What Every Owner Should Know About CFRP

EPRI BOP – June 24, 2024

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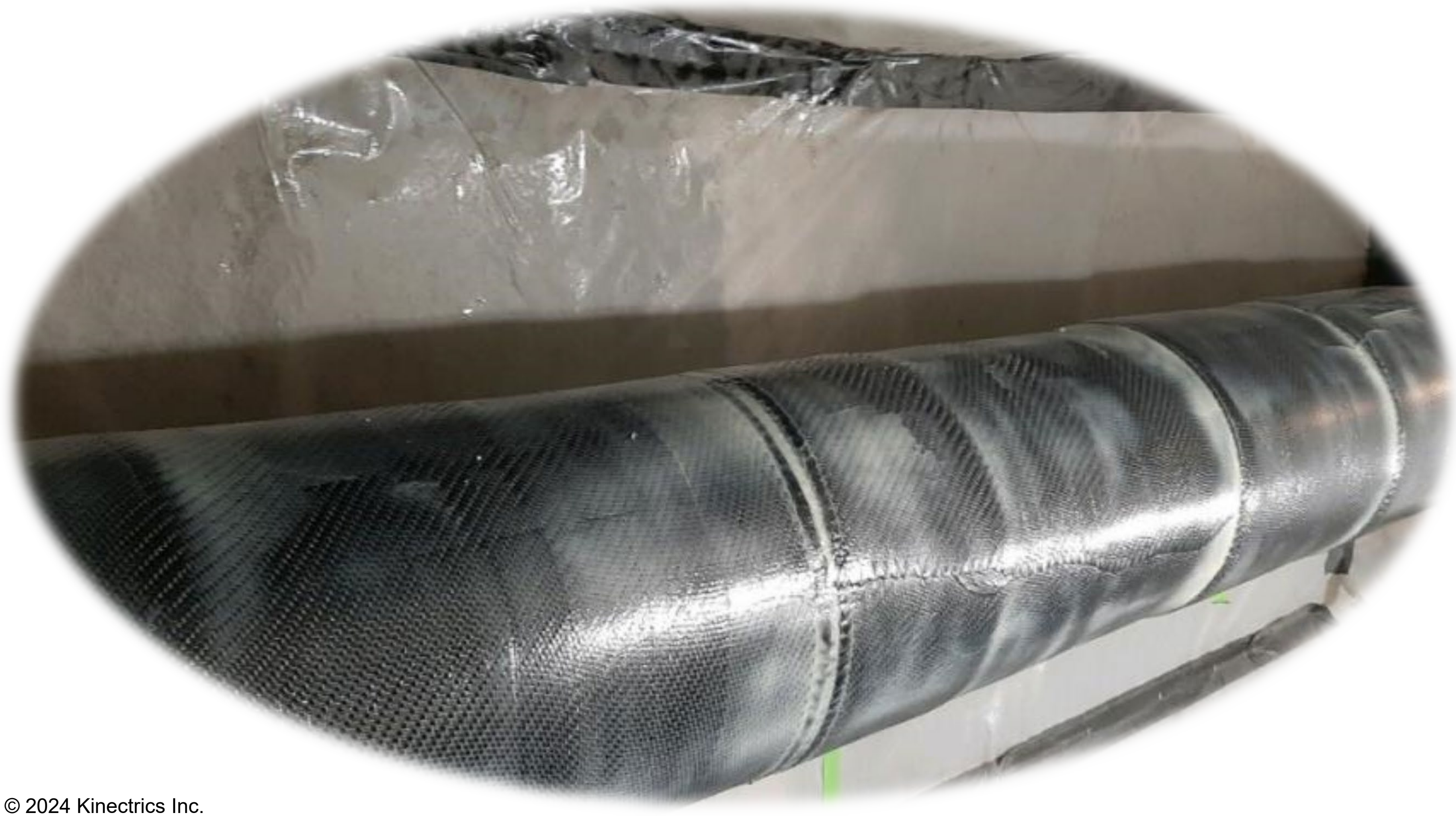
Agenda

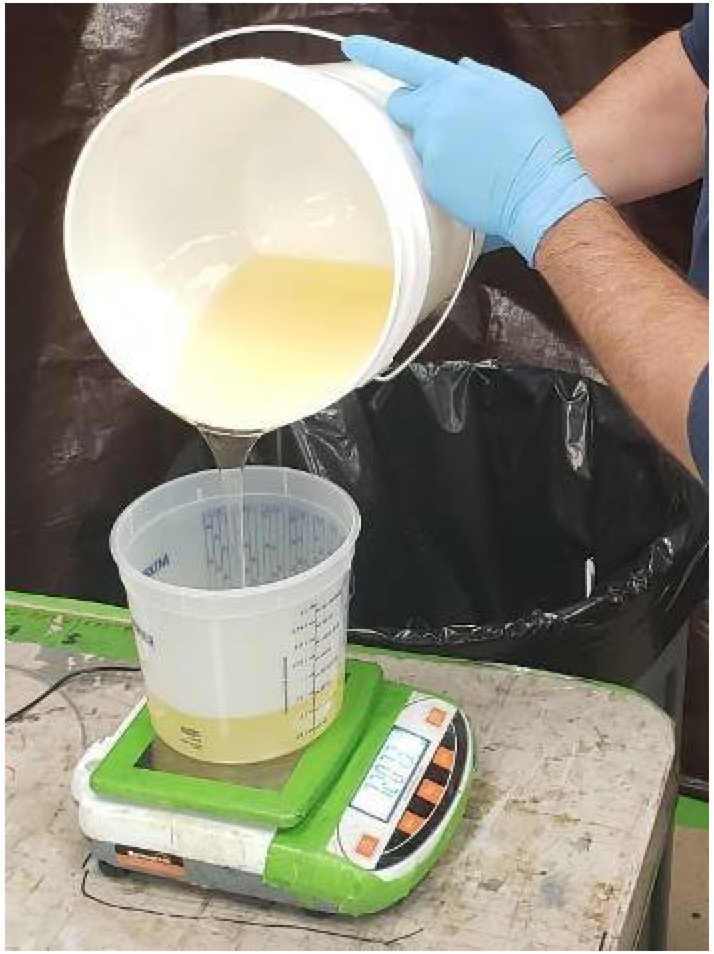
- Characteristics
- Design
- Installation
- Inspection and Repair
- Testing and Asset Management
- Key Takeaways

CFRP Characteristics

Carbon Fiber Reinforced Polymer (CFRP)

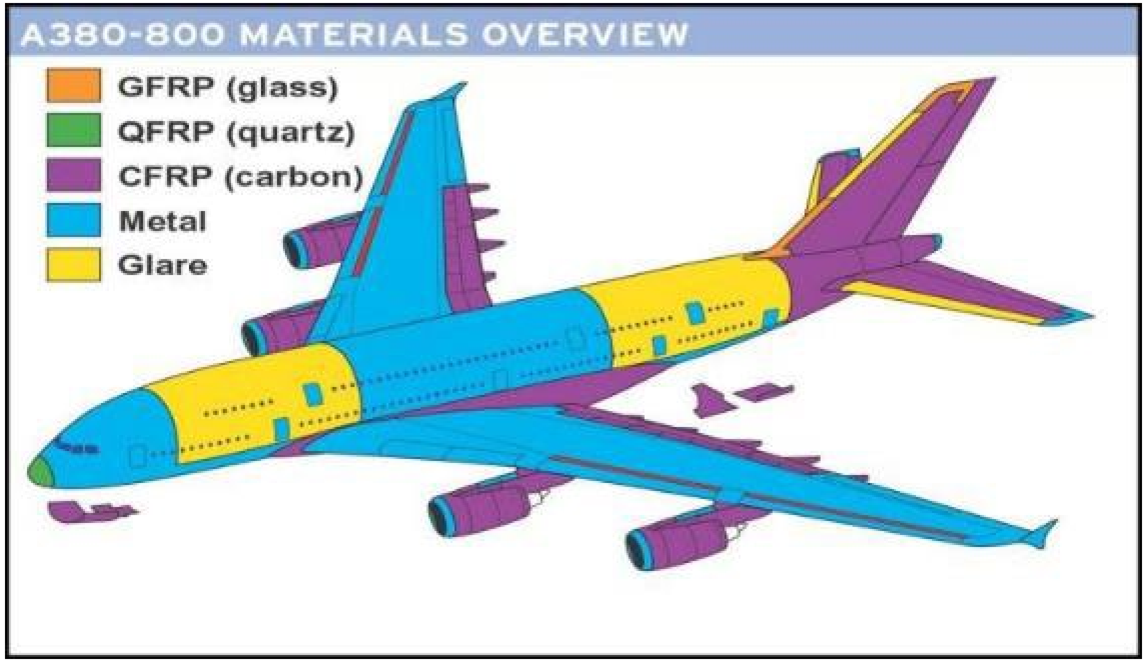


Carbon Fibers Plus Resin



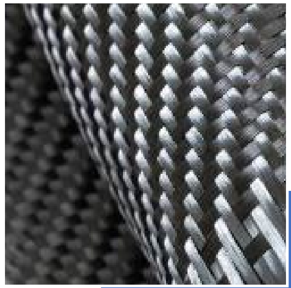
CFRP In Aerospace

CFRP: A composite consisting of strands of carbon fiber bound together with a polymer resin



Metallics vs Composites

- Prescriptive codes
- Operating experience
- Isotropic
- Standard design
- Delivered to site as a product
- Full physical replacement required



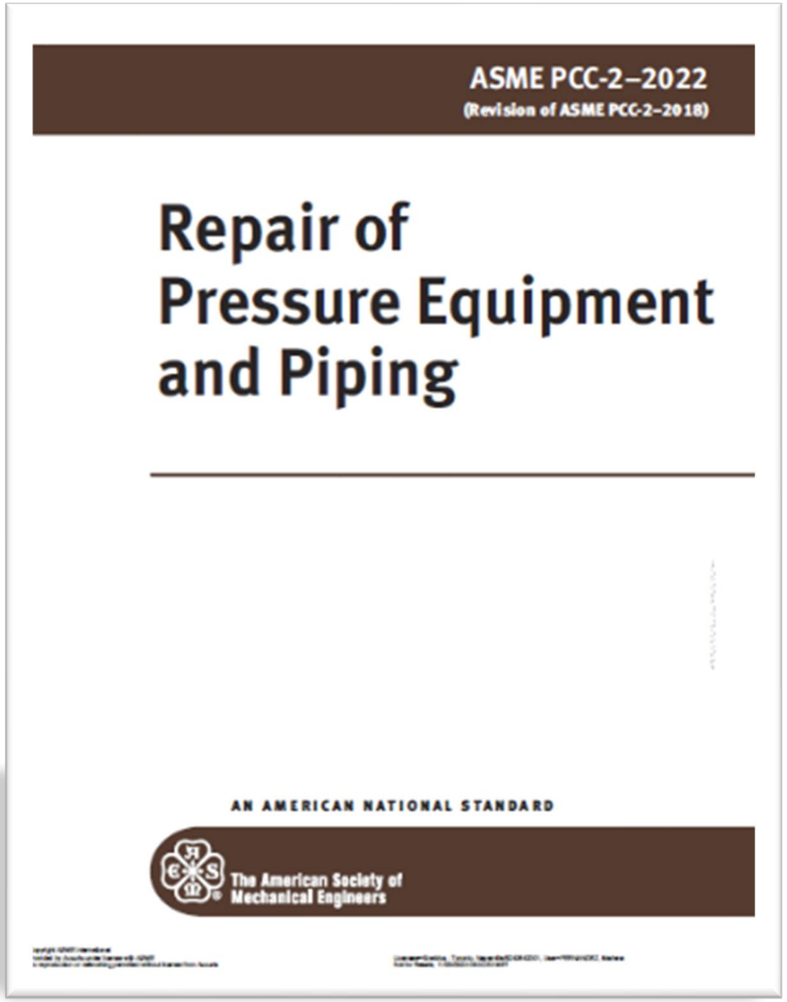
- Performance codes
- More recent development
- Anisotropic
- Customizable design
- Delivered to site as a kit
- Replace and repair in-situ

They may be new and different, but composites offer unique advantages

CFRP Design

Commercial Codes

Commercial Codes


ASME PCC-2–2022
(Revision of ASME PCC-2–2018)

Repair of Pressure Equipment and Piping

AN AMERICAN NATIONAL STANDARD

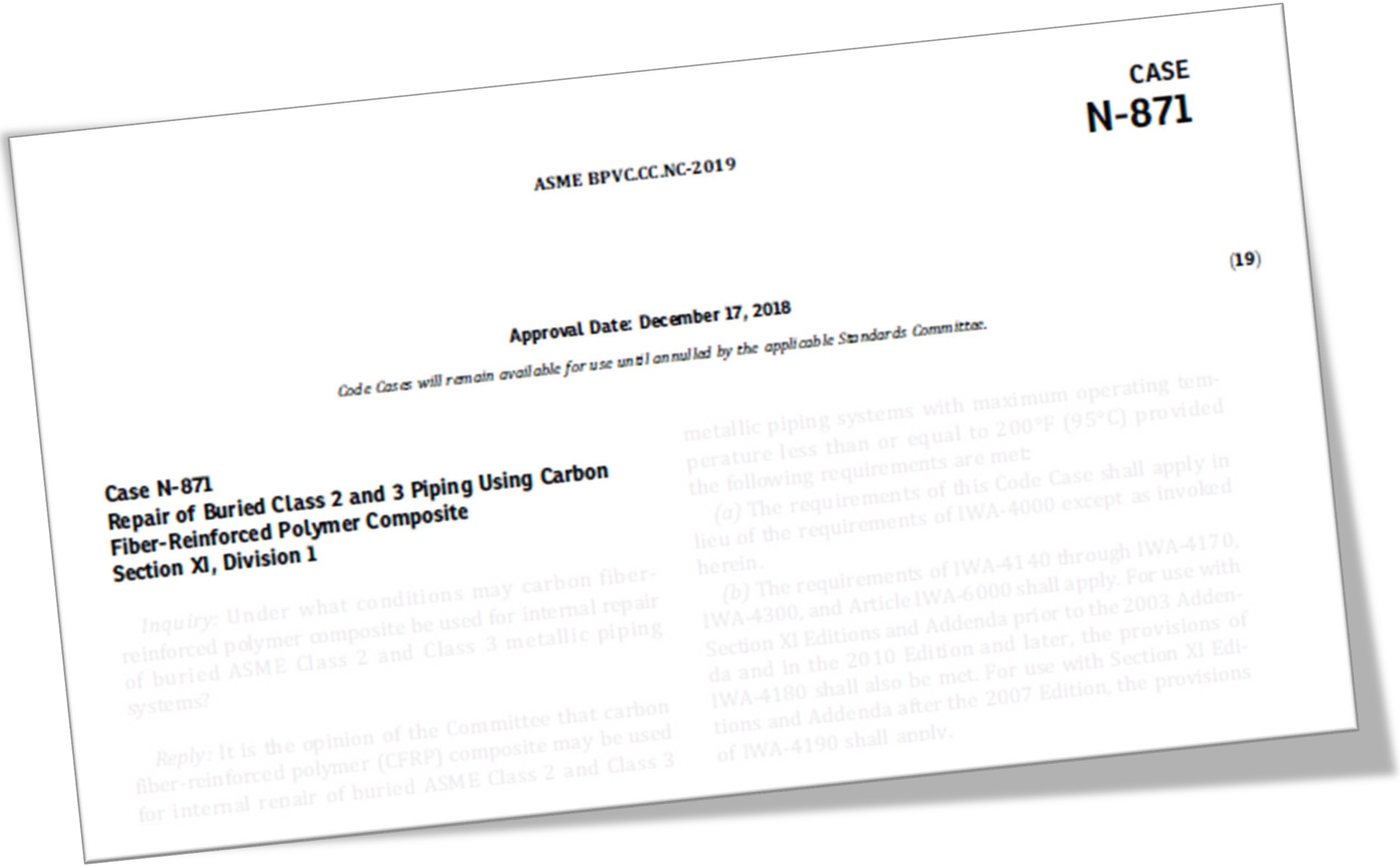
The American Society of Mechanical Engineers

ASME PCC-2–2022

PART 4
NONMETALLIC AND BONDED REPAIRS

Article 401
Nonmetallic Composite Repair Systems: High-Risk Applications (22)

Nuclear Safety-Related



CASE
N-871

ASME BPVC.CC.NC-2019

(19)

Approval Date: December 17, 2018

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-871
Repair of Buried Class 2 and 3 Piping Using Carbon Fiber-Reinforced Polymer Composite
Section XI, Division 1

Inquiry: Under what conditions may carbon fiber-reinforced polymer composite be used for internal repair of buried ASME Class 2 and Class 3 metallic piping systems?

Reply: It is the opinion of the Committee that carbon fiber-reinforced polymer (CFRP) composite may be used for internal repair of buried ASME Class 2 and Class 3 metallic piping systems with maximum operating temperature less than or equal to 200°F (95°C) provided the following requirements are met:

(a) The requirements of this Code Case shall apply in lieu of the requirements of IWA-4000 except as invoked herein.

(b) The requirements of IWA-4140 through IWA-4170, IWA-4300, and Article IWA-6000 shall apply. For use with Section XI Editions and Addenda prior to the 2003 Addenda and in the 2010 Edition and later, the provisions of IWA-4180 shall also be met. For use with Section XI Editions and Addenda after the 2007 Edition, the provisions of IWA-4190 shall apply.

Current Path of Code Case

Case N-871
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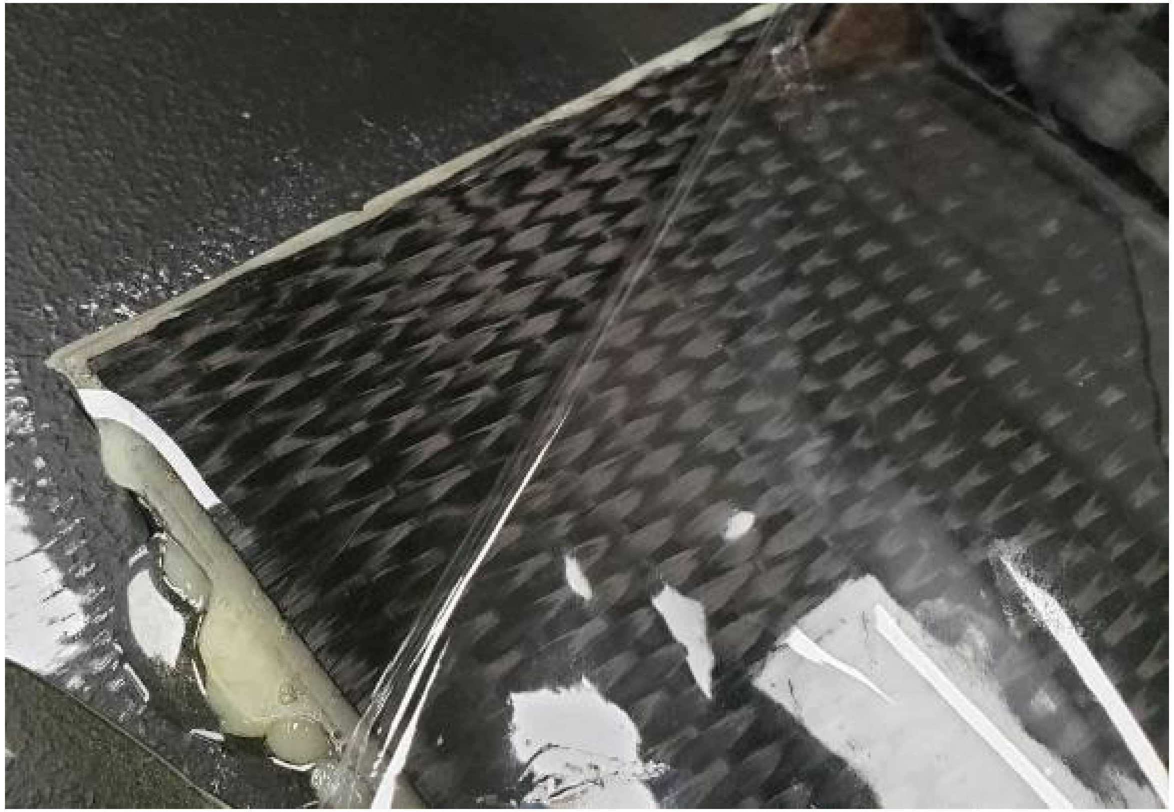
ASME PCC-2–2022
(Revision of ASME PCC-2–2018)

Repair of Pressure Equipment and Piping

Review and verify product testing data against code and design requirements

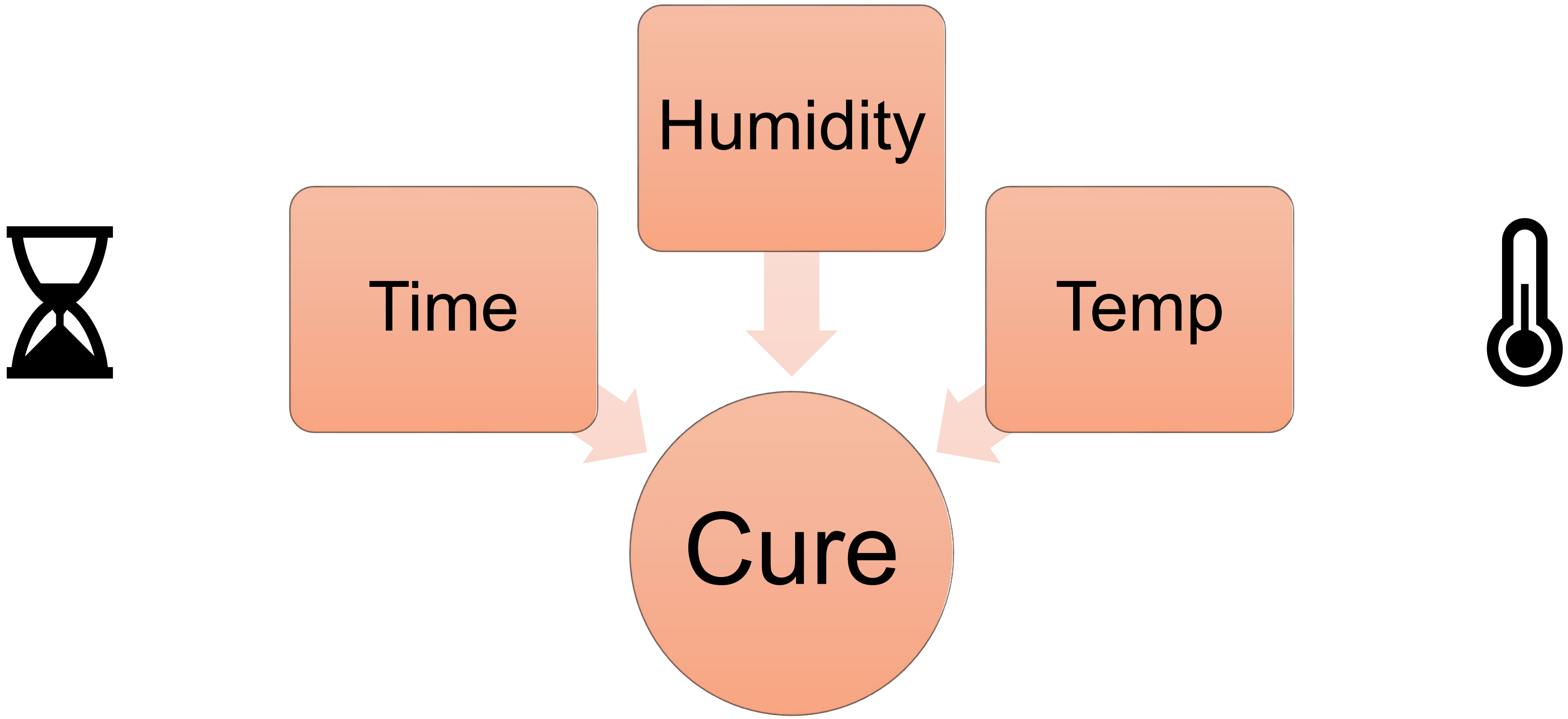
Key Properties

- Tensile strength
- Modulus – stiffness
- Hardness
- Glass transition temperature (Tg) – where behavior changes from hard and glassy to soft and rubbery
- Shear strength (between plies)
- Adhesion strength



Check that the Tg exceeds the design temperature of the system with margin (margin provided in codes).

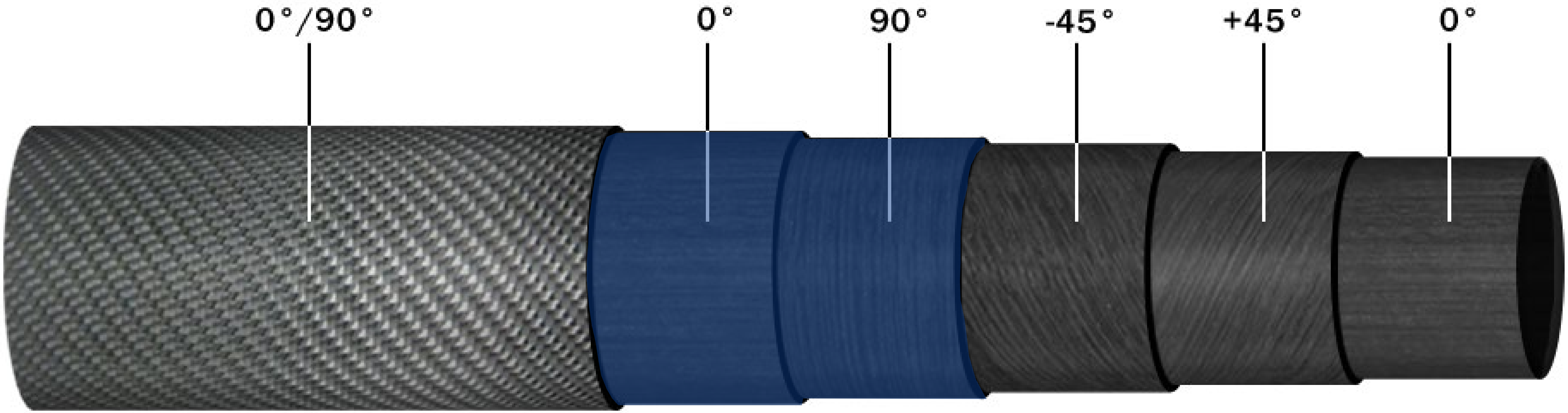
Cure and Tg



Check that the cure regimen (and associated properties) for the project matches the cure regimen on the technical datasheet.

Per Article 401-VIII-4 of PCC-2, the CFRP will not achieve the ultimate Tg found in testing unless the cure regimen is the same.

Unidirectional Design



Review design drawings for layer by layer CFRP construction

Check total layers, ply orientation, overlaps, terminal end length, termination slope, etc.

Design Key Takeaways

1. Review and verify product testing data against code and design requirements
2. Check that the Tg exceeds the design temperature of the system with margin (margin provided in codes).
3. Check that the cure regimen (and associated properties) for the project matches the cure regimen on the technical datasheet
   a. Per Article 401-VIII-4 of PCC-2, the CFRP will not achieve the ultimate Tg found in testing unless the cure regimen is the same.
4. Review design drawings for layer by layer CFRP construction
   a. Check total layers, ply orientation, overlaps, terminal end length, termination slope, etc.

CFRP Installation

Installation Goals

- CFRP system is installed within the existing outage window(s)
- CFRP system is installed per design with no defects
- CFRP system is installed under budget
- CFRP system lasts the life of the unit

Installation Steps

Installation plans should include provisions for the following items

- Establishing and maintaining environmental conditions
- Material storage
- Material handling
- Surface preparation
- Post blast cleaning
- Priming the substrate
- Thickened epoxy
- Saturation
- Layup
- Quality control
- Cure

Access Points

- Access points are bottlenecks.
  - How many do you have?
  - What are the size/shape?
  - Where are they?
    - Can you circulate air/heat, or do they hammer head?
    - Outside or inside (will weather or plant conditions impact them)?
- People
  - Number of manholes limits work areas.
  - Do you need a ladder?
  - Do you need fall protection and retrieval equipment?
- Equipment
  - Heat, dehumidification, grit lines, breathing lines, blast equipment, dust collection, vacuum lines, scaffolding, epoxy and fiber

Will additional access points save outage time?

Environmental Conditions

- Ambient temperature – depends on your product but usually between 60°F and 90°F
  - Heat or air conditioning may be required throughout the project
- Surface temperature – must be maintained at least 5°F above the dew point temperature
  - Heat or air conditioning will play a role in maintaining surface temperature
- Relative humidity and dew point
  - Heat, air conditioning, or dehumidification or a combination may be required

Environmental conditions are critical to a successful installation.

Environmental Conditions

What are the consequences if I can't maintain environmental conditions?

- Flash rusting
  - Poor adhesion to the substrate
- Condensation
  - Interlayer delamination
- Amine Blush
  - Interlayer delamination
- Uneven curing
  - Expected mechanical properties may not be achieved

What should I look for?

- Are the field conditions the same as test conditions
- Contractor should have a plan based on varying conditions
  - Check for monitoring equipment (the entire area not just a point)
  - Ask for alarm points and responses
  - Ask to see results on a regular basis
  - Make sure the plan accounts for weather, equipment failures, and other anomalies

Material Storage

Material storage requires proper environmental conditions

- Store CFRP materials per the manufacturer's recommendations (60ºF - 90ºF)
- Storage area should be clean, dry, and out of direct sunlight
- Material shall be stored in original unopened containers
- All containers shall be clearly marked with manufacturer's name, product identification, component designation, lot number, date of manufacture, and shelf life.
- Storage conditions must be monitored door to door (shipping included)

What should I look for?

- Ask for a copy of the Technical Data Sheets (TDS) for all products
- Ask for a receipt inspection
- Look at the condition of the material/containers as it arrives and in storage locations
- Ask for monitoring results to verify that proper conditions are being maintained

Material Handling

Epoxies

- Do not split kits (full kits must be used)
- Mix per the manufacturer's instructions
  - Box mixing is a best practice
- Use within specified pot life listed on the TDS

FRP (Fiberglass and Carbon)

- Handle with clean gloves (material transfer)
- Protect opened roll when not in use

What should I look for?

- Homogeneous mix
- Gloved hands
- Clean cutting surfaces (no dirt, debris, moisture)

Material must be the same as specified in the design

Surface Preparation

Surface preparation

- Remove all contamination before grit blasting – oil, debris, chlorides, etc.
- Remove all obstructions – old weld backing rings, exp joint covers, etc.
- Fix all holes, cracks, etc.
- Air for grit blasting must be dry and oil free
- Report and document all dents, ovality, or other anomalies

What should I look for?

- Chloride test results(remove per SSPC-Guide 15)
- White Blotter test results and frequency (ASTM D 4285)
- Profile testing results (comparator gauges, tapes, digital probes)
- Verify the SSPC standard is met (backside of welds, hard to reach areas)

Poor surface preparation will lead to poor adhesion values.

Post Blast Cleaning

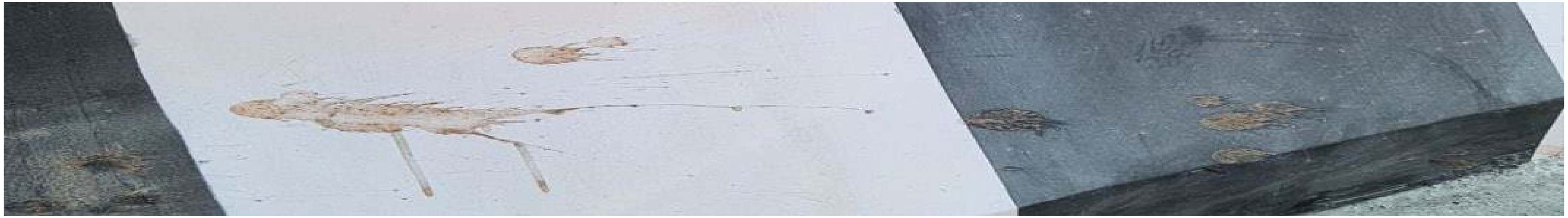
Post blast cleaning

- Cleaning after grit blasting is essential – dust/debris/corrosion are the enemy
- Don't contaminate your grit blasted surface – exclusion zones/controlled areas
- Blowdown and vacuuming may be required – check backside of welds, expansion joints, etc.

What should I look for?

- No dust, dirt, debris, or grit on the surface
- Moisture, wet spots, holes (report/document any new issues)
- Check hard to see and hard to reach areas

Don't contaminate your blasted surfaces.



Primer

Prime all blasted surfaces with specified epoxy primer

What should I look for?

- No dust, dirt, debris, or grit on the surface
- Primer mixed and applied per the manufacturer's instructions – check data sheets
- Primer applied within the overcoat window – check time and temperature records

Don’t lose the blast, prime it.

Thickened Epoxy

Pipe surfaces shall be smooth with no surface discontinuities

- Fabric will bridge/trap air if applied over discontinuities
- Fill all discontinuities with approved thickened epoxy
- Thickening agents include fumed silica, chopped fibers, Kevlar, etc.

What should I look for?

- Thickening agents are added per the manufacturer's recommendations
  - Correct additive, correct percentage added, properly mixed (no dry spots)
- Material should be cured sufficiently so it won't be pushed out
- Surface MUST be smooth
  - No fingers or sharp edges (if sanded watch out for dust)

Test results for Tg, strength, adhesion, etc. must include all constituents.

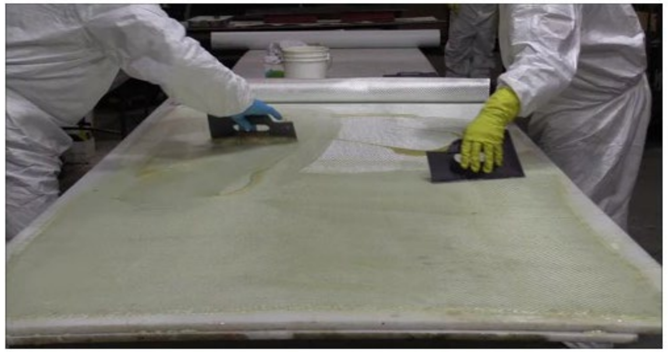
A&G INDUSTRIAL SERVICES

KINECTRICS

Saturation

Saturation can be manual or machine

- Manual saturation is done on a table and saturant is worked into the fabric by hand
- Machine saturation is done mechanically using a saturation machine to wet out the fabric



What should I look for?

- Saturation table/machine is clean throughout the process
- Saturant mixed per the manufacturer's instructions
- Saturant is used within the pot life of the material
- Fabric is fully saturated but not over saturated
  - Correct fabric to resin weight ratio (check the roller gap, test samples)
  - Check multiple times per shift, ambient temperature changes, etc.
- Take samples to verify the process (ASTM D 4541, ASTM D 3039)

Fabric to resin ratios must match testing

Layup

What is a wet lay-up process?

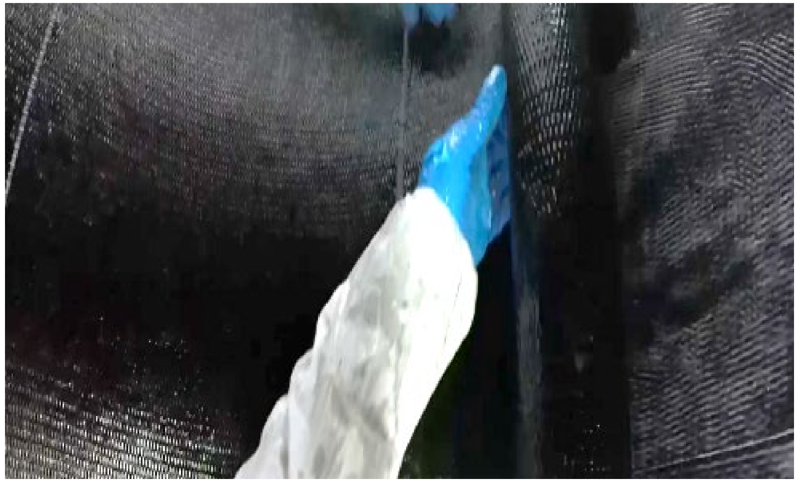
- Saturated fabric (hand or machine) applied to the surface, no dry or prepreg fabric

What does the design specify?

- Material, fabric weight, number of layers, orientation, overlaps
- Thickened epoxy (tack coat) for overhead and vertical applications
- Fiberglass (dielectric barrier, waterproof layer)

What should I look for?

- Surface is clean, tack coat applied evenly, within recoat window
- Orientation is correct
- No trapped air, wrinkles, gaps, bubbles, etc.
- Fabric is not misaligned (typically 1” per foot)
- Overlaps are per design drawings
- Overlaps, seams, ends sealed per design



Inspect after each layer.

Quality Control

The contractor will have a QC program, make sure they follow it.

- Inspections should be done after each step

What should I look for?

Receipt Inspection Report
Material Storage Log
Environmental Conditions Log
White Blotter Testing
Surface Preparation Checklist
Surface Profile Record
Fabric Saturation
Material Control Log

Fabric Installation Checklist
Epoxy Coating
ASTM D4541 Test Recording Sheet
ASTM D3039 Test Recording Sheet
UT Thickness Record
Nonconformance Log
Training Qualification Log
Equipment Calibration Log

Build inspections into the schedule

Cure

The cure is a critical step in the process

- Material selection and approval is based on lab testing
- The cure time and temperature must match test conditions to ensure proper results.
  - Were test samples post cured?
- Mechanical properties are obtained by a proper cure

- **What should I look for?**
  - Environmental conditions are maintained for the appropriate time.
  - Look for a profile not a point (top of the pipe may not be the same as the bottom)

Don’t let schedule pressure dictate the cure time.

Installation Key Takeaways

1. Environmental conditions must be maintained throughout the process
2. Proper surface preparation is required for adhesion
3. Field installation must match testing
4. Cure time and temperature are critical to obtaining mechanical properties
5. Inspect after each step to ensure success

Installation must match testing

CFRP Inspection and Repair

Composite Inspections

- Visual examination
- UT thickness
- Hardness testing

Applied during an outage

- Phased Array UT
- Thermography
- Shearography
- Acoustic Emission

Time consuming and impractical in an outage – used primarily for aerospace composites, wind turbine blades etc.

Defects and Repairs

- Two Types
  - Prior to cure – usually spotted by the installer and fixed prior to curing
  - After the cure
- Design document should address defects and repairs
  - Make sure this is well defined and a process is in place to address defects
  - The schedule can be impacted significantly if you are not prepared
- **What should I look for?**
  - Defects are being identified, tracked, and repaired per design documents
  - Repair is executed and allowed to cure properly
  - Cleanliness standards are being maintained
  - Overcoat windows are not missed while repairs are being executed
  - All repairs should be documented for future inspections

There will ALWAYS be defects – be prepared for them with approved procedures and Acceptance Criteria

Defects can Grow

- Defects – from manufacturing, installation or operation – can lead to local weakness or can initiate degradation
  - Onset of cracking
  - Moisture ingress
- Presence of voids or contaminants close to the surface can lead to the formation of blisters
  - Osmotic process

Don’t live with problems – Repair the defects early

CFRP Testing and Asset Management

Tests on a Datasheet

Technical Datasheet
Ashland Performance Materials

AROPOL™

AROPOL™ 7334 Resilient Isophthalic Resin

AROPOL 7334 resin is a low viscosity, unpromoted, non-thixotropic, resilient polyester resin. The raw materials used in the manufacture of this resin are listed as acceptable in FDA regulation Title 21 CFR 177.2420 for repeated use in contact with food subject to user's compliance with the prescribed limitations of that regulation.

APPLICATIONS AND USE

AROPOL 7334 resins provide:
- Good corrosion resistance to 66°C (150°F)
- High impact strength
- Excellent crack and craze resistance
- High tensile elongation
- Excellent wet-out

AROPOL 7334T series resins can be used for filament winding, hand lay-up, and spray-up. AROPOL 7241 series resins are less resilient and offer higher heat distortion temperatures.

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TYPICAL LIQUID RESIN PROPERTIES

Property[1] at 25°C (77°F)	Value	Unit
Viscosity, Brookfield, #3 spindle @ 60 rpm	450	mPas (cps)
Percent Solids	59	%
Specific Gravity	1.09	
Color	<4	Gardner
Appearance	Clear	

(1) Properties are typical values based on material tested in our laboratories. Typical values should not be construed as a guaranteed analysis of any specific lot or as specification items.

Gel time at 24°C (75°F)

Resin	100	100	100	100	100	100	100
6% Cobalt	0.6	0.6	0.6	0.6	0.6	0.6	0.6
DEA	02	0.15	0.1	0.08	0.05	0.03	0
DDM-9	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Gel Time, Minutes	14.7	16	22.1	29.6	34.1	47.7	64.5

TYPICAL MECHANICAL PROPERTIES

Property[1] of clear casting[4] at 25°C (77°F)	Value (SI)	Value (US)	Method
Tensile Strength	86 MPa	12,500 psi	ASTM D638
Tensile Modulus	3590 MPa	520 kpsi	ASTM D638
Tensile Elongation	4.4%	4.4%	ASTM D638
Flexural Strength	140 MPa	20,000 psi	ASTM D790
Flexural Modulus	3720 MPa	540 kpsi	ASTM D790
Compressive Strength	150 MPa	21,800 psi	ASTM D695
Compressive Modulus	3300 MPa	480 kpsi	ASTM D695
Deformation at Yield	7.3%	7.3%	ASTM D695
Izod Impact	112 J/m	2.1 Ft-Lbs/In	ASTM D256
Heat Distortion Temperature	94°C	202°F	ASTM D648
Barcol Hardness	40	40	ASTM D2538

(4) Catalyzed with 1.25% LUPERSOL DDM-9 catalyst, cured at room temperature for 24 hours, postcured for two hours at 138°C (280°F).

Read the fine print

Tests on a Datasheet

CF-500 BD

Heavy-Duty, Bi-Directional Carbon Fiber

Description

Advanced FRP Systems' **CF-500 BD** is a 12K, 2 x 2 twill weave, 19.5 oz/yd², bi-directional carbon fiber woven fabric**. CF-500 BD** is made in the USA and meets the most stringent quality requirements for aerospace applications. This material is engineered to provide extremely strong, durable and lightweight composites for long term structural reinforcement. **CF 500-BD** is easy to apply, corrosion resistant and can be applied at any thickness required to provide adequate structural reinforcement.

Product Advantages

- Bi-Directional weave provides outstanding strength in all directions
- ASME PCC-2 Compliant reinforcement
- Lightweight, pliable fabric easily conforms to any shape
- Stable twill weave orientation
- Only 37.5 mils (0.0375 inch) per layer
- Single or multi-layer systems available
- Coefficient of Thermal Expansion close to carbon steel

Suggested Application

CF-500 BD is part of an ASME PCC-2 compliant pipe, tank and vessel repair system in conjunction with the appropriate saturating resin, adhesive, and filler. It is commonly used for the reinforcement of steel pipes, concrete pipes, steel, and fiberglass tanks as well as heat exchangers and pressure vessels.

Performance Data

Cured with FRP Saturant 200

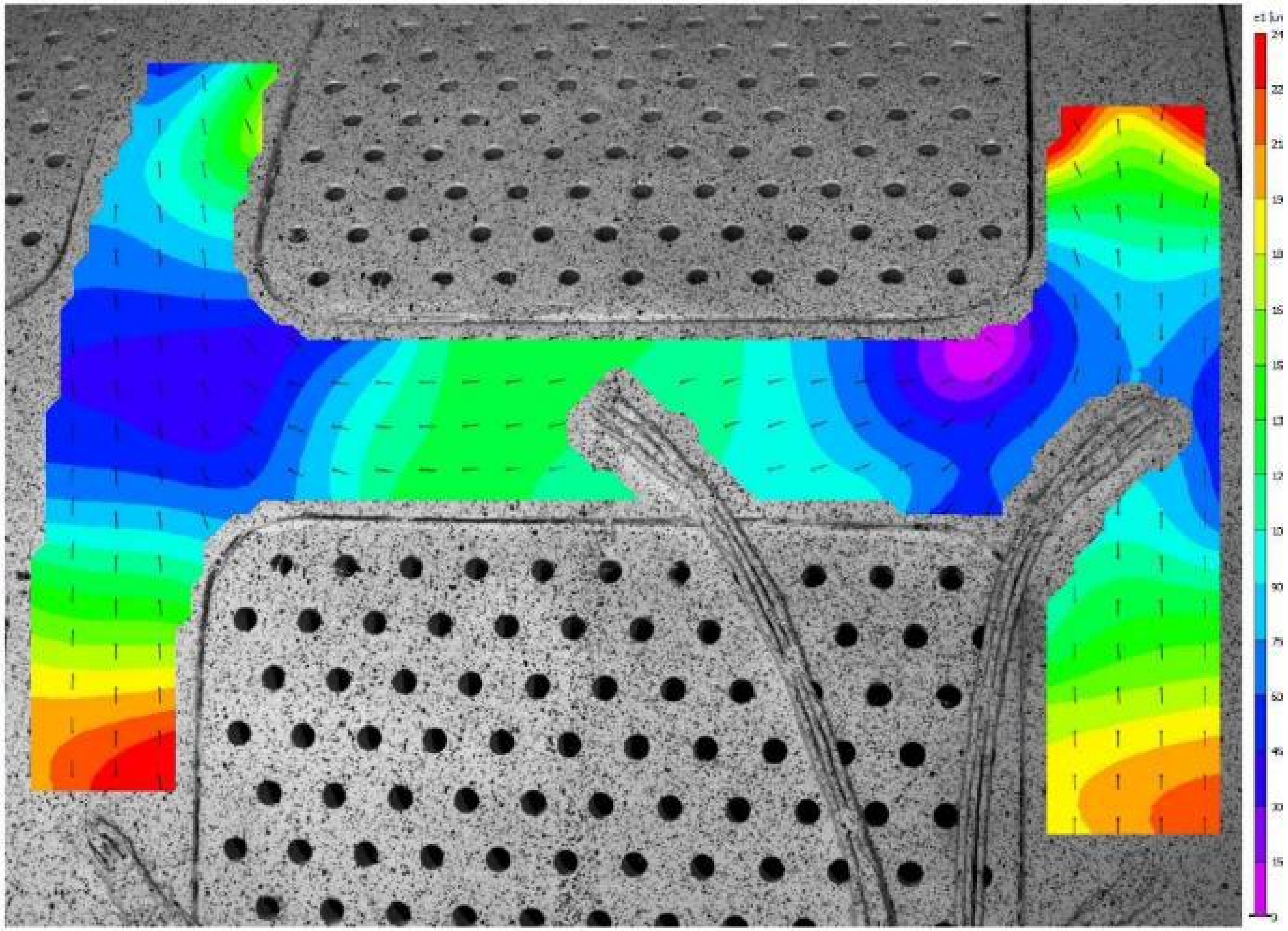
	Test Method	Results
Coefficient of Linear Thermal Exp.	ASTM E831	3.78 x 10^{-6} in/in °F
Tensile Strength	ASTM D3039	Actual Value: 102,000 psi Design Value: 77,000 psi
Young's Modulus	ASTM D3039	Actual Value: 5,667 ksi Design Value: 4.038 ksi
Poisson's Ratio	ASTM D3039	0.091
Lap Shear	ASTM D3165	3,450 psi
Sheer Modulus	ASTM D5379	362,650 psi
Flexural Strength	ASTM D790	Actual Value: 100,200 psi Design Value: 75,150 psi
Compressive Strength	ASTM D695	Actual Value: 111,750 psi Design Value: 88,125 psi
Elongation at Break	ASTM D3039	1.5%
Effective Fabric Thickness		0.0375 in

Tests Not on a Datasheet

- Long-term performance
- Testing at elevated temperature
- Testing in relevant field conditions
- Testing at scale (mock-up testing)

Coupon vs Scale Testing

Testing - DIC



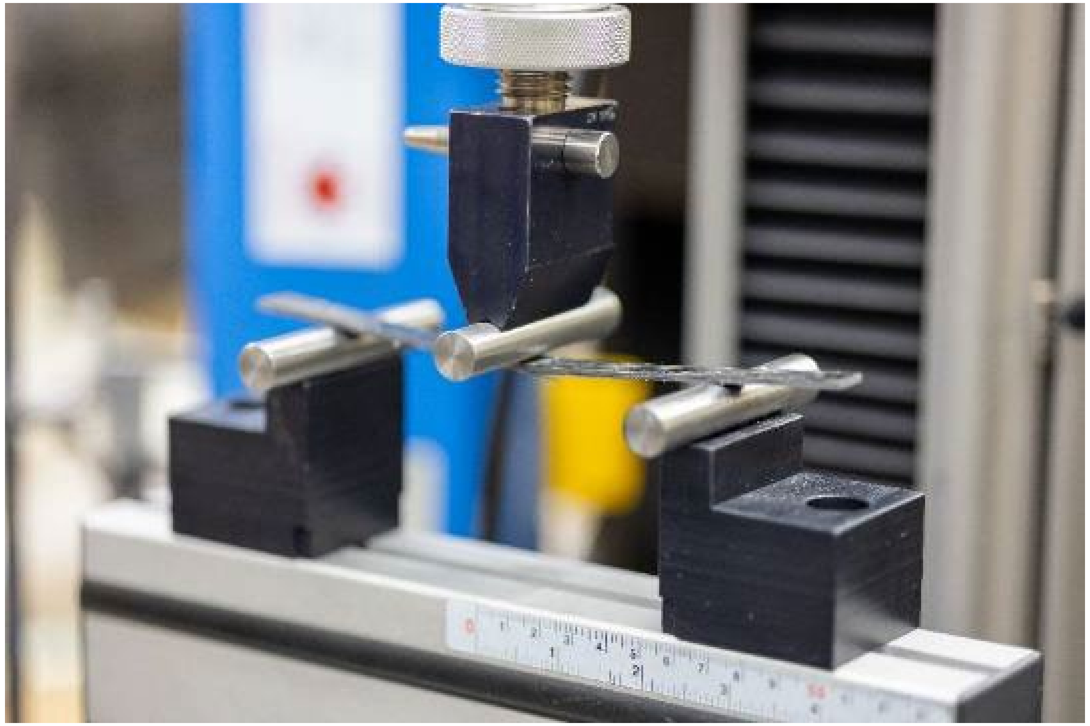
Quick Tests for Quick Answers

Field Tests

- Visual Inspection (non-destructive)
- Local tap testing (non-destructive)
- Hardness (non-destructive)
- Pull-off (destructive)
- UT with limits (non-destructive)

Ageing Mechanisms

- Thermo-oxidation
- Radiation degradation
  - UV exposure
  - Ionizing radiation
- Chemical degradation
  - Water ingress
  - Contact with corrosive chemical
- Long Term Mechanical stresses
  - Creep
  - Fatigue



Long-Term Testing Program

- Samples harvested from the field to assess the condition of the material
- Data used to trend material properties over time
- Data used in analytical model to predict components properties
- Outage work plan based on tests and model results
- Repairs and reinforcements performed on existing system

The best time to start an asset management program is during installation

Ageing Facility

- Tanks duplicate field conditions
- Pipe sections and rings stored
- Testing performed every 6 or every 12 years to assess condition of material
- Destructive and non-destructive testing

Testing Key Takeaways

1. Read the fine print on datasheets - datasheets are sales tools
2. ASTM provide guidelines
3. Gold standard for testing is representative, large scale, performance based
4. CFRP (especially hand lay-up) have inherent high variability in results
5. CFRP is very strong + high variability leads to expensive testing
6. Every CFRP product is unique

Key Takeaways

Design Key Takeaways

1. Check that the cure regimen (and associated properties) for the project matches the cure regimen on the technical datasheet
   a. Per Article 401-VIII-4 of PCC-2, the CFRP will not achieve the ultimate Tg found in testing unless the cure regimen is the same.
2. Check that the Tg exceeds the design temperature of the system with margin (margin provided in codes).
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5. Review design drawings for layer-by-layer CFRP construction
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1. Environmental conditions must be maintained throughout the process
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Thank you!