Electrodeposition Simulation with Edge-based Smoothed Finite Element Method using 4-node Tetrahedral Elements for Complex Car Body Shapes

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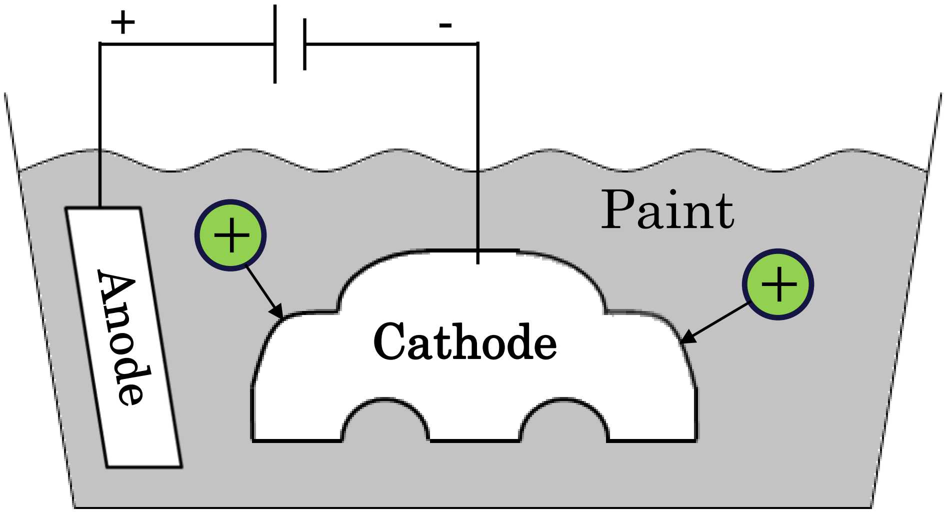
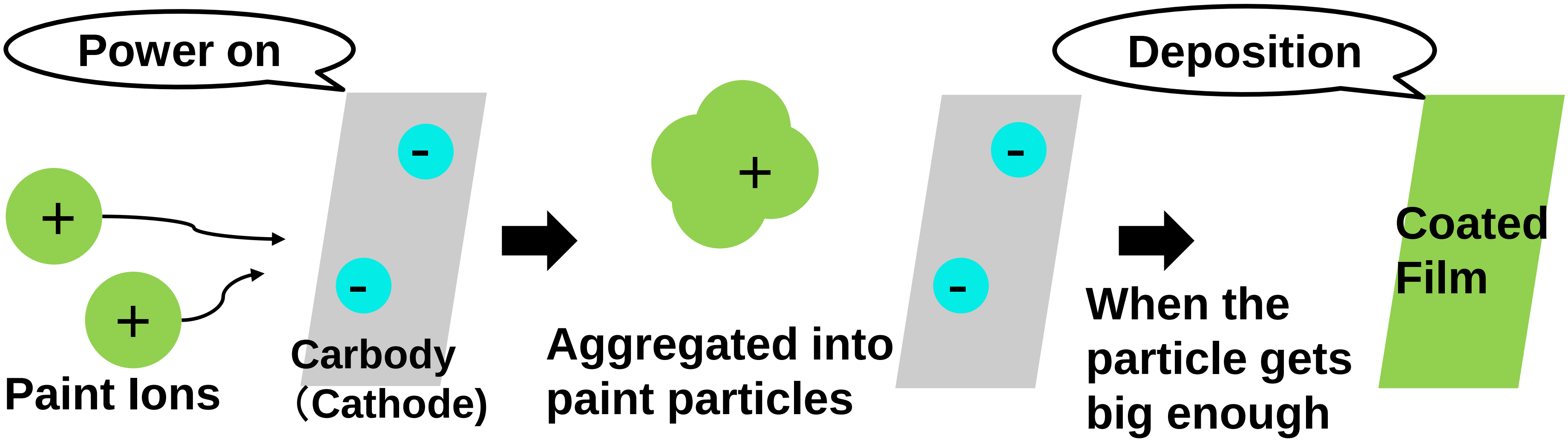
What is electrodeposition (ED) ?



- Most widely-used basecoat methods for car bodies.
- Making coated film by applying direct electric current in a paint pool.
- Relatively good at making uniform film thickness but not satisfactory uniform in actual production lines.
- ED simulator is necessary for optimizing carbody design and line coating conditions.

Mechanism of Electrodeposition



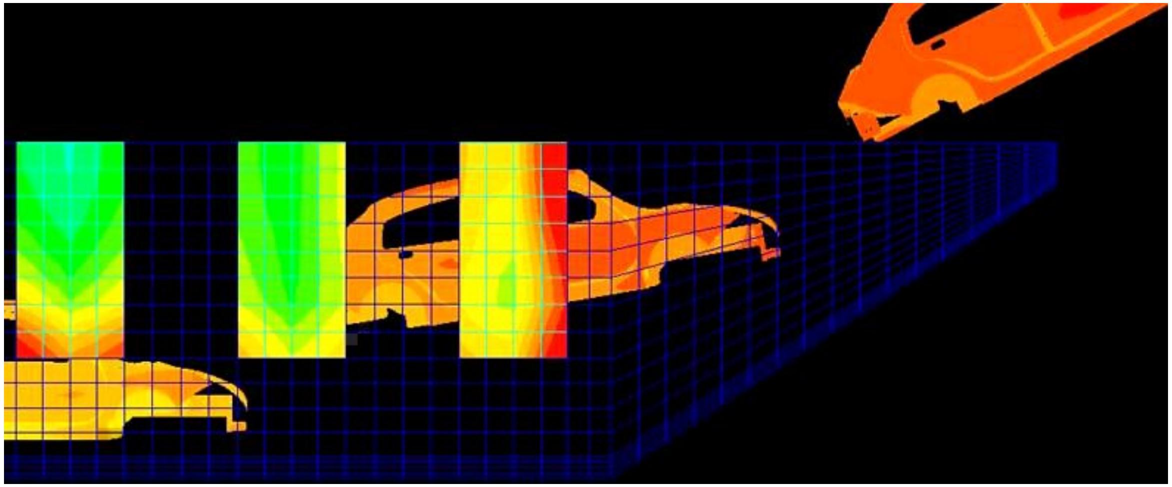
■Paint ions have positive (+) charge.

■The vicinity of the cathode has negative (-) charge because of OH^- generated by electrolysis of water.

■Some of the paint particles diffuse and dissolve.

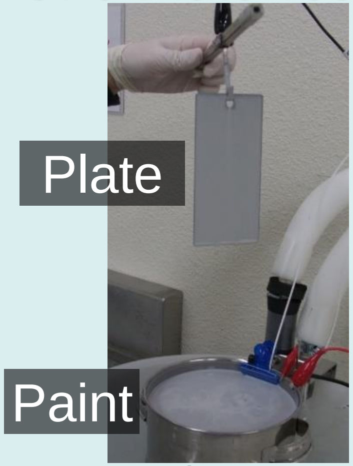
How to Develop an ED Simulator

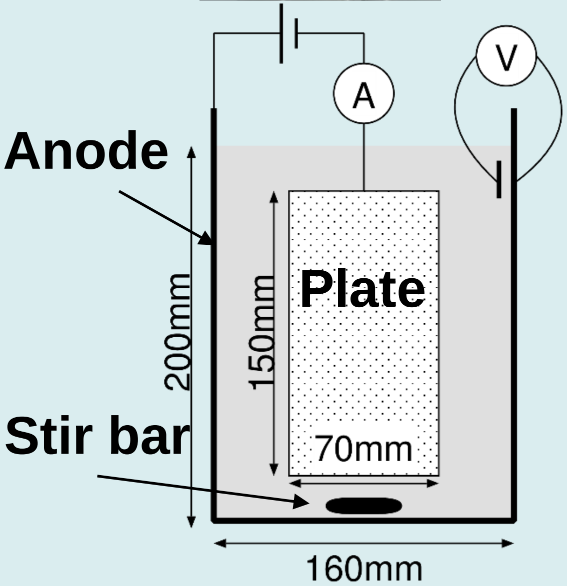
1. Experiments at lab in various coating conditions.
2. Identification of ED boundary model and its parameters.
3. Implementation to a FE code.



ED simulation for actual lines

One-Plate Test

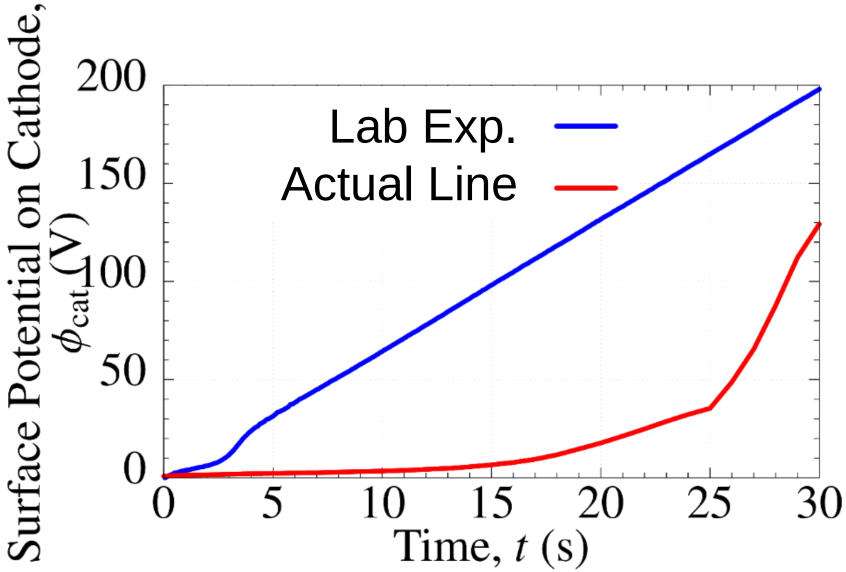




Two Issues in Previous Studies

1. Coating conditions in lab experiments are different from those in actual lines.

e.g.)



The conventional lab experiments did not reproduce the actual line condition.

2. Accuracy is insufficient in low voltage cases.

⟹ Poor accuracy on inner surfaces of carbodies.

The conventional ED constitutive model was too simple to reproduce the complex ED phenomena.

Objective

1. Propose a new lab experiment method
   to reproduce coating conditions of actual ED lines.
2. Propose a new ED boundary model
   to improve the accuracy of an ED simulation.

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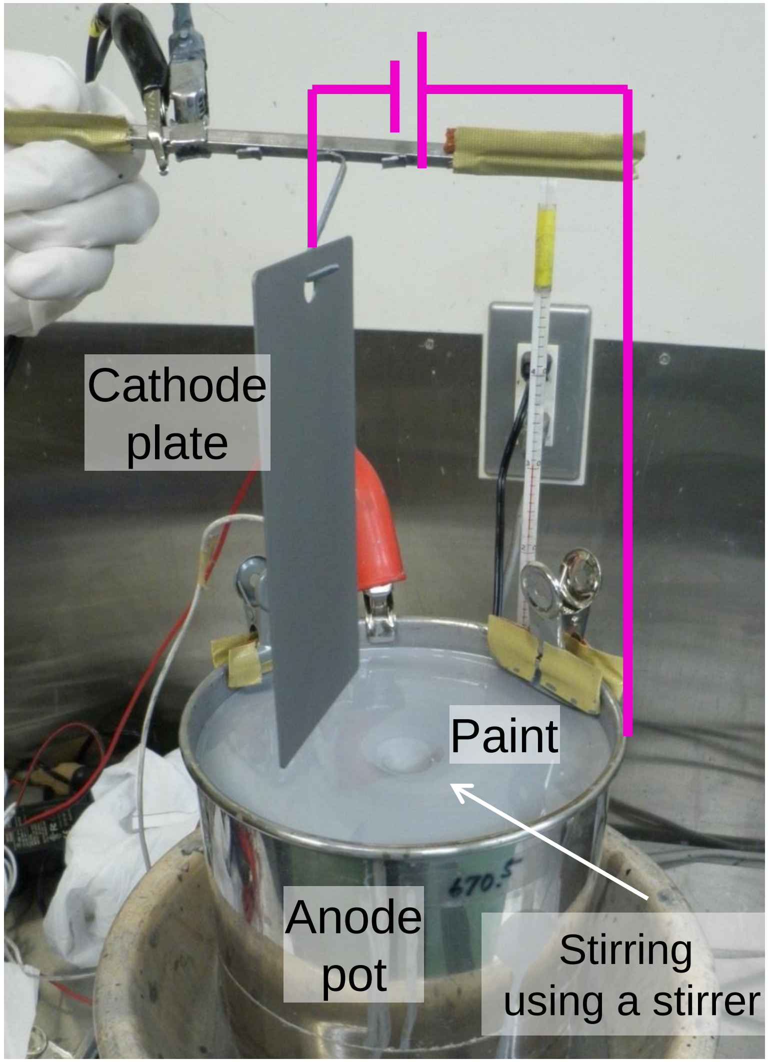
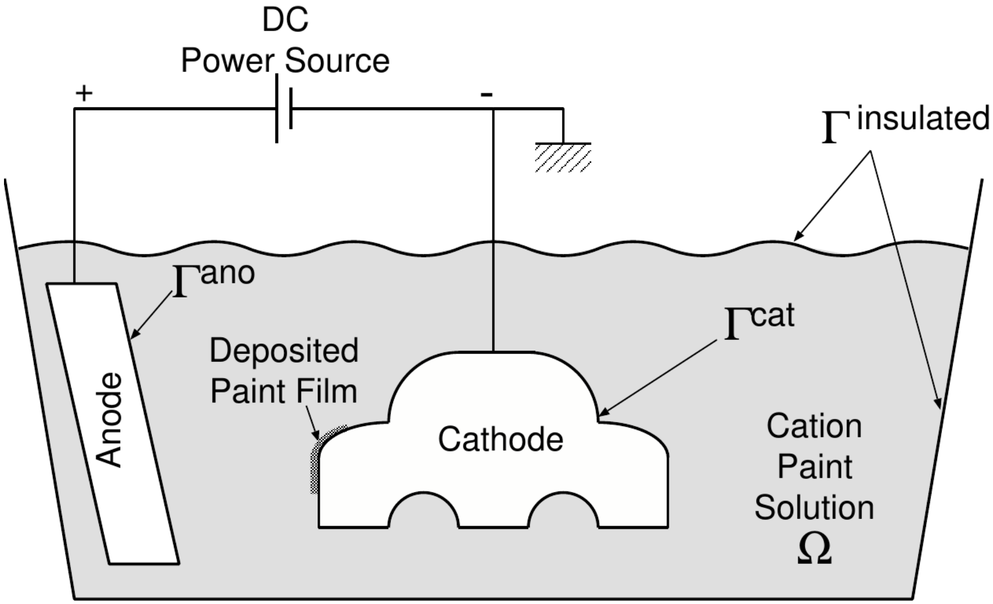
1. Our new Lab Experiment Method
2. Our new ED Boundary Model
3. Our S-FEM Code for ED Simulation
4. Validation & Demonstration Results

Our New
Lab Experiment Method

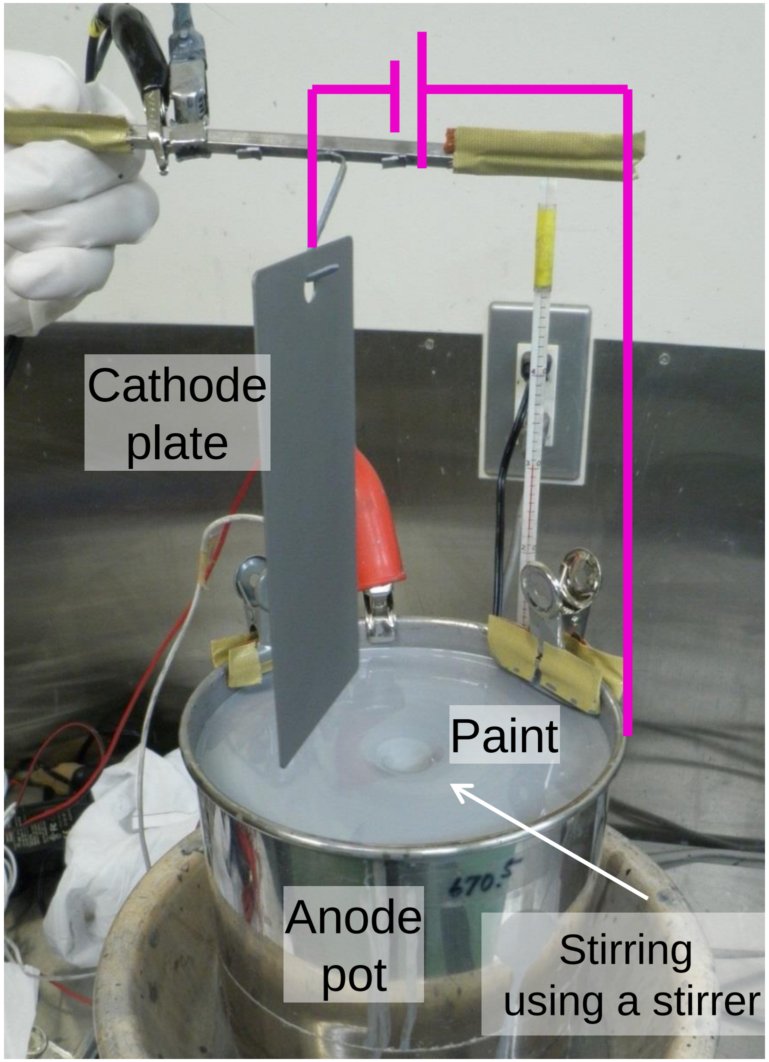
Outline of the One-Plate Test

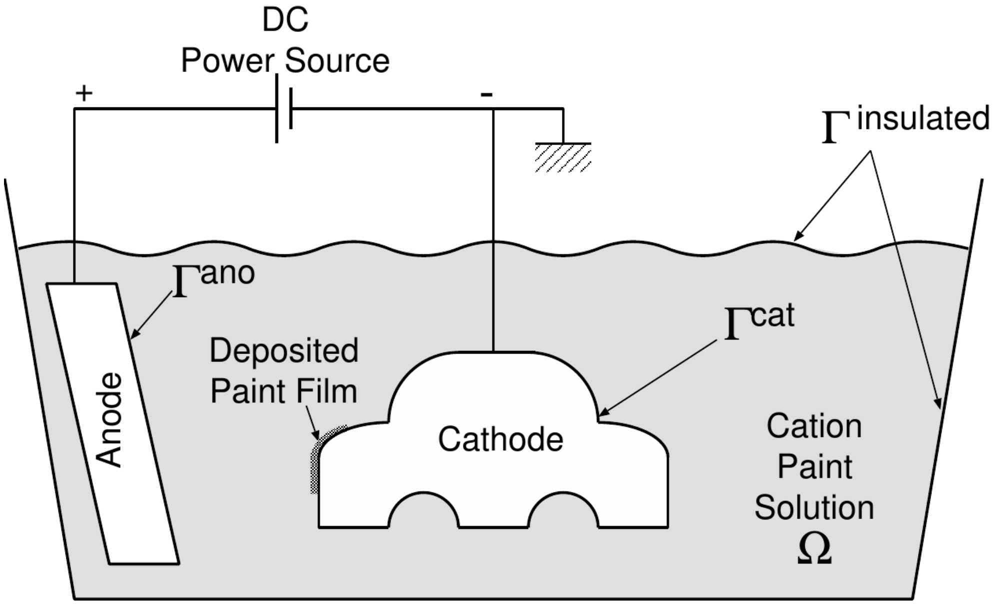




- Use a rectangular steel plate instead of a car body.
- Use a SS pot instead of the paint pool and anode electrodes.

Outline of the One-Plate Test





- Dip a steel plate into the paint pot.
- Apply voltage up to 270 V between the plate and pot.
- Measure time-histories of
  - applied voltage,
  - current
  - film thickness.

Our New Lab Experiment Method

Issue in the conventional lab experiment

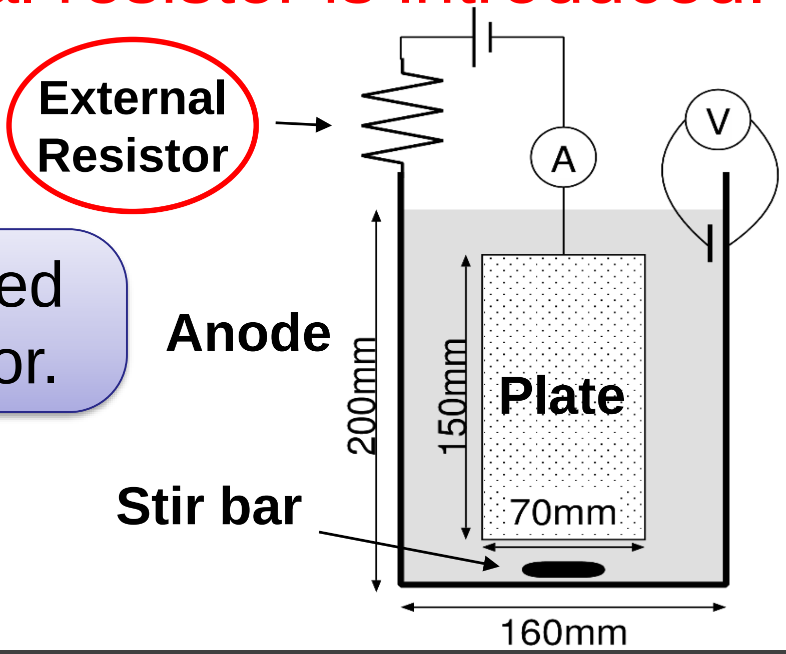
IR drop in solution is too small.

In an actual line, IR drop in solution is about 100 V at most; however, in the conventional lab experiment, that is only 10 V.

Modification in the new lab experiment

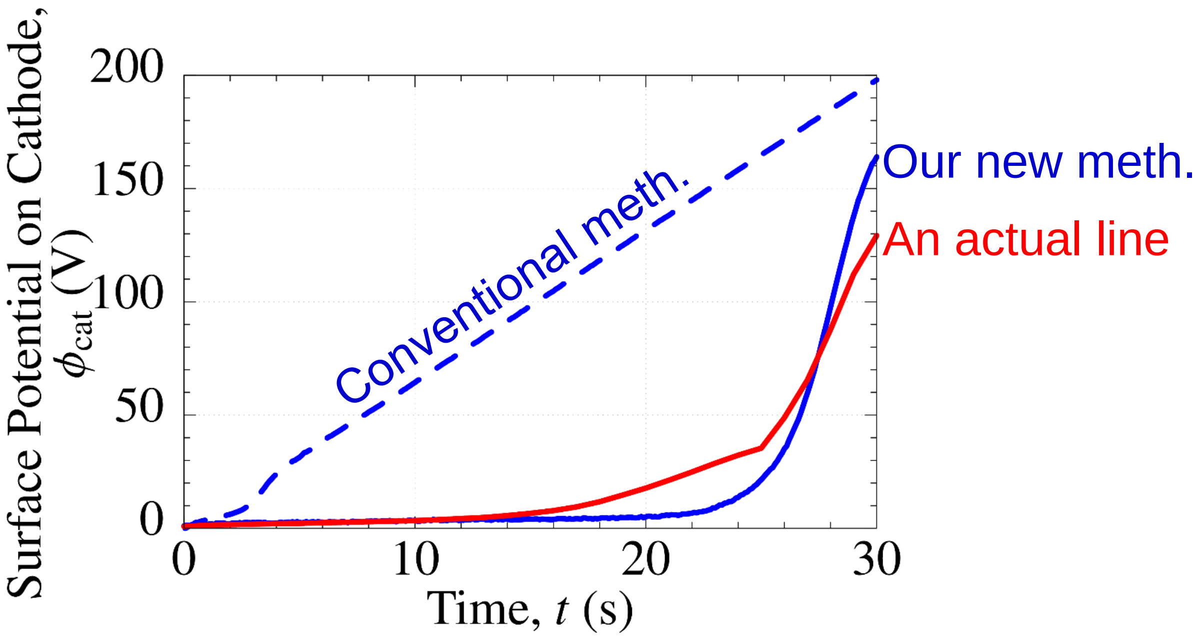
An external resistor is introduced.

Scale effect is canceled by the external resistor.



Our New Lab Experiment Method

Comparison of Surface Potential on Cathode



Our new lab experiment succeeded in reproducing the actual line condition.

⟹ ED boundary models should be identified with the new lab experiment data.

Our New
ED Boundary Model

Our ED Boundary Model

- The governing equation in paint is the electrostatic Laplace equation ($\nabla^2\phi = 0$).
- The difficulty in ED simulation arises on boundaries.
- Our ED boundary model consists of 2 sub-models:

1. Film growth model

   Film growth rate $\dot{h}$ is NOT linear to current density j:
   $\dot{h} \neq \alpha\, j$, where α is a constant. It should be like

   $$\dot{h} = \mathrm{NonlinearFunc}(j, h).$$

2. Film resistance model

   Film resistance R is NOT linear to film thickness h:
   $R \neq \beta\, h$, where β is a constant. It should be like

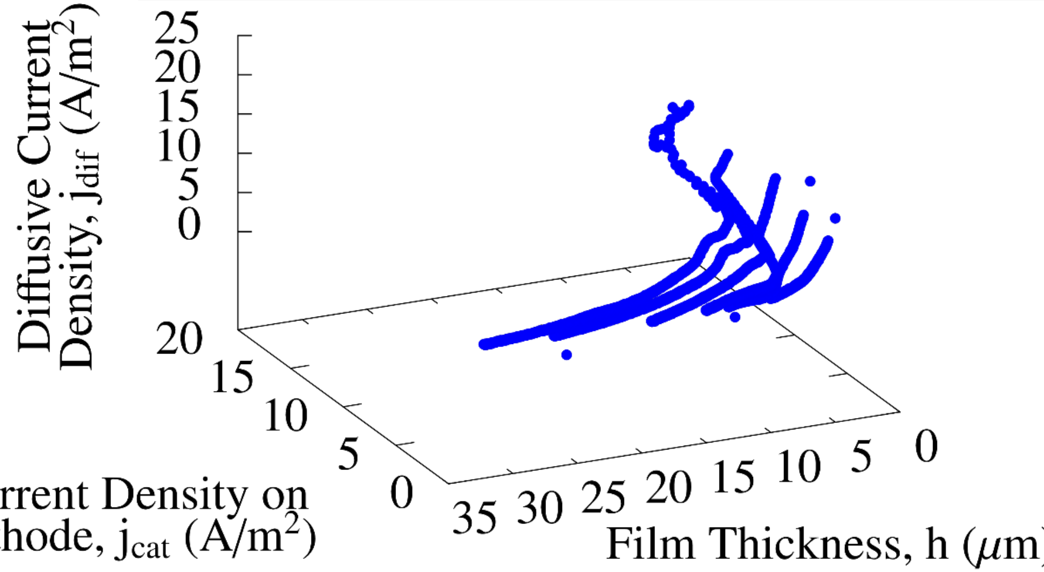
   $$R = \mathrm{NonlinearFunc}(j, h).$$

Procedure to Identify Film Growth Model

1. One-plate tests

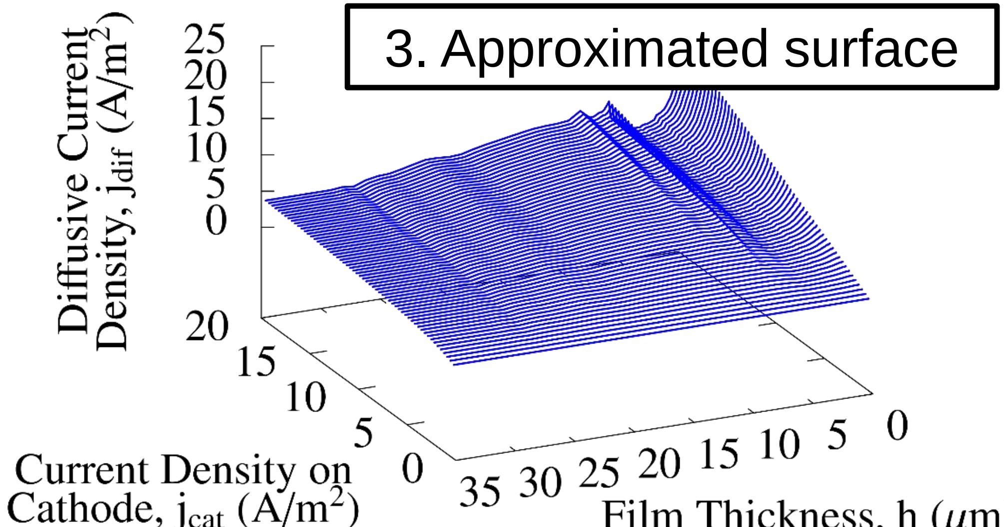
Plot

2. Scatter diagram of j_{cat}, h and $\dot{h}$



Data fitting

3. Approximated surface

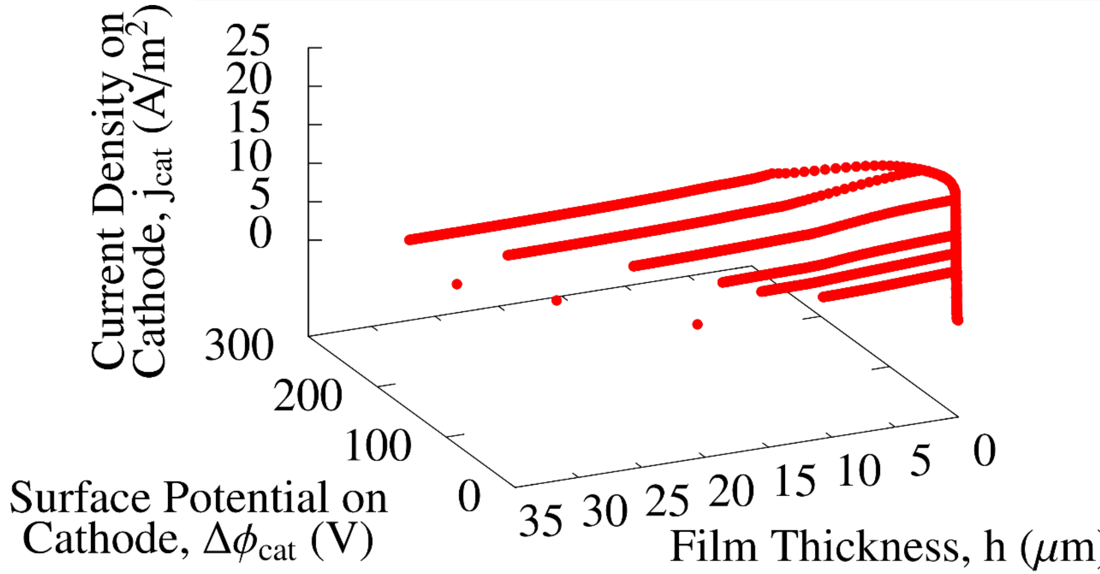


Procedure to Identify Film Resistance Model

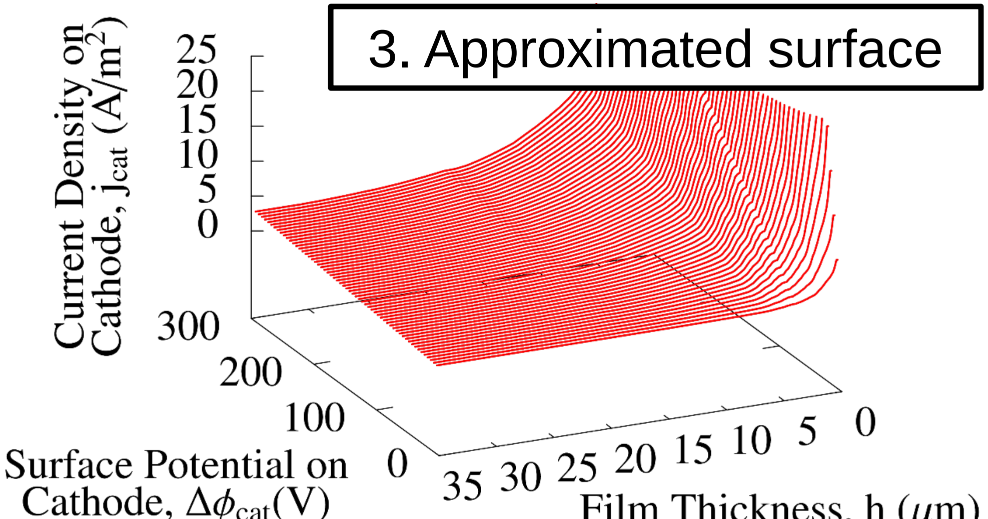
1. One-plate tests

Plot

2. Scatter diagram of ϕ_{cat}, h and j_{cat}



3. Approximated surface



Data fitting

Our S-FEM Code for ED Simulation

Our S-FEM Code for ED Simulation

We adopt the edge-based S-FEM using
4-node Tetrahedral Elements（ES-FEM-T4）.

What is ES-FEM-T4?

- A kind of strain smoothing method.
- Using element edges as Gauss points.
- Robust against element skew.
- Superlinear convergence rate with T4 mesh.

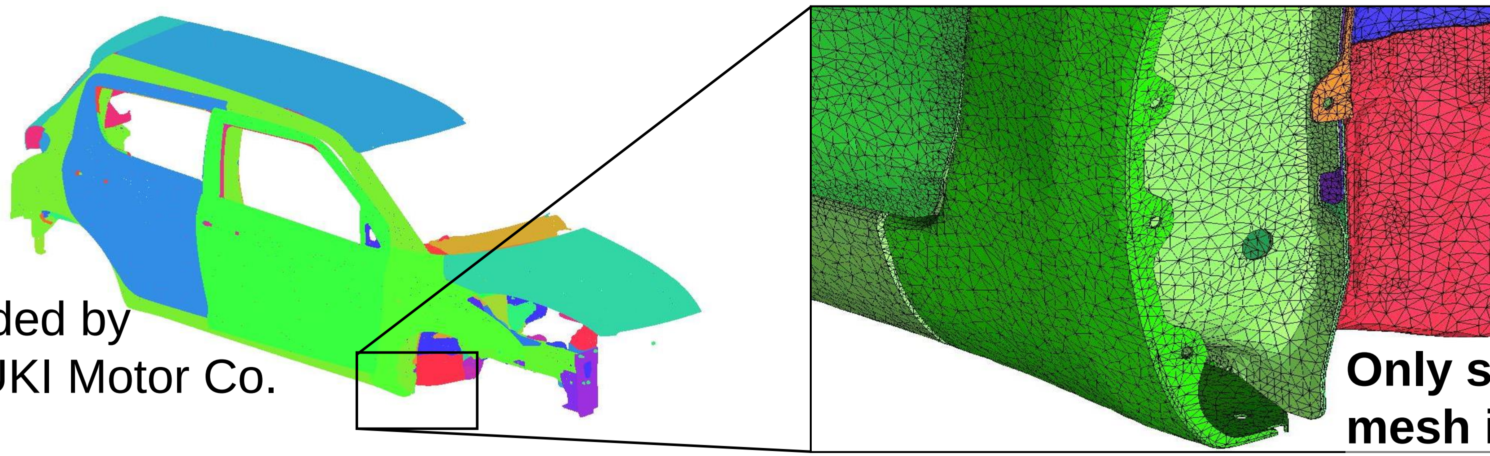
ES-FEM-T4 is always more efficient than FEM-T4.

Our S-FEM Code for ED Simulation

Why not FEM-T10 but ES-FEM-T4?

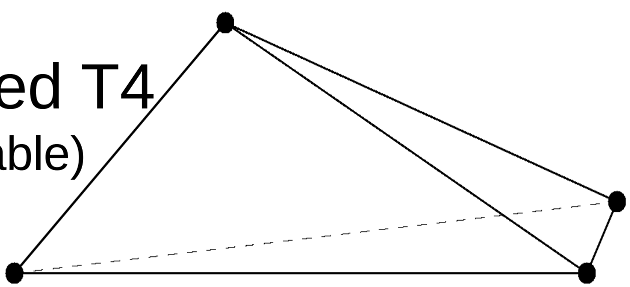
- T10 mesh generally requires more large number of nodes than T4 mesh to represent a complex shape.

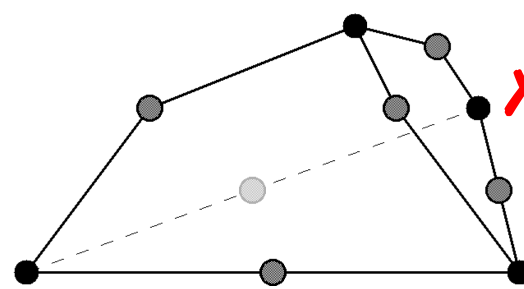
Provided by
SUZUKI Motor Co.



- Kinked T10 element causes severe accuracy loss.

✓ Skewed T4
(acceptable)





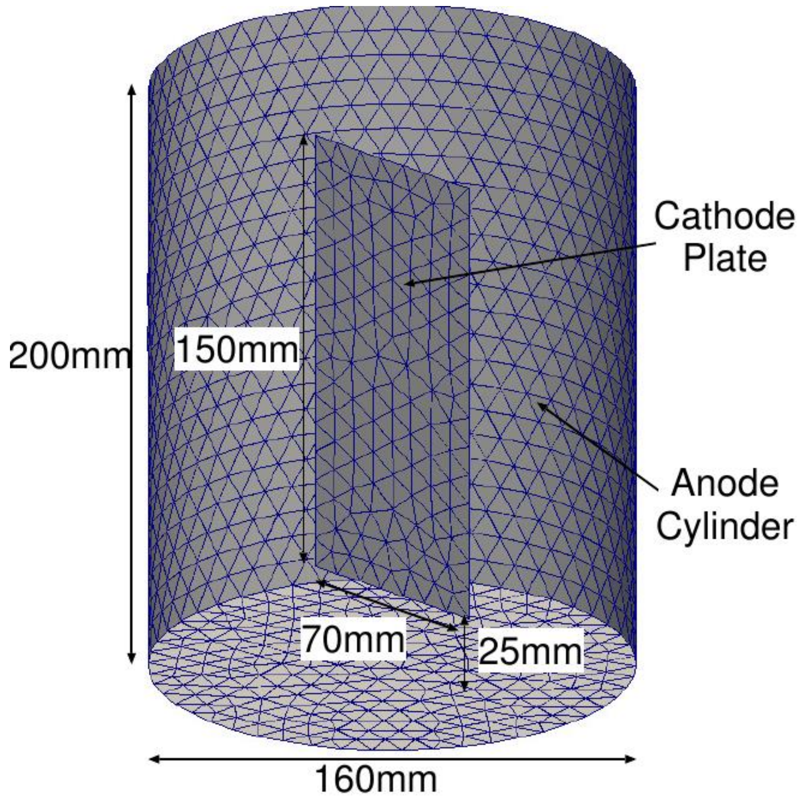
✗ Kinked T10
(unacceptable)

ES-FEM-T4 is always more practical than FEM-T10.

Validation & Demonstration Results

One-plate Test

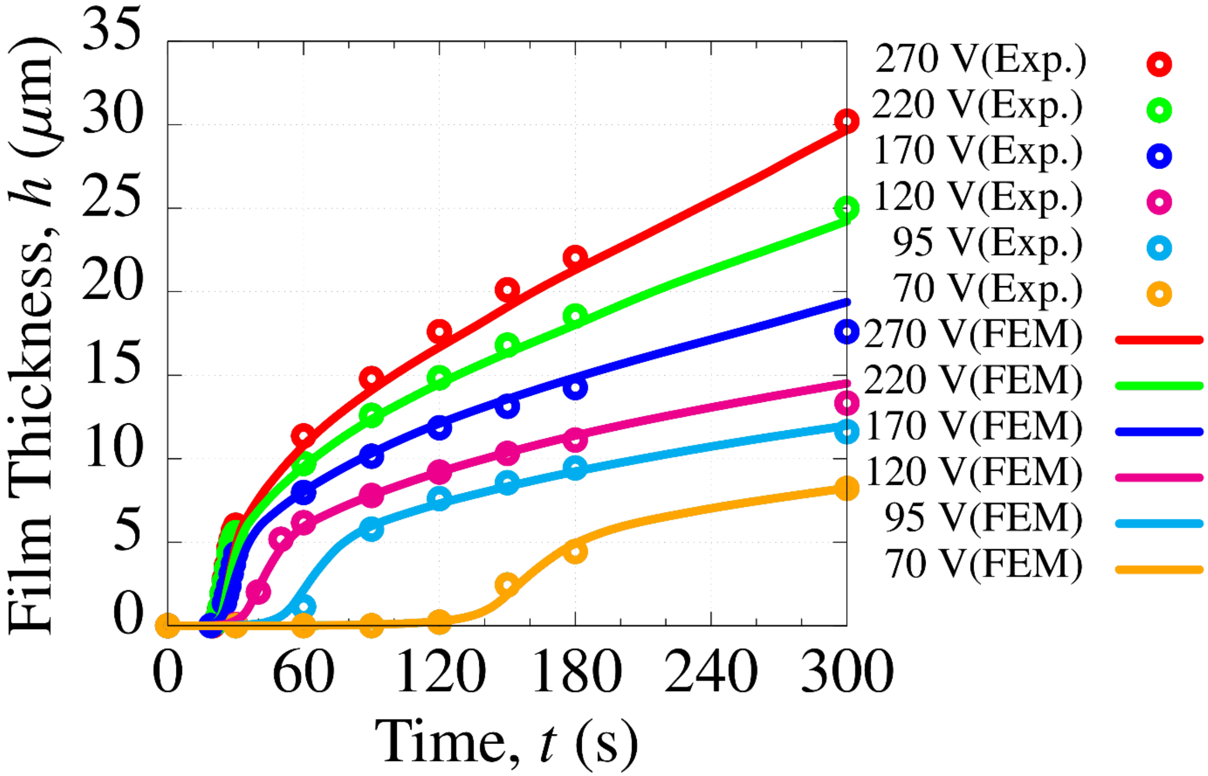
Outline



- The most basic lab experiment.
- 500 Ω external resistor is considered.
- Simulation results are compared to experiment data.

One-plate Test

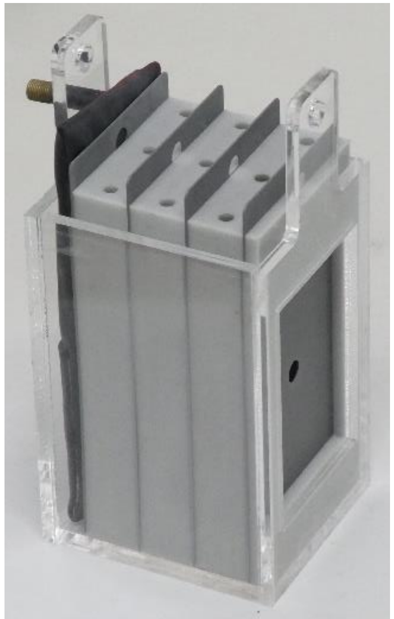
Comparison of time history of film thickness

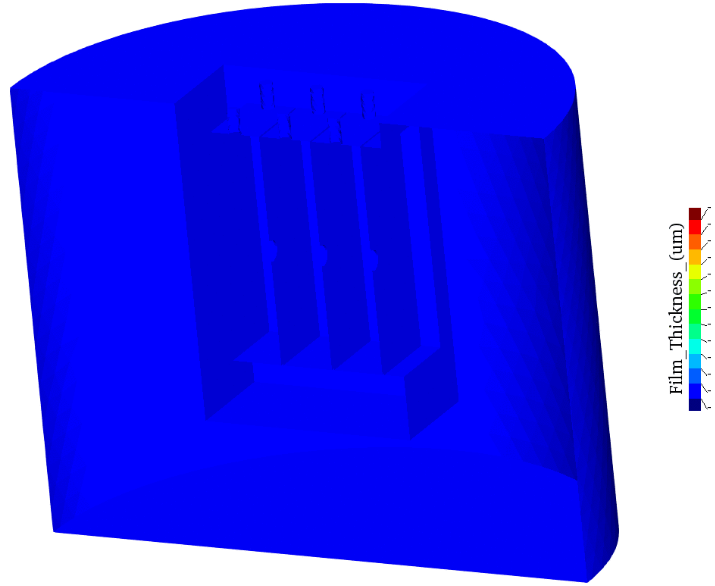


Our new ED simulator succeeded in
reproducing experimental results with high accuracy
from high voltage to low voltage.

4-Plate BOX Test

Outline

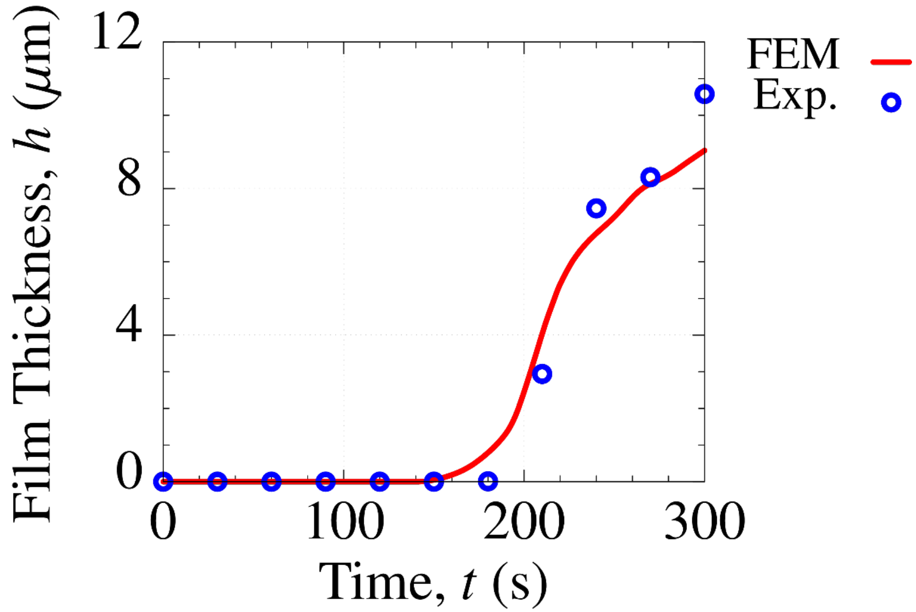




- Imitating a multiple bag-like structure.
- Accuracy on the innermost surface (left side in Figs) is the most important; i.e., “maximize the minimum”.
- Objective is to confirm the validity of the ED boundary model identified with the one-plate data.

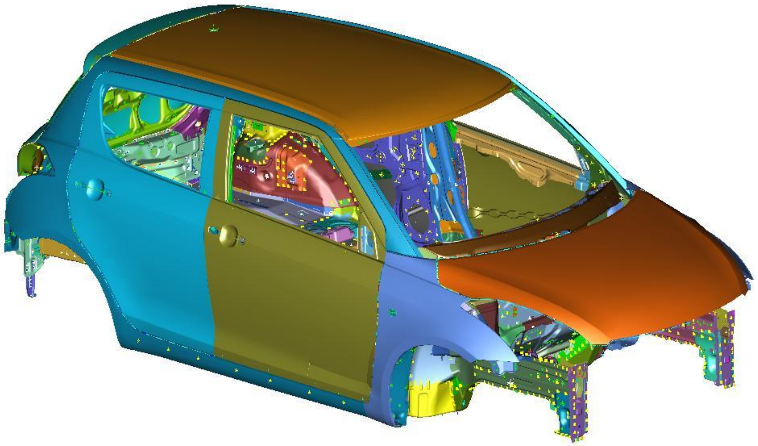
4-Plate BOX Test

Comparison of film thickness on the innermost surface

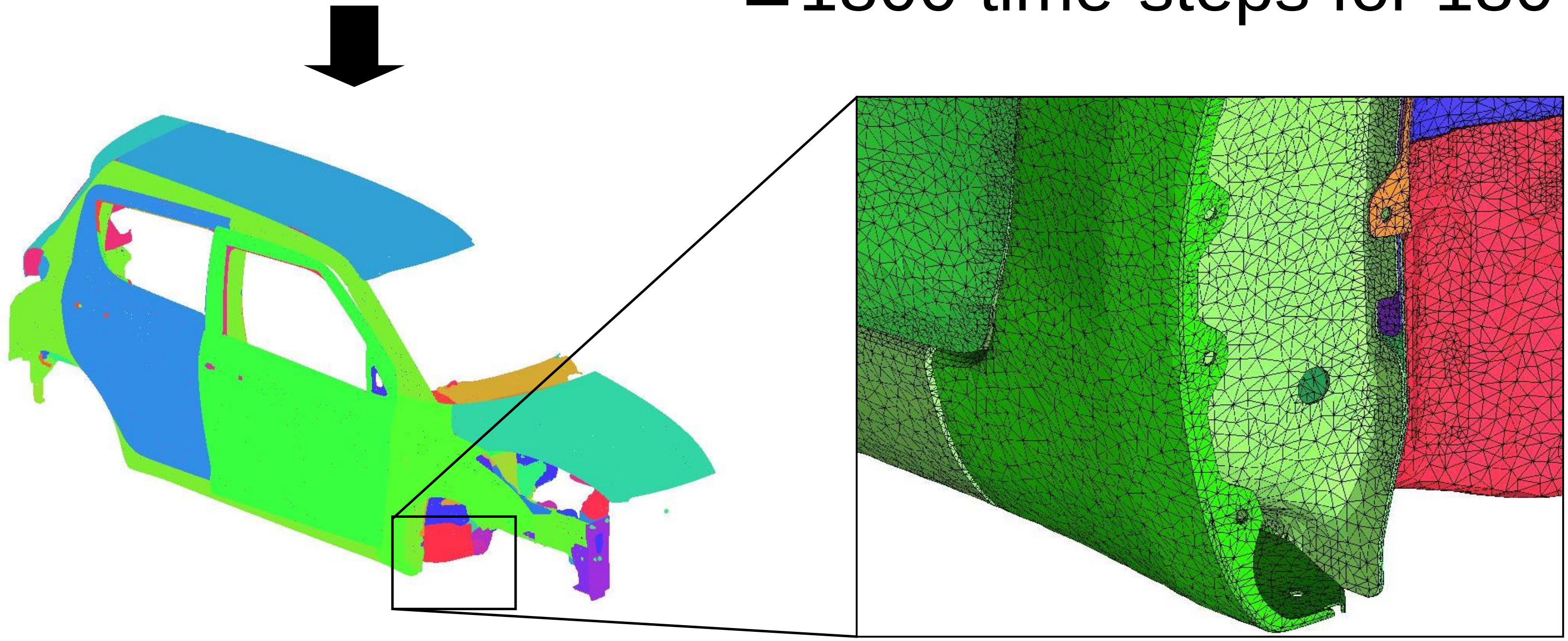


Our new ED simulator has sufficient accuracy to predict the film thickness on the innermost surface.

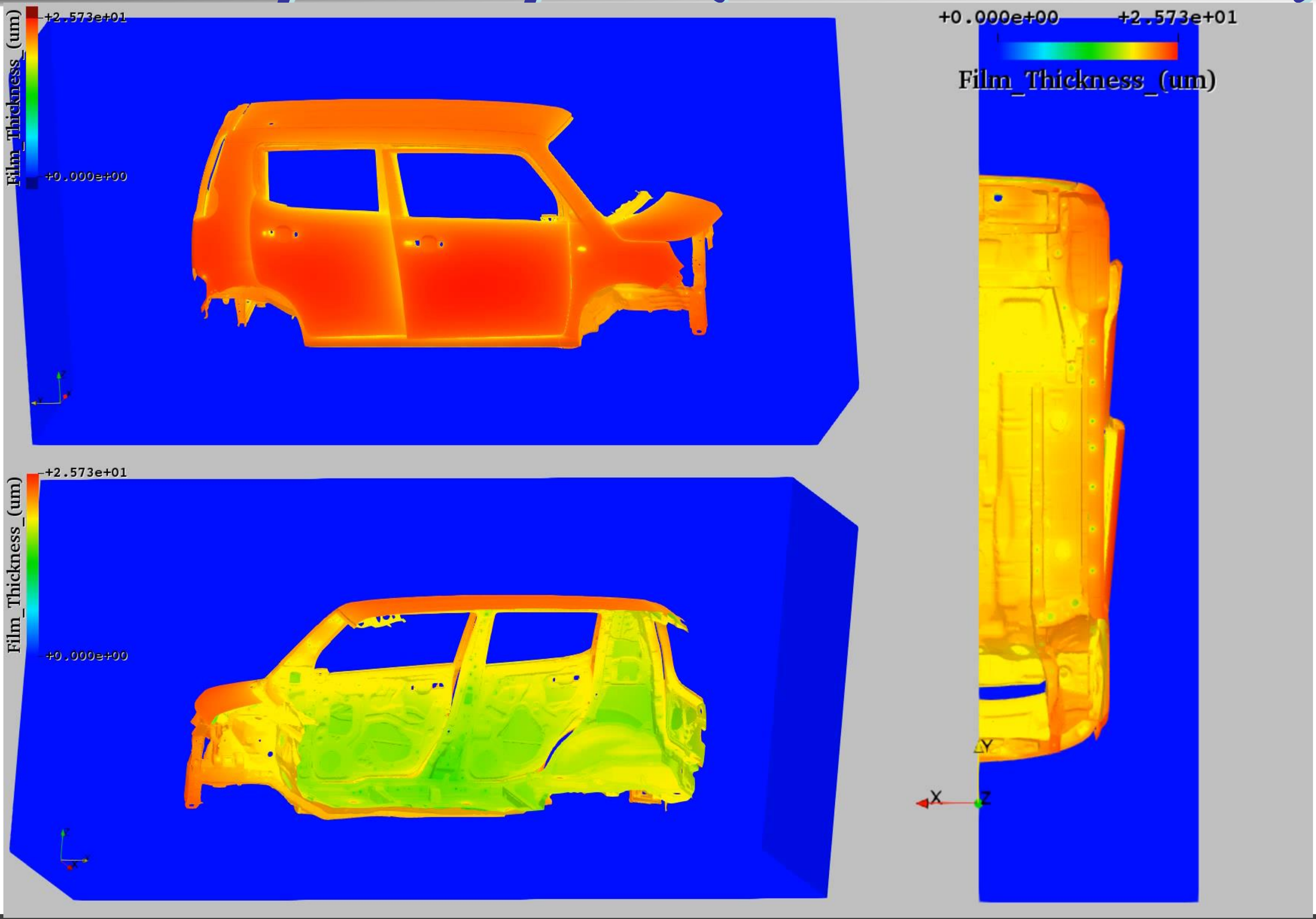
Carbody Analysis (Outline)



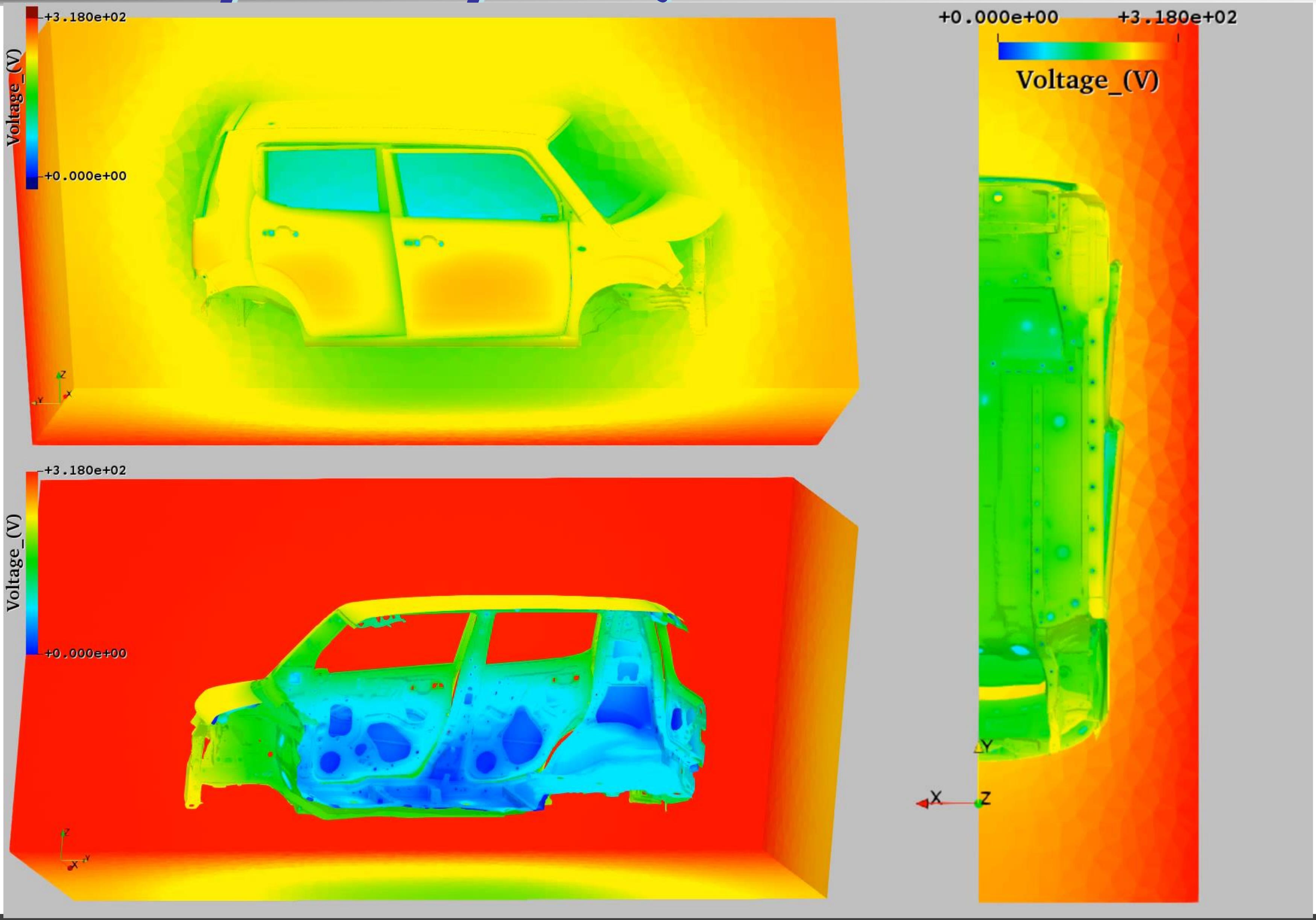
- Demonstration analysis.
- A half carbody in a box pool.
- No motion.
- 3M nodes, 13M elements, and 18M edges for ES-FEM-T4.
- 1800 time-steps for 180 s.



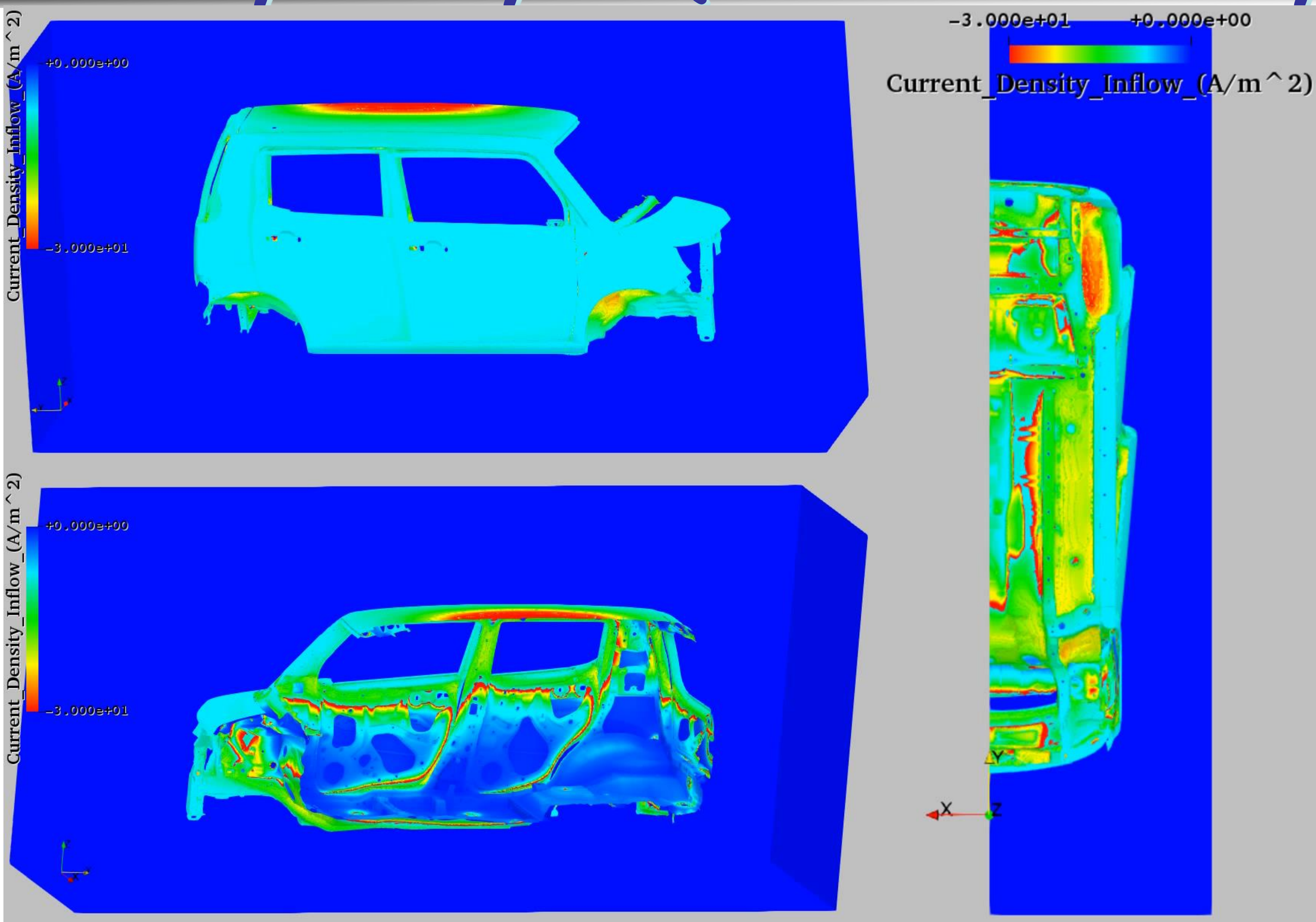
Carbody Analysis (Film Thickness)



Carbody Analysis (Surface Potential)



Carbody Analysis (Current Density)



Summary

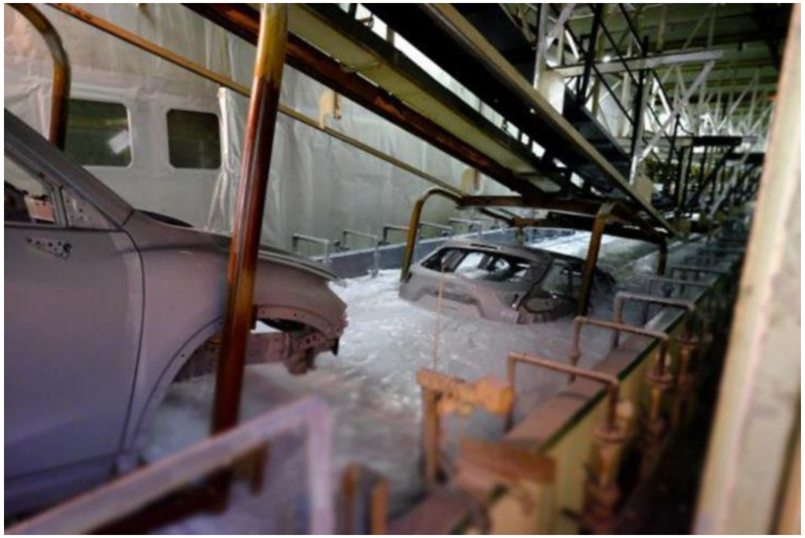
Summary

- A new ED lab experiment method with external resistor to reproduce the actual line conditions was proposed.
- A new ED boundary model considering more complex nonlinear relations was proposed.
- ES-FEM-T4 was introduced in order to improve the accuracy of our ED simulator using T4 mesh.
- Our new ED simulator improved the accuracy in lab tests (one-plate test & 4-plate box test).
- Validation on an actual line is our issue in the future.

Thank you for your kind attention.

Appendix

Photos of ED process line



1. dipping and deposition process

2. water rinse process

We focus on this.

3. baking process

Film Resistance Model

Model Function for Film Resistance Model

$c(h)$ means model parameters.

(1) With Stirring

$$j_{\mathrm{cat}}\left(\Delta\phi_{\mathrm{cat}}, c(h)\right)$$
$$= c(h)\,\Delta\phi_{\mathrm{cat}}$$

(2) Without Stirring

$$j_{\mathrm{cat}}\left(\Delta\phi_{\mathrm{cat}}, \boldsymbol{c}(h)\right)$$
$$= c_1(h)\left(\mathrm{e}^{c_2(h)\Delta\phi_{\mathrm{cat}}} - \mathrm{e}^{-c_2(h)\Delta\phi_{\mathrm{cat}}}\right)$$