Corrosion Control in Carbon Fiber Reinforced Plastic (CFRP) Composite-Aluminum Closure Panel Hem Joints

Project ID: MAT131

Award DE-EE0007760

Project Team:

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Overview

Timeline

- Project start – 10/1/16
- Project end – 3/31/20
- Percent complete – 66%

Budget

- Total project funding - $2,950,025
  - DOE share - $2,212,519
  - Contractor share - $737,506
- Funding for FY 2017 - $1,357,334
- Funding for FY 2018 - $955,123
- Funding for FY 2019 - $637,568

Barriers addressed[1]

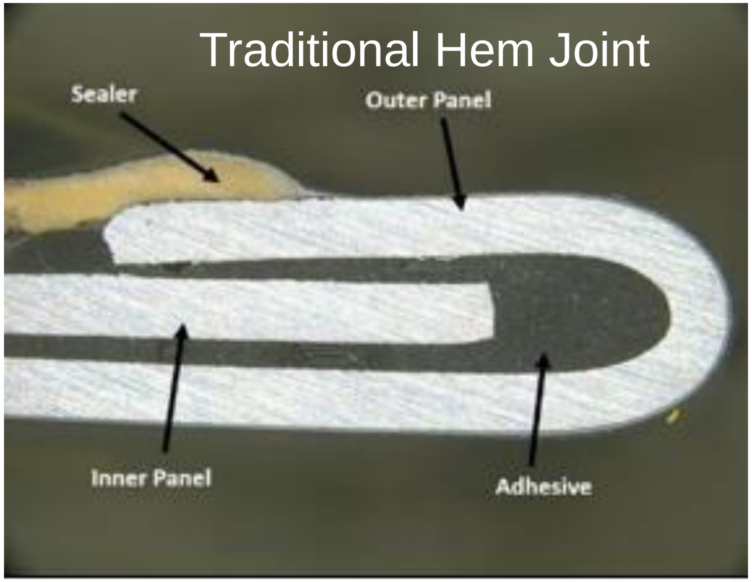
- Corrosion evaluation of mixed material joints
- Predictive corrosion modeling
- High volume use of CFRP materials (automotive line)

[1] Source: 2017 U.S. Drive MTT Roadmap Report, Section 4.

Partners

Project Relevance/Objectives

- Enable vehicle weight reduction replacing all-aluminum closure panels with carbon fiber reinforced polymer inner/aluminum outer (CFRP/Al) closures in a high-volume application
- Identify specific dissimilar material joining and or corrosion protection challenges and predictive models
- Develop novel technologies addressing these challenges to near-commercial readiness



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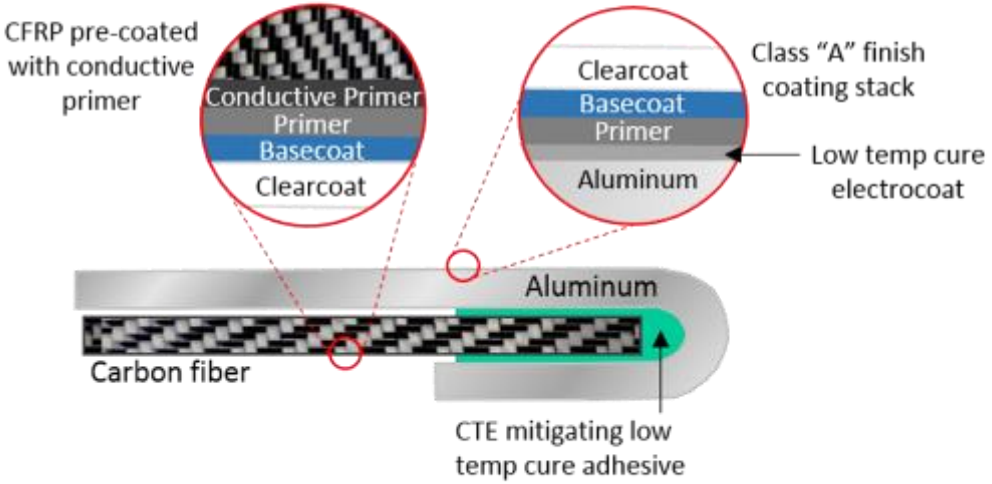
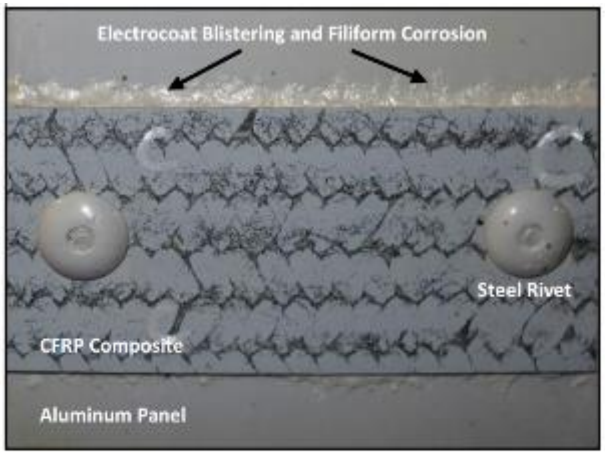


Objectives / Challenges

Technical Challenges

1. CFRPs are inherently cathodic to aluminum or other metals that could be present in the closure construction, setting up a corrosive galvanic cell.

2. A significant differential coefficient of thermal expansion (CTE) between CFRP and Al will impart dimensional stresses and displacement during the paint bake process.



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3. Affordable CFRP matrix materials are not stable at current paint bake oven temperatures.

4. Conventional automotive coatings and adhesives are not compatible with CFRP or the required lower bake temperatures.

5. Predictive accelerated corrosion tests for CFRP/aluminum joints have not been determined.

Milestones & Approach

Budget Period 1: Understanding Nature/Extent of Problem

- Understand the nature and extent of the corrosion problem
- Identify the susceptibility to galvanic corrosion and stress corrosion cracking
- Determine the level of conductivity that promotes electrostatic painting but not galvanic coupling
- Identify pathways to low-cure adhesives and coatings

Budget Period 2: Developing Solutions

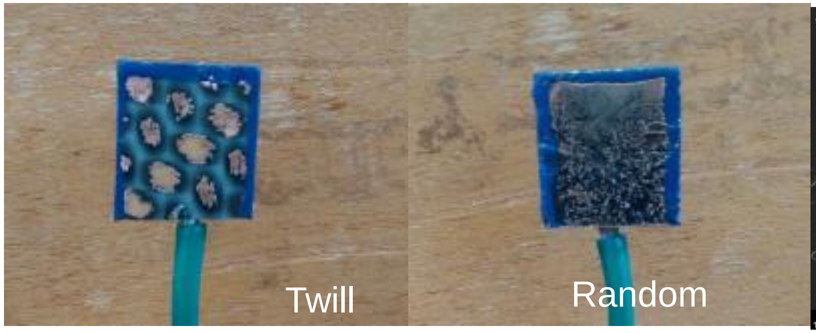
- Develop prototype conductive primers, adhesives, and electrocoats
- Identify hem geometries to mitigate galvanic coupling and coefficient of thermal expansion (CTE) mismatches
- Galvanic assessment of CFRP type and joined samples
- Accelerated testing of CFRP/Al couples

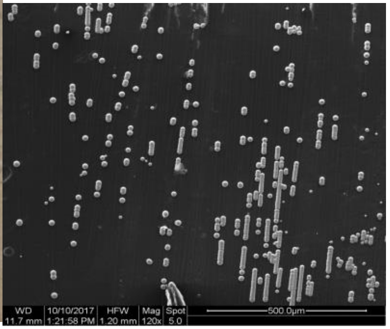
Budget Period 3: Optimization and Validation

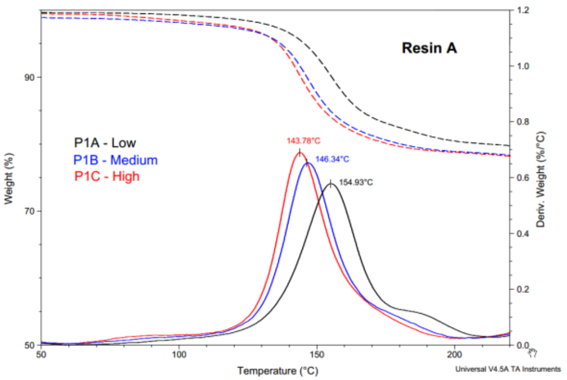
- Optimize and validate the solutions developed in BP 2
- Construct a surrogate aluminum outer/CFRP inner closure capable of passing Ford specifications and being processed through a typical paint shop operation

Prior Technical Accomplishments

- Increased corrosion of CFRP/Al coupons observed
- Test track and cabinet testing correlated well
- CFRP type influences electrochemical activity
- Low cure electrocoat and adhesive prototypes were identified with good corrosion resistance







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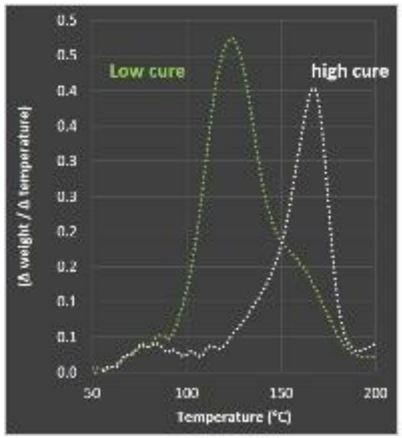
Technical Accomplishments & Progress: Low Cure Electrocoat Formulation (PPG)

Optimization of electrocoat cure utilizing complementary cure evaluation measurements
- Thermogravimetric Analysis (TGA)
- Rheology

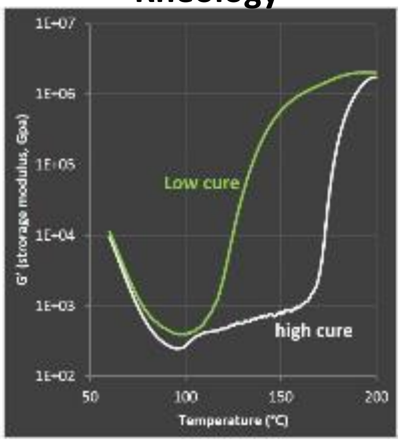
CURE WINDOW
Results from the best-performing prototype formulation

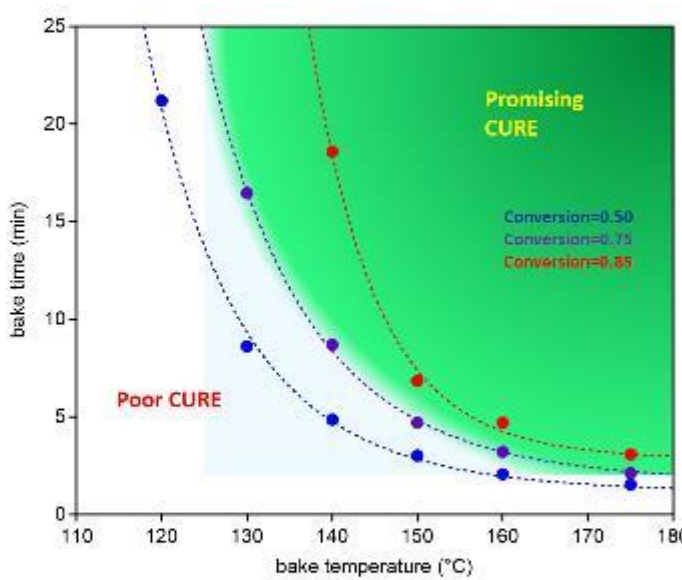
Excellent correlation with solvent rub tests

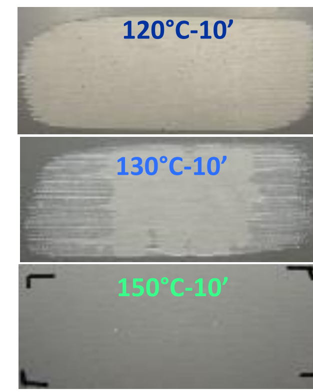
TGA



Rheology







Sample ID	Formulation Variables				Cure -150°C 10 min	Appearance W_b (µm)	Corrosion G-85 (vs. control)	Box Throwpower (G/A)
	Resin	XL	Additive	Catalyst				
P1-B	A	XL1	C	E	pass	0.12	better	69%
P11	B	XL2	G	F	pass	0.13	better	51%
Control	C	XL3	C	E	N/A	0.11	N/A	55%

Identified electrocoat prototype with balanced key properties (CURE/APPEARANCE/CORROSION)

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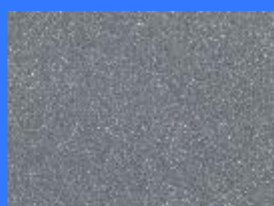
Technical Accomplishments & Progress: Conductive Primer Formulation (PPG)

APPEARANCE

Enhance coatability of CFRP

High conductivity primer/CFRP



Low conductivity primer/CFRP

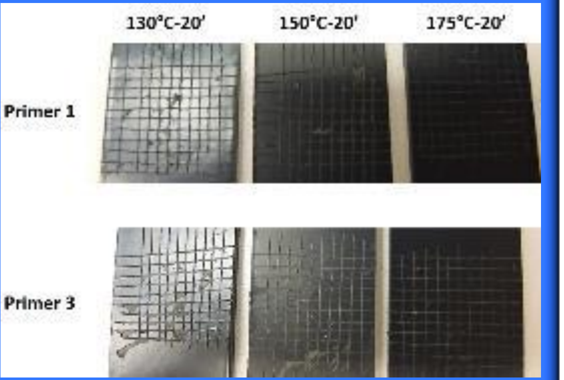
SURFACE CONDUCTIVITY

Tailor surface conductivity in a wide range

sample	solid resistivity	Ransburg sprayability
CFRP substrate	0	>>> 155
Non-Conductive primer	infinity	< 85
Conductive primer 1	0.3 MΩ	165
conductive primer 2	0.002 MΩ	>>> 155
conductive primer 3	0.005 MΩ	>>> 156
conductive primer 4	0.011 MΩ	>>> 157
conductive primer 5	10 MΩ	142

ADHESION

Adhesion of primer/CFRP optimized in a wide bake window



Identified conductive primer formulations with balanced key properties and varied conductivity

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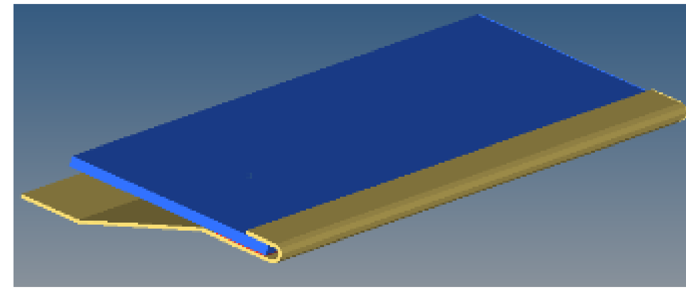
Technical Accomplishments & Progress: Modeling Impact of CTE mismatch (Ford)

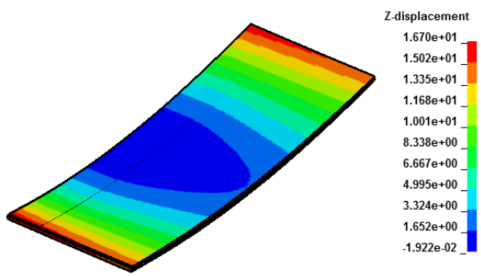
Inputs

- Temperature dependent thermo-mechanical properties
- Adhesive cure kinetics
- Cure schedule (ramp and maximum T)
- Geometry – bonded bi-material plate (CFRP/Al)

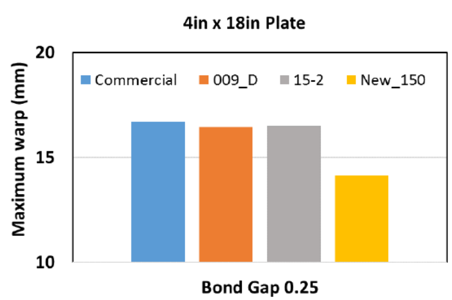


Prior CAD geometry of hem coupon (blue CFRP, yellow Al)

Al/CFRP Beam Coupon

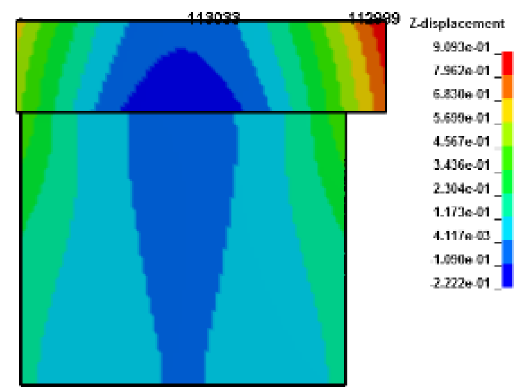


Z Displacement Contour under Room Temperature (mm) (Commercial Material)



Comparison of maximum deflection

Al/CFRP Overlap Coupon



Modeling being used to drive formulation targets for adhesives

Beam geometries and overlap coupons included in modeling efforts

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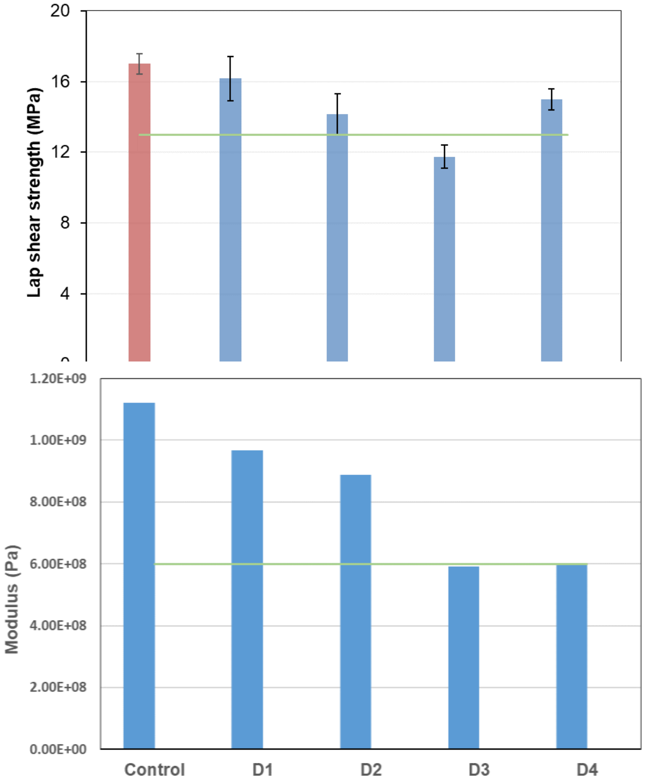
Technical Accomplishments & Progress: Adhesive Prototype (PPG)

- **Mechanical properties measured - strength, modulus, glass transition temperature (Tg), elongation**
- **CTE measurements also measured for modeling inputs**



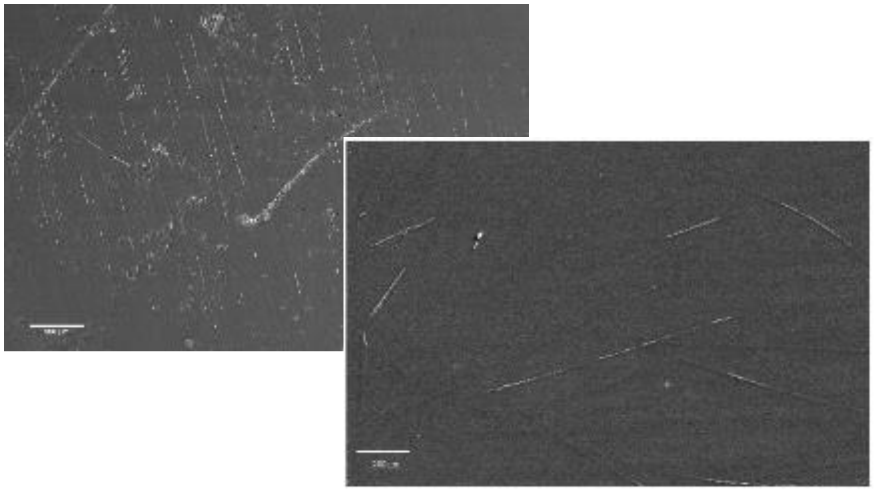
Adhesive	CTE below softening point [ppm/°C)]	CTE above softening point [ppm/°C)]
High Bake Ctrl (175°C)	86	202
002A (150°C)	90	228
002B (150°C)	119	200

D4 adhesive system balances lap shear strength, low modulus, and high Tg.

Low cure adhesive prototype comparable to control
Low modulus high strength materials achieved

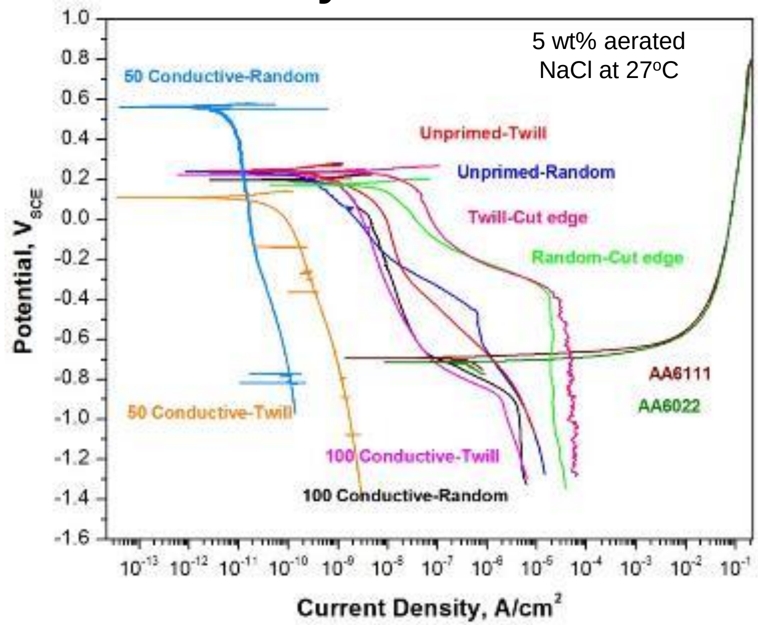
Technical Accomplishments & Progress: CFRP Substrate Characterization (OSU)

Copper deposition to evaluate electrochemical nature of CFRP



- Electrodeposition of Cu used to indicate location and number of active sites and allowing estimation of electrochemical behavior
- Average area of Cu deposits determined to be 18.7 (twill) and 3.2 % (random)
- Results do not correspond to potentiodynamic polarization wherein i_{galv} of CFRP-Twill and Random coupled with AA are almost equal

Potentiodynamic Polarization



- Cathodic kinetics of CFRP at cut edges are faster than top surfaces leading to higher galvanic current density (i_{galv}) when coupled with Al
- Conductive Primer (CP)-CFRP showed lower electrochemical activity than unprimed CFRP.
- Conductivity of 0 CP was so low that currents through potentiodynamic polarization were not recorded.

Twill CFRP has more active sites decorated by Cu deposits than Random CFRP, but the rates of the cathodic oxygen reduction reaction are similar
Primer can be sufficiently conductive but still reduce electrochemical activity

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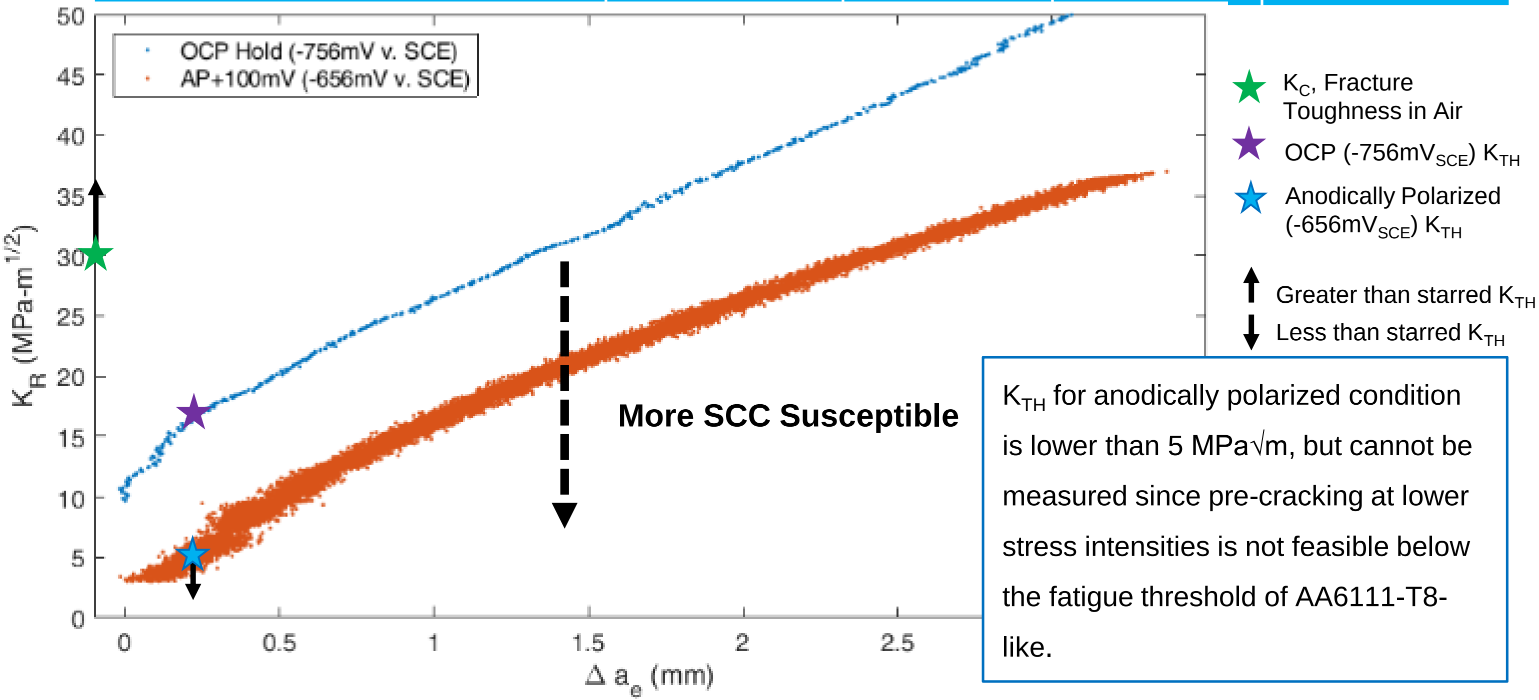
Technical Accomplishments & Progress: Stress-Corrosion Analysis for Al/CFRP (OSU)

- SCC behavior can also be represented by a resistance curve (ASTM E561) which is a plot of stress intensity vs. change in crack length
- Under conditions where a material exhibits lower SCC resistance, crack growth will begin to occur at decreasing stress intensities

$$K = \sigma\sqrt{\pi a}\, f$$

f is a geometric factor

Test Condition	Strain Rate, dx/dt (in/sec)	Starting dK/dt (MPa√m / h)	Pre-cracking K_{max} (MPa√m)	K-Threshold (MPa√m)
OCP Hold (-756mV$_{SCE}$)	1.05×10^{-7}	0.594	7	16 - 18
AP +100mV (-656mV$_{SCE}$)	1.05×10^{-7}	0.575	3.2	<5



K_{TH} for anodically polarized condition is lower than 5 MPa√m, but cannot be measured since pre-cracking at lower stress intensities is not feasible below the fatigue threshold of AA6111-T8-like.

Anodic polarization facilitates propagation of an existing crack at lower stress intensities than the un-coupled freely corroding state

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Technical Accomplishments & Progress: Corrosion Testing (OSU)

Accelerated chamber testing

- No difference in polarization curves observed for AA6111 and AA6022
- Accelerated testing for 12 weeks confirmed that AA6111 is more susceptible to corrosion.

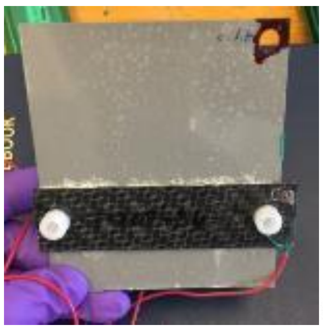
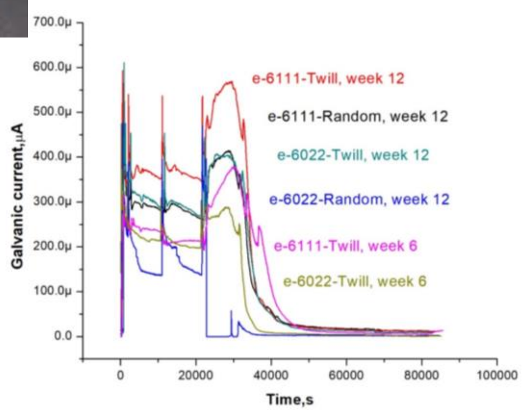
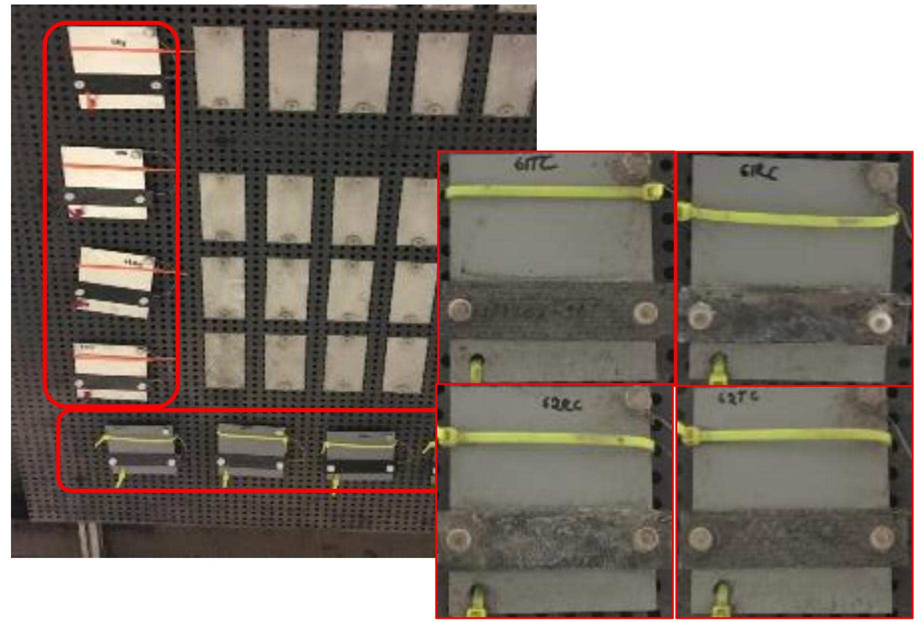


Image showing the coupon assembly-accelerated corrosion testing



Galvanic current measurements of electrocoated coupons during exposure testing

On-Vehicle On-Road Testing



Panels of Al alloy coupled with CFRP during 3 month-on vehicle (bus) exposure testing

- Al/CFRP coupons were mounted onto OSU buses and are currently in 4th month of exposure
- Detailed characterization of materials will be carried out after 6/12 months

Differences observed in electrochemical and accelerated testing

On-vehicle testing underway

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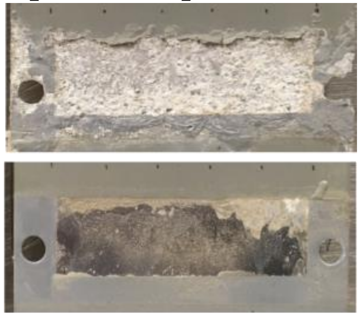
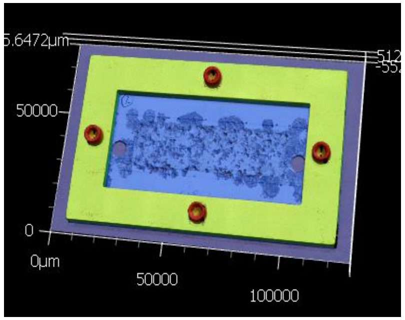
Technical Accomplishments & Progress: Volumetric Analysis of Corrosion (Ford)

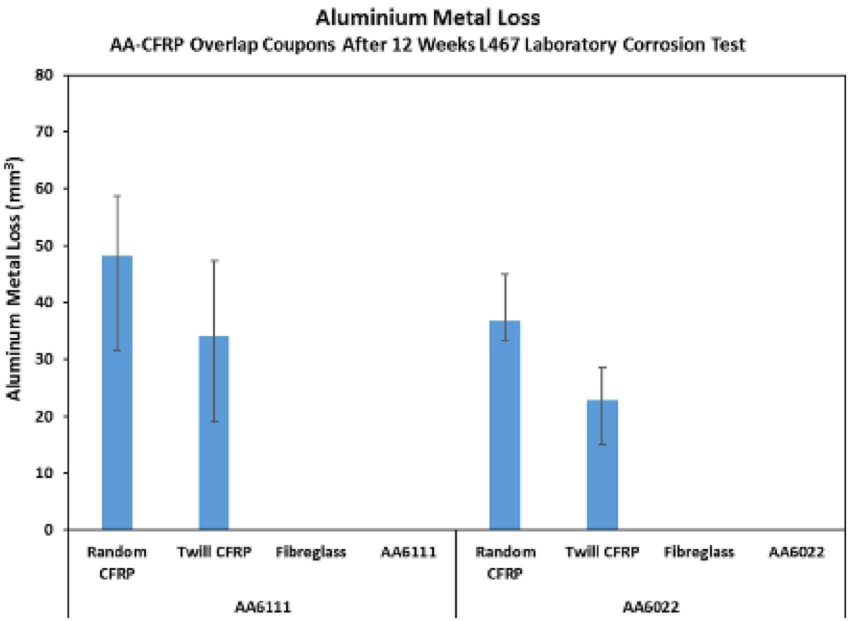
Inputs
- Baseplate alloy (AA6111 or AA6022)
- Top plate materials (CFRP, fiberglass, Al)

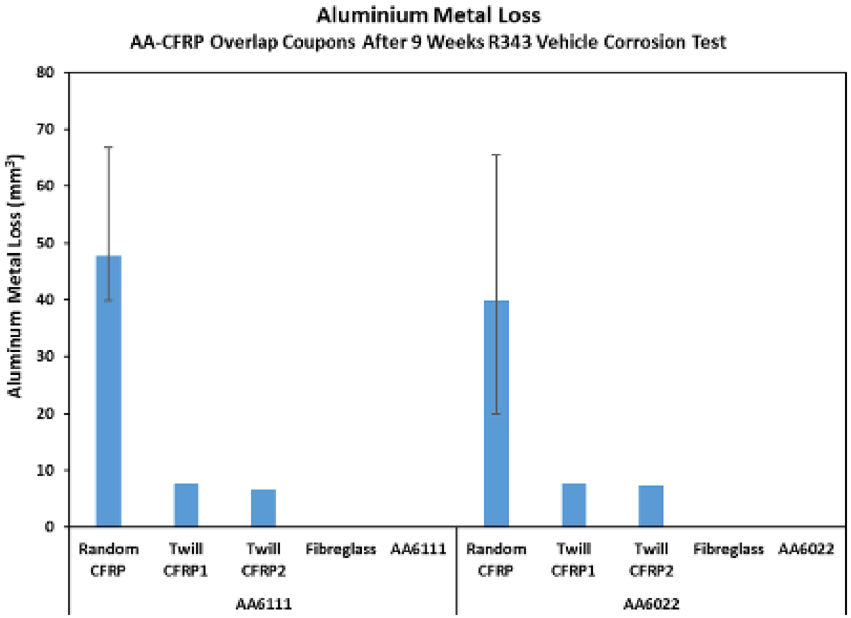
Tests
- Laboratory L467 cyclic corrosion test
- On-vehicle R343 proving ground test


AA6111 panels after testing and top-plate removed



3D visualization for volume loss measurement





Galvanic corrosion of AA6111/CFRP observed in cabinet and on-vehicle testing

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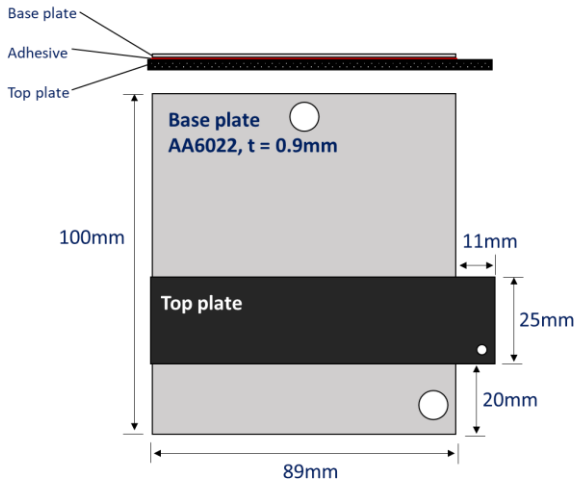
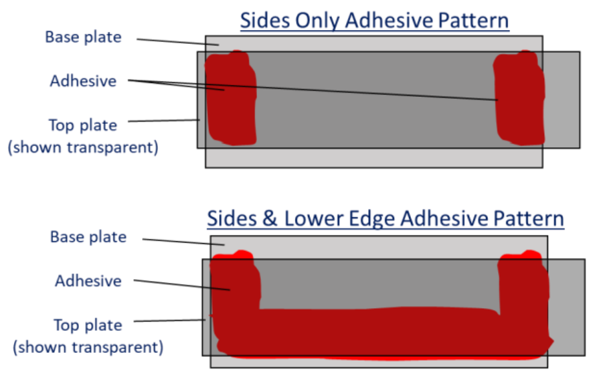
Technical Accomplishments & Progress: Corrosion Testing of CFRP/Al Overlaps (Ford/PPG)



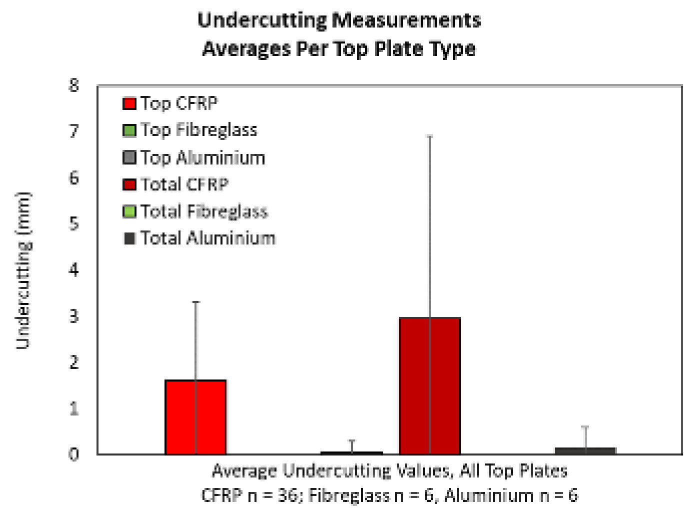


Inputs

- Conductive primer type and application
- Adhesive type and application
- E-coat cure

Tests

- Laboratory L467 cyclic corrosion test
- On-vehicle R343 proving ground test



No undercutting for coupons with fiberglass top plates
Significant undercutting with CFRP top plates

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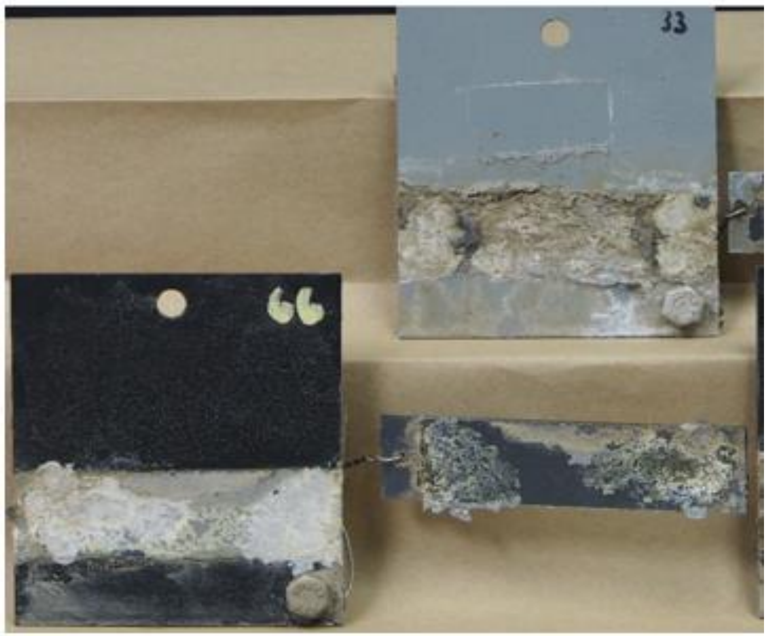
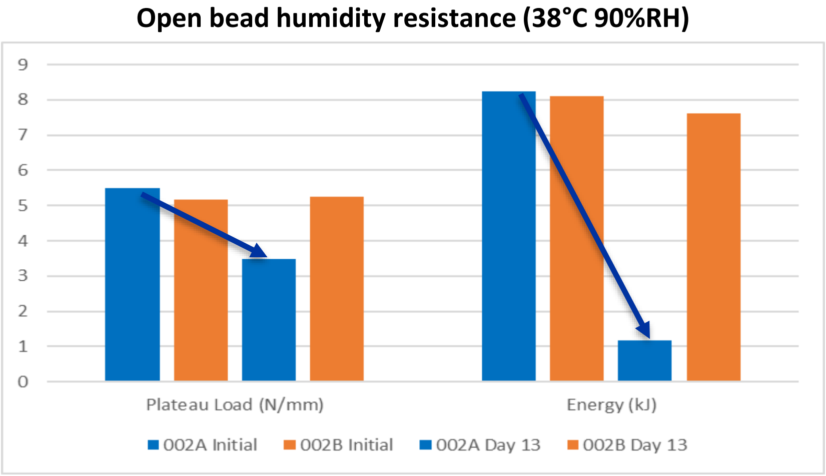
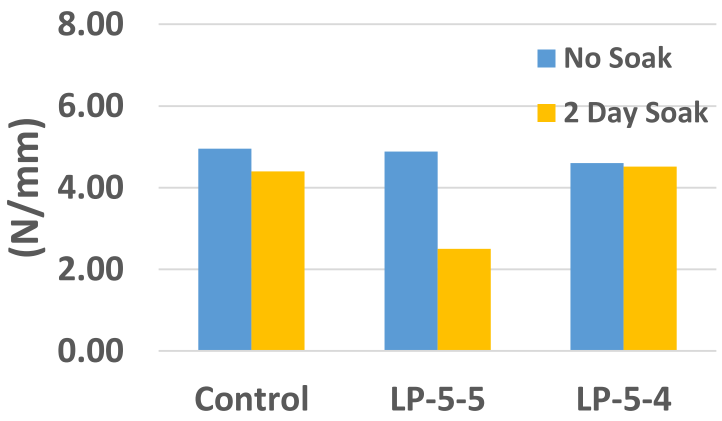
Technical Accomplishments & Progress: Corrosion Testing of CFRP/Al Overlaps (Ford/PPG)



- Adhesion failures noted in early prototype after exposure to corrosive environment





Exposure test: Salt Water Soak, 5% Salt in Deionized Water at 55°C

Early low cure adhesives sensitive to humidity exposure
Current prototypes under evaluation

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Responses to Previous Year Reviewers’ Comments

1. The size of the CTE mismatch samples should be longer
   - The length of the CTE mismatch coupons was determined by our OEM partner and chosen to enable simple lab-scale experimentation. These coupons are used in predictive models used to guide adhesive development. Results of the coupons tests and modeling efforts will be compared with the prototype part.
2. What is the relationship between testing by observation and a numeric/modeling approach in this project?
   - The project team is taking an approach that incorporates fundamental and industry-relevant aspects. Predictive tools are used to assess corrosion of mixed CFRP/Al joints as well as the impact of CTE mismatch. Modeling tools were used to provide feedback on adhesive development. Deficiencies in test coupon design were identified that do not simulate real-world corrosion results. The results of the prototype testing will guide future work in coupon test design.
3. How do activities from one partner support another?
   - Samples from cabinet testing by PPG/Ford were sent to OSU for further electrochemical analysis and outdoor exposure. Modeling efforts at Ford were used to guide adhesive development by PPG.

Project Collaboration

PPG Industries, Inc.

- Project coordination
- Coating test coupons for corrosion evaluation at Ford
- Providing samples of conductive primers to OSU for electrochemical evaluations
- Prototype coating

Ford Motor Company

- Providing substrate materials for testing
- Conducting track testing of coated samples
- Providing input on electrochemical evaluations
- Modeling adhesive formulation / CTE mismatch
- Prototype development and testing

The Ohio State University

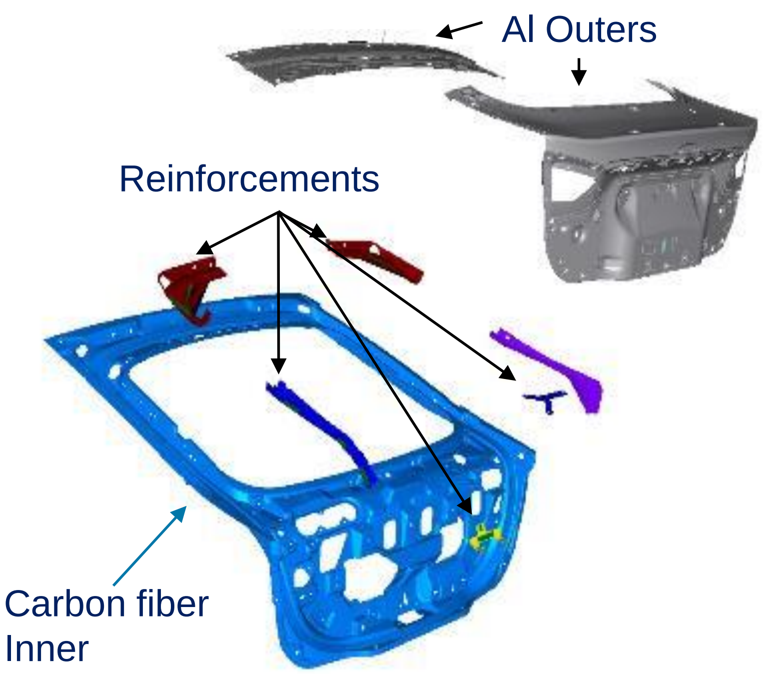
- Measuring uniformity of conductivity of Ford CFRP substrate
- Conducting electrochemical evaluation of corrosion panels during corrosion testing
- Outdoor exposure of test samples (OSU bus system)
- Understanding of stress-corrosion behavior

Remaining Challenges and Barriers

- **Production of prototype parts is challenging:**
  - Multiple facilities to produce/coat/analyze parts
  - Unknown factors in coating CFRP/Al hem joints
- **Unknowns with coating/testing large CFRP parts:**
  - Reproducibility of part shape and coating process
  - Impact of CTE mismatch in actual part design

Proposed Future Work

- Final prototype build (build, manufacturing, testing, analysis)
- Confirmation of accelerated corrosion testing



Inputs:
- Conductive primer conductivity
- Conductive primer placement
- Adhesive type (low/high cure)
- E-Coat type (low/high cure)

Assessments:
- Dimensional stability through assembly and coating
- Corrosion resistance of painted liftgates

Any proposed future work is subject to change based on funding levels.

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Summary

Objectives

- Implement the high-volume use of lightweight materials, such as CFRP and Al, to improve fuel economy for OEMs
- Develop predictive corrosion tests for lightweight materials

Approach

- Benchmarking corrosion of CFRP/Al joints (corrosion/cure)
- Develop low-temperature cure capable materials
- Develop predictive corrosion tests for lightweight materials
- Build and test prototype CFRP/Al component

Technical Accomplishments

- Low-temperature cure prototypes near completion
- Predictive models for CTE mismatch developed and used for adhesive development
- Preliminary cyclic, outdoor, and electrochemical corrosion analysis

Future Research

- Continued assessment of electrochemical properties of painted mixed-material joints
- Confirmation of CTE mismatch impact on corrosion/adhesion with prototype design

Any proposed future work is subject to change based on funding levels.