements as inputs are found to be greater than 0.98 and lower than 2×10^{-4}, respectively



Summary

- Laser induced graphene is a novel technique to produce highly conductive graphitic materials at ambient temperature and pressure
- Process raster's a CO_2 laser on the surface of certain polymers to create the graphitic structure
- Our results have shown that multifunctional composites can be fabricated that provide both improved strength and embedded sensing
- Have measured damage progression on static and dynamics loading environments
- Machine learning approach has been demonstrated to accurate predict remaining life in composite specimens

Acknowledgements

- This work has been supported by the following organizations

Questions?