Since 1960...

- Composites have grown 16 times
- Aluminum has quadrupled
- GDP has nearly quadrupled
- Steel has doubled

Source:
Evolution of Composite Materials

Military Aerospace

- Initial Fibers and Resins
- Metallic Designs
- Hand Layup Fabrication
- Autoclave Processing
- Destructive Inspection

Generation I
1940s-1970s
Evolution of Composite Materials

System Characteristics

- Initial Fibers and Resins
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- Hand Layup Fabrication
- Autoclave Processing
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Military Aerospace
- Generation I
  - 1940s-1970s

Military Aerospace
- Generation II
  - 1980s-2010s

Military Aerospace
- Commercial Aerospace
- Sporting Goods

- Intermediate Modulus Fibers
- Design and Analysis Tools
- Designs for Composites
- Automation
- Autoclave Processing
- Liquid Composite Molding
- Non-Destructive Evaluation (NDE)
Evolution of Composite Materials

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Military Aerospace

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Core Markets & Adjacent Markets

- Aerospace
- Advanced Batteries
- Capacitors
- Energy
- Electronics
- Automobile
- Medical Devices
- Infrastructure

Generation I
1940s-1970s

Generation II
1980s-2010s

Generation III
2020s-

Georgia Tech Manufacturing Institute
Outline

- Multifunctionality
- Scalable manufacturing
- ICME
Disruptive Composite Materials Technology Needed To Meet Future Requirements

Future Requirements

System’s Benefits

Generation I

Generation II

Generation III

Multi-functionality
Scalable Nanomanufacturing of High-Performance and High Quality Buckypaper with Aligned and Crosslinked Carbon Nanotubes

- Integrated continuous sonication, filtration, functionalization, alignment stations
- Physics-based process modeling for manufacturing process control
- In-line sensing and control capabilities

Sponsor: NSF Scalable Nanomanufacturing (SNM) Program
New Manufacturing Technologies must undergo extensive qualification and certification testing

Typical Aircraft Qualification/Certification Path

- Range is determined by extent of new material, process and technology being introduced; and the amount of iterations
- Rotor and UAV platform costs are lower, large transport costs can be higher

<table>
<thead>
<tr>
<th></th>
<th>Specimen Count</th>
<th>Cost ($M)</th>
<th>Time (Yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-scale article</td>
<td>2-3</td>
<td>100-125</td>
<td>4</td>
</tr>
<tr>
<td>Components</td>
<td>10-30</td>
<td>10-20</td>
<td>3</td>
</tr>
<tr>
<td>Sub-components</td>
<td>25-50</td>
<td>10-35</td>
<td>3</td>
</tr>
<tr>
<td>Elements</td>
<td>2000-5000</td>
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<td>3</td>
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<tr>
<td>Coupons</td>
<td>5000-100,000</td>
<td>8-15</td>
<td>2</td>
</tr>
</tbody>
</table>

Risk of unplanned cost and schedule impacts causes barrier to manufacturing innovation

(Credit: Michael “Mick” Maher)
Enabling nano-material composites

- Gen I nano-material composites
  - E-glass
  - S-glass
- Carbon fiber composites
  - T300
  - IM7
  - T1000
- Glass fiber composites
- Gen II nano-material composites
  - Improved BP
  - CNT Yarn
- Gen III nano-material composites
  - Initial BP
  - Applied/translational and scalable manufacturing R&D
  - Fundamental and basic research

COST vs. BENEFIT/PERFORMANCE
Summary

- Multifunctionality
- Scalable manufacturing
- ICME
- Additive manufacturing
- Composite repair
Additive Manufacturing

Tooling...
Molds...
Sensors...
Innovative ideas?
GTMI’s Additive Manufacturing Capabilities: Printed/Flexible Electronics with Aerosol Jet Printing

- Optomec Aerosol Jet® Printing (AJP) system with high resolution printing (~10μm printed line width and nanometers thickness)
- Characterization tools for materials and printed devices
- Printed electronics prototypes fabricated at GTMI with the AJP system: strain, temperature and gas sensors, pressure sensors and actuators, organic transistors, RFID tag, high frequency antenna, and energy storage devices
Prototypes/Samples Printed at GTMI

- Strain sensor array printed with silver ink
- Interconnects linked with IC chip pins
- RFID tag on silicone
- Biosensors electrodes on paper
- RFID tag and antenna array on carbon fiber prepreg
- High frequency antenna

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CALLAC: Consortium for Accelerated Innovation and Insertion of Advanced Composites

“KAYAK”
Composite Joining and Repair (CJAR) Challenges

41 foot high tail vs. 38 foot tall hanger door opening
Source: Abaris

- Current bonded repair techniques are:
  - slow
  - costly
  - unreliable
  - unrepeateable
  - unpredictable
And often bonded repairs have to be bolted to comply with certification

Severely damaged aircraft radome
Source: Iowa State University

Qantas A380 Engine Failure
Source: REUTERS

Ethiopian Airlines Boeing 787 caught fire
Source: sky.com

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Financial Impact of CJAR

- **Lifecycle airframe** MRO cost (mainly composite repairs) is estimated at **7.7%** of the initial aircraft purchase cost.

- **A350**
  - Purchase cost: $270M
  - Airframe MRO: $20.8M

- **B787**
  - Purchase cost: $218M
  - Airframe MRO: $16.8M

- Total airframe lifecycle MRO cost for all A350 and B787 aircraft delivered by Year 2021 is estimated to be at ~$34.1B.
# Example Roadmap Chart

<table>
<thead>
<tr>
<th>SOTA</th>
<th>Technology Polymers</th>
<th>2016-2020</th>
<th>2021-2025</th>
<th>2026-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A wide variety of materials with ambiguous selection criteria</td>
<td>Thermoplastics</td>
<td>High performance thermoplastics; automotive and secondary aerospace structure</td>
<td>T4 M4 Bc6</td>
<td>T8 M10 Bc6</td>
</tr>
<tr>
<td>• Slow processing speed</td>
<td>Thermosets</td>
<td>High speed curing</td>
<td>T4 M4 Bc5</td>
<td>T8 M9 Bc8</td>
</tr>
<tr>
<td>• Complex supply chain interference</td>
<td>Nanocomposite based low moisture absorption and low oil swell resin system</td>
<td>T4 M4 Bc5</td>
<td>T8 M9 Bc8</td>
<td></td>
</tr>
<tr>
<td>• Lack of standardized material properties databases</td>
<td>Shape Memory Polymers</td>
<td>Shape memory polymers as a tooling aide or in a structural patch for rapid onsite repair</td>
<td>T6 M5 Bc5</td>
<td>T9 M10 Bc9</td>
</tr>
<tr>
<td>• Inadequate lifecycle analysis data</td>
<td>Self-healing Polymers</td>
<td>Self healing; non-structural application</td>
<td>T2 M3 Bc3</td>
<td>T8 M9 Bc9</td>
</tr>
<tr>
<td>• Limited recycling and repair options</td>
<td>Fibers &amp; Prepregs</td>
<td>Advanced resins (Benzoxazines, nanotoughened EPs) for prepregs</td>
<td>T2 M2 Bc3</td>
<td>T8 M8 Bc7</td>
</tr>
<tr>
<td>• Increased viscosity and stagnated resin flow limit improvements of nanomaterial inclusion</td>
<td>Thermoset Prepregs</td>
<td>Complex shape forming capability</td>
<td>T2 M2 Bc4</td>
<td>T9 M10 Bc9</td>
</tr>
<tr>
<td>• Short shelf life and difficulty of storage (prepreg)</td>
<td>Thermoplastic Prepregs</td>
<td>New self-healing platform as a healing agent container and reinforcement</td>
<td>T1 M2 Bc2</td>
<td>T8 M8 Bc8</td>
</tr>
<tr>
<td>• Standardized fiber property</td>
<td>Hollow Fiber</td>
<td>Universal thermostet fiber sizing for different polymer matrices and metal hybrid composites</td>
<td>T1 M2 Bc2</td>
<td>T8 M8 Bc6</td>
</tr>
<tr>
<td>• No general-purpose fiber sizing</td>
<td>Fiber Sizing</td>
<td>Performance</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Processing Speed</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td>Affordability</td>
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