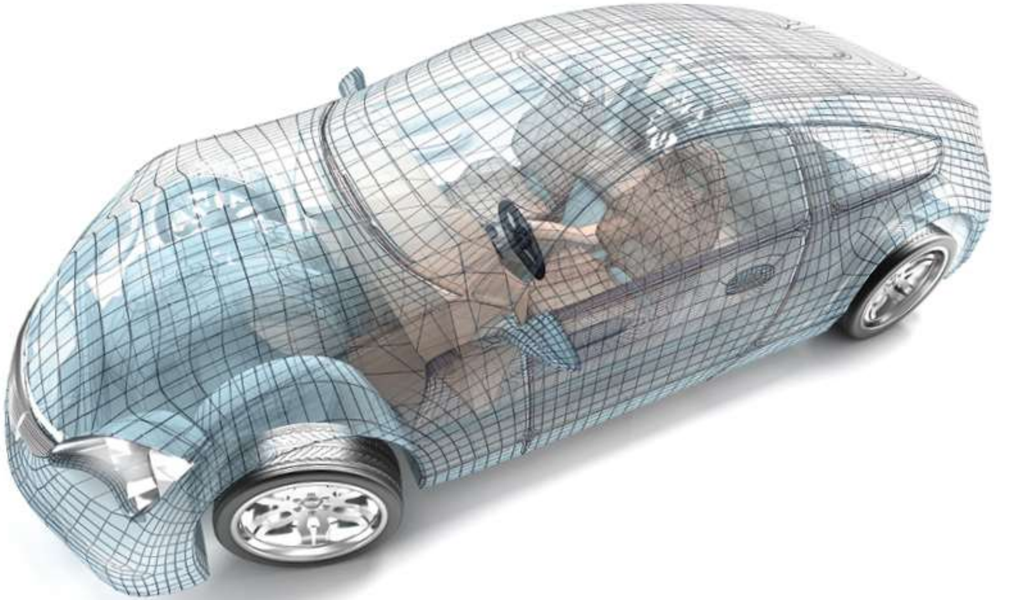
TCC 2020

THERMOPLASTIC COMPOSITES CONFERENCE

A VIRTUAL EVENT

APRIL 29 – MAY 1, 2020



# Aerospace Applications for High Performance Thermoplastic Composites

Presented By: Randy Wilkerson
Technical Fellow
The Boeing Company

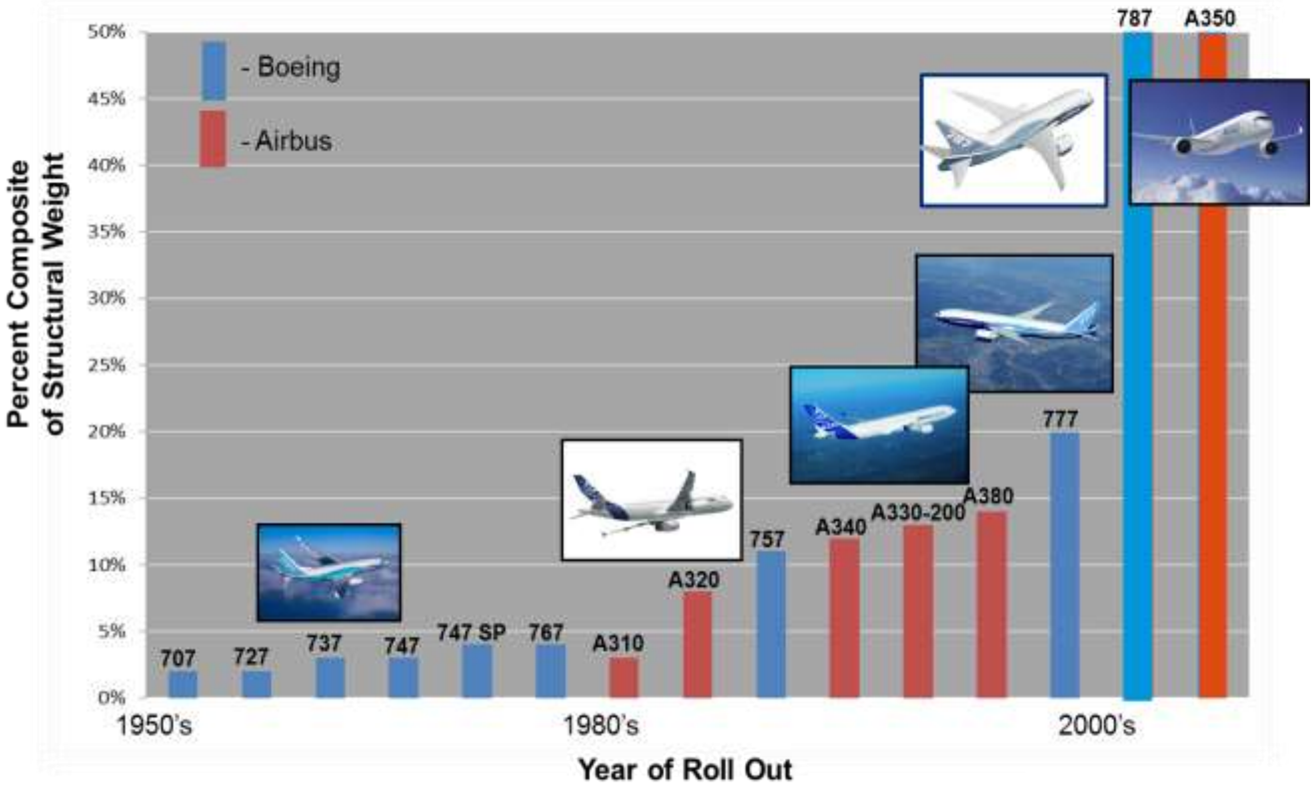
# Contents

- Early Thermoplastic Composites (TPC) Experiences
- Why Thermoplastic Composites?
- Current State of the Art
- Achieving higher manufacturing rates for Thermoplastic Composites
- Scaling Thermoplastic Composite Structures

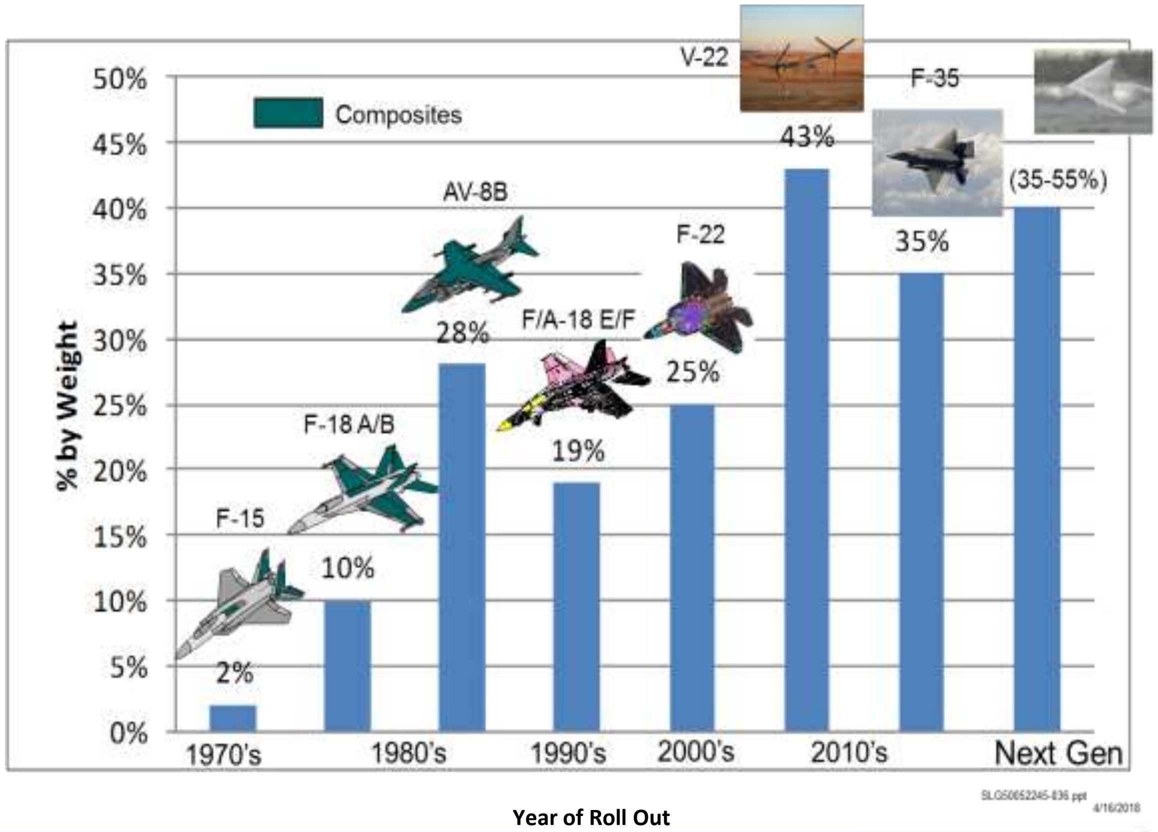
# Early Thermoplastic Composites Experiences

# Increased Usage is Driving Higher Manufacturing Rate Needs for Composite Structure

## Commercial Transport




## Military Aircraft



# TPC In the Evolution of Composites

| | 1970's | 1980's | 1990's | 2000's | 2010's | 2020's |
|---|---|---|---|---|---|---|
| | SM Fibers Epoxies | | IM Fiber Toughened Epoxies | | IM+ Fiber Thermoplastics, ... | High Rate Production |
| | Generation 1 | | Generation 2 | | Generation 3 | |
| Composite Material Systems – Fiber | Boron<br>T300<br>Fiberglass | AS4<br>IM6 | IM7 | T800 | IM8<br>IM10<br>IM+ | High stiffness fibers<br>Low cost fibers |
| Composite Material Systems – Resin | 934<br>3501-6 | PMR-15<br>PEEK<br>R6376<br>Net resin Prepregs<br>8551-7 | PEKK<br>BMI / PMI<br>8552<br>5250-4<br>977-3<br>BMS8-276<br>3900 | 5215 | 5320-1<br>Thermoplastics | Fast curing resin<br>Resins for improved producibility |
| Manufacturing Techniques | <br>Hand Layup<br>Fiber winding | Pre-preg tape<br>CTLM | Fiber Placement<br>RTM<br>VARTM | Hot Drape Forming<br>AFP | Additive<br>OoA<br>Thermal-forming<br>Full charge forming<br>Over-molding | Innovative joining<br>High Volume Infusion |
| Applications | Fairings<br>Radomes<br>Control Surfaces | Cocures<br>Wing Skins<br>Spars | Thick Structure<br>Empennage<br>Commercial Control Surfaces | Commercial Wing | Commercial Fuselage Monocoque | Large Components At Higher Rates<br>More Integration<br>Multifunctional |

# Early Years of TPC vs. Present

### 1980's-1990's

- Processed similar to thermosets
- Immediately scaled to large parts
- Low maturity level of materials
- Difficult & slow to hand layup & tack plies
- Used Insitu-AFP
- Lack of robustness w/high temp bagging materials and autoclaves

### Early 2000's – Present

- Developed TPC-specific processes to take advantage of characteristics of materials: "boardiness" and rapid cycles (minutes vs. hours in a/c).
- Avoid hand layup, tacking, high-temp bagging, & autoclaves
- Multiple processes developed based on part geometry, quality requirements, and rate
- Started with simple, small parts and scaling as we learn
- Better understanding of materials
- Materials/processes co-developed for producibility
- Improved automation - AFP, ATL, Pick & Place, etc.
- Introduced novel processes for creating unitized structures

# Why Thermoplastic Composites?

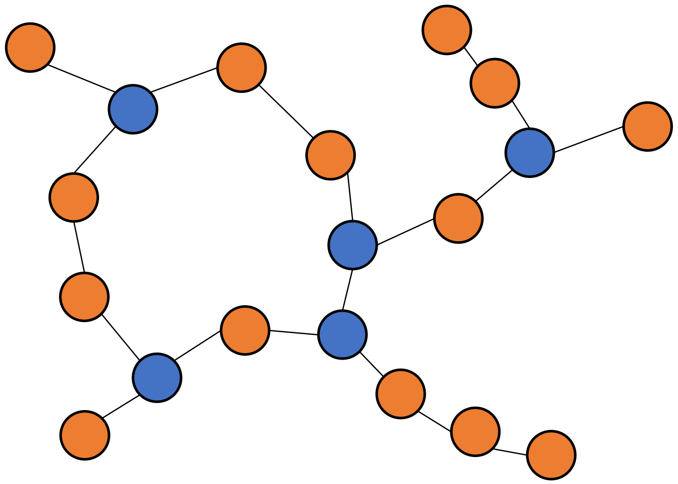
# Thermoset/Thermoplastic Composite Comparison

**Thermoset Composites:**

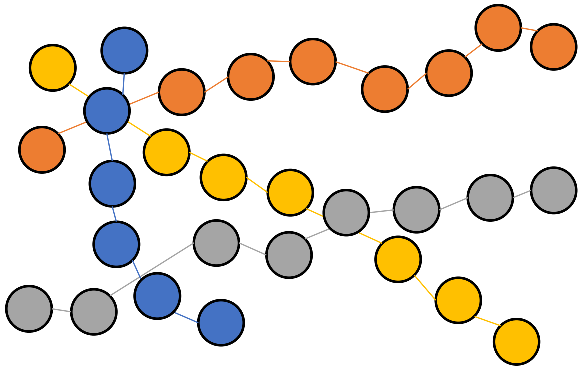
- Chemical reaction
- Amorphous material
- ‘Toughened system’
- Low viscosity
- Low processing temperatures
- Controlled heating
- High water uptake
- High solvent uptake

**Thermoplastic Composites:**

- No chemical reaction
- Semi-crystalline material
- Inherent ‘toughness’
- High viscosity
- High processing temperatures
- Controlled cooling
- Low water uptake
- Low solvent uptake



Thermoset Network Diagram



Thermoplastic Polymer Diagram

# Why Thermoplastic Composites for Structural parts?

## Design Benefits –performance improvement (weight savings):

- Improved durability, toughness, impact resistance
- Better interlaminar tension properties –enables part configuration not practical in thermoset
- Meets Aerospace Operating Temperature
- Excellent flammability properties –significantly better fire, smoke & toxicity resistance
- Low moisture uptake and thermal stability (0.25% RH vs. >1.0% RH for TS)
- Enabler: expand design space using innovative joining methods

## Manufacturing Benefits – cost / flow improvement:

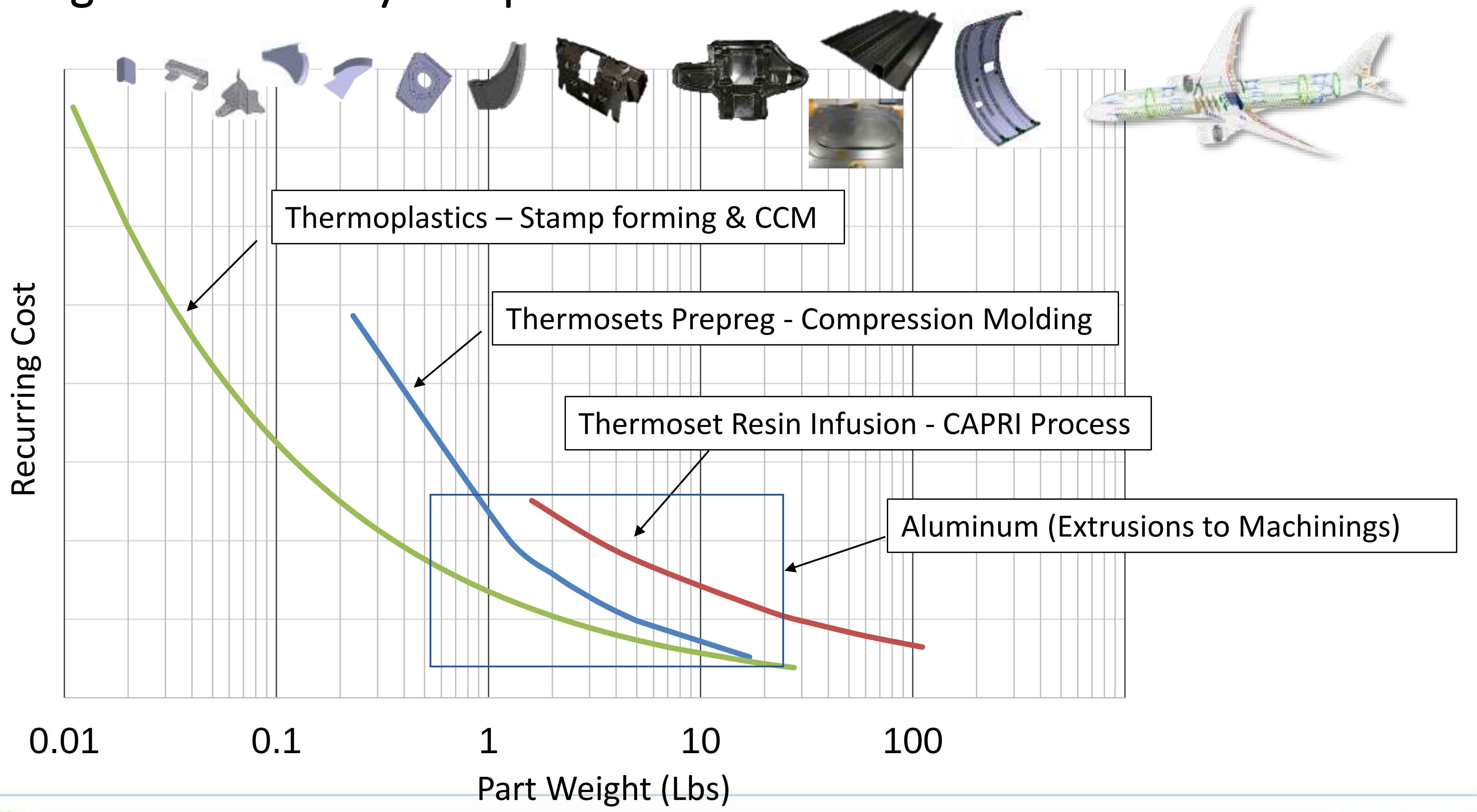
- No material out time limitation, no freezer needed for storage, indefinite shelf life
- Chemically inert, no chemical reaction, only heating & cooling
- Much lower part cycle time (no autoclave and preparation for it), enables higher rate capability
- Eliminates costly and time consuming bagging
- Production processes can be highly automated
- Clean hole drilling and machining, no fabric surface ply needed
- Offer more assembly joining methods –Welding, co-consolidation, secondary forming & etc.
- Reduced waste and consumables (bagging) and recyclable
- Production Cost Savings

# Sustainability Strategic Initiative

**Description**
- **Embrace United Nations Sustainability Development Goals**


- Invest as Boeing; Catalyze the industry, secure support from broader interests
- Develop and implement sustainable/recyclable materials
- Emphasize Lifecycle Utilization and Recycling in Aircraft Design

# Recurring Cost Trends by Component Size

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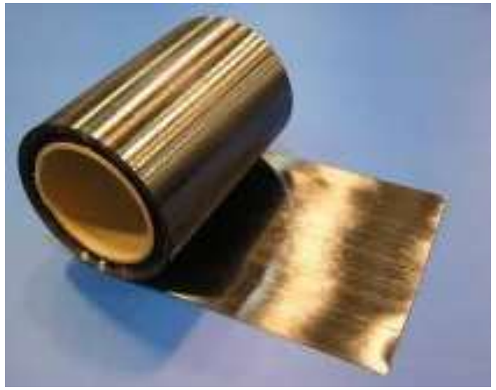
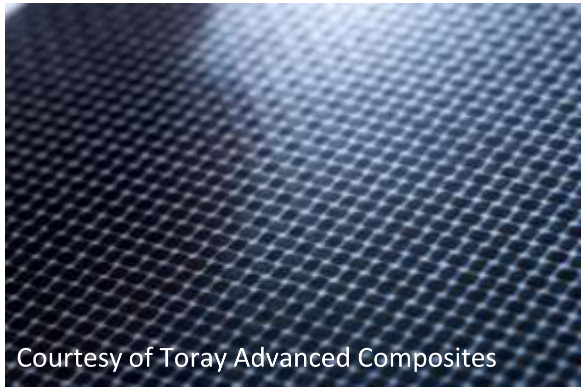
# Current State of the Art

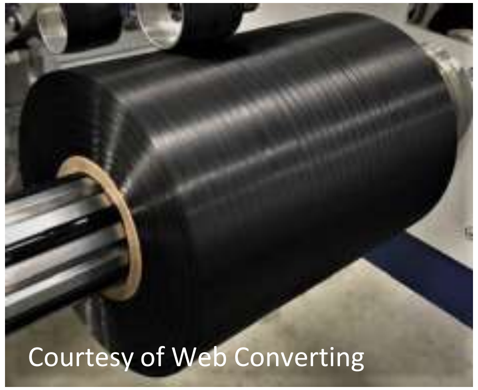
# Typical TPC Materials used in Aerospace

| Fibers | Polymers | Forms | Manufacturers (polymer/prepreg/sheets) |
|---|---|---|---|
| • SM<br>• IM<br>• S glass<br>• E glass | • PEEK<br>• PEKK<br>• PAEK<br>• PPS<br>• PEI | • 12” wide UD tape<br>• 2” wide UD tape<br>• Fabric Semi-preg<br>• Pre-consolidated fabric or tape panels (a.k.a. organo sheets) | • Solvay (Cytec)<br>• Toray (TenCate)<br>• Teijin (Toho)<br>• Barrday<br>• Victrex<br>• Porcher<br>• Cramer<br>• Evonik<br>• Arkema<br>• Bond |





Courtesy of Toray Advanced Composites



Courtesy of Web Converting

Courtesy of Trelleborg Sealing Solutions, Albany (TSS Albany).

# Processes for High Rate TPC Manufacturing


Automated Tape Layup (ATL)


Pick & Place Layup


Automated Fiber Placement (AFP)


Braiding


Automated Material Conversion (Off-axis rolls)


Press Consolidation / Compression Molding


Stamp Forming (Thermoforming)

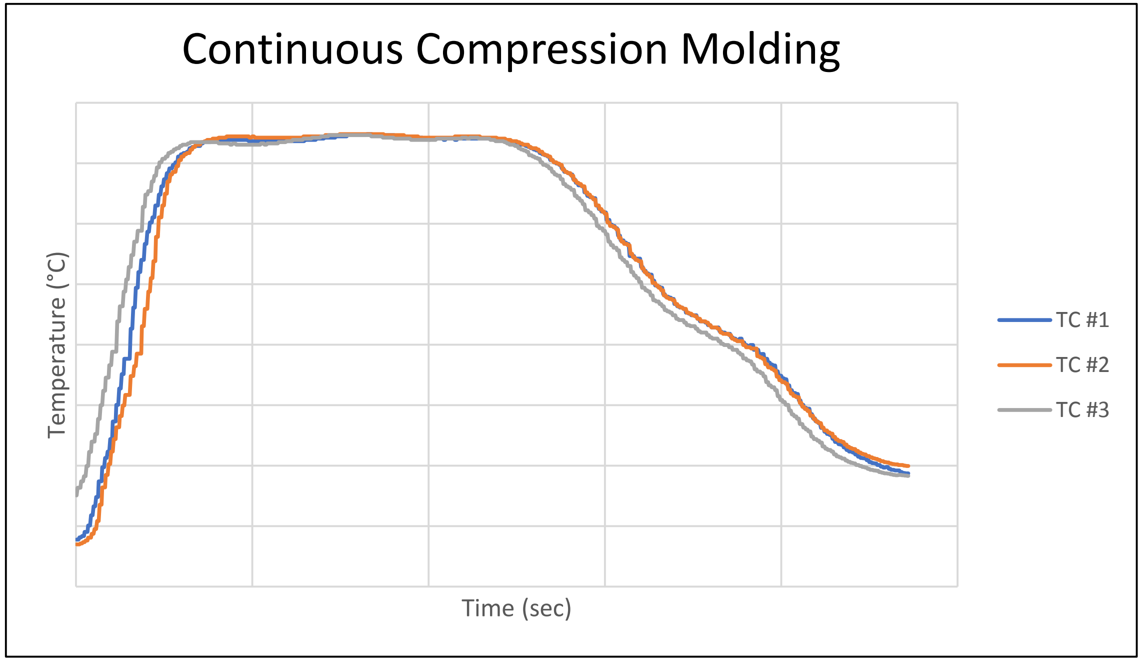

Continuous Compression Molding (CCM)

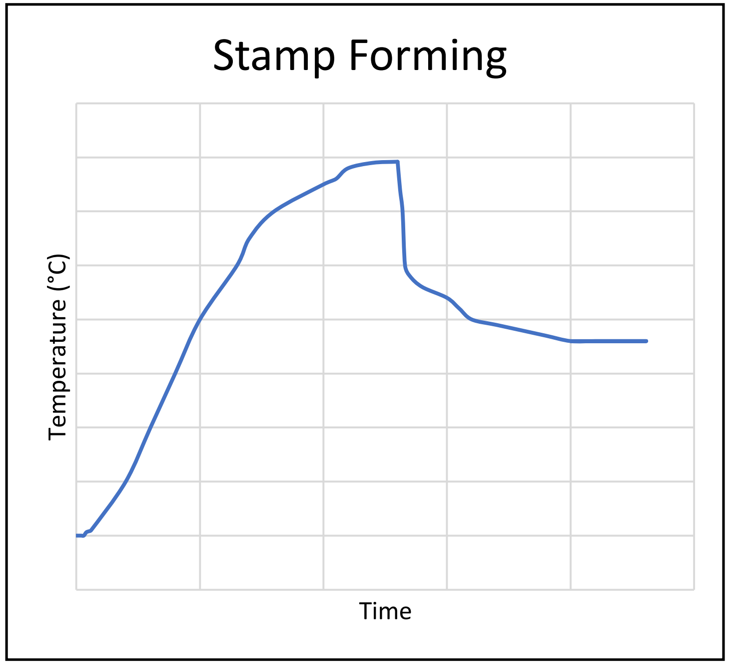

Self-Heated Tooling


Thermoplastic Welding

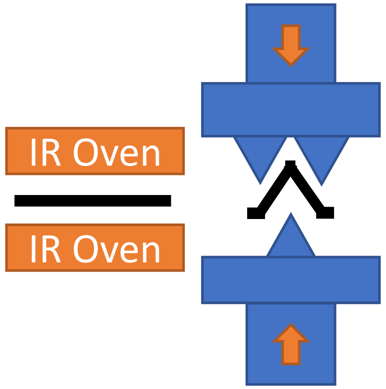

Advanced Assembly

# Different TPC Processes Result in the Similar Mechanical Properties







# Challenges in Composite Fabrication Automation

## Achieve Ply Laydown Definition and Requirements

- Meet Material Placement Specification Tolerances at High Laydown Rates (AFP, ATL, Braiding, Auto Rolls,…)
- Layup Complexity (Ply Drop-Offs/Ramps) Affects Laydown Speeds
- In-Process Inspection of Gaps and Overlaps
- Optimize Processes for Material Tolerances, Bulk Factor, and Environmental Condition Variability
- Laydown Equipment Reliability and Cost
- Hybrid Laminate Layups: Tape and Cloth, Tape Width
- Optimize materials for producibility, cost savings will follow

## Following Complex Contours for Sealing and Coating Applications

- Automated Fay, Fillet, and Edge Sealing
- Placement of Erosion Protection and Other Coatings

## Automated Forming to Produce Parts Without Wrinkles and Other Defects

- Thermoplastics: Thermoforming, Continuous Compression Molding, Compression Molding,
- Accurate Sensor/Monitoring During Consolidation

## Drilling and Fastener Installation for Composite Assemblies

- Complex Interfaces and Fit Up Issues due to Ply Drops, Ramps, and Bag-Side Surfaces
- Composite-to-Metal Joints
- Maintaining High Tolerance (.005” to .008”) Gap Allowances for Complex Moldline Mating Surfaces

# Examples of Low Cost/High Rate TPC Components

What will it take to achieve even higher manufacturing rates for TPC?

- In-depth Understanding and Analytical Trade Tools for Materials, Processes, Tooling, and Equipment
- Design for Producibility
- Robust Production System

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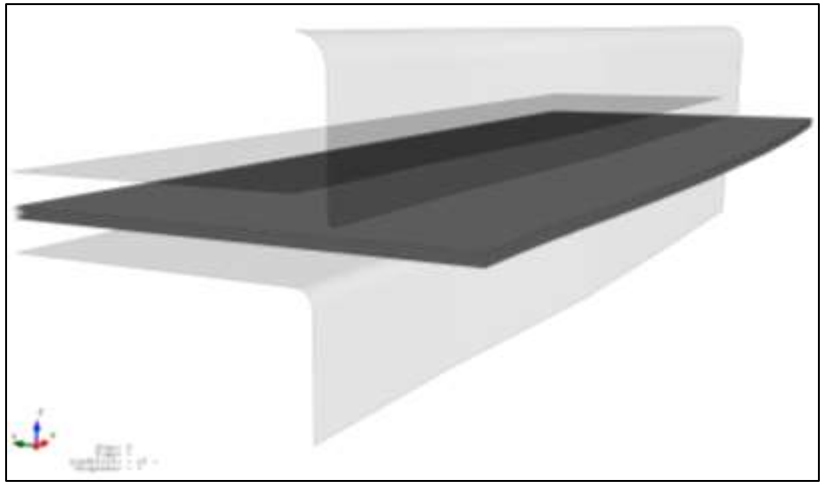
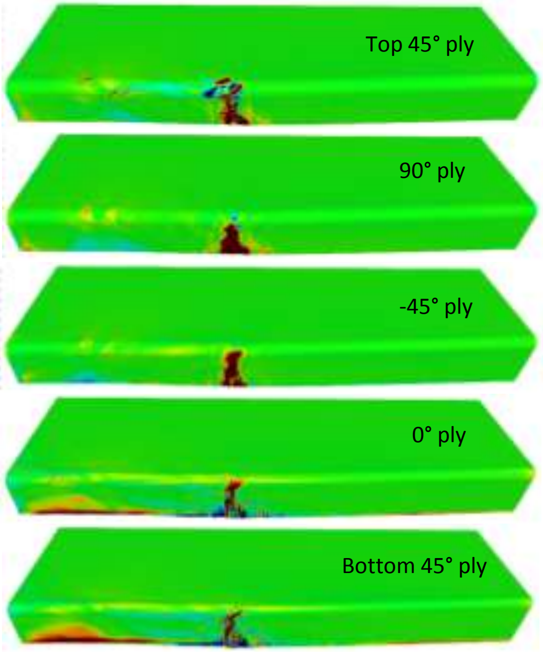
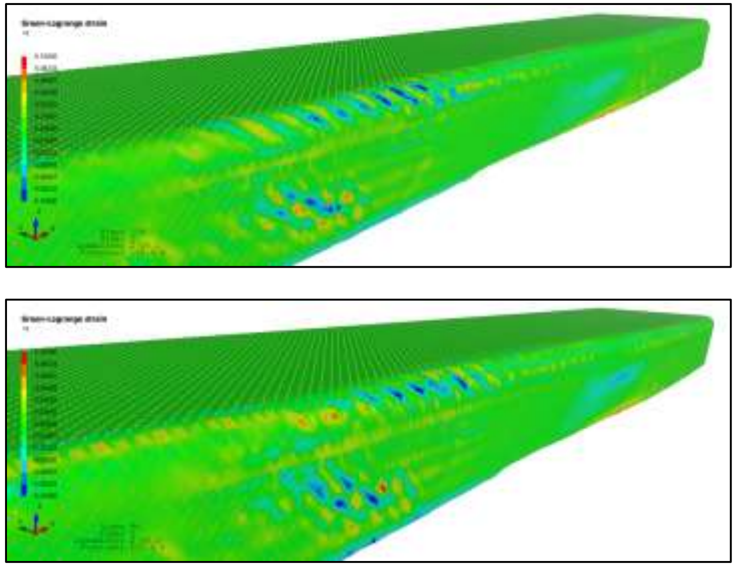
# Analysis & Predictive Capabilities



## Process Modeling

- Forming/Wrinkling
- Thermal/Tooling Compensations
- Consolidation Process: Polymer Kinetics, Shrinkage, etc.
- Effects of processing on polymer
- Environmental Effects

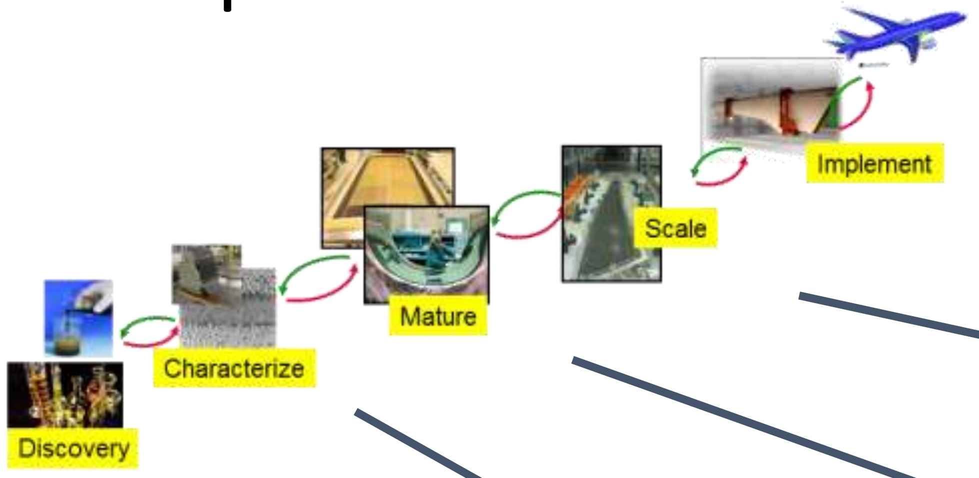


## Big Data / Analytics

- DataHub; Data-mining
- Value stream mapping
- Cost models
- Machine Learning
- Production System Modeling

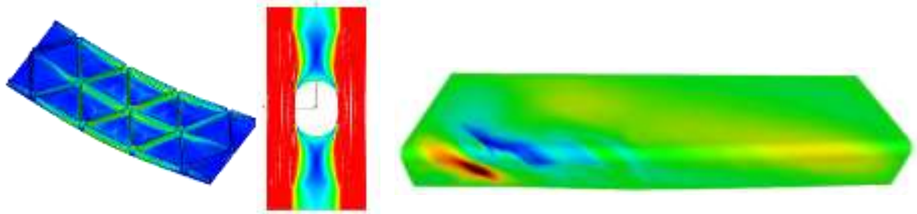
# Composite Materials & Processes Development in the Digital Lab




**Demonstrate**

**Improved Production Rates and Part Quality**

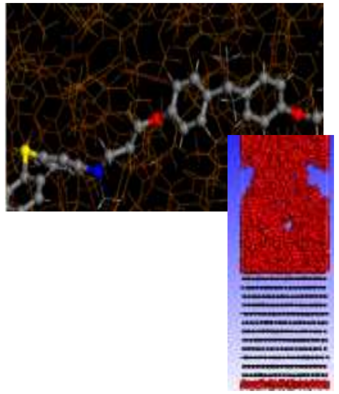
**Scale**



**Failure Theory and FEM Predict Full Scale Part Properties**

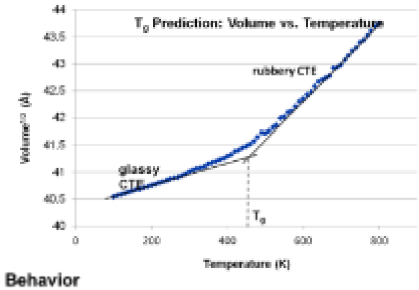
**Process Window, Process Robustness, Dimensional Tolerances, Acceptable Part Anomalies Predict Full Scale Part Processing Parameters**

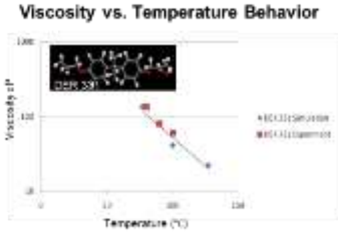
**Discovery**



**Atomistic Models Predict Molecular Motion and Material Interactions**

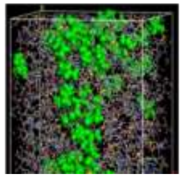
**Characterize**



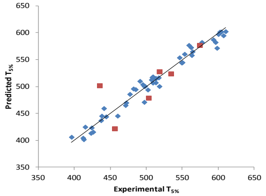

**Atomistic Models Predict Bulk Material Properties**

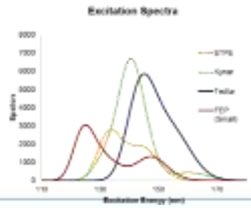
**Mature**



Fluid uptake

Thermal oxidative stability



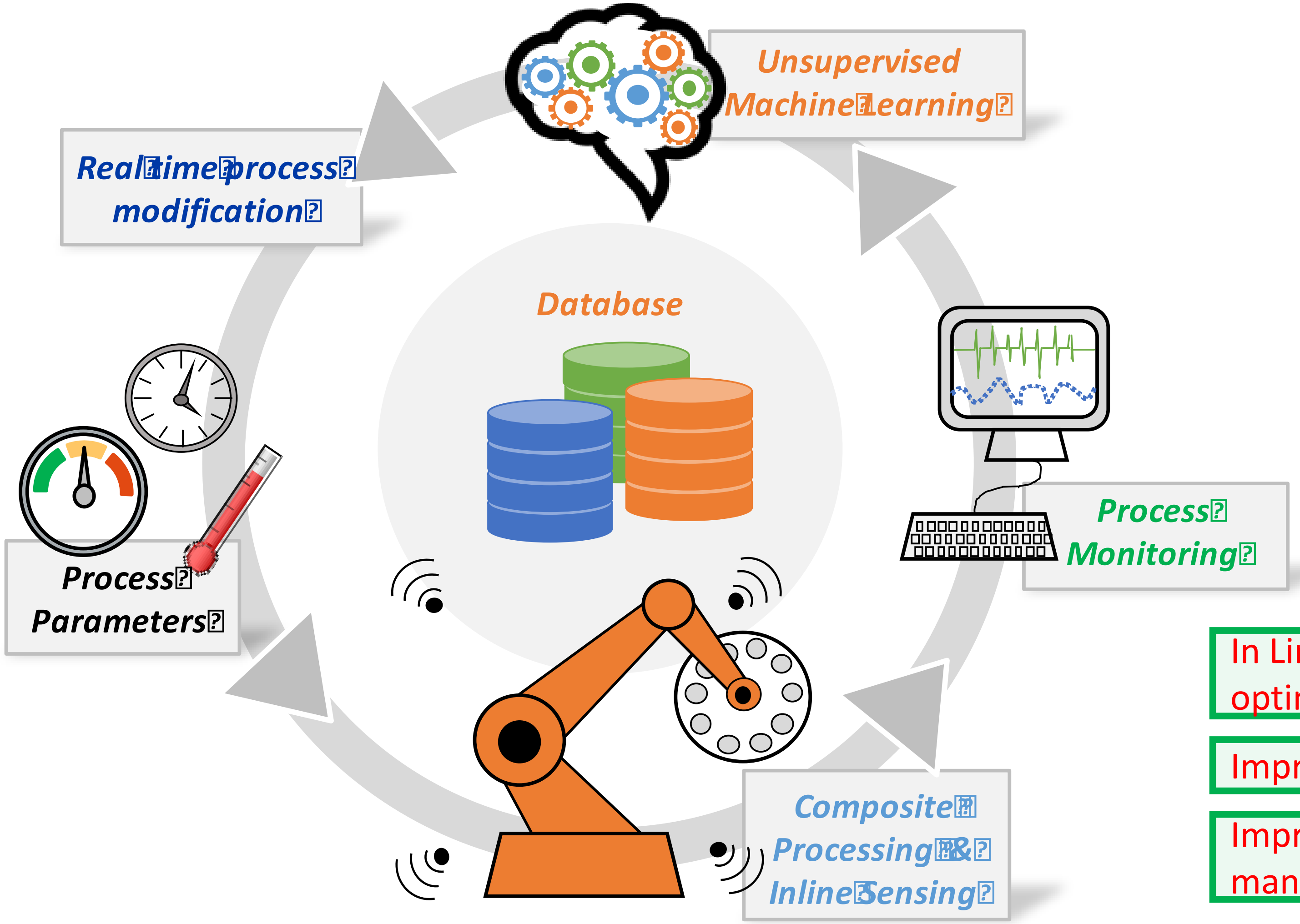




UV sensitivity

**Informatic, Quantum, and Atomistic Models Predict Aging Effects**

# New Approaches for Using Data Analytics for Manufacturing Processes:

## Real-Time, In-Line Process Optimization through Unsupervised Machine Learning




In Line, real time process optimization

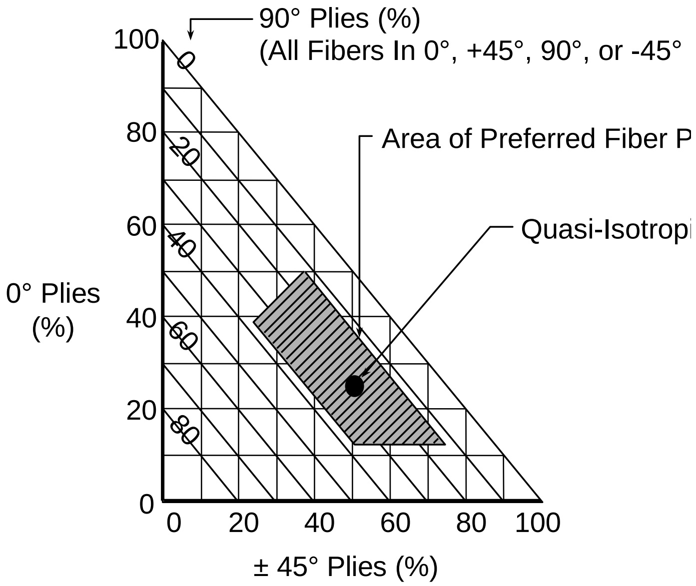
Improved Specifications

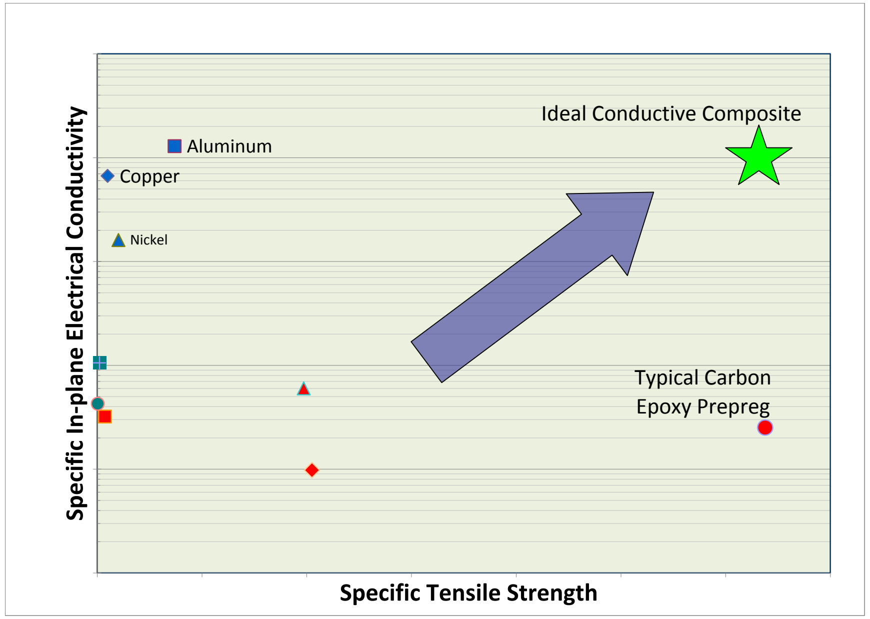
Improved Design for manufacturing

New skills in simulation, sensors, data, computers, integration are required

# Challenges for Certification of Composite Structures

- Design & Analysis Guides for Composites
- Models for Multi-Functional Properties
- Accurate Failure Predictions
- Standardized Test Methods



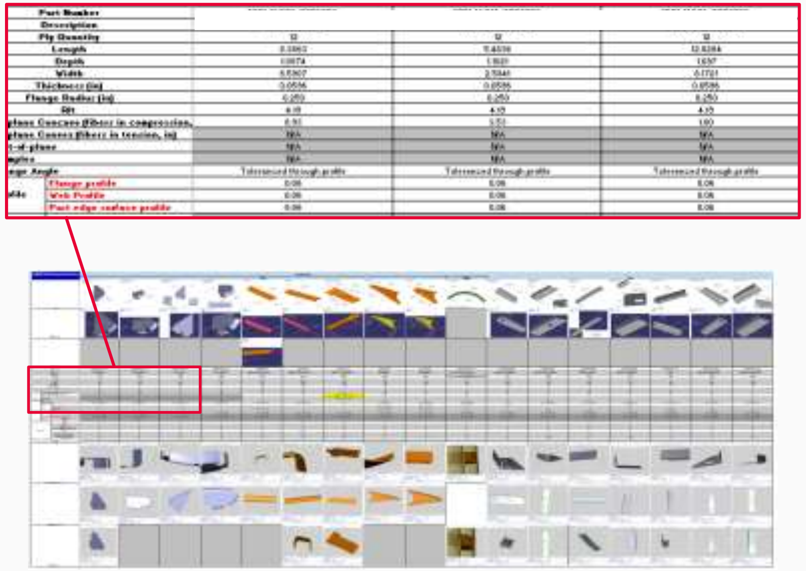

2 Layups – 2 Different Failures

# What will it take to achieve even higher manufacturing rates for TPC?

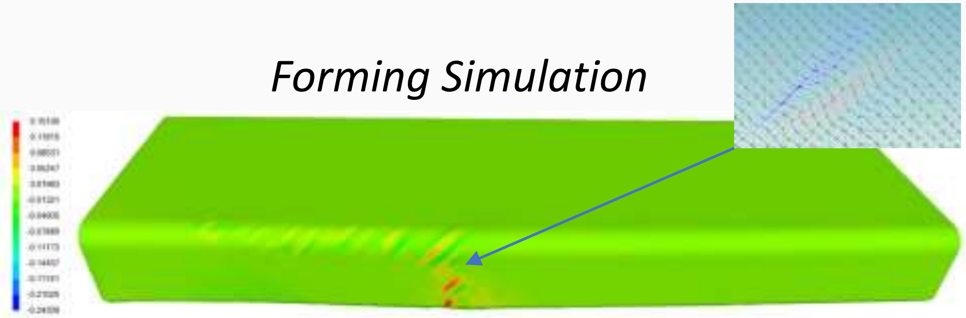
- In-depth Understanding and Analytical Trade Tools for Materials, Processes, Tooling, and Equipment
- Design for Producibility
- Robust Production System

# Continuous Improvement of Producibility Guidelines for Thermoplastic Composites

*Produced Part Evaluations*



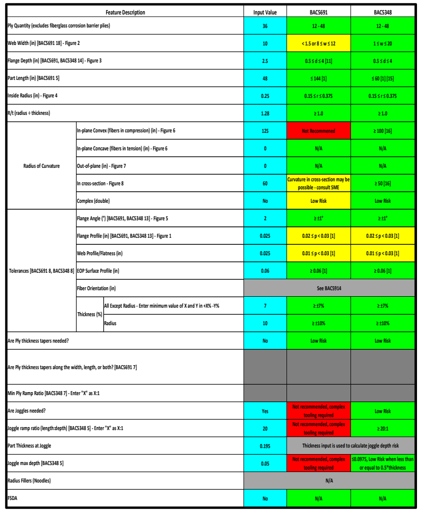
*Forming Simulation*



*+ Experiences*

*Producibility Guidelines*

*Producibility Checklist*



Boeing Design Manual

Tool Design Manual

Process Specifications

## What will it take to achieve even higher manufacturing rates for TPC?

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# Production Modeling and Simulation

**Project Examples**

- New Production Lines
- Existing Production Lines
- Multi-Program
- Suppliers

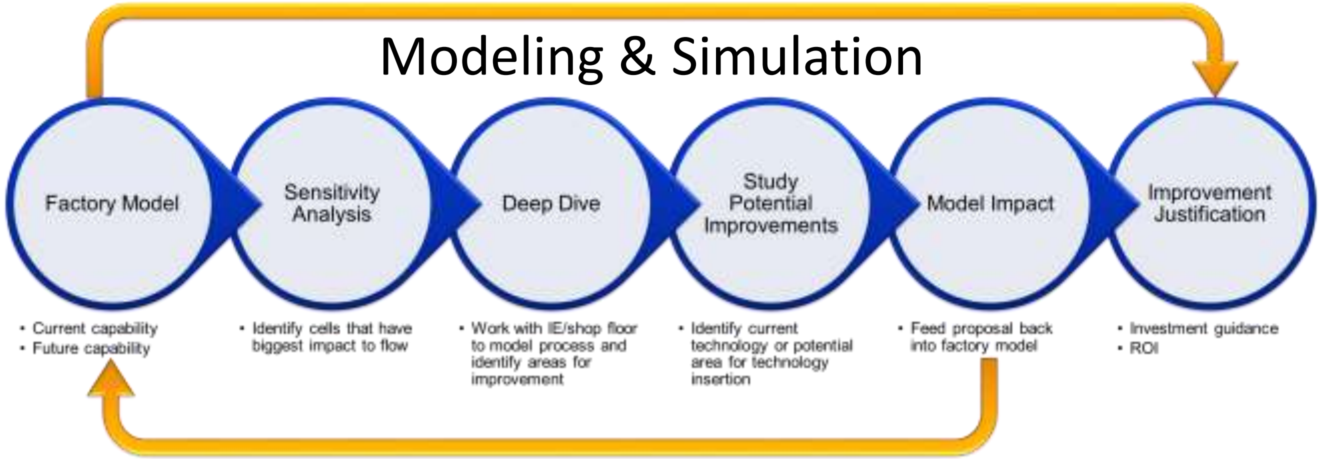
**Examples Scenarios**

- Rate Ramp Up
- Factory Layout Creation/Comparison
- Incorporation of Model Mix
- Capability Across Multiple Programs

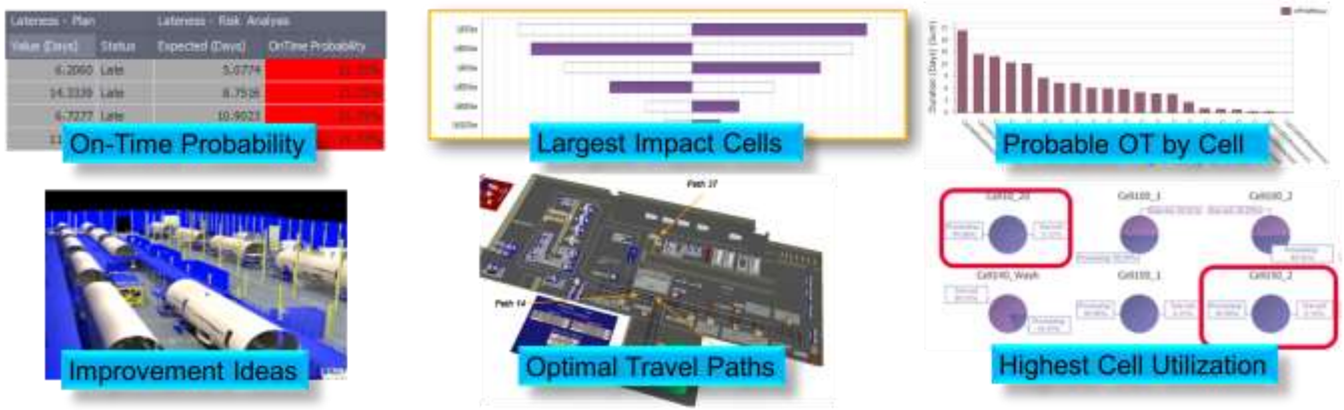
**Example Outputs**

- Highest Risk Cells/Builds
  - Focuses Improvement Projects/Investments
- Rate Capability
  - Incorporation of Learning Curves, etc.
  - Probability of Delivery On-time
    - With Overtime
    - Without Overtime

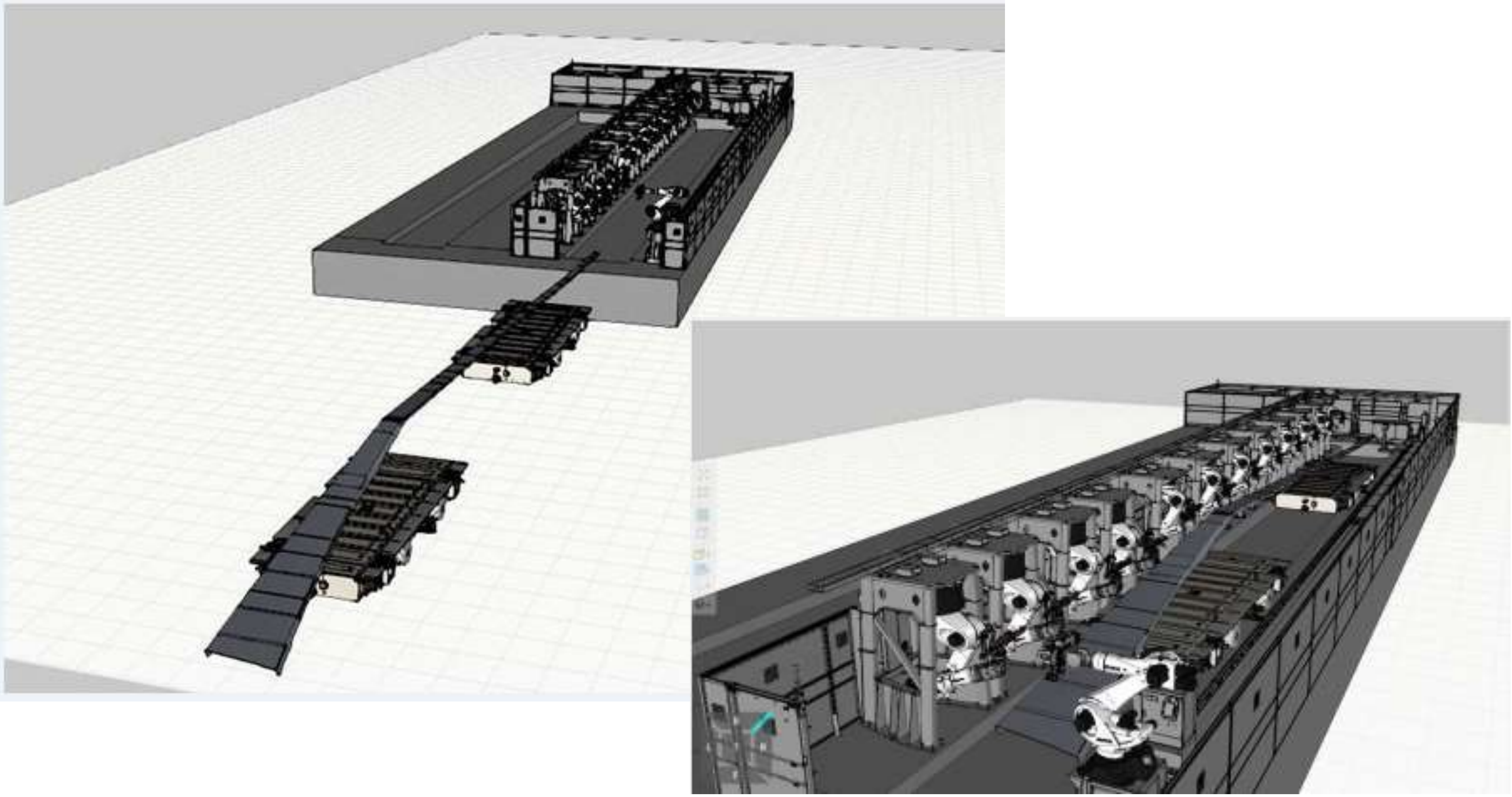
## Efficient Factory for High Rate Production

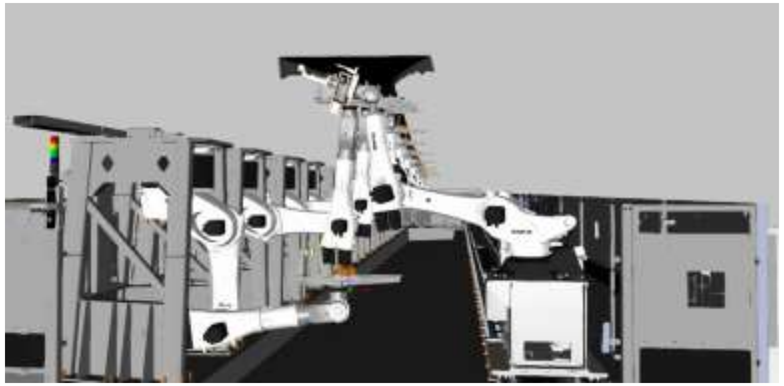



**Outputs**



# EXAMPLE: In-Line Process Control & NDI





Need to leverage thermoset inspection systems but optimize for TPC

Images provided by Genesis Systems Group

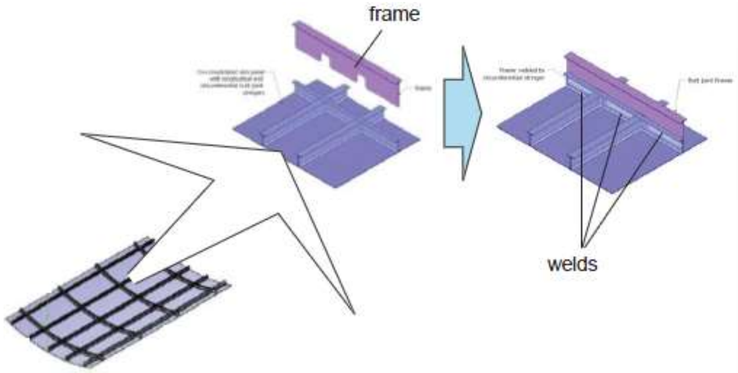
# Scaling Thermoplastic Composite Structures

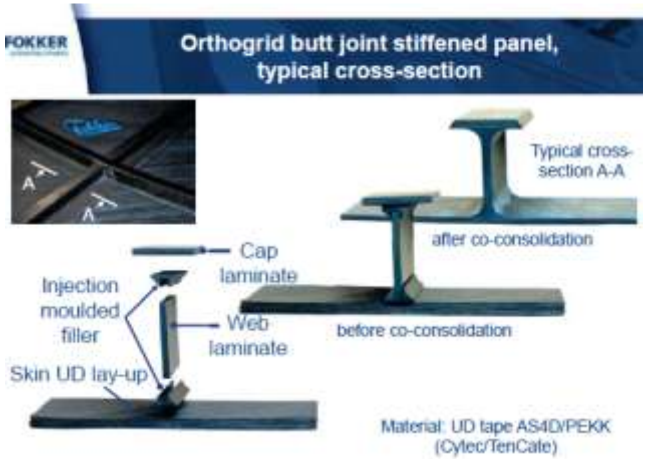
# Continue Improving High Rate TPC Production Technologies

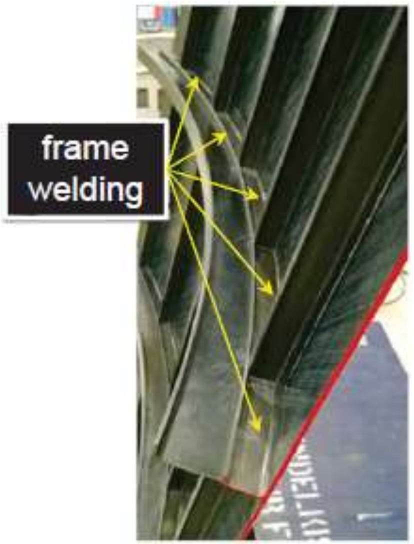
- Multiple New Materials and Manufacturing Processes are needed to improve producibility for high-rate manufacturing processes
- Even More Efficient Automation Processes Required
  (ATL, AFP, Pick & Place, Including Prime, Paint, Seal, Drill & Fasten)
- Improve Producibility & Achieve Quality
  Assurance at High Rates (at Boeing and Suppliers)
- Repair Methods for TPC
- Improved Non-Destruction Inspection methods
  - Optimize inspection criteria for TPC versus straight adoption of thermoset requirements

# EXAMPLE: Orthogrid Thermoplastic Butt Joint Stiffened Panel with Welded Frames

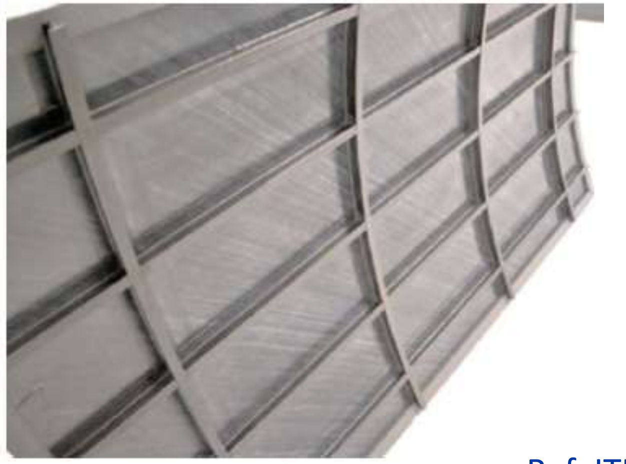
- GKN Fokker Demonstrated Their Butt-Joint Technology to Create an Orthogrid Structure, after which Frames Are Welded On Using Hot Plate Welding. Trade Study on a 10ft Diameter Fuselage Showed ~30% Weight Savings for Equivalent Cost.







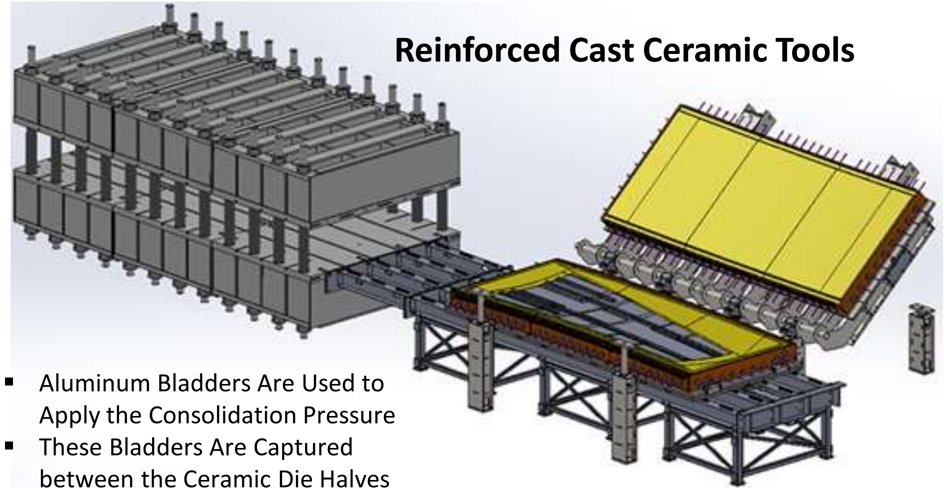
Ref: ITHEC Bremen, Oct 2014 (Fokker)

# EXAMPLE: Consolidation of Thermoplastic Composites Using Induction Coils and Smart Susceptors for Enhanced Press Heating and Temperature Control for High Rate Production


- Restraint and Tooling Handling System Are in Place
- Reinforced Cast Ceramic Tools Are Currently Being Fabricated

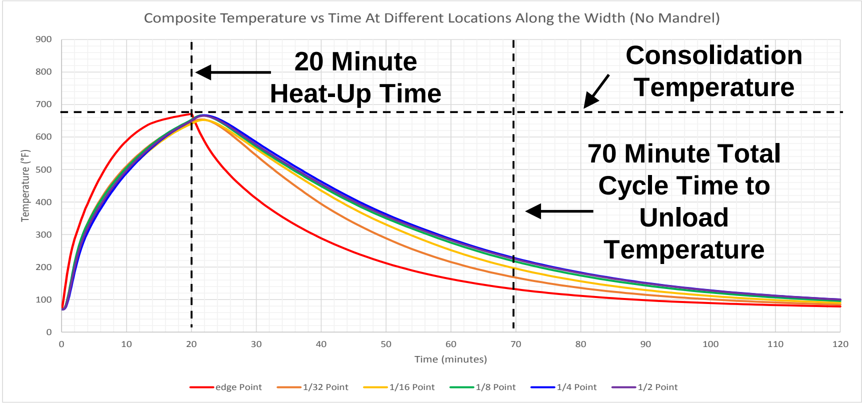
**Objective:** Consolidation of Large Complex Shaped Thermoplastic Composite Aerospace Structures with Cycle Times Measured in Minutes Rather Than Hours

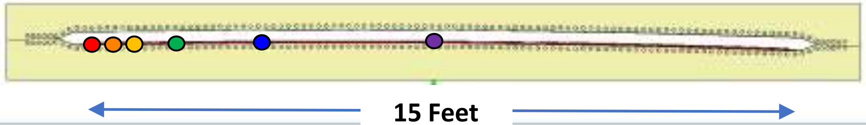

**Reinforced Cast Ceramic Tools**



- Aluminum Bladders Are Used to Apply the Consolidation Pressure
- These Bladders Are Captured between the Ceramic Die Halves

**EM and Thermal Analysis Predicted Cycle Times**




POC: Marc Matsen
Boeing Research & Technology (BR&T)

# Potential for Scaling TPC



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BOEING
Economic Center
Urban Center
Urban Airport
Suburban Airport
Neighborhood
Suburban Vertiport
Suburban Airport

# Boeing | Poised for Another Century of Innovation


Questions?