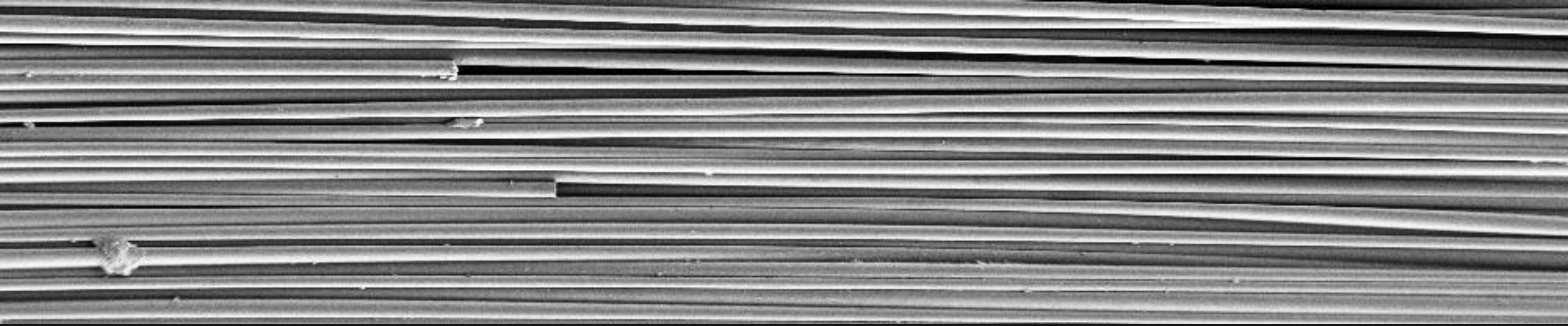


Stretch Broken Carbon Fiber for Primary Aircraft Structures

Montana State University (MSU)
Bozeman, MT, USA

Sponsorship and structure: Stretch Broken Carbon Fiber for Primary Aircraft Structures

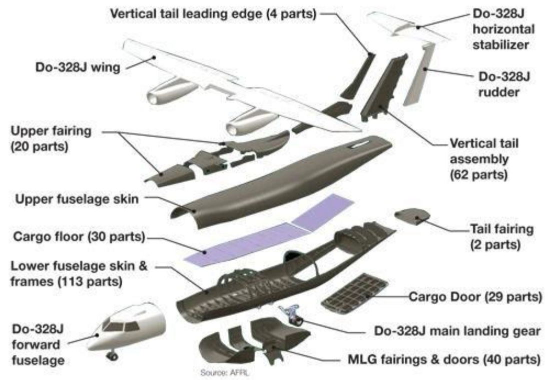
- **Principal Investigator:** Douglas S. Cairns, Ph.D.
- **Program Manager:** Cambrie Monfort
- **Technical Program Manager:** Chris Ridgard
- **Technical Task Leaders:**
  - Task 4: Stretch Breaking: Daniel Schwendtner (Research Engineer)
  - Task 5: Forming and Characterization: Roberta Amendola, Ph.D.
  - Task 6: Manufacturing: Alexey Dynkin (Research Engineer)

Background: Carbon Fiber Composites are the Go To for DOD Aerospace Structures

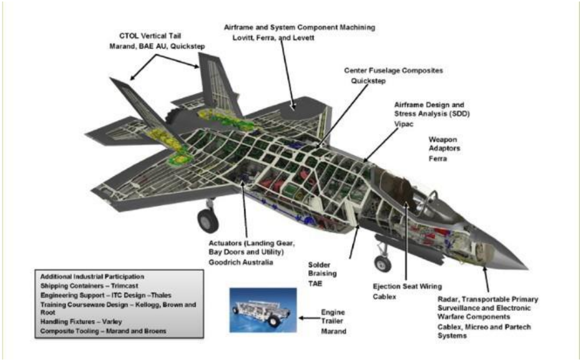
- Compared to Metals
  - Better Stiffness to Weight
  - Better Strength to Weight
  - Better Fatigue
  - Better Corrosion Resistance

- Unfortunately, more expensive than metals to convert to structural forms
- Tens of $ materials become Thousands of $ Structures
- No new structural materials on the horizon

Sikorsky-Boeing Defiant and Bell Valor



Composite Transport Aircraft



F-35 Extensive Use

What is needed is a lower cost, faster way to convert fiber reinforced composites to aircraft structures – More numbers procured for same $!

Motivation: Large-scale adaptation of composites to aircraft materials

- Carbon fiber composites are widely used on military and other aerospace platforms
- Unidirectional tapes offer better performance than fabrics but are difficult to process into complex shapes
- *High-capital* (ATL, AFP, autoclaves) and/or *high labor* (hand layup, vacuum bagging) costs -> **very high cost for finished part compared with feedstock material**
  - **$100s/lb raw material -> $2000/lb finished part!**
- Composite skins are often used with metallic substructure because of the cost and technical difficulties of producing complex composite shapes such as flute stiffened shear webs or sine wave spars
- The combination of composite skins and aluminum substructure frequently results in corrosion issues

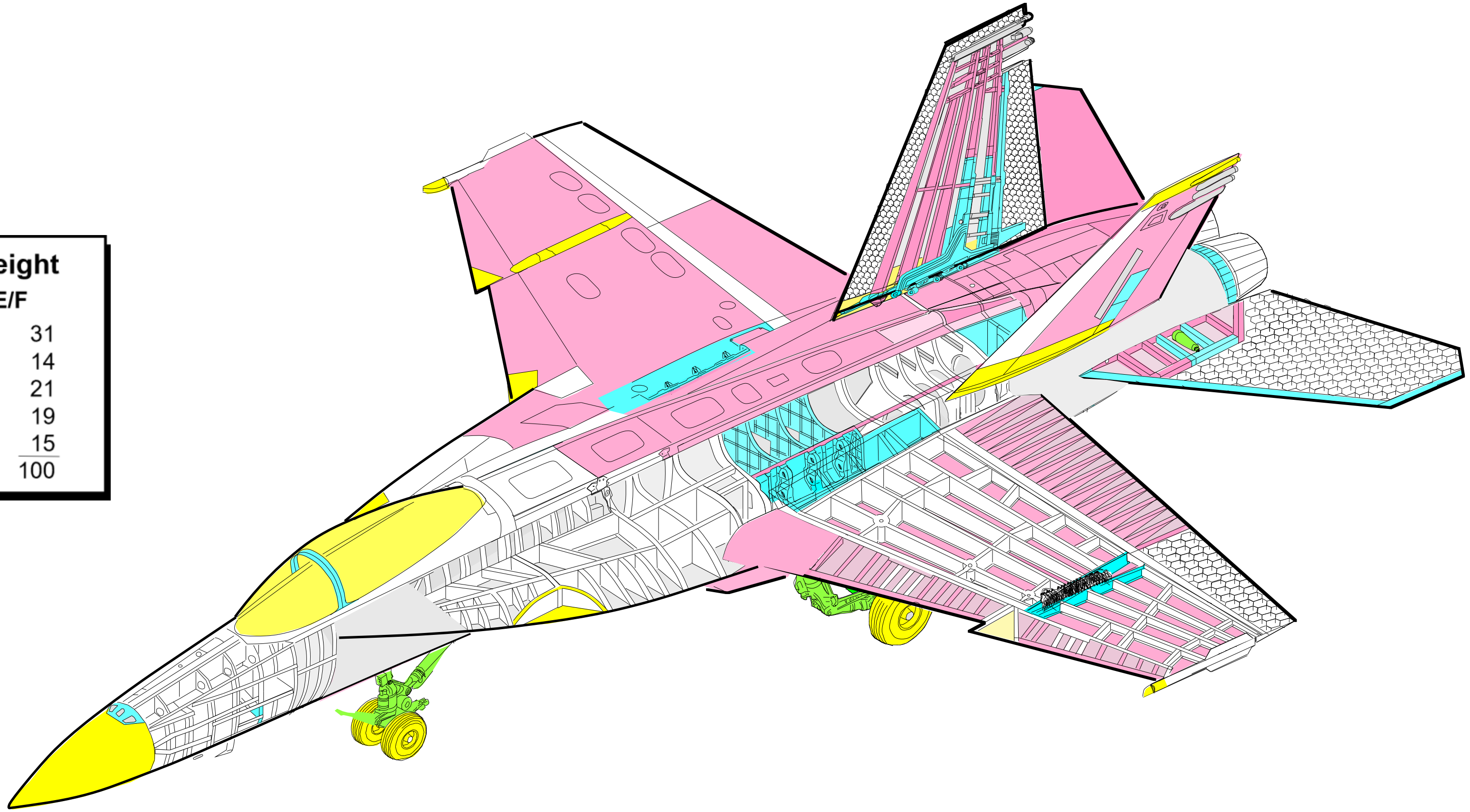
Derivatives of the V22 Osprey

- Derivative development of the V22 Osprey Tilt Rotor, Vertical Takeoff, max cruise 287 kts in airplane mode
- It has widespread use of IM7/8552 composite materials
- The aft fuselage is a hybrid structure – composite skins, metal frames – corrosion problems
- Significant opportunity for SBCF to replace frames and other complex structure

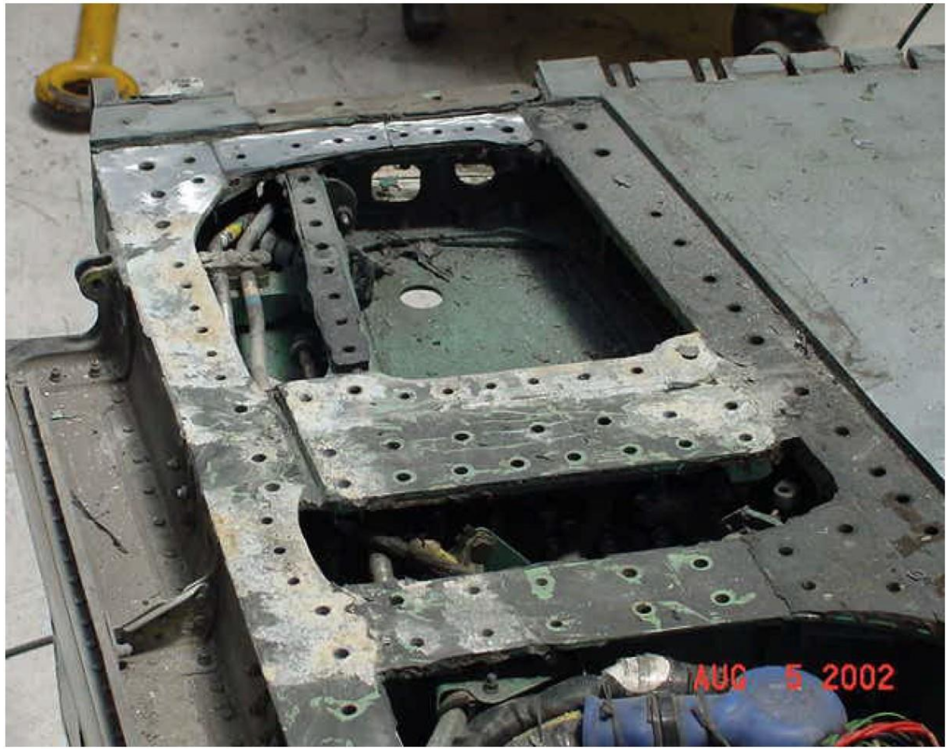
Broader Implications: Corrosion of Composite/Metal Hybrid Structure

Percent of Structural Weight

	F/A-18C/D	F/A-18E/F
Aluminum	49	31
Steel	15	14
Titanium	13	21
Carbon epoxy	10	19
Other	13	15
	100	100



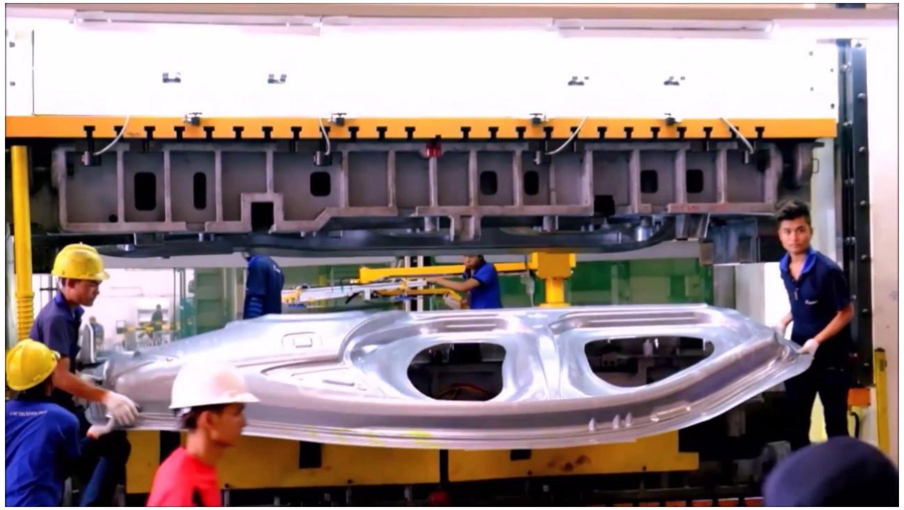
Broader Implications: Corrosion of Composite/Metal Hybrid Structure (cont.)

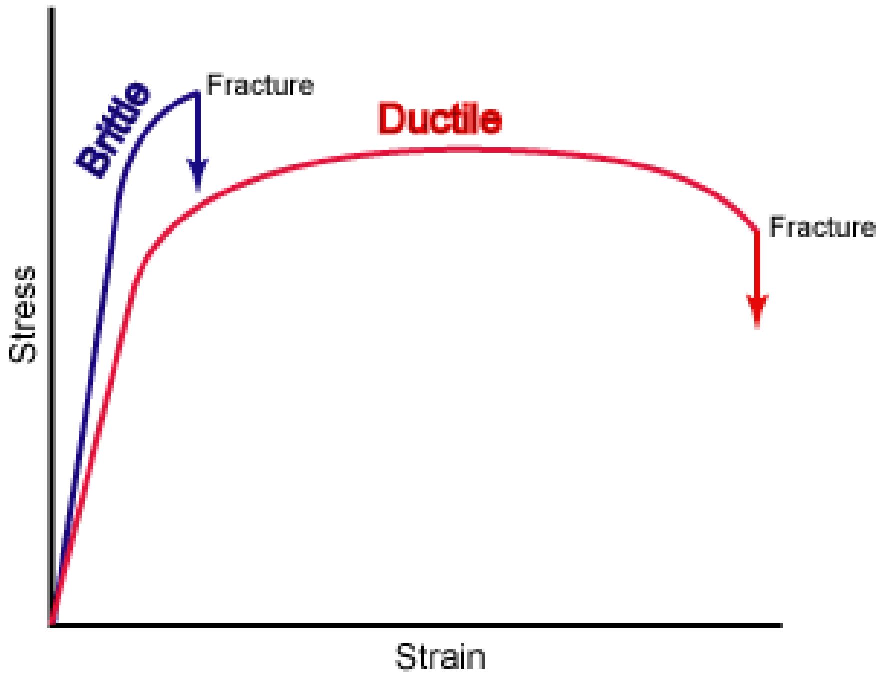


Broader Implications: Corrosion of Composite/Metal Hybrid Structure (cont.)

F18s Awaiting Deport Induction at North Island due to Corrosion

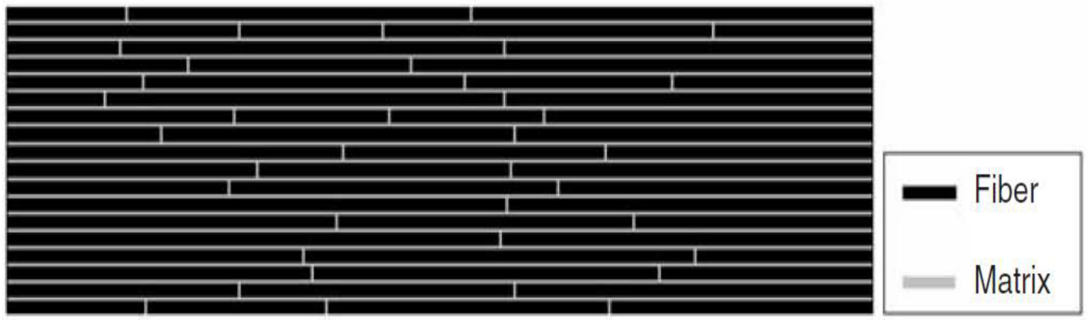
Ideal material: Forms like a metal, acts like a composite



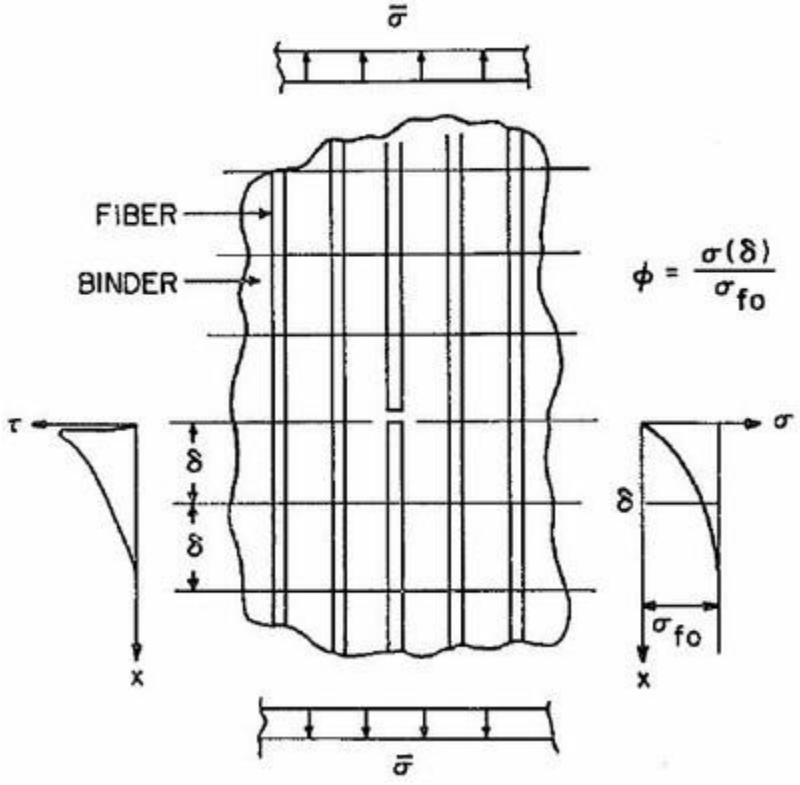


Theory: How does Stretch Broken Carbon Fiber work?

- Continuous carbon fiber tows are broken in tension in continuous process, creating Stretch Broken Carbon Fiber (SBCF)
- Breaks occur randomly at natural flaws
  - **Tensile strength of continuous composites is preserved through shear load transfer**
- Forming is facilitated by ability of fibers to slide and move when matrix is at low viscosity



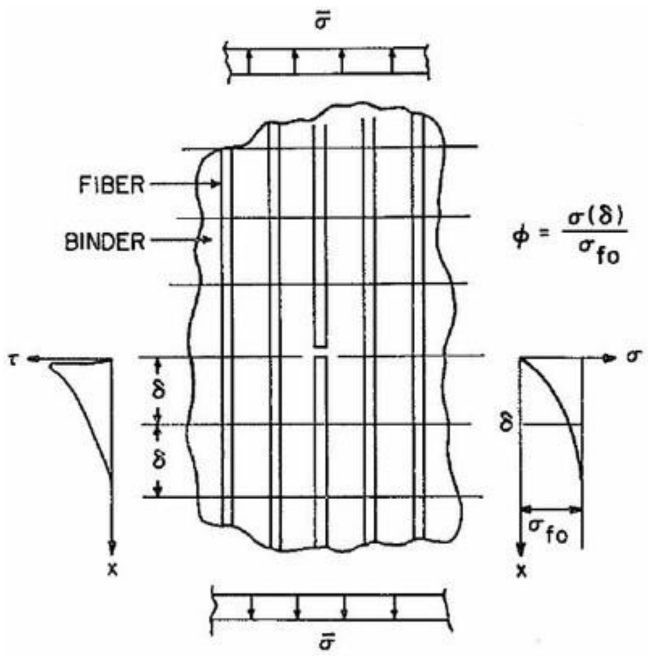
How Continuous Fiber Composites Work: Local Load Sharing



A fiber breaks. At its broken end, it carries no load, but it "shear lags" load back into the surrounding region. Ineffective length δ, is defined as the length where 90% of the tensile stress is recovered in the fiber.

Sometimes called the "band aid effect."

How Continuous Fiber Composites Work: Local Load Sharing (cont.)



δ_e = "ineffective length" where load is transferred back to the discontinuous fiber via shear.

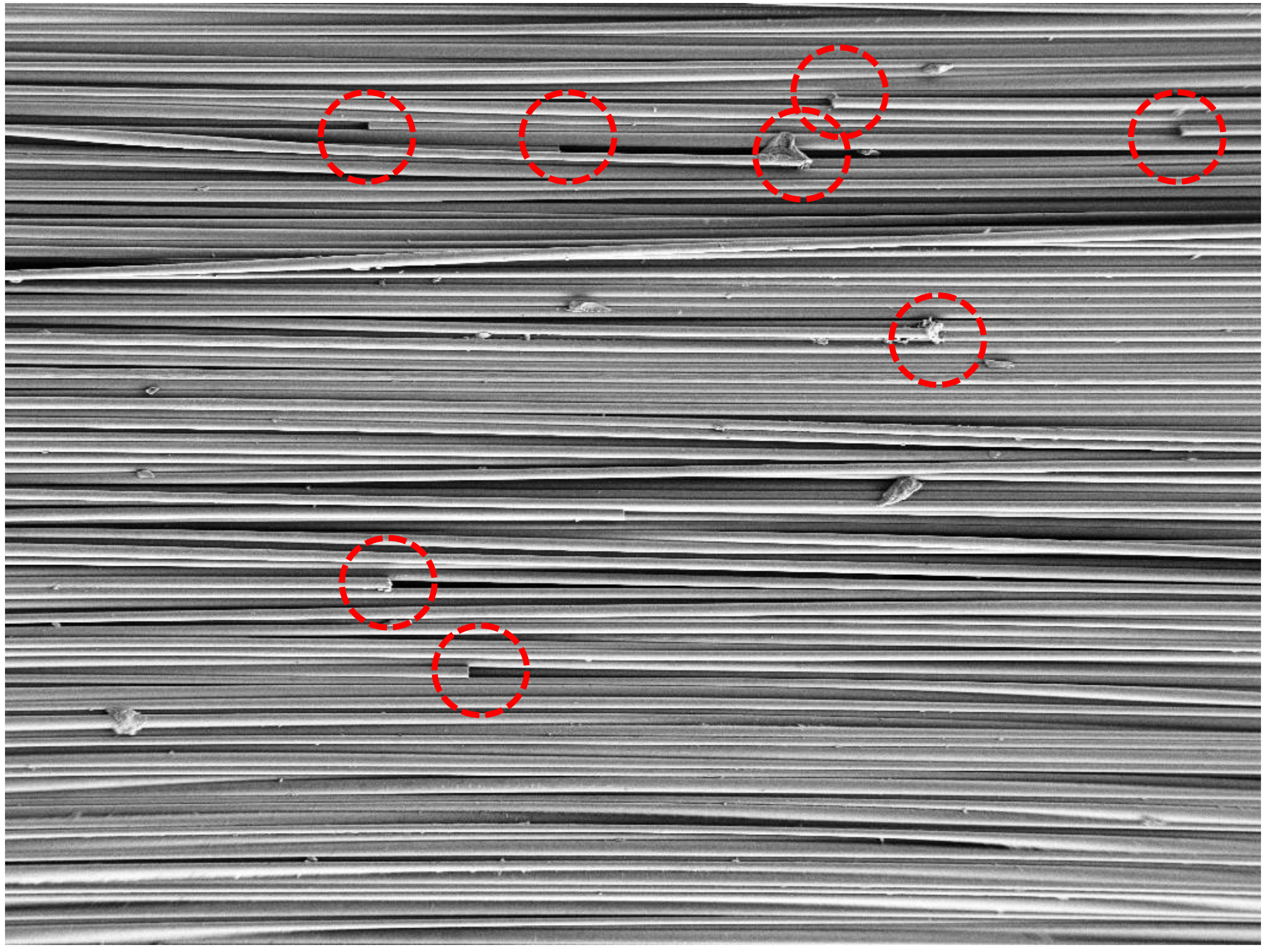
$$\delta_e/d_f \approx (G_f/E_m)^{1/2}\{(1-V_f)^{1/2}/(2V_f)^{1/2}\}^{1/2}$$

Where
d_f is the fiber diameter
G_f is the matrix shear modulus E_m is the matrix Young's modulus
And V_f is the fiber volume fraction

In practical terms, with polymer matrix composites and carbon fibers, the ineffective length ranges between 5-10 fiber diameters.

Implication: If another flaw does not occur within 10 d_f (5.5 µm diameter fiber = 2.2x 10^{-4} in, it should have miminal influence on the tensile strength, compression ?)

Example: Scanning Electron Microscope (SEM) image of stretch broken tow



Breaks occur at random locations throughout tow corresponding to pre-existing flaws in individual fibers

Previous Work: Past efforts to produce SBCF

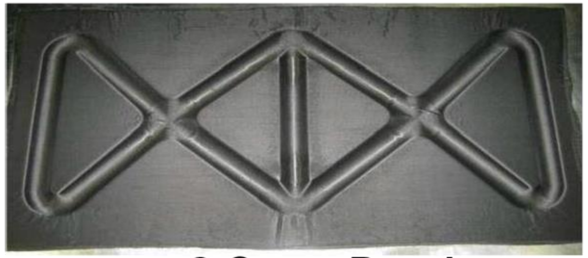
- Several past programs have attempted to develop SBCF for aircraft applications
  - ARL/Penn State
  - Hexcel
  - Albany
  - Schappe (commercially available)
- Feasibility and equivalent mechanical strength has been demonstrated
- **Previous efforts not formable enough for replacement of continuous fiber composites; evolutionary, not disruptive**

Yr 3&4: 11-Bead Panel

ARL/Penn State

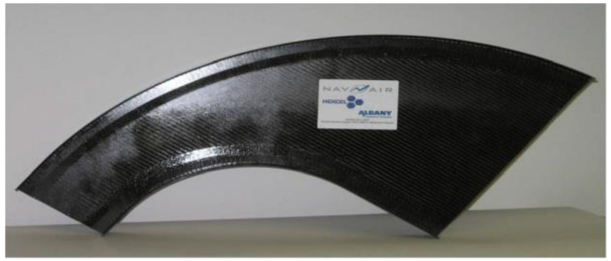
Box & Cross Panel 24” x 24”

Aurora Design



2-Cross Panel

Formability Scale-up Article



Year 3&4: Web-stiffened Frame

Albany Engineered Composites

Adaptability: SBCF strength equivalency with continuous composites has been shown

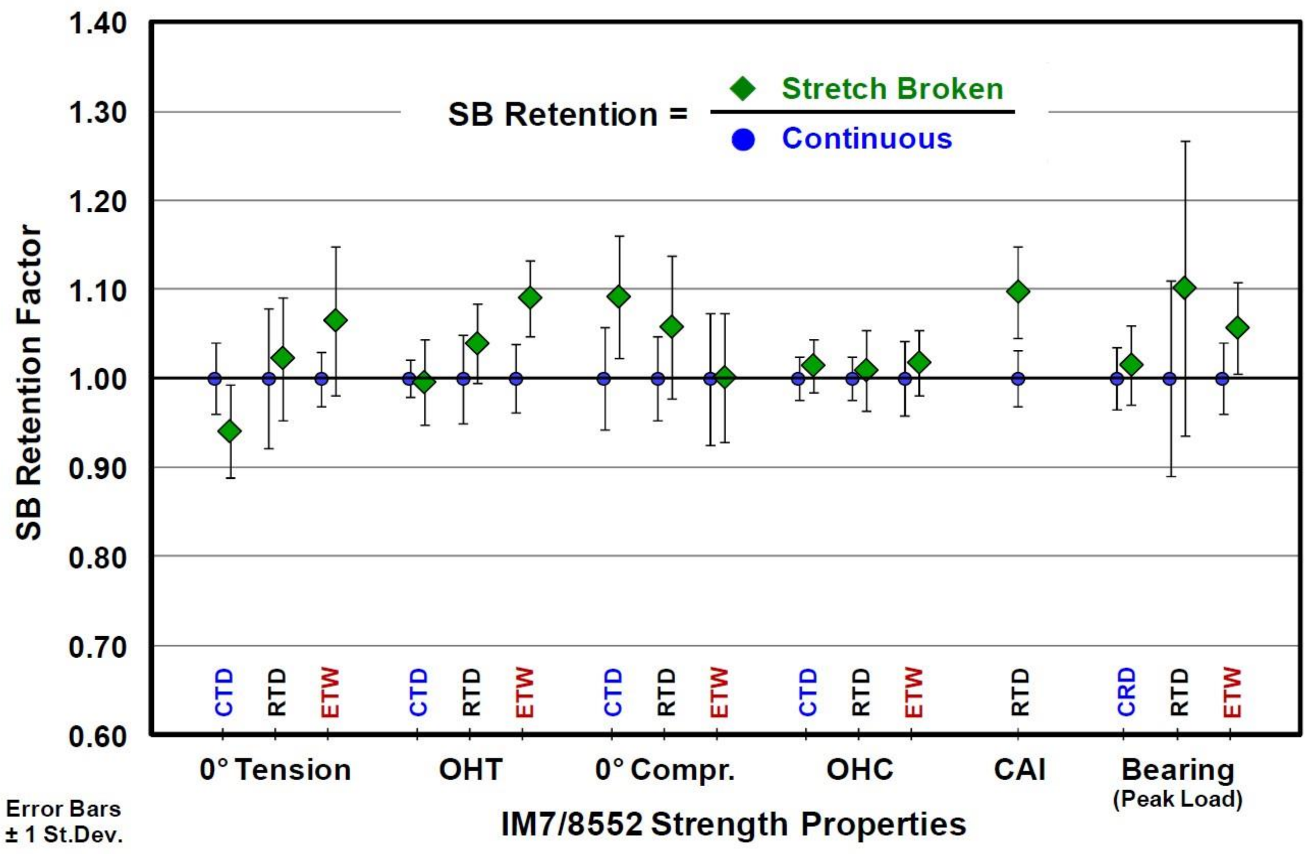


Figure 1: SB Retention Factors of IM7/8552 Fiber-Dominated Strength Properties

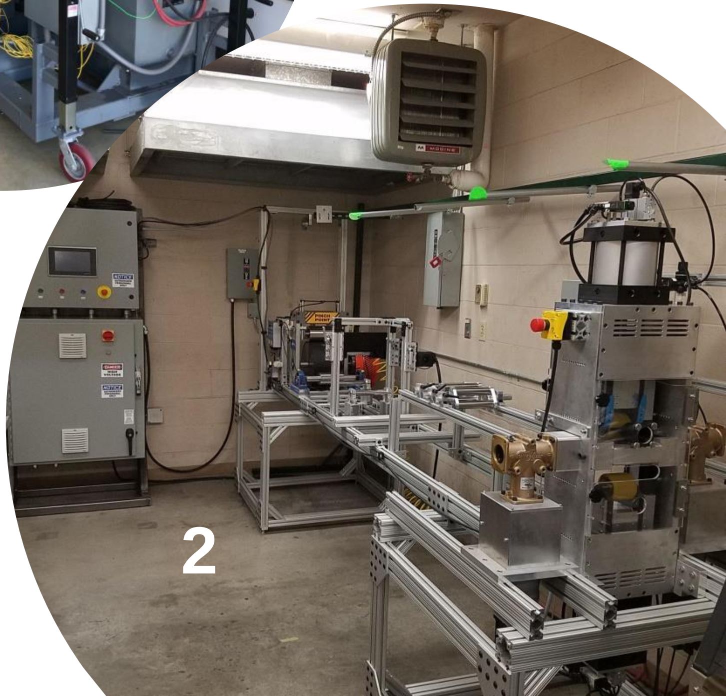
Mechanical testing data from previous efforts show no reduction in mechanical strength properties from continuous composite material

The Challenge:

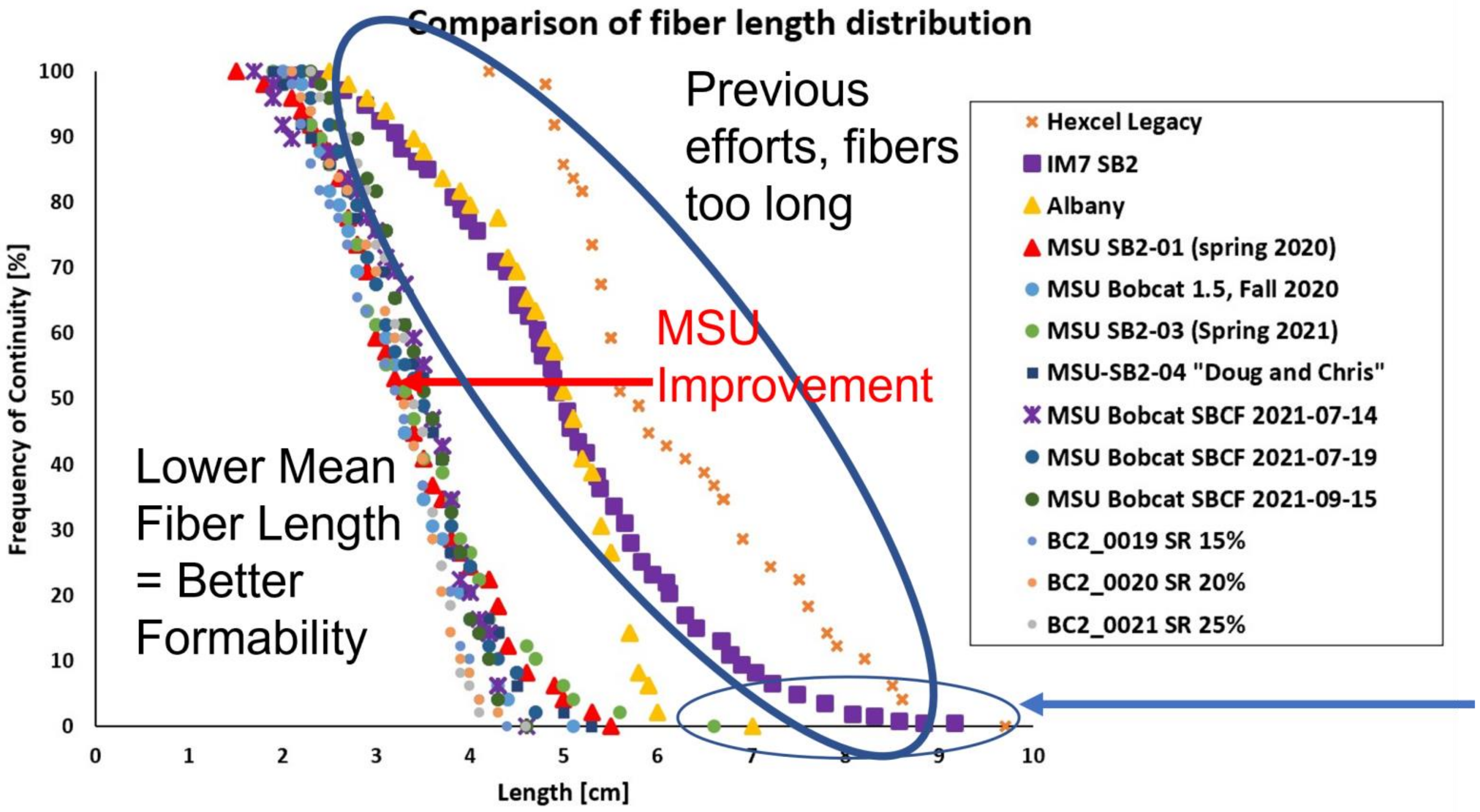
Need shorter fibers for greater formability plus increased SBCF material manufacturing capacity to minimize basic material cost

MSU SBCF Technology: Unique stretch breaking capabilities developed at MSU

- Two machines currently in operation in parallel at MSU
  - 1: Retrofitted **commercial-scale** machine from previous effort (Albany Corp. “SB2” machine)
  - 2: **Prototype-scale** machine built from ground up (“Bobcat head”)
- Both have been able to reduce fiber length to ~1.5” – the shortest known SBCF made to date
- Other capabilities (prepreg line, autoclave) enable complete process
  - **Continuous carbon fiber feedstock → Manufactured SBCF part**



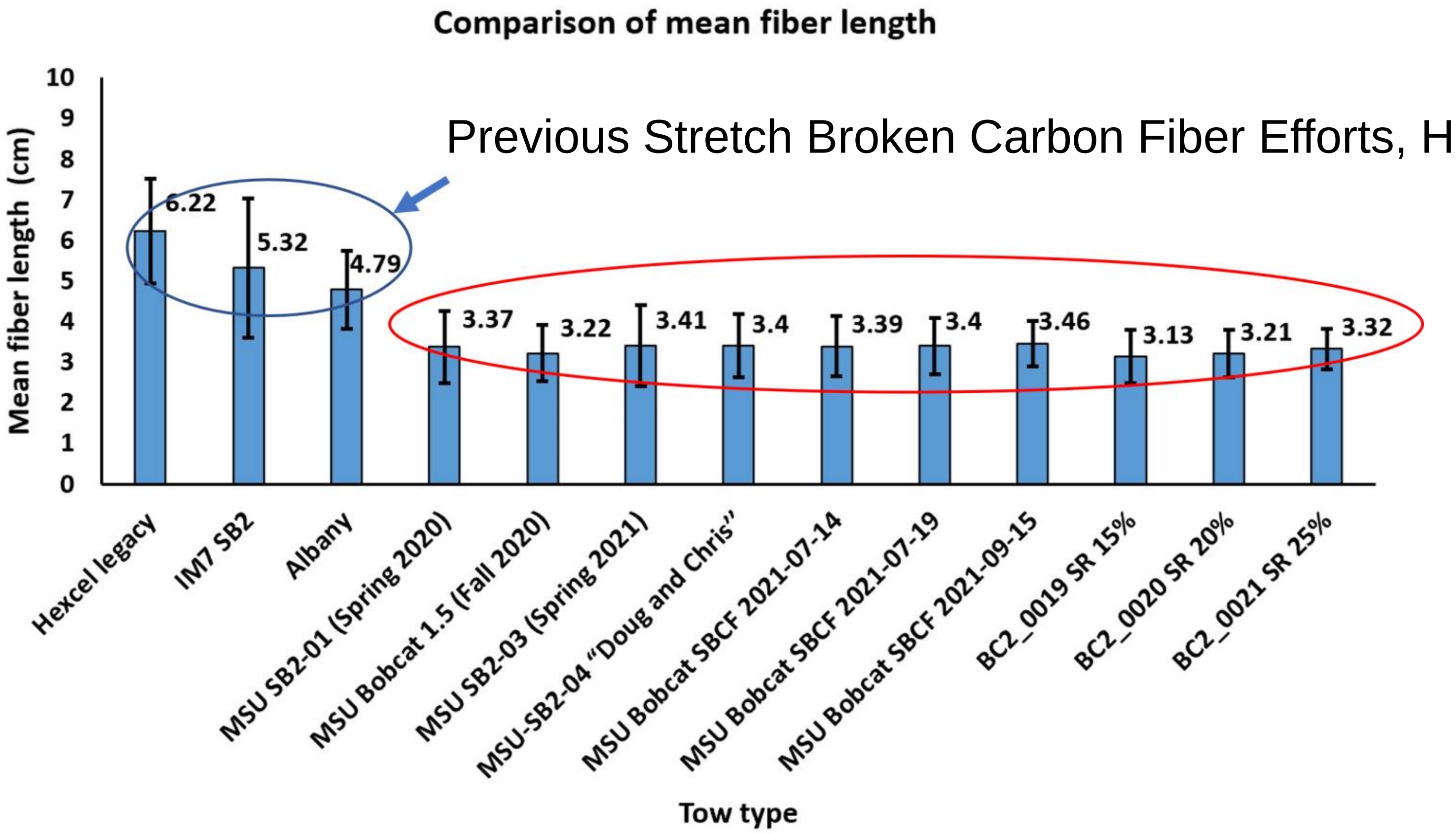
Main Breakthrough: MSU has produced SBCF with the shortest fiber lengths yet



	Average [cm]	Median [cm]	Std Dev [cm]
IM7 SB2	5.3	5.07	1.72
Hexcel Legacy	6.2	5.7	1.29
Albany	4.8	5	0.96
MSU SB2	**3.4**	**3.3**	**0.9**

Small fraction of long fibers can limit formability – carbon fibers are stiff and strong

Main Breakthrough: MSU has produced SBCF with the shortest fiber lengths yet



Previous Stretch Broken Carbon Fiber Efforts, Higher Fiber Length, some very long

MSU, Lower Mean Fiber Length, Truncated Long Fiber Lengths, significantly improved formability

Two Basic Material Forms

- Direct to Prepreg (DTP) – resin film introduced during the stretch breaking of multiple tows in order to produce unidirectional prepreg tape ribbon

- Single tow – fiber is stretch broken, sizing is applied and spooled to provide handleable material in conventional spool presentation form for prepregging or weaving

The program has to date used Hexcel IM7 12K fiber as the reinforcement plus Hexcel 8552 and Solvay 977-3 toughened epoxy resins. Other materials may be introduced in future

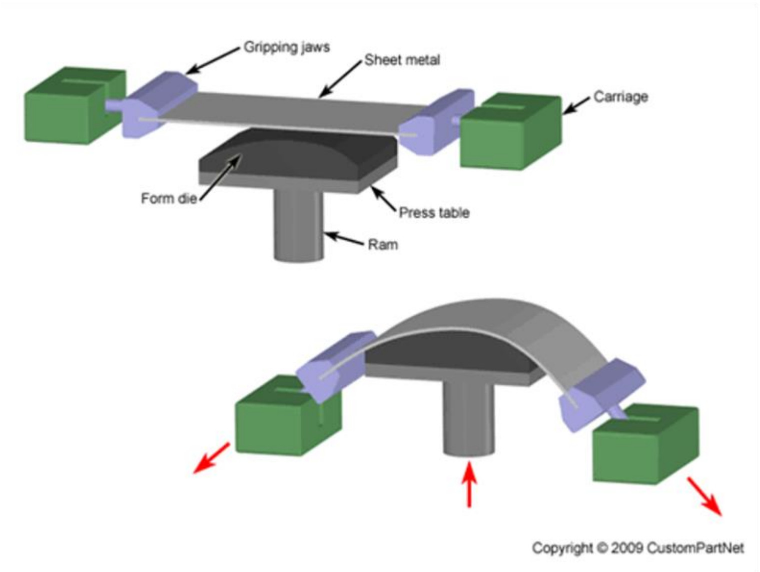
Direct To Prepreg (DTP)

- Film Resin and Fiber combined During Stretch Breaking Process

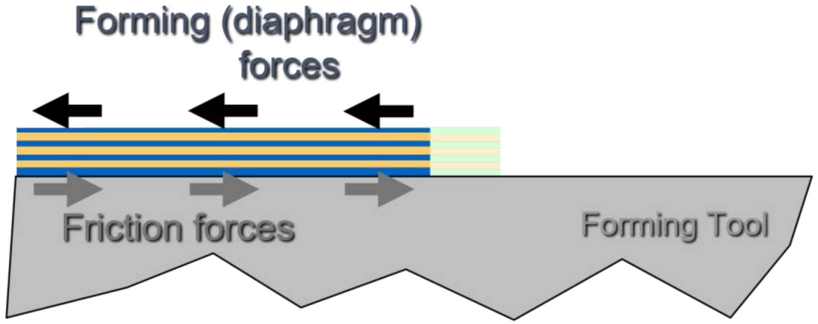
- Multiple reels can be combined edge to edge to produce a wider product – once scaled up and productionized will offer an alternative to conventional spools and creel used to produce unidirectional prepreg tape

- New BC3 ‘Bobcat 3’ line is being manufactured, capable of handling higher fiber areal weights and widths for DTP as well as multiple single tow production– scale up for both SBCF processes

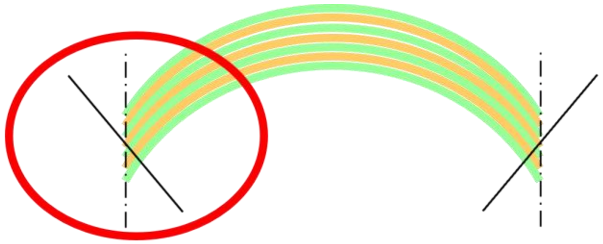
Basic Forming Mechanisms: Flat Layups to Complex Shapes



Membrane Stretching

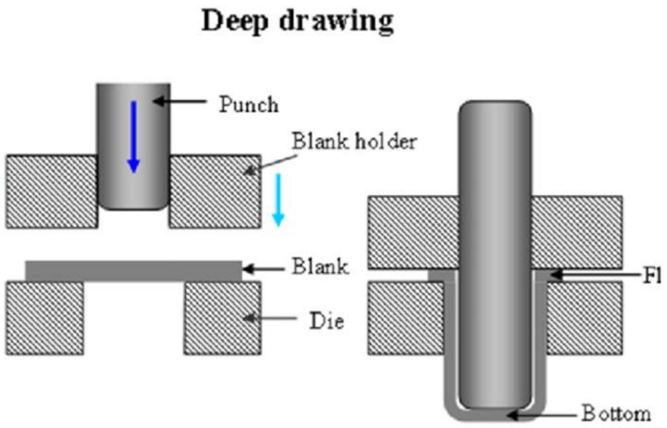


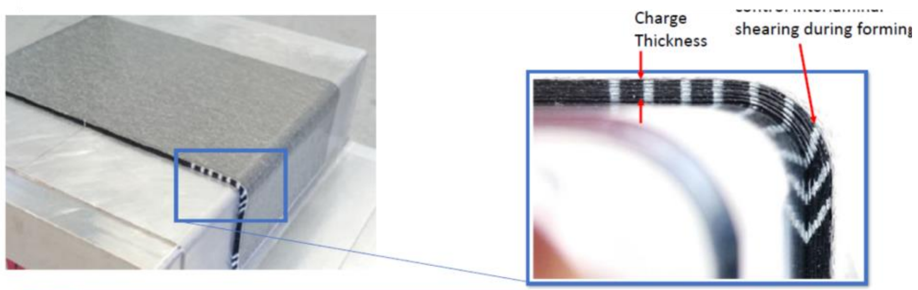
Friction/traction



Fyz Interlaminar shear or slip

Planes DON'T remain Plane





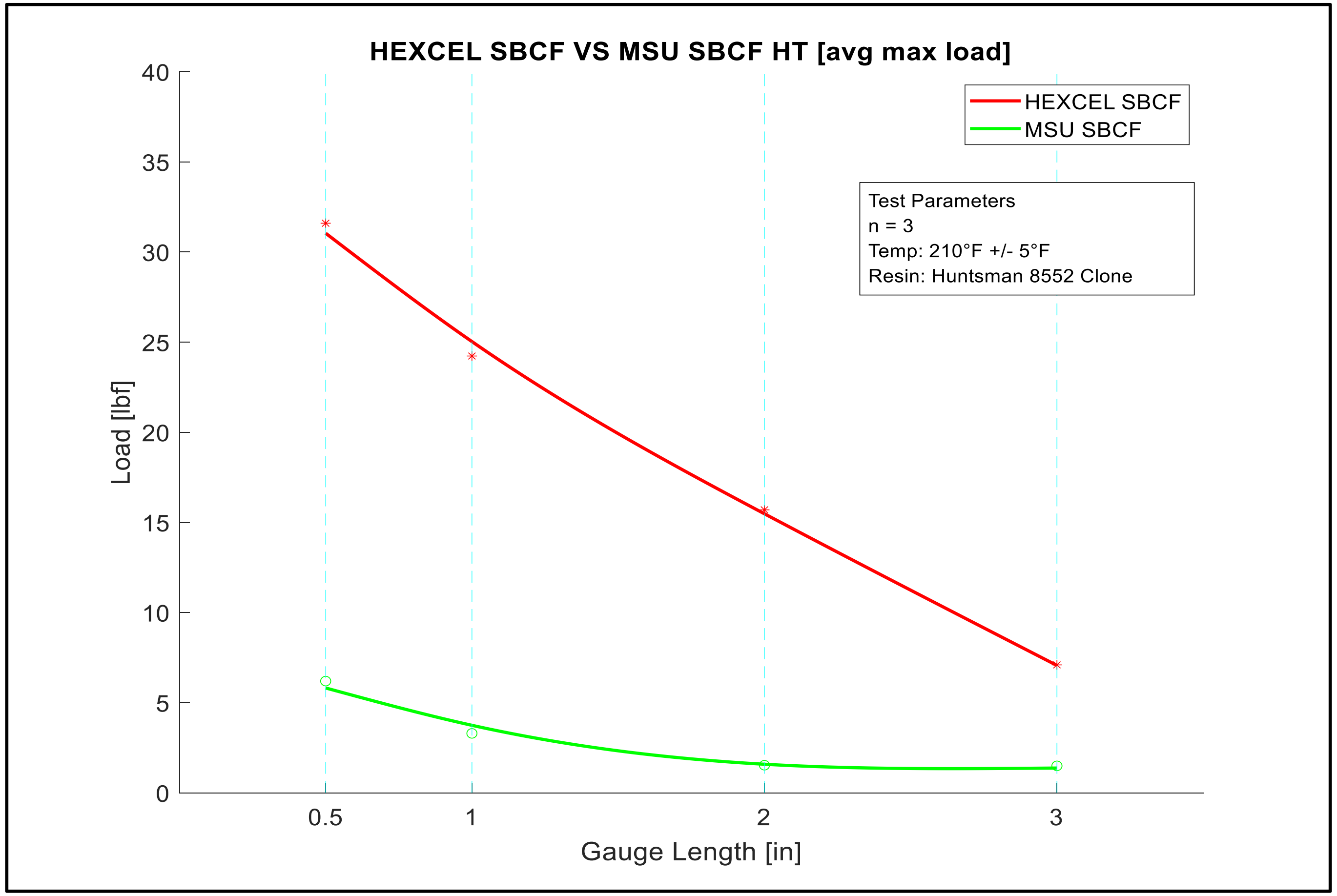
*Pictures from: Advanced Manufacturing: Polymer & Composites Science - E. Kappel & M. Albrecht (2019)

Basic Forming Mechanisms: Flat Layups – Complex Shapes

- Drawing – entire laminate slips with respect to tool
- Interlaminar Slippage (aka Drape Forming, aka Laminate Shear forming)
- Membrane Stretching – ONLY POSSIBLE with SBCF

  - Drawing and interlaminar slippage are desirable if limited, but typically occur only towards the edges of a feature in a large part.
  - Excessive drawing or interlaminar slippage results in wrinkles with continuous fiber prepregs.
  - Natural clamping' from autoclave pressure can limit these effects.
  - Membrane stretching with SBCF allows consolidation into complex features while avoiding wrinkling etc.

Significance: Shorter fiber lengths translate to lower deformation force

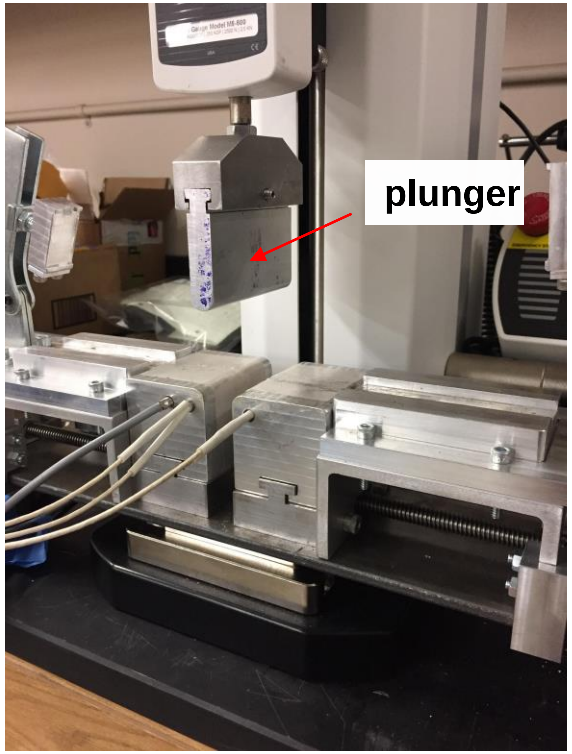


- Tensile forming test at elevated temperature for different gauge lengths
- Takeaway: **MSU SBCF forms at ~5x lower load than previous generation SBCF**

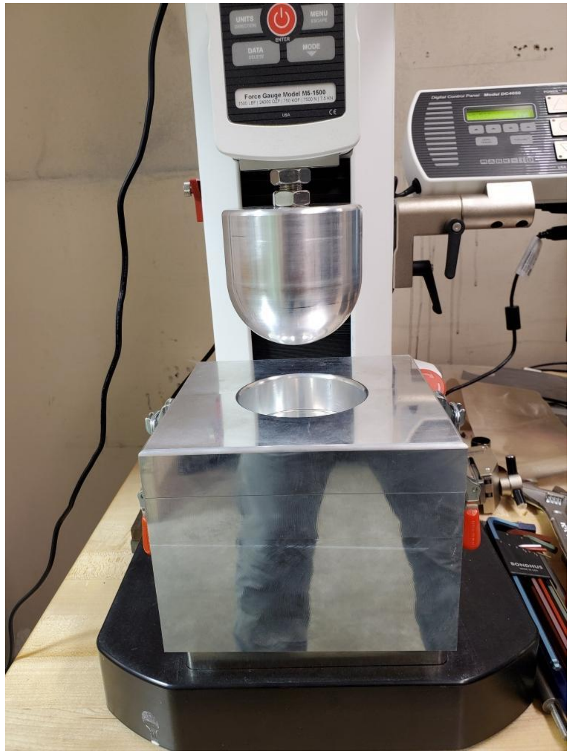
Janicki et al. 2021. Gauge Length and Temperature Influence on the Tensile Properties of Stretch Broken Carbon Fiber Tows. Composites Part A (Article in Press).

Assessing Formability: Forming Test Methodologies and Fixturing

- Problem: How to quantitatively evaluate formability?
- Solution: We have developed a series of processes and fixtures designed to measure formability of composite materials as a function of forming load, at different length scales:
  - **Tow forming fixture** – mesoscale/tow level
  - **Dome forming fixture** – macroscale/laminate level
- Other analytical tools and methods
  - Inter-ply friction fixture
  - Evaluation of sizing “tenacity” → important for downstream handling

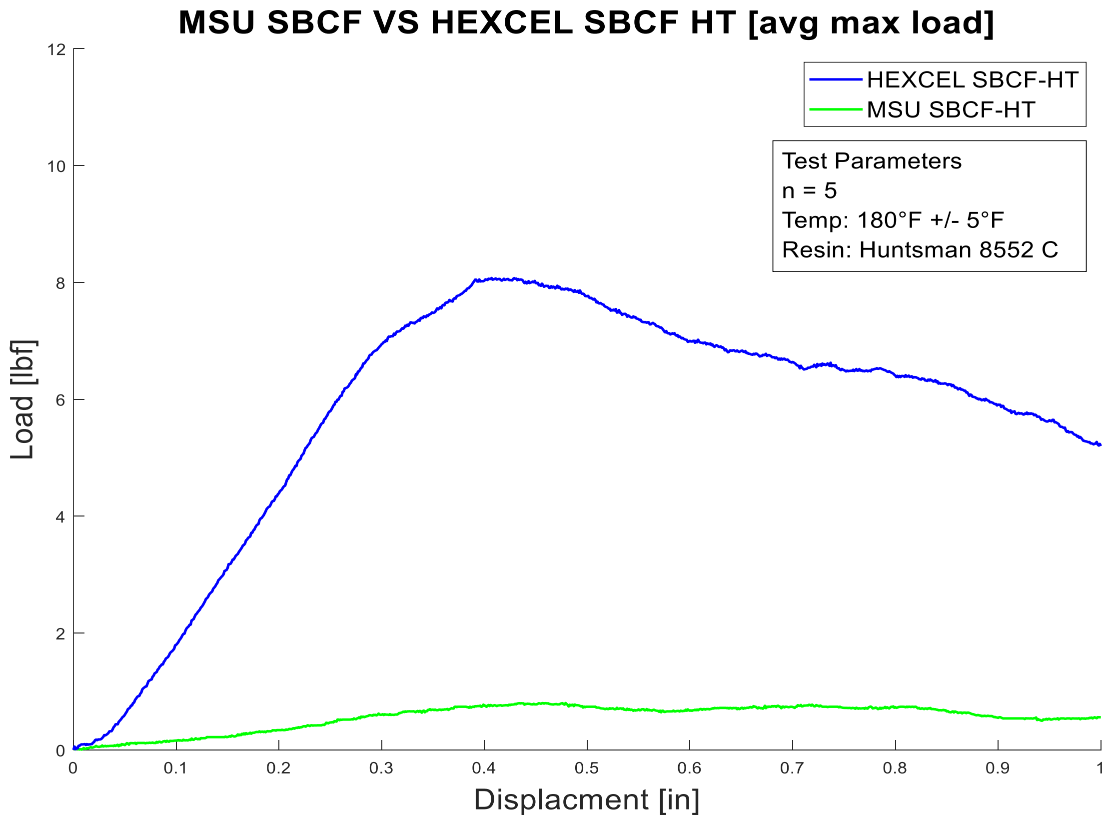


Heated tow forming fixture



Dome/Erichsen-style fixture

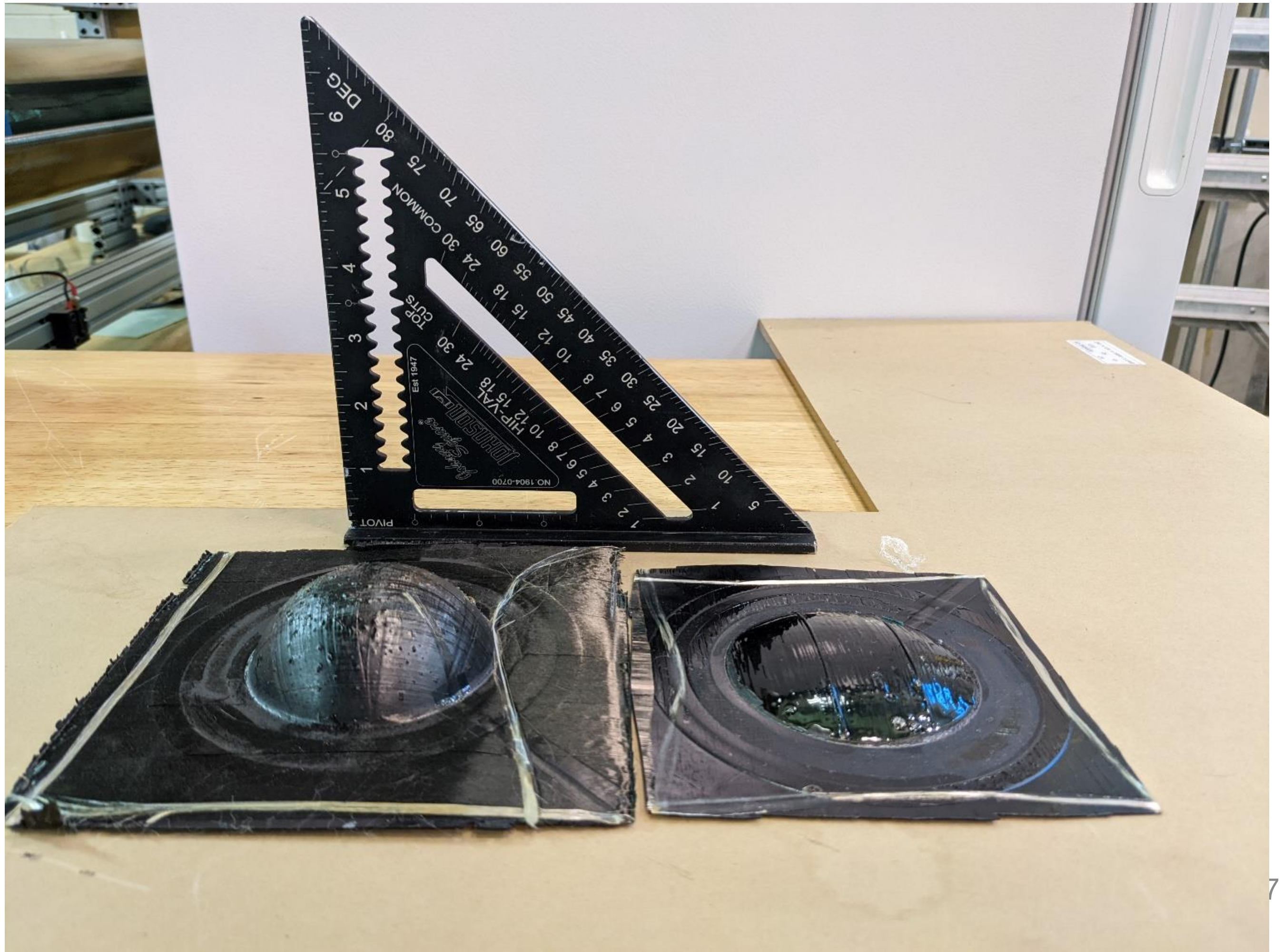
MSU SBCF is the most formable yet! Tow forming test data support short-fiber formability hypothesis



- Tow forming fixture data at elevated temperature
- Takeaway: **MSU SBCF is ~10x more formable in deep draw condition than previous generation material!**

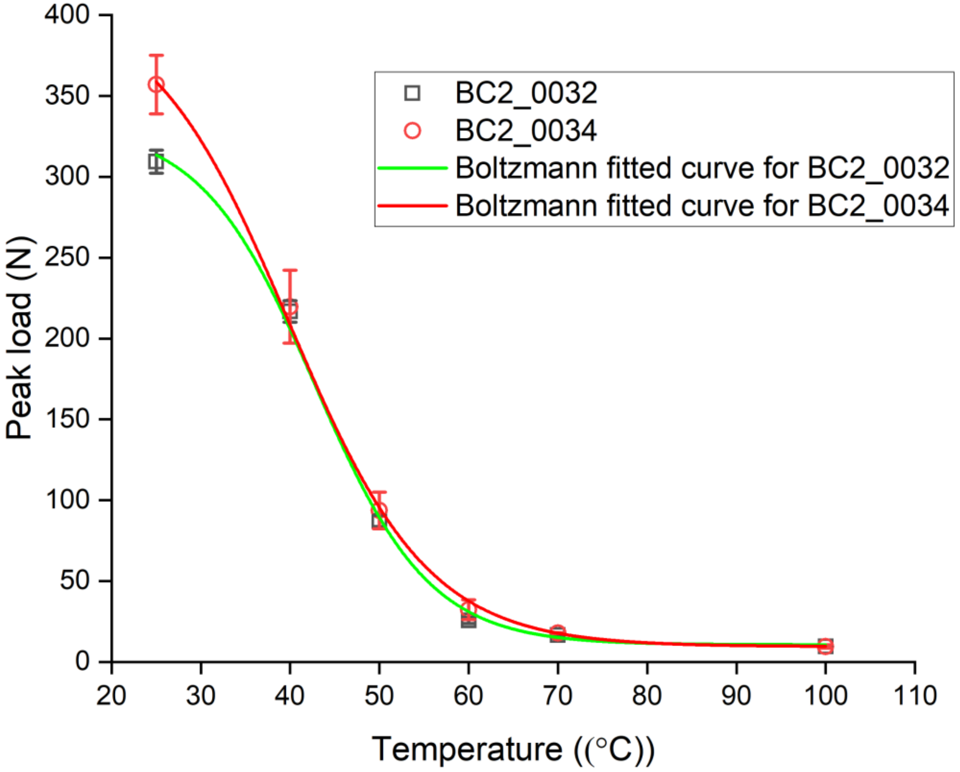
Membrane Forming Mechanisms: Dome formability tests conducted using autoclave cure cycle. SBCF prepreg left, continuous fiber prepreg right

- 0°90° layups initially flat and span hemispherical concave mold cavity
- Edges clamped to minimize slip (layup/tool drawing and interlaminar slippage) and encourage membrane stretching
- 85 psi pressure plus temperature/time cure cycle including an intermediate temperature ‘forming’ dwell
- SBCF prepreg forms into dome tool; Continuous fiber prepreg does not

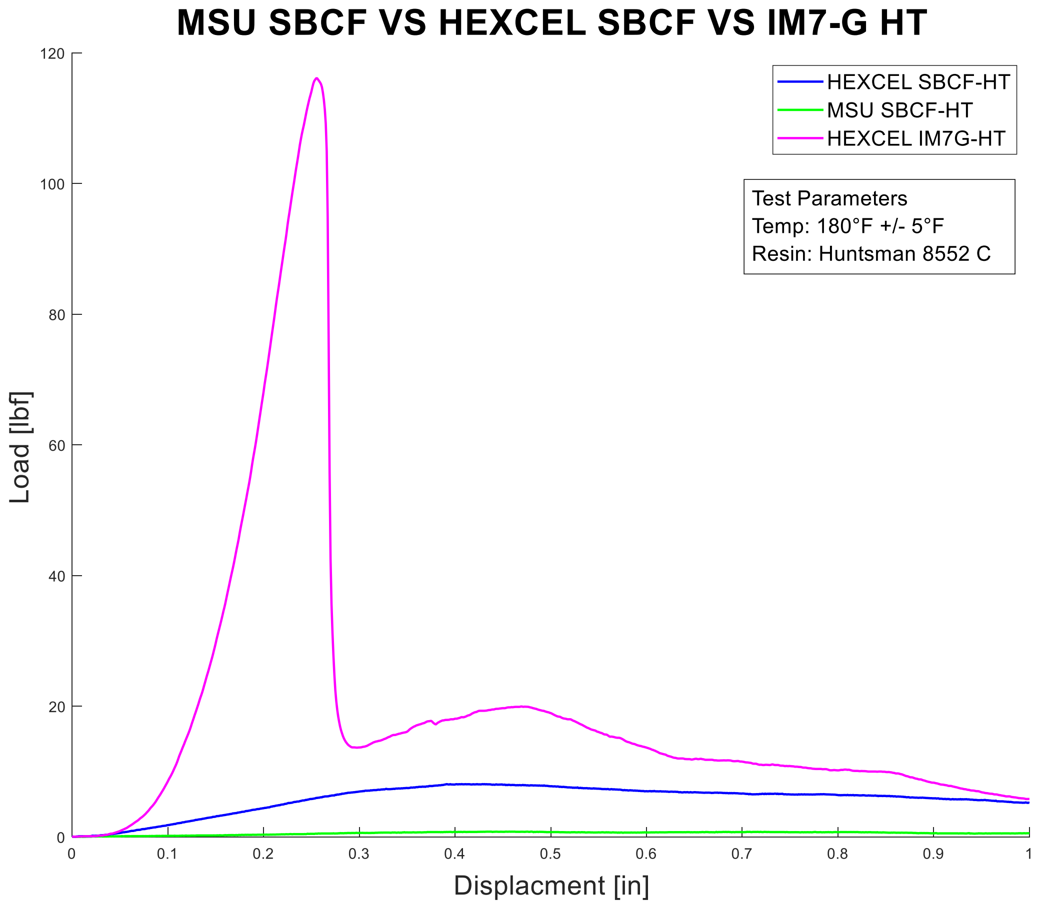


Single Tow SBCF: Tow tenacity vs. Temperature

- A sizing is applied at low level (~1% -~2% by weight) to SBCF tows and cured to a handleable condition prior to spooling.
- Tenacity of the sized SBCF tow at lower temperatures is sufficient for e.g. prepregging or weaving operations
- Tow tenacity at higher temperatures is low enough to permit the stretch forming of prepreg during part manufacturing, prior to the cure of the matrix resin
- Multiple spools of creel mounted, sized, SBCF tow would be used for prepregging using a structural resin matrix

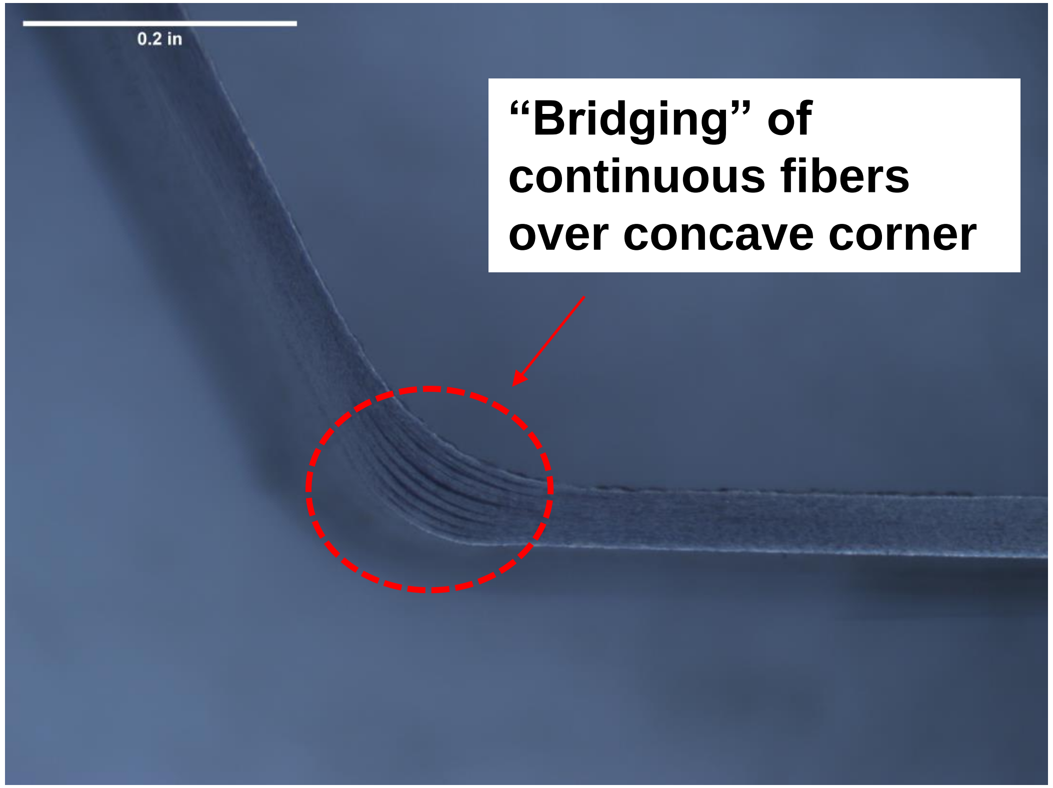


Comparison of forming load for MSU SBCF, previous generation SBCF and continuous fiber

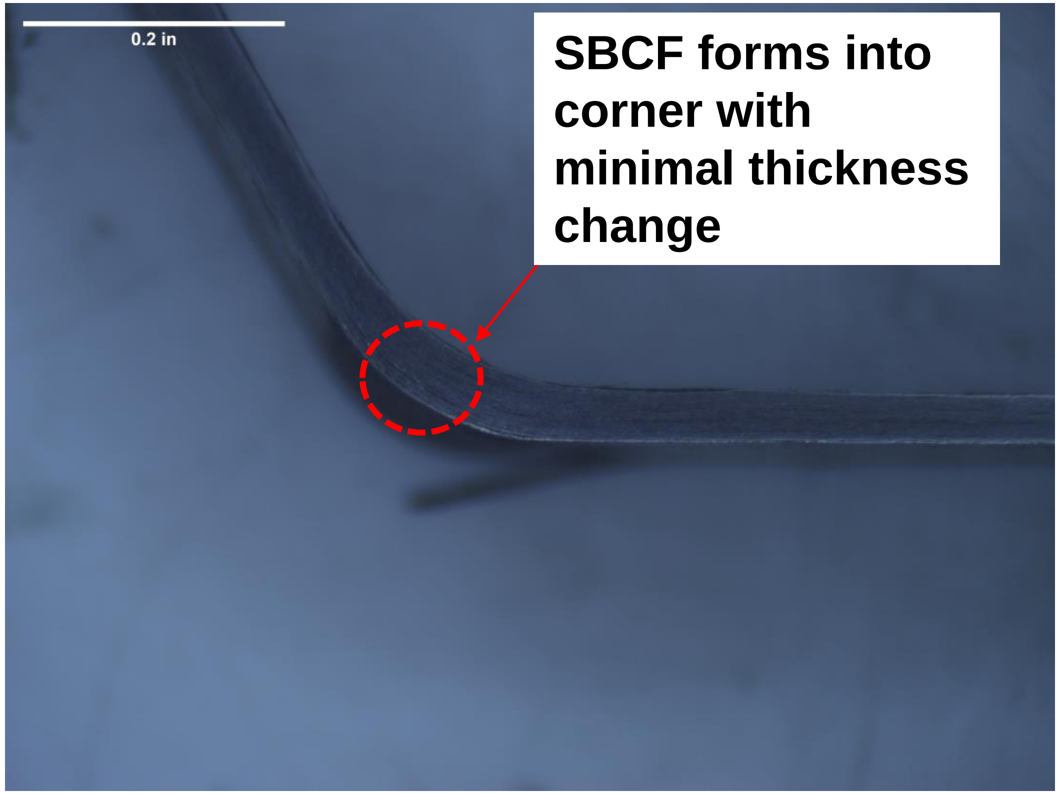


MSU SBCF is ~10x more formable than previous generation SBCF, which is itself ~10x more formable that continuous fiber, so **SBCF has ~100x lower forming load than continuous fiber**

SBCF can mitigate corner effects: “bridging” over female radii is reduced with SBCF

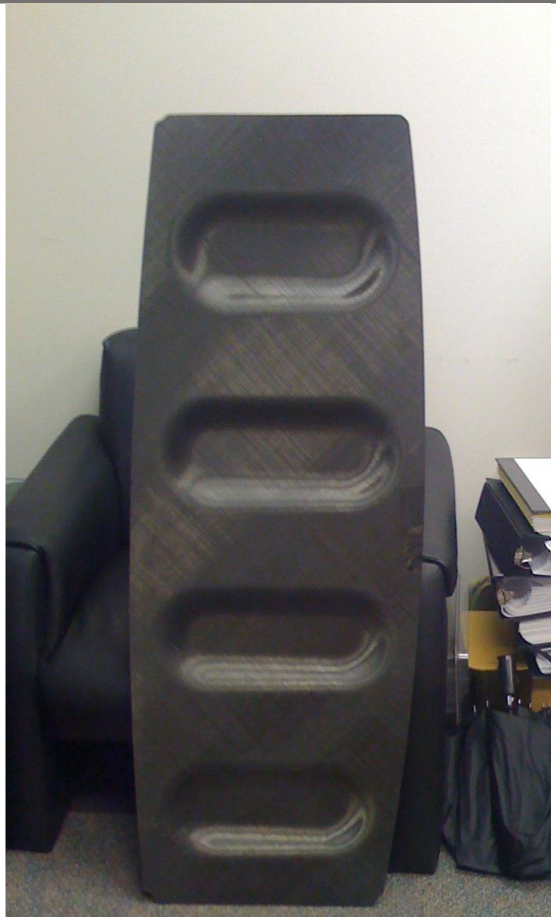


Continuous IM7/8552 Laminate

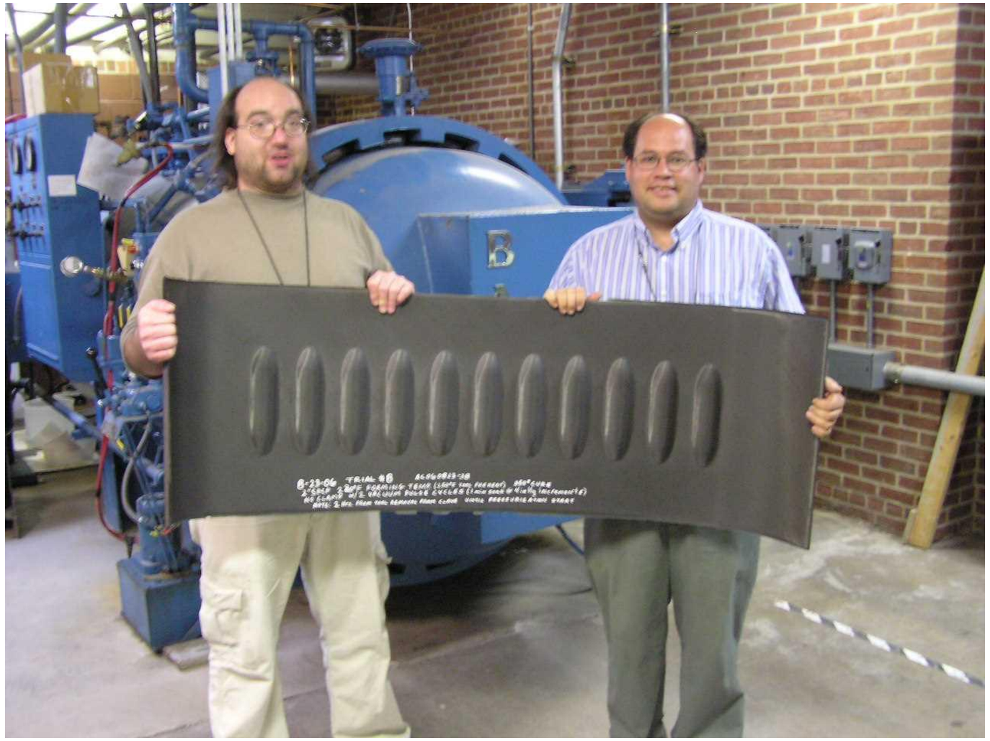


MSU-made SBCF Laminate

Large Complex Structures Made as Easy as Simple Laminates



V22 Wing Rib



Curved Beaded Panels made with conventional tools and autoclave processing

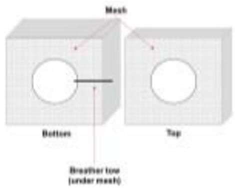
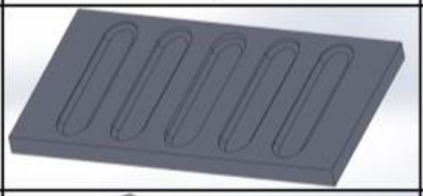
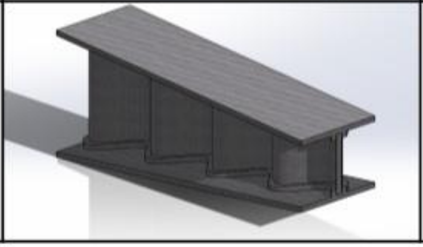
NO MORE METAL SUBSTRUCTURE

Blackhawk Transmission Support Beaded Panel

MSU SBCF is readily formed into complex shapes: shorter fibers form around contours

- Complex shapes similar to metals
- Compound and reverse curvatures
- Sharp features typical of deep drawing in metals
- Significantly less setup time compared to typical continuous carbon fiber
- Lower cost tooling and manufacturing equipment

Complex Composite Structure:
Roadmap outline for formability

Geometry type	Example	Purpose	Metric
Dome Forming		Stretch forming evaluation; cure cycle optimization	Forming depth; forming limit with aid of in-situ LVDT measurement
Simple Beads		Combined stretch & slip forming (simple)	Material thinning
Beaded Panel		Combined stretch & slip forming (complex)	Material thinning AND forming limit
Complex structure		Demonstration of SBCF potential for challenging geometries	Geometric tolerance, part quality, defects, etc.

Ongoing Work

- Scale-up of SBCF prepreg and tow generation for downstream tasks
- Increasingly complex forming studies – (road map)
- Database of mechanical properties
- Increasing complexity of manufactured parts and methods – (road map)

- **Ultimate objective: full-scale SBCF demonstration aircraft part and validated SBCF material manufacturing technology to support industry implementation**

Summary:

- Stretch Broken Carbon Fiber has the potential to transform the adaptation of composites through lowered manufacturing costs and the elimination of hybrid composite/metal structures and the associated corrosion problems

- **Montana State University has made the most formable SBCF material known to date** and two alternative SBCF production processes – direct to prepreg and spooled tow – have been developed. The scale up of these processes is in progress

- The program will develop a mechanical property database plus part forming and manufacturing processes which will culminate in the production of a full-scale aerospace part demonstrator item

This Technology is Vital to Advancement and Sustainability of Structural Composites

- This technology is Disruptive (or whatever “breakthrough” words you want to apply)
- From a former head of NAVAIR Structures “You (MSU) are working on the most important technology in advanced composites in 30 years”
- Training the next generation materials science and composite aircraft engineers – a flat organization Students, Faculty, Professionals working side by side for a common goal, “Plug n’ Play” Graduates for the advanced composites workforce
- SBCF solves multiple material supply chain problems, including the potential disruption in titanium supply

We are OPEN FOR BUSINESS

- Universities are not in the business of production – We are looking for technology transfer partners
  - Composite Material Suppliers
  - Composite Structure OEMs

- Looking for complex shapes enabled with SBCF; GIVE US YOUR BIGGEST CHALLENGES

- Key Contacts

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  - Cambrie Monfort, Program Manager
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The SBCF Team at MSU

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Questions?