FILAMENT WINDING - A TRADITIONAL MANUFACTURING METHOD REINVENTED

CO-HOSTED BY:

CKN
Composites Knowledge Network

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THE PRESENTER

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Professor in Mechanical Engineering, University of Alberta
Associate Dean (Undergraduate Programs), Faculty of Engineering
Principal Investigator - Advanced Composite Materials Engineering Group

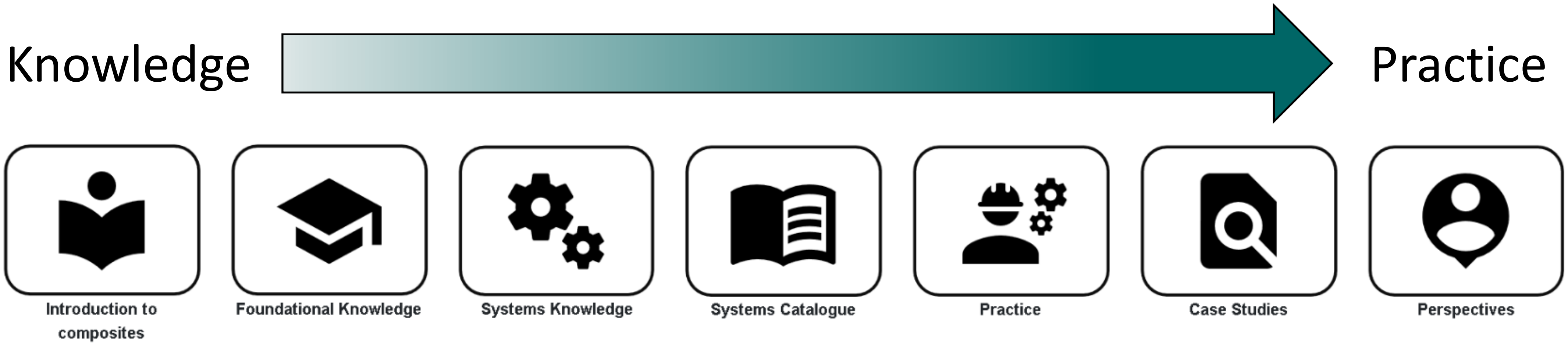
- Over 20 years of experience in R&D from technology conception to prototyping in the field of polymers and polymer composites
- Focus on energy industry and energy storage applications
- Collaborated nationally and internationally as university researcher and worked as private consultant
- Executive Member of Pressure Vessel and Piping Division of the American Society for Mechanical Engineers (ASME)
- Past President of the Canadian Association for Composite Structures and Materials (CACSMA)

KNOWLEDGE IN PRACTICE CENTRE (KPC)

- A freely available online resource for composite materials engineering:

compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



Knowledge

Practice

Introduction to composites

Foundational Knowledge

Systems Knowledge

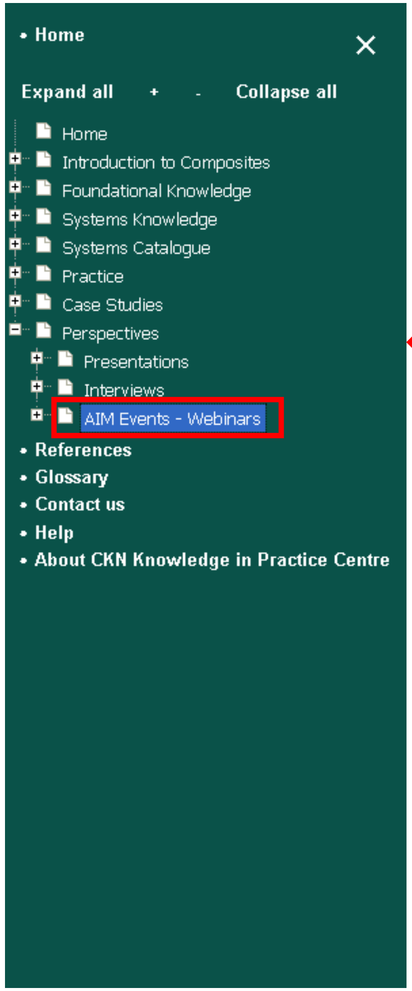
Systems Catalogue

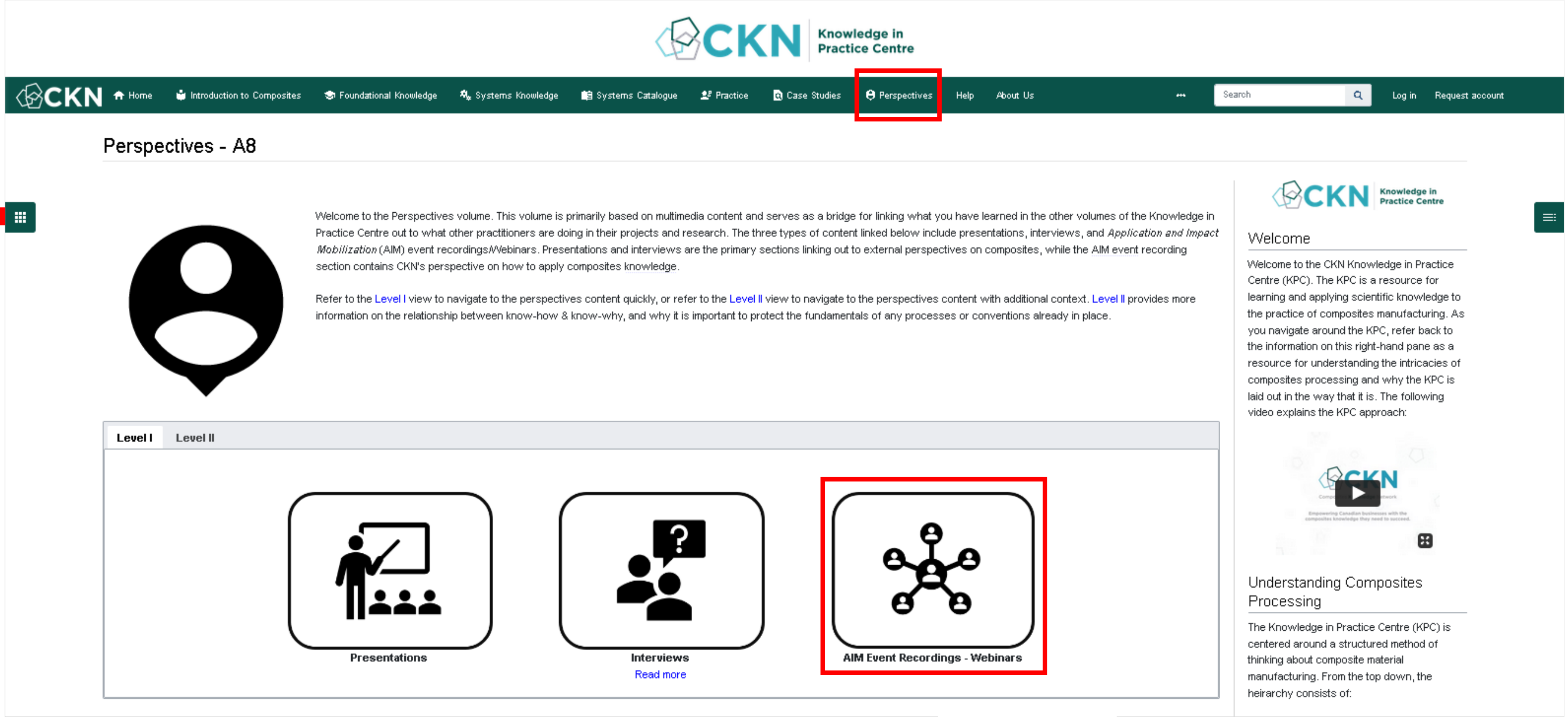
Practice

Case Studies

Perspectives

PAST WEBINAR RECORDINGS AVAILABLE





Perspectives - A8

Welcome to the Perspectives volume. This volume is primarily based on multimedia content and serves as a bridge for linking what you have learned in the other volumes of the Knowledge in Practice Centre out to what other practitioners are doing in their projects and research. The three types of content linked below include presentations, interviews, and *Application and Impact Mobilization* (AIM) event recordings/Webinars. Presentations and interviews are the primary sections linking out to external perspectives on composites, while the AIM event recording section contains CKN's perspective on how to apply composites knowledge.

Refer to the Level I view to navigate to the perspectives content quickly, or refer to the Level II view to navigate to the perspectives content with additional context. Level II provides more information on the relationship between know-how & know-why, and why it is important to protect the fundamentals of any processes or conventions already in place.

Welcome

Welcome to the CKN Knowledge in Practice Centre (KPC). The KPC is a resource for learning and applying scientific knowledge to the practice of composites manufacturing. As you navigate around the KPC, refer back to the information on this right-hand pane as a resource for understanding the intricacies of composites processing and why the KPC is laid out in the way that it is. The following video explains the KPC approach:

Understanding Composites Processing

The Knowledge in Practice Centre (KPC) is centered around a structured method of thinking about composite material manufacturing. From the top down, the heirarchy consists of:

Today’s Webinar will be posted at:
https://compositeskn.org/KPC/A370

TODAY'S TOPIC:

Filament Winding - A traditional manufacturing method reinvented

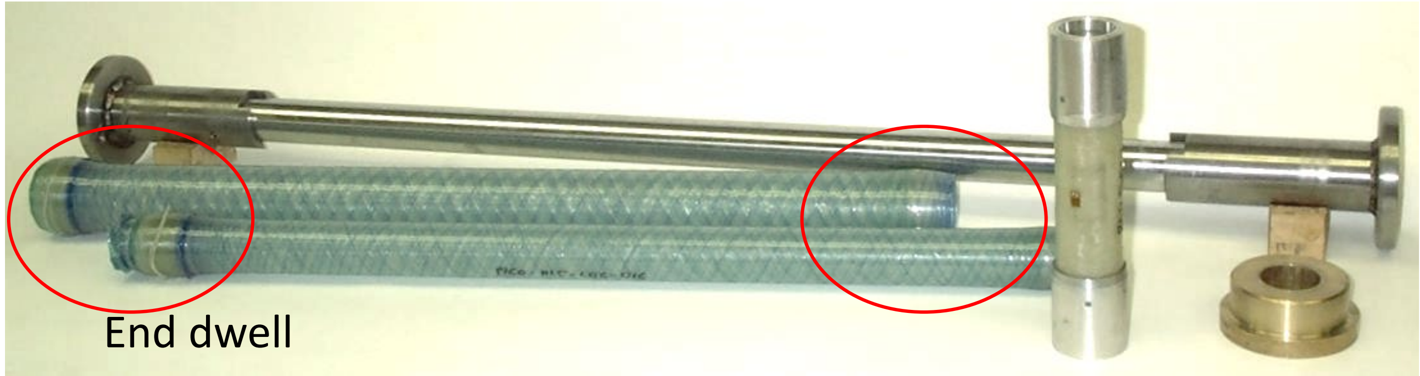
OUTLINE

- **Introduction FW systems**
  FW basics, FW machines, Fibers and creels, Fiber delivery and tensioning equipment, Resin impregnation, Mandrels, Curing
- **FW Process**
  Process Parameters and control, Fiber band and interweaving
- **Engineering Design for FW**
  Material systems, Liners, Additional considerations
- **Testing and Quality Control**
  Overview
- **Emerging Technologies**
  Materials systems, Multifunctional composites, Embedded sensors
- **Application Examples**
  Filament-wound structures in industry

INTRODUCTION FW SYSTEMS

FW basics

- Wet filament winding (additive manufacturing)



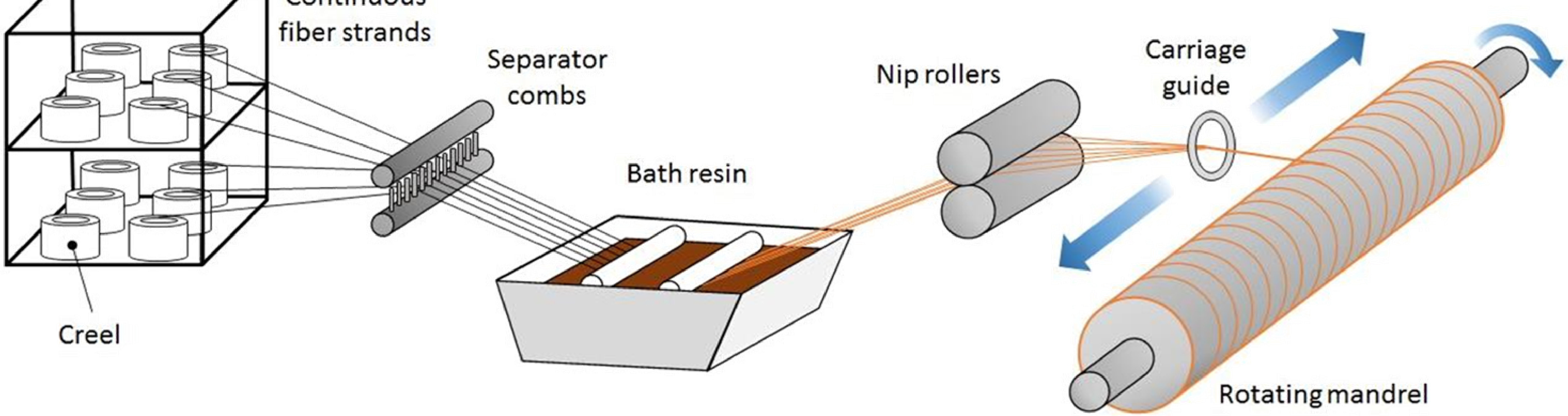


Image source: Author; Reproduced from Nuplex Industries Ltd. 2014

INTRODUCTION FW SYSTEMS

FW machines

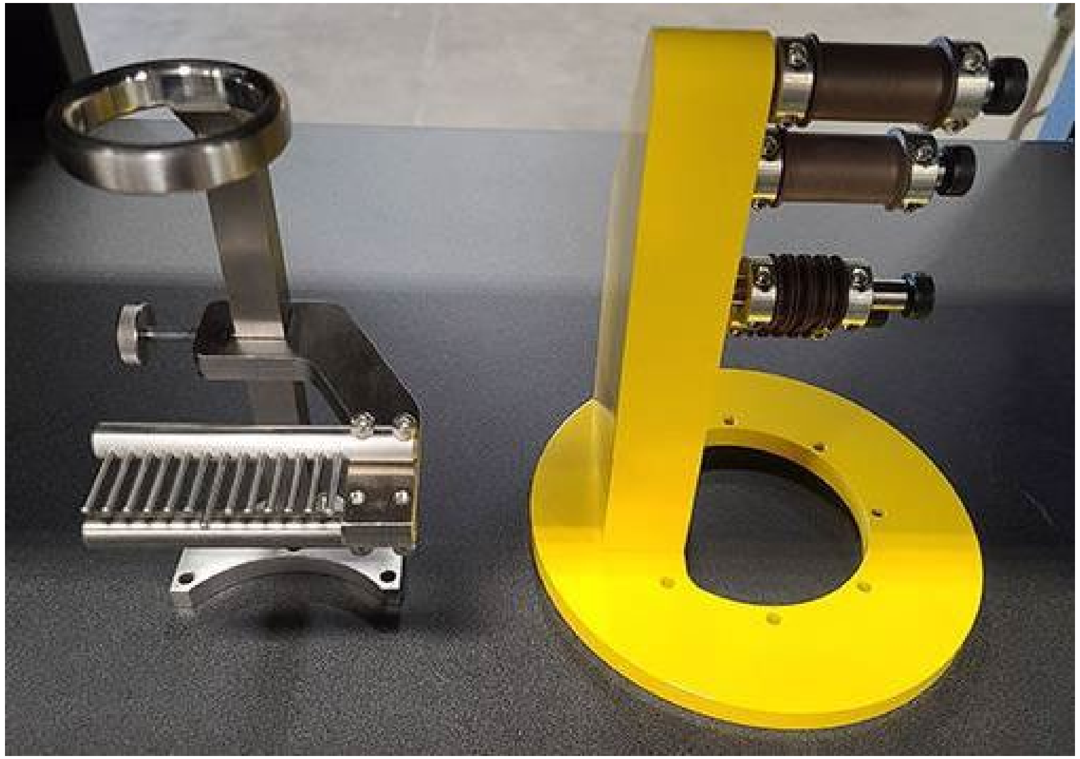
- Commonly 4-axis machines
  - Mandrel rotation
  - Carriage translation, cross feed
  - Guide rotation (bar, ring or roller)
- Continuous FW equipment
  - Product translates in axial direction with fiber feed stationary
  - More complex equipment
  - Rapid production
  - Avoid waste (end dwell)
  - Used mainly for tubular product

Source: Magnum Venus Products

INTRODUCTION FW SYSTEMS

FW machines

- Guides
  - Wet FW provides ‘lubrication’ to avoid friction of fibers so static guides are suitable
  - Rollers/pulleys avoid friction but increase cleaning needs
  - Material selection for guides important (e.g., stainless steel, PTFE)
- Cleaning
  - Often overlooked
  - Wet FW inherently messy
  - Process design important to reduce costs and environmental impact (use of solvents like acetone)



Source: McClean Anderson

INTRODUCTION FW SYSTEMS

Fibers and creels

- Broad availability of fiber materials, including glasses, carbons, aramids
- Outside-pull creels (have core tube) versus center-pull creels
  ➔ Center-pull creels can easily be daisy-chained (inside end of one creel spliced to outside end of a second creel)

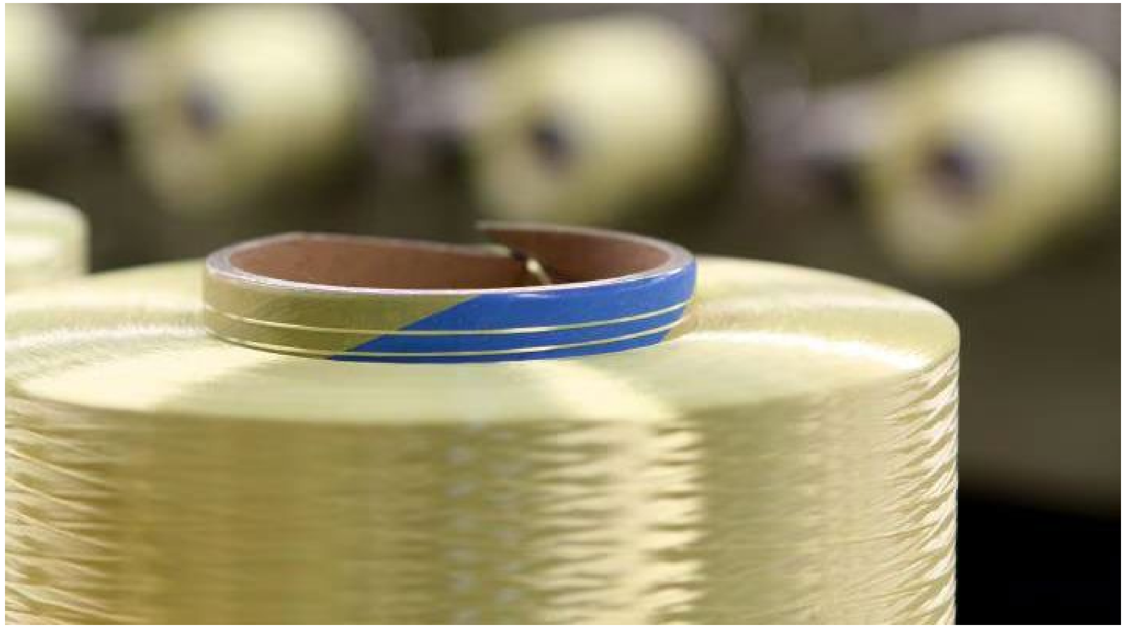


Image source: Teijin Aramid

INTRODUCTION FW SYSTEMS

Fibers and creels

- Direct (single-end) roving versus assembled roving
  - Direct roving: Filaments spun to directly form a roving
  - Assembled roving: Multiple strands assembled to form a heavier roving
- Watch out for catenary effects in assembled roving
  - Small differences in length may exist between strands
    ➔ fiber misalignment, unequal load bearing between strands
- Rovings are classified by filament count (e.g, carbon fibers) or linear mass measure (e.g., glass fibers)
  - Denier: Mass in grams for 9,000 m of roving [g]
  - TEX: Mass in grams per 1,000 m of roving [g/km]
  - Yield: Length of roving in yards per pound [yd/lb]
- Heavier rovings speed up production but may reduce part quality and performance

Image source: Teijin Aramid

INTRODUCTION FW SYSTEMS

Fiber delivery/tensioning equipment

- Tension control desirable
  - Control of fiber volume fraction
  - Consistent properties
- Two types depending on use of center-pull or outside-pull creels
  - Outside-pull: Fiber dispenser with computer-controlled motor tensioner
  - Center-pull: Creel shelves with mechanical system e.g. s-wrap tension bars
- Note: Center-pull creels can be converted to outside-pull creels by affixing a core with expanding polymer foam

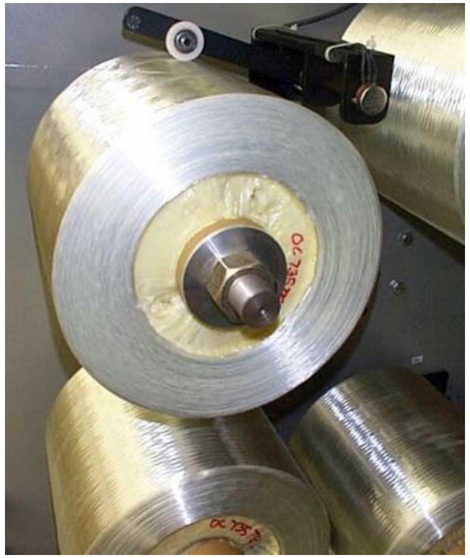


Image source: McClean Anderson, Author

INTRODUCTION FW SYSTEMS

Resin impregnation

- Resin baths for (liquid) thermosets
- Two types:
  - Dip type: Fiber immersed in tank filled with resin; resin metering by squeegee
  - Drum type: Bottom of drum immersed in resin, fibers run over top of drum to pick up resin; resin metering controlled by doctor blade
    ➔ Minimizes friction on fibers
- Baths typically heated to lower resin viscosity, promote thorough resin impregnation of filaments
- Notice colored threads in image: Validate winding angles, product identification

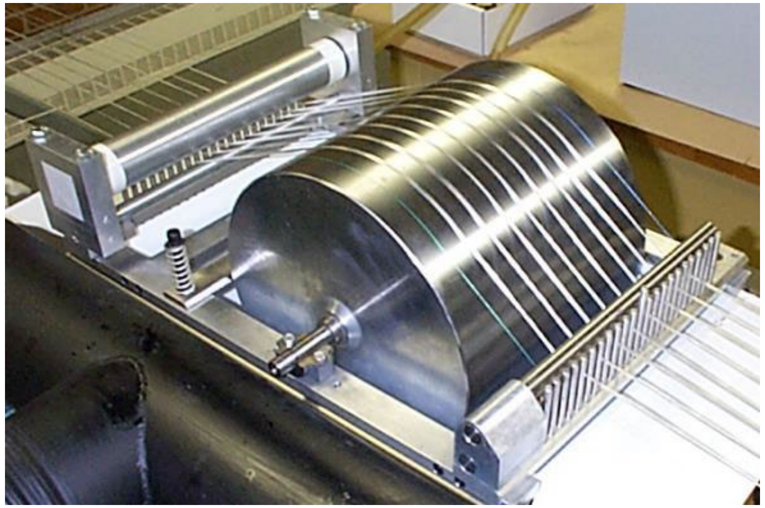


Image source: McClean Anderson, Author

INTRODUCTION FW SYSTEMS

Mandrels

- Either removable after curing or become part of fabricated components (e.g., certain pressure vessel types)
- If removal needed:
  - Slightly tapering cylindrical sections eases extraction
  - Avoid resin adhesion using release agents on mandrel surface
- Mandrels must have sufficient stiffness to withstand compression imposed by fiber windings
- Multi-part mandrels can allow for undercuts
- Mandrel cross sections can be non-axisymmetric
  - But, such shapes (e.g. square) may hinder composite consolidation
- Mandrel heating possible to maintain defined temperature during winding
  - Mandrel filled with phase-change material
  - Heat pipe technology (may even allow for curing)

Image source: Acrolab

INTRODUCTION FW SYSTEMS

Curing

- Thermoset composite systems typically heat cured
- Wet filament winding requires mandrel rotation during curing to avoid resin drip-off and promote part roundness
- After curing, mandrel removal may require specialized equipment (mandrel extractor)

Image source: Author

FW PROCESS

Process parameters and control

- Winding angle θ
- Mandrel diameter D
- Pitch P (distance fiber delivery/carriage travels per mandrel rotation)

$$\tan\theta = \frac{\pi D}{P}$$

- Fiber band width W
- Number of circuits C

$$W = \frac{\pi D \cos\theta}{C}$$

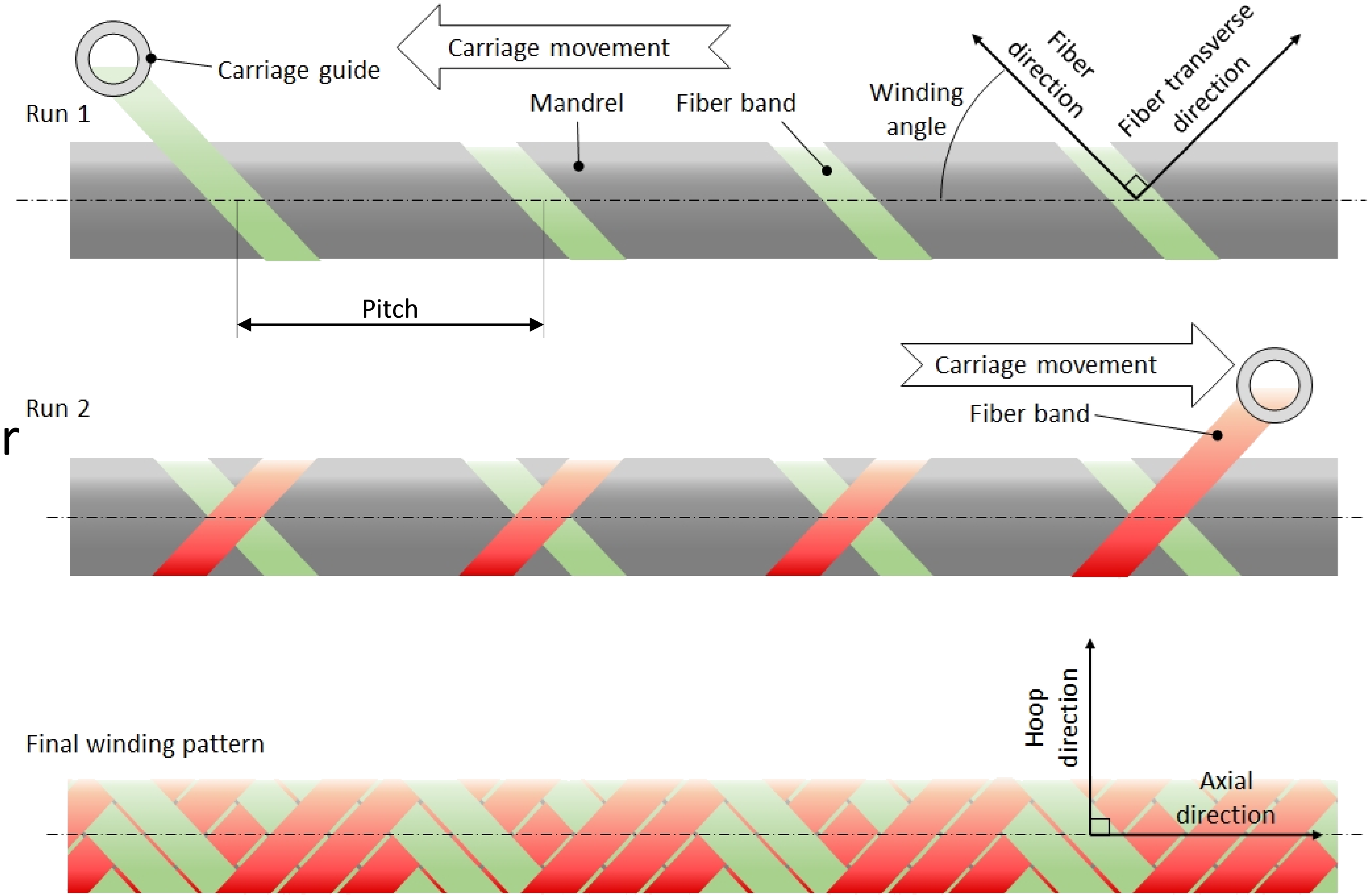


Image source: Author

FW PROCESS

Process parameters and control

- Interweaving of winding bands typical
- Path planning seeks to avoid gaps in coverage
- Suppliers offer sophisticated design software
- Software tools allow for path planning and parameter optimization
- Design difficult for complex geometries (e.g., bottles, variable diameter shapes) ➔ deviations from desired winding angle, overlap of winding bands
- ‘Trail and error’ approach often necessary

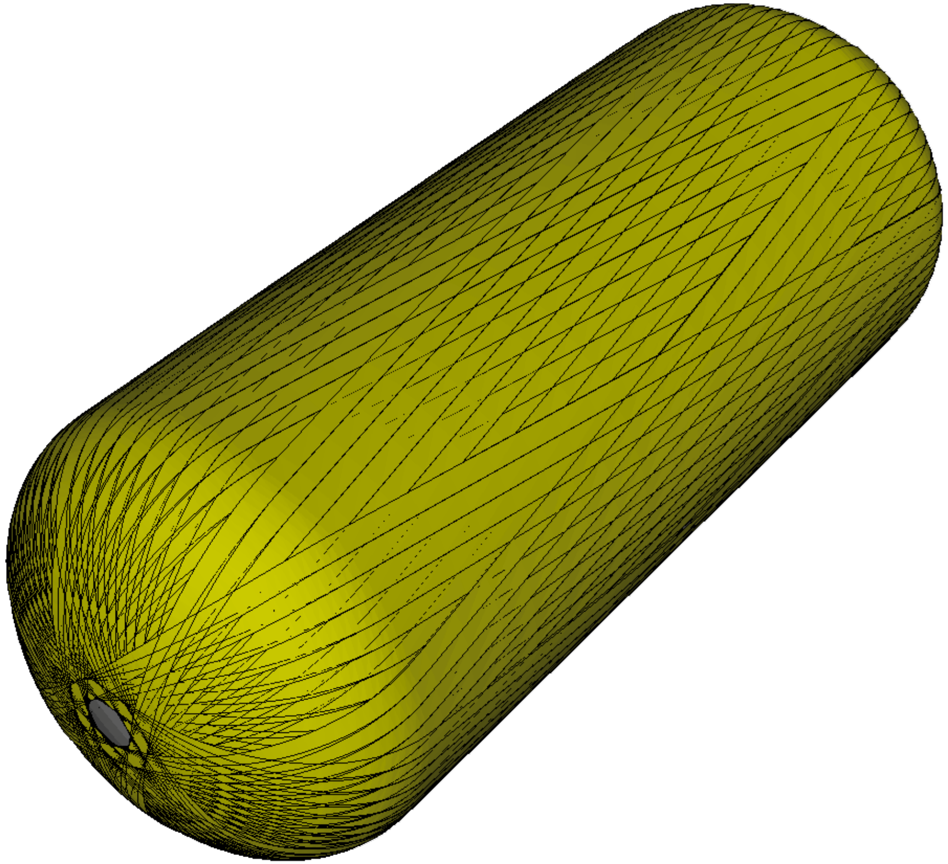


Image source: J. Multhoff

ENGINEERING DESIGN FOR FW

Material systems

- Dry fibers
    - Inexpensive reinforcement system
    - Has internal liner, outer polymer jacket
    - Used to create e.g. steel pipe with augmented hoop strength (FAST-Pipe^{TM}); spoolable composite pipe (Flexpipe)
- Fiber-reinforced thermosets
    - Most common material systems (e.g., glass reinforced epoxy or polyester)
    - Wet winding most 'forgiving' due to ease of fiber alignment, liquid resin reducing friction between fibers and guides

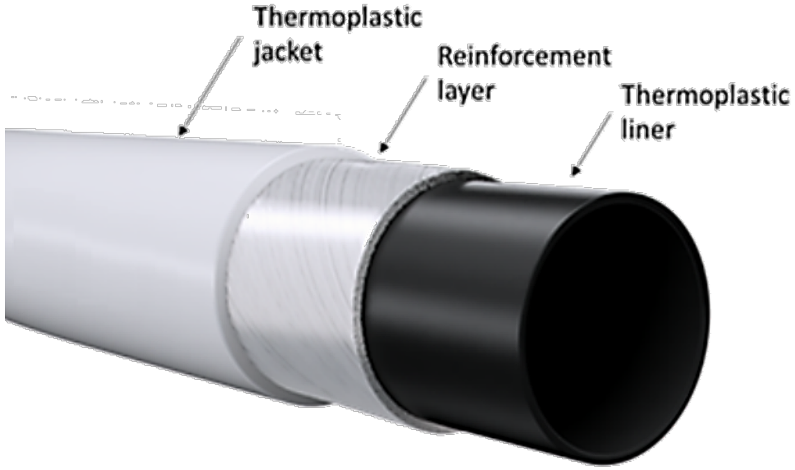


Image source: ConocoPhillips and Flexpipe

ENGINEERING DESIGN FOR FW

Material systems

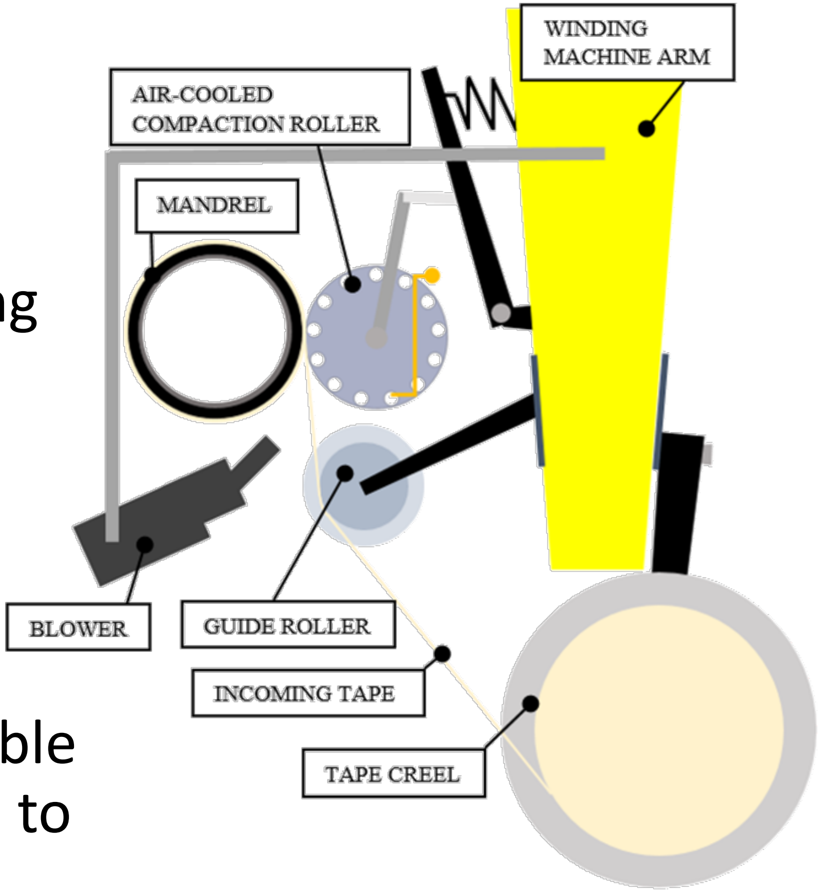
- Thermoset towpreg
  - Fiber rovings pre-impregnated with resin
  - Resin phase solid at room temperature: ‘B-stage resin’ (partially pre-cured) or frozen (e.g. polyimides)
  - Typically require heating to liquify resin upon deposition on mandrel (hot air blower, infrared heater)
  - Heat cure required after winding
  - Expensive material systems

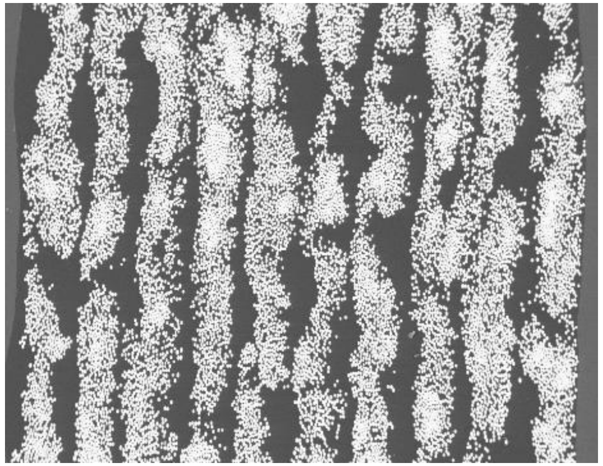
Image source: Author

ENGINEERING DESIGN FOR FW

Material systems

- Thermoplastic tow or tape
  - Tape width and mandrel diameter determine winding angle
  - Nip-point heating and compaction roller used to 'fuse' layers under defined pressure
  - Complete melting undesirable to avoid fiber waviness due to 'catenary' effect in tape
  - Distinct polymer-rich layers





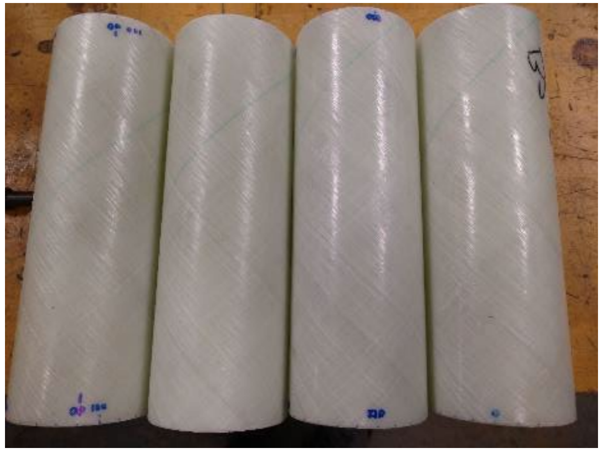


Image source: Author

ENGINEERING DESIGN FOR FW

Liners

- Thermoset matrices are typically brittle ➔ micro-cracking along fiber direction upon mechanical loading (pressurization) *(Image: Micro-cracking visualized by dye fluorescent in fluid used for pipe pressurization)*
- Leakage (functional) failure usually occurs at much lower loads than structural failure (rupture/burst)
- Liners can inhibit functional failure (and provide mandrel that becomes part of the product, e.g., class 2/3/4 pressure vessels)

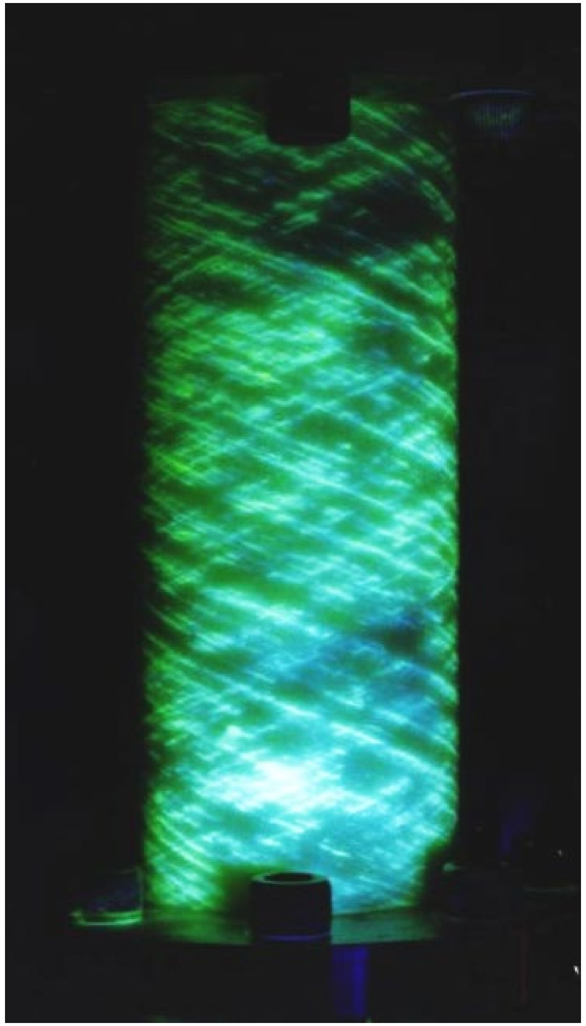


Image source: Author

ENGINEERING DESIGN FOR FW

Liners

- Provide barrier to stop fluid ingress
- Surfacing veils (glass or polymeric) ➔ drapable, easy wet-out with resin
- Polymer liners made via casting, extrusion (e.g. epoxy composite on polyurethane liner) ➔ also used to protect against abrasion

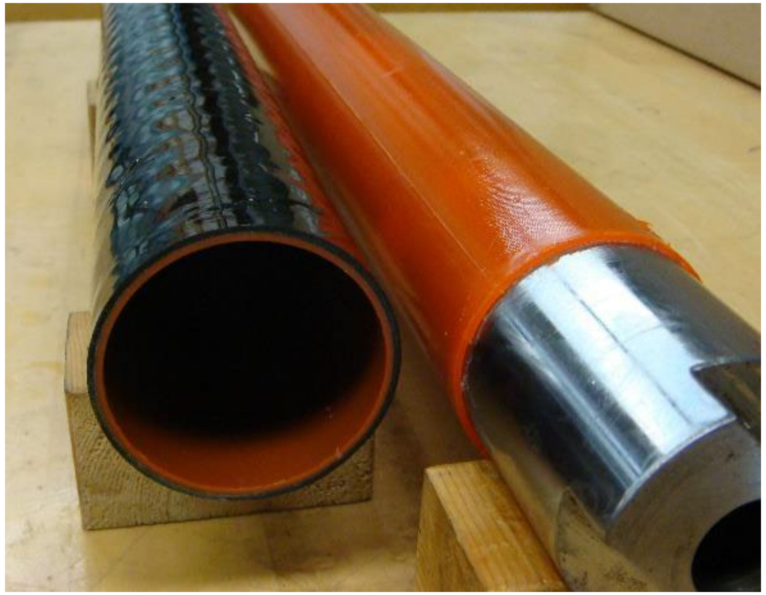


Image source: Author

ENGINEERING DESIGN FOR FW

Additional considerations

- Low winding angles ($\theta \rightarrow 0°$)
  - Tension causes fiber slippage along mandrel
  - Pin rings facilitate low winding angles
- High winding angles ($\theta \rightarrow 90°$)
  - Ideal to consolidate preceding layers, especially in the case of low winding angles

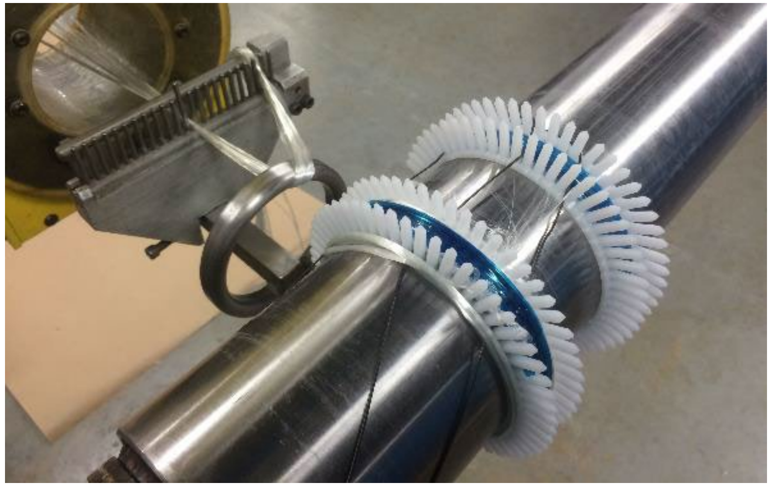


Image source: Author

ENGINEERING DESIGN FOR FW

Additional considerations

- Increasing part rigidity (bending stiffness)
  - Increase wall thickness to raise area moment of inertia
  - Can be achieved by merely adding low-cost aggregate layer, e.g., chopped fibers, sand
- Improving part consolidation (fiber volume fraction, void content)
  - Autoclave curing typically too expensive
  - Wrapping part with peel ply and shrink tape prior to curing

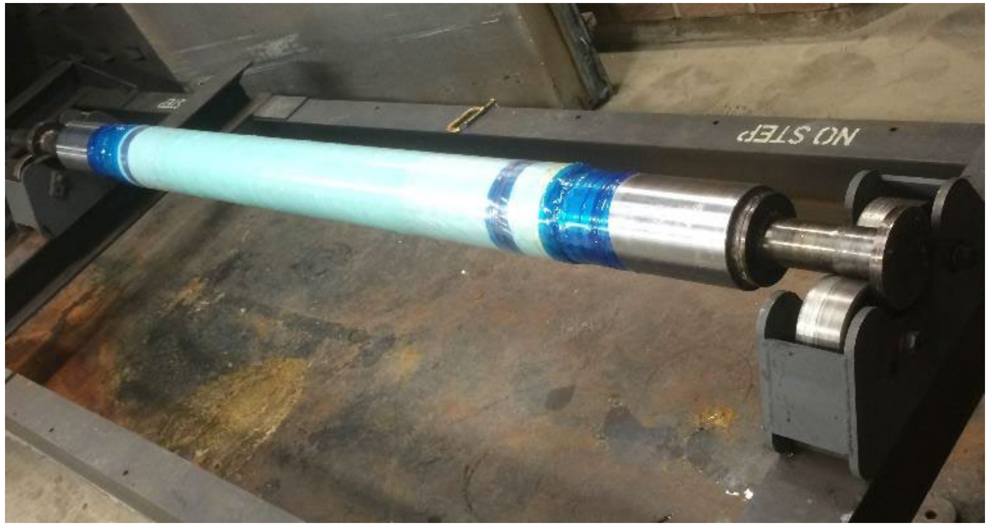


Image source: Author

TESTING AND QUALITY CONTROL

- FW structures hardly suited for typical flat coupon testing, e.g., for screening materials and process parameters
  - Curvature effects
  - Hoop properties typically critical
- Difficult to extrapolate result from other fabrication methods (flat laminates)
  - Fiber volume fraction, void content (both usually higher in FW)
- Tubular specimen pressure testing
  - Better reflect material behavior
  - Ability to test for functional and structural performance
- Full-scale testing and qualification required
  - Standards specific to certain product types
  - ASME NM standards for glass/thermoset piping

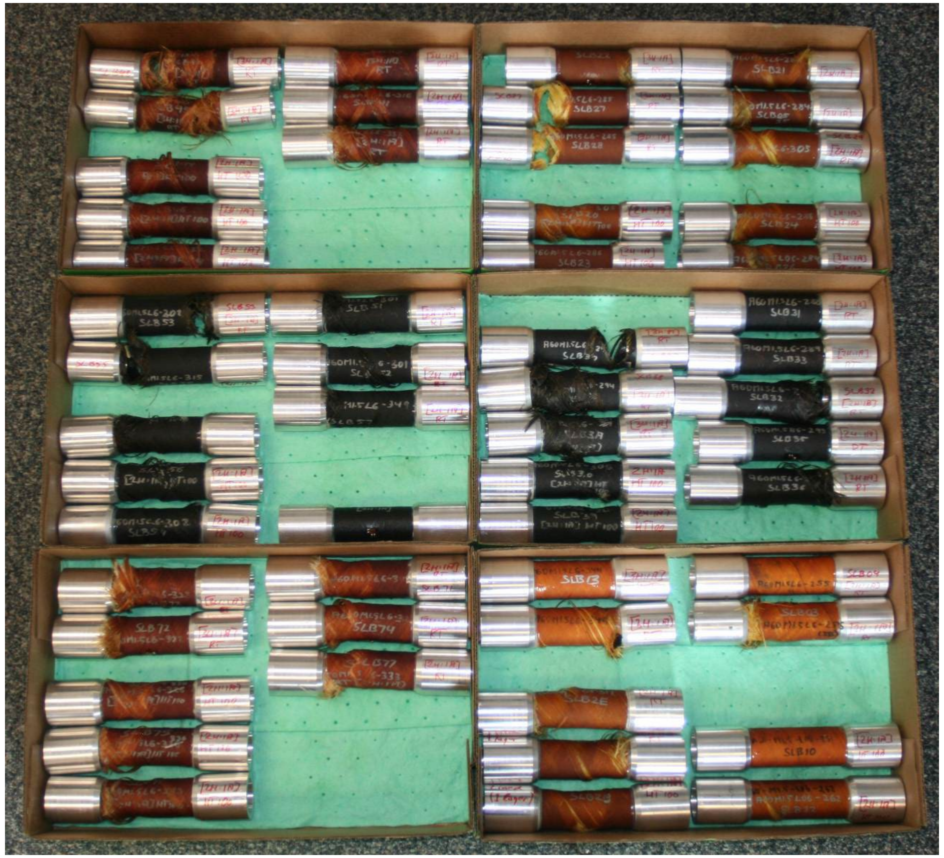


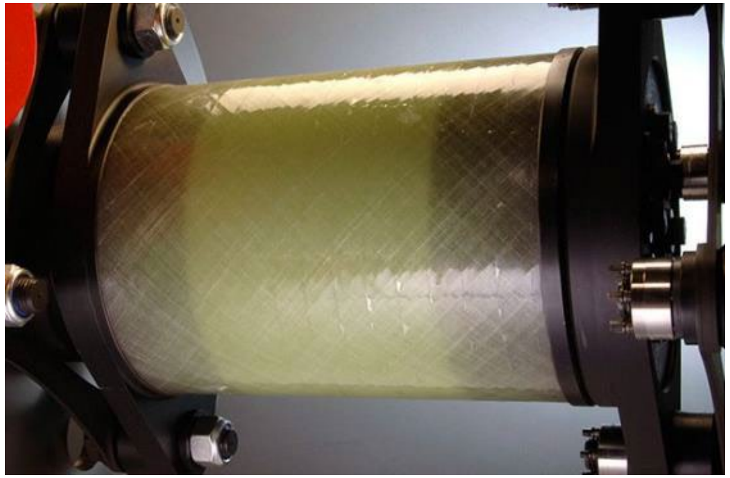
Image source: Author

EMERGING TECHNOLOGIES

- Materials systems
  - Towpregs, tapes
  - Thermoplastic composites
  - Multi-material systems
  - High-temperature resins (e.g., polyimides)
- Multifunctional composites / structures
  - Augmenting composite structure with added functionality
  - Filler-modified resins (e.g., electrically conductive fillers like graphene)
  - Static electricity discharge, EMF shielding
- Embedded sensors (e.g., RFID tags)

APPLICATION EXAMPLES

- Pressure vessels, bottles
  - Specific strength
- Tubular products, piping
  - Corrosion/degradation resistance, lightweight
- Drive shafts / couplings
  - Lightweight, insulating
- Utility poles
  - Degradation resistance, ease of transportation
- Flywheel rotors
  - Specific strength



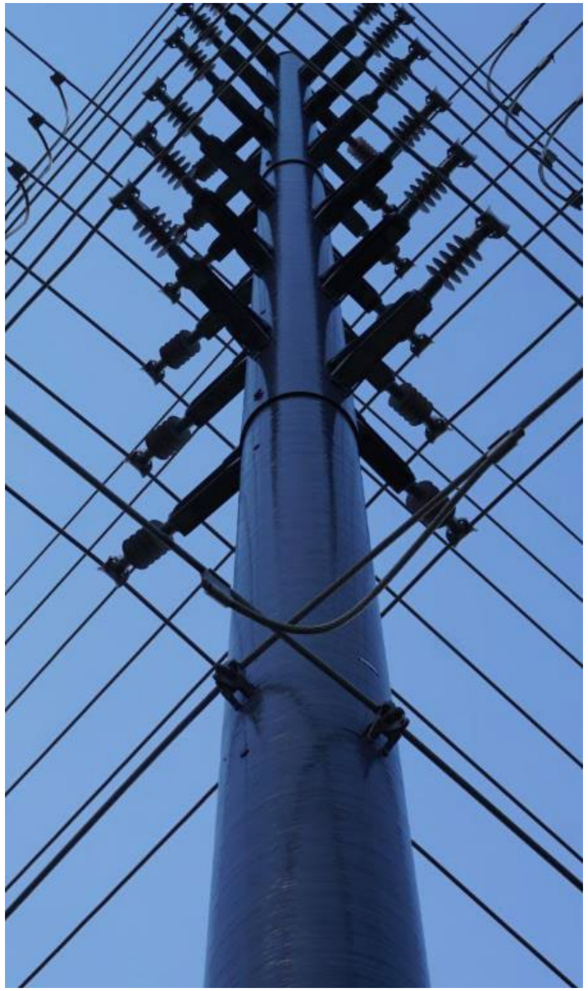


Image source: DYNEXA, RS Technologies, Author

Thank you for joining us!

Keep an eye out for upcoming AIM events:

Implementing Bolted Joints in Composites
Hosted by Dr. Casey Keulen
October 30, 2024
https://compositeskn.org/KPC/A373

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A370

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