A Hybrid Physics-Based, Data-Driven Approach to Model Damage Accumulation in Corrosion of Polymeric Adhesives

Presenter: Roozbeh Dargazany (MSU)
Collaborating Team:
- Emad Poshtan (Bosch)
- John Harworth (Bosch)
- William V. Mars (Endurica)

2020 U.S. DOE Vehicle Technologies Office Annual Merit Review

Project ID #: MAT152  June 3, 2020
### Project overview

#### Partners
- Michigan State University (Lead)
- Robert Bosch LLC.
- Endurica LLC.
- JdV Lightweight Strategies, LLC.
- Composite Center at MSU

#### Timeline
- Start: January 2019
- End: December 2021
- Completion: 41%

#### Barriers*
1. Lack of reliable joining technology for dissimilar materials
2. Lack of cost-effective tests for evaluation of corrosion
3. Lack of constitutive model capable of predicting corrosion
4. Predictive modeling tools
   - Prediction error <10%
   - Lack of validated test protocols

#### Budget
- Total Project Funding: $1,442,188
- DOE Share: $967,662
- Collaborators Share: $474,526
- Cost Share: 32.9%
- FY 2020 DOE Share: $612,311

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Relevance & Objectives

Overall Objectives:

- A software to predict corrosion-induced failure in cross-linked polymeric adhesives with respect to damage accumulation by corrosion and fatigue with a 10% error.
- A theoretical model to describe damage accumulation in constitutive behavior with respect to (1) deformation, (2) vibration, (3) hydrolysis, (4) thermo-oxidation and (5) photo-oxidation.

Impact/Relevance to DOE

Predicting corrosion failure in joints of dissimilar materials is necessary to
- facilitate use of lightweight material for vehicle mass reduction
- Speed up the application of composites in vehicle structures for lightweighting to address DOE 2030 targets
- reduce time required for testing corrosion failure which makes the use of lightweight materials more attractive for OEM
- Improve CAE prediction capability to achieve a reliable design of joints
Critical segments

Lights and reflector housing
Electronics
Cockpit
Exterior Trim
Door Cap & Modules
Spoiler

Bumper
Filters
Motor Parts
Seats
Structural modules
Brake shoes, pads & clutch material
### Approach & Milestones

<table>
<thead>
<tr>
<th>Year</th>
<th>Development</th>
<th>FY-2019</th>
<th>FY-2020</th>
<th>FY-2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY-2019</td>
<td>Development of a theoretical platform for constitutive modeling of adhesives</td>
<td>Quasi-Static deformation</td>
<td>Hydro + Thermo</td>
<td>Validation of hybrid platform on combined mechanism in the lab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vibration</td>
<td>Predict corrosion-induced failure with multi-vector input parameters</td>
<td>Validation of hybrid platform on combined mechanism in the lab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermo-oxidative</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Photo-oxidative</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Hydrolysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>In Progress</td>
<td>Finished</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FY-2020</td>
<td><em>BOSCH</em></td>
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<td></td>
</tr>
<tr>
<td>FY-2020</td>
<td><em>BOSCH</em></td>
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</tr>
<tr>
<td>FY-2021</td>
<td><em>BOSCH</em></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>FY-2021</td>
<td><em>BOSCH</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**In Progress**

- Quasi-Static deformation
- Hydro + Thermo
- Thermo-oxidative
- Photo + Thermo
- Photo + Thermo + Hydro
- Micro- to macro- scale modeling, Central Experimental Database

**Finished**

- Vibration
- Photo-oxidative
- Hydrolysis

**FY-2019**

- Development of a theoretical platform for constitutive modeling of adhesives

**FY-2020**

- Quasi-Static deformation
- Hydro + Thermo
- Thermo-oxidative
- Photo-oxidative
- Hydrolysis

**FY-2021**

- Validation of hybrid platform on combined mechanism in the lab
- Software predictions under lab condition against sample adhesives exposed to all combination mechanisms
## Milestones

<table>
<thead>
<tr>
<th>Finished FY19</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derivation &amp; Validation of the quasi-static model</td>
<td></td>
</tr>
<tr>
<td>Derivation &amp; Validation of the vibration induced damage model</td>
<td></td>
</tr>
<tr>
<td>Derivation of the Hydrolysis model</td>
<td></td>
</tr>
<tr>
<td>Derivation &amp; Validation of Thermo-oxidation model with multiple adhesives</td>
<td>Go/No-Go</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ongoing FY20</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validation of Hydrolysis model with multiple adhesives</td>
<td>Go/No-Go</td>
</tr>
<tr>
<td>Validation of the modular platform concept</td>
<td>Milestone</td>
</tr>
<tr>
<td>Accumulative Damage Failure Model</td>
<td></td>
</tr>
<tr>
<td>Derivation &amp; Validation of photo-oxidation model with multiple adhesives</td>
<td>Go/No-Go</td>
</tr>
<tr>
<td>Validation of Fatigue Failure model on samples with no degradation</td>
<td>Milestone</td>
</tr>
<tr>
<td>Derivation of coupled Thermo- &amp; photo-oxidative model</td>
<td>Milestone</td>
</tr>
<tr>
<td>Derivation of coupled Thermo-oxidative &amp; Hydrolysis model</td>
<td>Milestone</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Planned FY21</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Training/Fitting Neural network engine on samples with different degradation</td>
<td></td>
</tr>
<tr>
<td>Validation of hybrid platform on combined degradation mechanisms, lab and outdoor</td>
<td></td>
</tr>
<tr>
<td>Software predictions against sample adhesives exposed to all combination mechanisms for all degradation mechanisms</td>
<td></td>
</tr>
</tbody>
</table>

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

Application/Data ➔ Structural and Mechanical Analysis ➔ Neural Network and Experimental Data Base ➔ Failure Prediction and Software Development

- Softening Damage
- Radiation Damage
- Hydrolysis
- Adhesive
- Thermo-oxidative Aging

Multiscale Modeling of each Phenomena

Neural Network Fatigue Model

Analytical Fatigue Failure Model

Hybrid Framework

Endurica

Get Durability Right
## Approach - Experimental

### Adhesive pool

<table>
<thead>
<tr>
<th>Company</th>
<th>Product number</th>
<th>type</th>
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</thead>
<tbody>
<tr>
<td>LORD</td>
<td>810</td>
<td>Acrylic (ACR)</td>
</tr>
<tr>
<td>Dow Corning</td>
<td>DOWSILTM 7091</td>
<td>Silicon (DC)</td>
</tr>
<tr>
<td>3M</td>
<td>DP 6310NS</td>
<td>Urethane (PUG)</td>
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<tr>
<td>3M</td>
<td>590</td>
<td>Urethane (PUB)</td>
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<tr>
<td>LORD</td>
<td>Versilok 253/254</td>
<td>Acrylic</td>
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<tr>
<td>LORD</td>
<td>Versilok 271/331</td>
<td>Acrylic</td>
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<tr>
<td>LORD</td>
<td>850</td>
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<tr>
<td>LORD</td>
<td>320/322</td>
<td>Epoxy</td>
</tr>
<tr>
<td>LORD</td>
<td>310-A/310-B</td>
<td>Epoxy</td>
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<tr>
<td>LORD</td>
<td>320/310-B</td>
<td>Epoxy</td>
</tr>
<tr>
<td>3M</td>
<td>550</td>
<td>Urethane</td>
</tr>
<tr>
<td>3M</td>
<td>560</td>
<td>Urethane</td>
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</table>

### Selection Criteria

<table>
<thead>
<tr>
<th></th>
<th>PI</th>
<th>Consult-ant</th>
<th>Collabo-rators</th>
<th>Industry</th>
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<td>Application</td>
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<td>Manufacturer</td>
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<td>Recommend.</td>
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<td>Damage resolution</td>
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<td>Reproducability</td>
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Central Experimental Database

<table>
<thead>
<tr>
<th>Condition</th>
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<tbody>
<tr>
<td>$T_{\text{storage}}$</td>
<td>1 day – 2 years</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>0 – 80 %</td>
</tr>
<tr>
<td>Temperature</td>
<td>-5 – 200 °C</td>
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<tr>
<td>UV</td>
<td>1 – 2 kW/m²/nm</td>
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</table>

<table>
<thead>
<tr>
<th>Test Type \ Material</th>
<th>ACR</th>
<th>DC</th>
<th>PU</th>
<th>B</th>
<th>PUG</th>
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<tr>
<td>Reliability Test</td>
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<tr>
<td>Failure Test for Virgin Material</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Failure Test for Aged Material</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Cyclic Test</td>
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<td>✓</td>
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<table>
<thead>
<tr>
<th>Test Type \ Material</th>
<th>ACR</th>
<th>DC</th>
<th>PUB</th>
<th>PUG</th>
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<tr>
<td>Chemical tests</td>
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<td>FTIR</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
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<tr>
<td>DSC</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
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<tr>
<td>Cross link Density Measurement</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
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</table>
3D- to 1D- scale transition

\[ \Psi_M = \frac{1}{A_s} \int_S W_{M} d\bar{d} u \bar{d} \cong \sum_{i=1}^{k} W_{M} \omega_i \]

Chains distribution among two aggregates

\[ W_{M}^{\bar{d}} = \int_{D_A(\lambda_{\text{max}})} N(n) \psi_c(n, \bar{r}) dn \]

Set of all possible chain lengths

\[ \uparrow \text{Strain energy of a chain with n segments and end to-end distance } \bar{r} \]

Chains distribution
Concept and validation

\[ \Psi_M = \Psi_1 + \Psi_2 + \ldots \]

\[ \Psi_M = \frac{1}{A_S} \int_S W_M^{d_i} du_i^{d_i} \approx \sum_{i=1}^{k} W_M^{d_i} \omega_i \]
Thermo-oxidative Experiments

Observations for mechanical tests:

- Continuous hardening occurs for PUB
- Initial overcuring followed by softening occurs for DC
- Initial Loss in ultimate strength and strain for DC
- Increase in ultimate strength, accompanied by drop in ultimate strength for PUB
- Deterioration in the material exhibited as softening can be observed at higher temperatures for both materials
Thermo-oxidation Model

Symptoms
- Embrittlement
- Network rearrangement
- Polymer scission/reformation

Challenges
- Accelerated aging tests are not reliable
- Diffusion limited oxidation should be excluded
- Chemical anomalies must be ruled out
- Lack of global decay function

Dual network hypothesis
- \( \psi_M = \rho_0(t) \psi_0 + \rho_\infty(t) \psi_\infty \)
- \( \psi_M \) is the whole strain energy of the matrix
- \( \rho \) is the concentration of each network
- \( \frac{d[p]}{dt} = k[p]^n \)
- \( [p] \) is the concentration
- \( E_a \): activation energy
- \( R \): is the ideal gas constant
- \( \tau_0 \): is pre-exponential factor
- \( n \): is the order of reaction

Decay function
- \( k = \tau_0 \exp\left(-\frac{E_a}{RT}\right) \)

Average error at 60
- 2%

Average error at 80
- 9%

Average error at 100
- 37%
Plots of stress change due to aging (Modeling vs experimental Results)
Photo-oxidation Experiments

**Chemical Tests**
(FTIR test for DC)

- Increased absorbance
  - (decreased crosslinking)

**Mechanical Tests**

- $\Theta = 80^\circ C$
  - Stress [MPa]
    - Silicon
    - PUB

- $\Theta = 45^\circ C$
  - Stress [MPa]
    - PUB

**Observations:**
- Over-curing results in material hardening
- Photo/oxidative damage can cause hardening or softening
- Higher temperatures speed up the damage process
Photo-oxidative Model

- Losing properties through time
- Chain scission
- Decrease of cross-link density

**Challenges**
- Effect of thermo- and photo-oxidative is inseparable
- Mechanism of aging dependency to temperature
- Lack of experimental data
- Inconsistency in experimental results

**Concept and validation**

\[ \varphi_{\text{photo} + \text{thermo}} = \rho_{\text{thermo}} \varphi_0 + (1 - \rho_{\text{thermo}}) (\rho_{\text{photo}} \varphi_{\text{thermo}} + (1 - \rho_{\text{photo}}) \varphi_{\text{photo}}) \]

\[ \rho_{\text{thermo}} = A_1 \exp \left( -\frac{E_a}{RT} t \right) \]

\[ \rho_{\text{photo}} = A_2 \exp \left( -I^\alpha t \right) \]

- \( A_1, A_2, \alpha \): Constants
- \( I \): Radiation intensity
- \( E_a \): Activation energy
Hydrolysis Experiments

Damage in the polymer matrix will take place with respect to two different mechanisms:

i) Deformation-induced damage

ii) Environmental-induced damage

Relative stress softening $\sigma^*$

$$\sigma^* = \frac{\sigma_1}{\sigma_{max}}$$

Relative Residual strain $e^*$

$$e^* = \frac{e_1}{e_{max}}$$

Hysteresis Loss $W^*$

$$W^* = \frac{W}{\Delta W}$$

✓ Validation

---

**Figure**: Graphs showing stress-strain relationships and hysteresis loss for different conditions.

**Legend**:
- Virgin
- 60°C 1-Day
- 60°C 10-Day
- 80°C 1-Day
- 80°C 10-Day
- 95°C 1-Day
- 95°C 10-Day
- 80°C 30-Day
- 95°C 30-Day

**Notations**:
- $\sigma_{max}$: Maximum stress
- $\sigma_1$: Initial stress
- $e_{max}$: Maximum strain
- $W$: Hysteresis loss
- $\Delta W$: Change in hysteresis loss
Hydrolysis Model

\[ \Psi_M(t, T, F) = N(t, T)\Psi_0(F) + N'(t, T)\Psi_\infty(F) \]

\[ N(t, T) = \exp\left(-\gamma \exp\left(-\frac{E_a}{RT}t\right)\right) \]

- Strain energy of a single chain

\[ \hat{\psi}_c(n, \vec{r}) = nK_B T \int_0^\varphi \hat{\beta} d\varphi, \quad \hat{\beta} = \left[1 - \frac{1 + \varphi^2}{n}\right] \beta \]

- Probability Distribution Function of a Polymer Chain

\[ P_\ast(n) = \frac{1}{2 \sqrt{\pi\sigma^2}} \exp\left(\frac{(n - \mu_\ast)^2}{2\sigma^2}\right) \]

- Networks and Subnetworks

\[ \Psi_\ast = \frac{1}{A_s} \int_S d\Psi \ast d\alpha = \sum_{i=1}^k d_i \Psi_i \cdot w_i \]

- Inverse Langevin Function approximation

\[ \mathcal{L}^{-1}(x) \cong \frac{1}{1 - x} + x - \frac{8}{9} x^2 \]

- Kintetics (Esters, Amide, Imide, Carbonate)

\[ -\frac{d[COOH]}{dt} = \xi[Esters][Water][COOH] = \kappa[COOH] \]
Observations for Silicon adhesive:
• Initial over-curing
• Softening with time
• Loss in ultimate strength
• Loss in ultimate strain

Observations Polyurethane adhesive
• Higher temperature results in increased hardening with time
• Higher temp result in loss in ultimate stretch
Hygrothermal Model

“Accelerated aging using moisture and heat cycles”

- loss of the mechanical performance
- of polymeric materials.
- Reduction of cross-link density
- Chain scission due to oxygen attack on backbone
- Increased rate of degradation due to oxidation

\[
\Psi_M(t, T, F) = N(t, T)\Psi_0(F) + N'(t, T)\Psi_\infty(F)
\]

\[
N(t, T) = \exp \left( -\gamma \exp \left( -\frac{E_a}{RT} \right) t \right)
\]

\[
\Psi_\infty = (1 - \beta)\Psi_T + \beta \alpha \Psi_m
\]

\[
\beta = \theta RH \sqrt{t} \exp \left( -\frac{E_b}{RT} \right)
\]

Zero Humidity

\[
0 < \beta < 1
\]

Submerged condition

\[
\Psi_M(t, T, F) = \exp \left( -\gamma \exp \left( \frac{E_a}{RT} \right) t \right)\Psi_0 + \\
\left( 1 - \exp \left( -\gamma \exp \left( \frac{E_a}{RT} \right) t \right) \right) \left( 1 - \theta RH \sqrt{t} \exp \left( -\frac{E_b}{RT} \right) \right) \Psi_T + \theta RH \sqrt{t} \exp \left( -\frac{E_b}{RT} \right) \alpha \Psi_m
\]
Central Exp. Dataset - Virtual datapoints

**Experiment design**
- Experiment conditions
  - $S_1$, $t_1$, $D_1$, $T_1$, $RH_1$, $UV_1$
- Experiment investigation
  - $D_i$, $T_i$, $RHi$, $Uvi$
  - Mechanical tests
  - Chemical Tests

**Feature Extraction**
- Condense the experimental data based on change on the microstructure of material
  - $Tg$
  - Specific peaks in FTIR
  - Toughness
  - Energy dissipation
  - Viscoelastic parameters

**Learning process**
- Inputs
  - $S_i = \{ t_s, T, RH, UV, \ldots \}$
- Conditions
- Properties
- Outputs
  - $O_i = \{ D, Tg, FTIR, \delta, \ldots \}$

**Minimization process**
- Aging time minimization to yield same properties
  - $O_{Targeted}(S_t) = O_i(S_i)$?
  - Trained Network
  - $S_i \rightarrow O_i$
  - $S_i \big|_{O_t(S_t)=O_i(S_i)}$

Challenges of Blackbox Neural Network (NN) Engines in constitutive modeling
- Incomplete Data (Mapping n-dimensional chebyshev space into m-dimensions)
- Polyconvexity
- Frame-indifference
- Convergence

$\alpha$: Experimental Point
$\bigcirc$: Virtual Point
Physics-informed Neural Network Engines

Proposing a physics-informed cluster of super-simplified NN engines

- Valid for amorphous networks
- Micro sphere model convert 3D to 1D
- Simplify complex micro-mechanical models
- Two subnetwork to predict all deformation states, e.g. biaxial and compression
- Just useful for directional damage, fracture, deterioration
- Inelastic behavior such as Mullins effect

Implementation of NN engines Clusters

- Non-stationary and 3-D loading in reality and its effect on the lifetime
- Limited number of data on each phenomena and their combination
- Crack generation due to environmental conditions
- Size-effect (the models are developed based on the assumption of uniform aging in the material)
- Complicated nature of aging with multiple agents
Technical Accomplishments

Vibration
- Moravati & Dargazany, IMECE2020

Thermo
- Mohammadi et al., ECCMR 2019
- Morovati & Dargazany, IEC 2019

Hydro
- Bahrololoumi et al., Int. J. Plasticity 1. (2020)
  - Bahrololoumi & Dargazany IEC 2019

Hygro
- Wanru et al. IMECE2020
- Bahrololoumi et al. IMECE 2020

Photo

Modular Platform publication
- Khalili et al. (2019), Rubber Chem. & Tech. 92(1), 51-68
- Morovati & Dargazany (2019), SoftwareX 100229
- Morovati & Dargazany (2019), Phys Rev. E. 100229

Machine learned Engine

Model Free approaches
Response to Previous Year Review Comments

- **Approach Clarity:** “The breadth of the approach is impressive, but it is not clear how the progress gets integrated for a cohesive tool or set of tools.” “It is recommended to include data input/output flow chart among team members in next year's presentation.”

  - Two descriptive slides were added to illustrate the integration of different parts of the project to validate and merge the concepts toward development of the predictive software.

- **Relevance to Auto. Industry:** “Relevancy to joining with adhesives for automotive construction is missing.” “The team is highly motivated and needs proper steering towards the actual goal.” “World examples of adhesive joining used in automotive” “struggling with the selection of the adhesives” “having input from car manufacturers, National labs, or Adhesive Manufactures”

  - The team are collaborating with two of the largest adhesive manufacturers for auto industry on compound types, Test design, and characterization procedure for hybrid aging
    - Parker-Lord chemicals Inc. (NDA signed)
    - Dow Chemicals Inc.
    - Dan Houston: Auto-Manufacturing consultant

- **Cost-optimization:** “minimum critical number of experiments-> target accuracy”. “it studies all failure modes of networked structured adhesive” “The project should be more focused on selecting/identifying features that can efficiently capture the underlying mechanics/physics/chemistry of the system.”

  - In pilot-phase for each compound 3,218 tests were planned. Depending on the material behaviour, sensitivity analysis will be performed to derive the number of additional necessary tests needed to train the Neural Network engine to predict the rest of the Experimental Database.

- **Scope limitation:** “The project is over-ambitious”. “…whether the damage mechanism of joints/adhesives can be all related to the mechanism listed for the approach.”

  - The project is focused on understanding/simulation of bulk adhesive properties, and does not include (1) Actively varying enviromental load, (2) Interface damage, (3) delamination, (5) substrate damage.
Collaboration and Coordination

Dow Chemicals Inc.
- Parker-Lord Chemicals Inc.
- Auto. Industry Joining Expert
  - Material selection
  - Test design
  - Error Mitigation

HPM (High Performance Material Group)
- Modeling Individual Degradation Mechanism
- Modeling Damage Accumulation by Parallel Degradation Mechanism
- Experimental Characterization
- Digital Data Management
- Central Experimental Database
- Neural Network Failure Prediction Model
- Fatigue Failure Framework
- Finite Element Implementation and Software Development

Endurica
- Fatigue Failure Model
- Finite Element Implementation
- Software Development
- Software Validation

BOSCH
- Experimental Characterization
- Central Experimental Database
- Neural Network Failure Prediction Engine

MSU-CMSC
- Tensile Test
- Cyclic Test
- Vibration
- Failure
- SEM
- FTIR
- TEM

JDV
- Quality Check
- Standards for Tests
- Uncertainty Quantification
- Adhesives

Funding Agency
- Principal Investigator
- MSU - HPM
- Consultants
- Collaborator
Remaining Challenges and Barriers

COVID-19 labs shut down:
- Forced shut down of all Aging Tests
- Removal of all ultra-long aging samples
- Capacity shift by industrial collaborators (uncertainty on resource allocation)
- Budget expenditure on halted operations

<table>
<thead>
<tr>
<th>Modeling</th>
<th>Experiment (amir and hamid and EXP)</th>
</tr>
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<tbody>
<tr>
<td>Various nonlinear behaviors with specific features for different adhesives</td>
<td>The cost and complexity of corrosion mechanisms aging to achieve isolation of single mechanism</td>
</tr>
<tr>
<td>Extrapolation capabilities of the NN models</td>
<td>Impurities (compound, and curing) can expedite corrosion-induced failure of bulk samples</td>
</tr>
<tr>
<td>Non-uniform damage mechanism in the material</td>
<td>Design of hybrid accelerated tests depends on assuming similar mechanisms at different conditions</td>
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<tr>
<td>Complicated and inseparable sources of degradations mechanism</td>
<td>Inconsistency between accelerated and normal aging tests results</td>
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</table>
Summary

Accomplishments
• Established a systematic procedure of screening and selection of adhesives
• Finished Pilot-tests on 4 selected compounds
• Developed and validated a modular platform that allows different damage mechanisms to be integrated together
• Hypothesized/Developed & verified models of vibration and thermo-induced damage on three adhesive types
• Developed the concept development for photo-oxidation and hydrolysis damage mechanisms verified on pilot adhesive

Future Research
• Outdoor chemical, mechanical and physical characterization of bulk adhesives at different climate zones
• Development of minimized set of tests for training/validation of NN engines for different compounds
• Integration of other damage mechanisms such as bio-degradation, and diffusion limited oxidation

Any proposed future work is subject to change based on funding levels.
Technical back-up slides
Vibration-induced damage

Softening of the material due to large time usage
To model the constitutive behavior of adhesives through vibration

Approach

Experiment:

Constitutive model:
Using kinetics of irreversible chain scission

\[ \frac{d_i}{P(n)} = P_0(n) e^{-c_s(n)} j \]
\[ c_s(n) = \int_{cycle} \exp \left[ \frac{\alpha}{k_B T} \left( L^{-1} \left( \frac{R \lambda^{d_i}}{n} \right) - f_a \right) \right] dt \]
**Thermo-Oxidative Aging**

**Goal:** To model the constitutive behavior of adhesives through thermo-oxidative aging

**Challenge**
Finding the correct decay function

**Approach**
Dual network hypothesis

Arrhenius functions as decay function

\[ \psi_M(t, T, F) = \rho(t, T)\psi_0(F) + (1 - \rho(t, T))\psi_\infty(F) \]

\[ \rho(t, T) = A_1 \exp(-\alpha t) + A_2 \exp(-\beta t) \]

Time-temperature superposition

\[ a_T = \exp\left(\frac{E_a}{R} \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right) \]
To model the constitutive behavior of adhesives through photo-oxidative aging

**Challenge**
Effects of photo- and thermo-oxidation are inseparable

**Approach**
Find a decay function that can consider the effect of both phenomena

\[
\rho (t,T) = A_1 \exp\left(-\tau_1 \exp\left(-\frac{E_{a1} + E_{\text{photo}} \gamma}{RT}\right) t\right) + A_2 \exp\left(-\tau_2 \exp\left(-\frac{E_{a2} + E_{\text{photo}} \gamma}{RT}\right) t\right)
\]

**Result**
Constitutive behavior of the dog-bone samples
To model the constitutive behavior of adhesives through hydrolytic aging

Approach

Experiment:

\[ \Psi_M(t, T, F) = N(t, T)\Psi_0(F) + N'(t, T)\Psi_\infty(F), \]

where \[ N(t, T) = \exp\left(-\gamma\exp\left(-\frac{E_a}{RT}\right)t\right) \]

Constitutive model:

Using Arrhenius functions as shape function
Once water attacks network, it causes the two phenomena:

(i) Reduction of the cross-links, which results in a network with longer chains (morphed network)

(ii) Energy dissipation due to the reduction of active chains (deactived network)

\[ \Psi_\infty = \alpha \Psi_m + (1 - \alpha) \Psi_d \]