Electrodeposition Coating Simulation Based on Lab Experiments and Manufacturing Line Monitoring for Automotive Design

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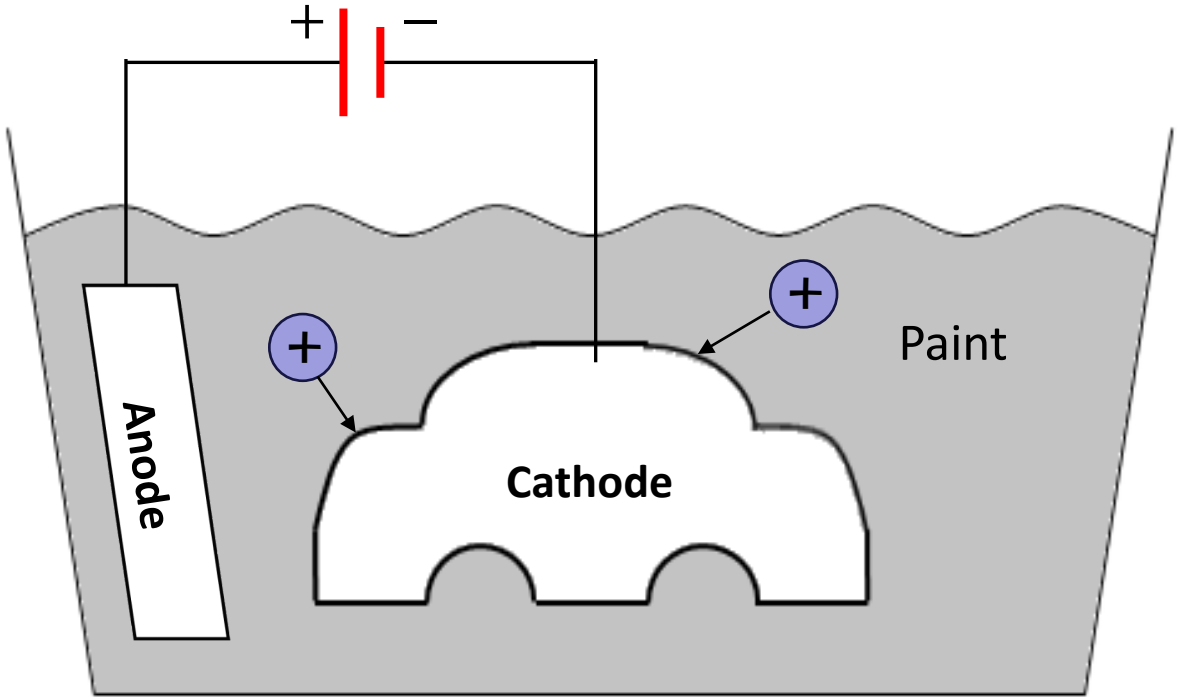
What is Electrodeposition (ED) ?



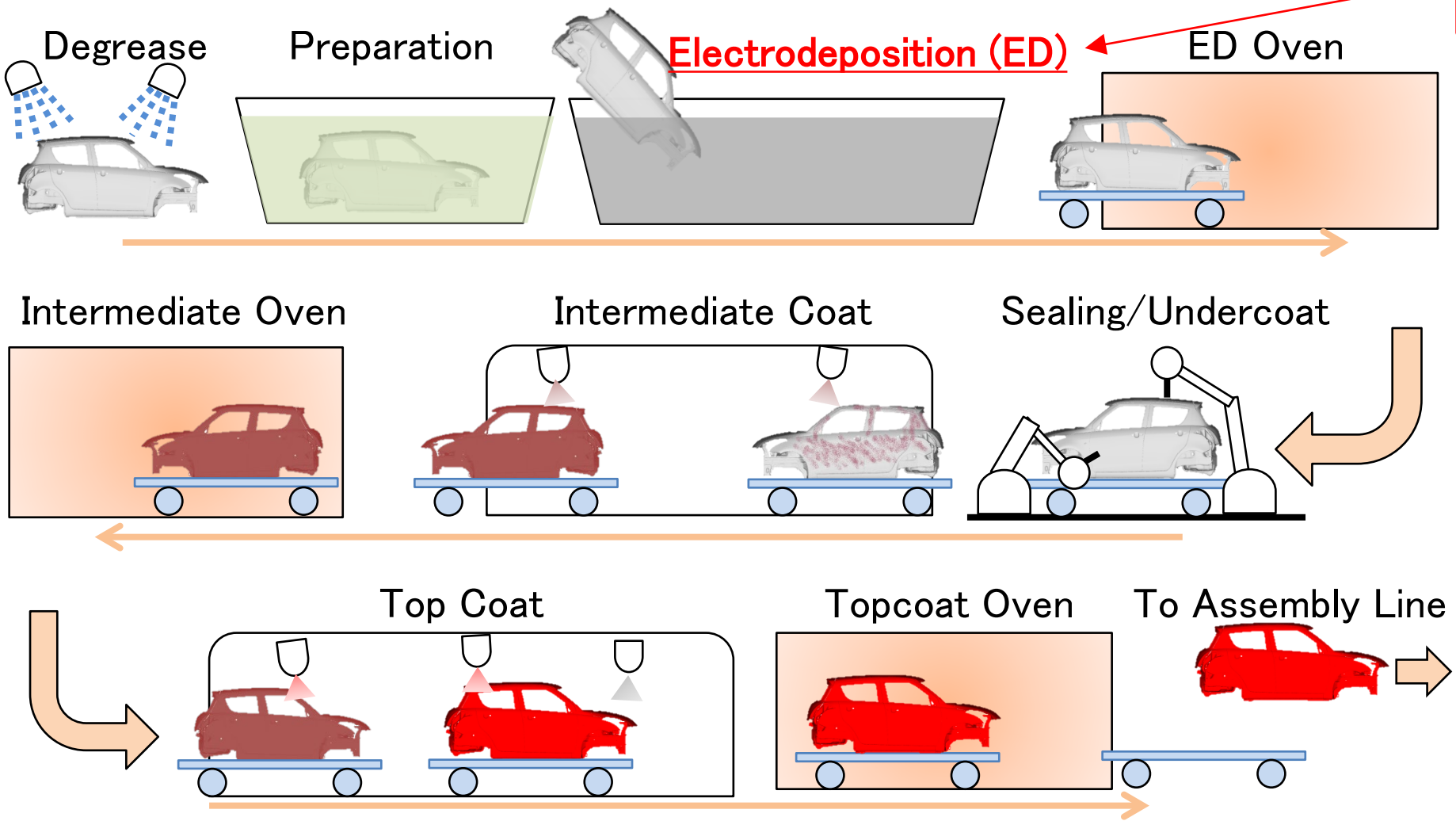
- Most widely-used **anti-rust base-coat** methods for various metal products including auto carbodies.
- Depositing coating film by applying **direct electric current** in a paint pool.
- In the actual car manufacturing line, the carbodies are moving in the paint pool.
- Relatively good at depositing a **uniform film** on complex shapes such as carbody.

What is Electrodeposition (ED) ?

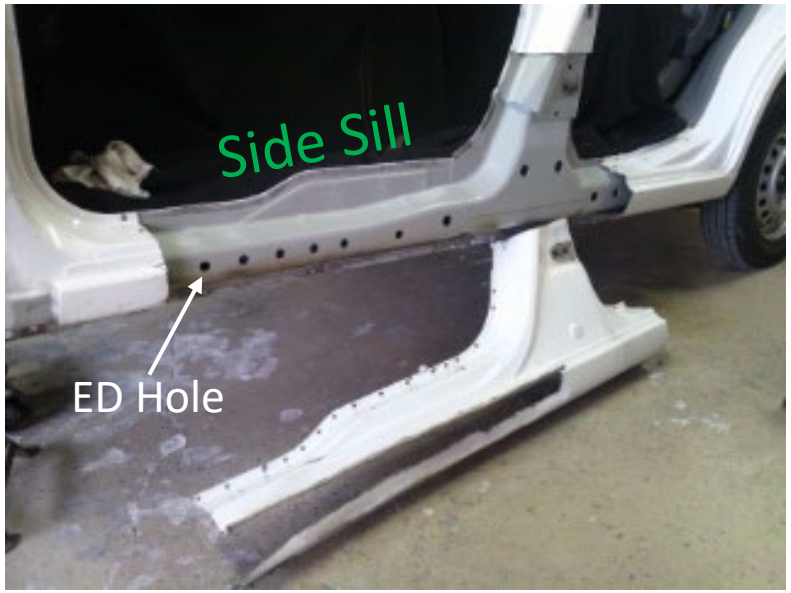
Simplified Overview of the Entire Carbody Paint Shop

We focus on this process.

1. Base-coat
2. Intermediate -coat
3. Top-coat



Impact of ED Process on Carbody Design

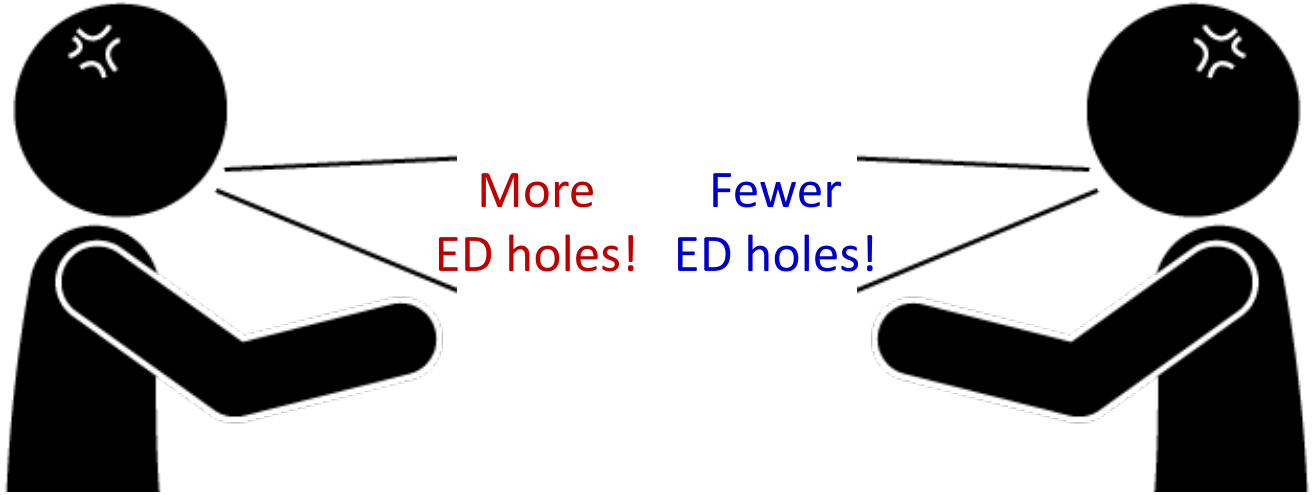


- Undercarriages are exposed to severe corrosive environments.
- ED film thickness must be above minimum over the entire surface of the undercarriages.
- Some undercarriage parts (e.g., side sills) have bag-like structures with multiple plates.
- It is necessary to drill **many ED holes** to allow the electric current to pass through in the paint pool.

∴ Carbody designers should understand and consider the ED process, including the location, size, and number of ED holes.

Need for ED Simulation

- ED holes are essential for corrosion protection,
  but they are NOT welcome for strength or stiffness.
- Thus, the following conflict always occurs between carbody designers.



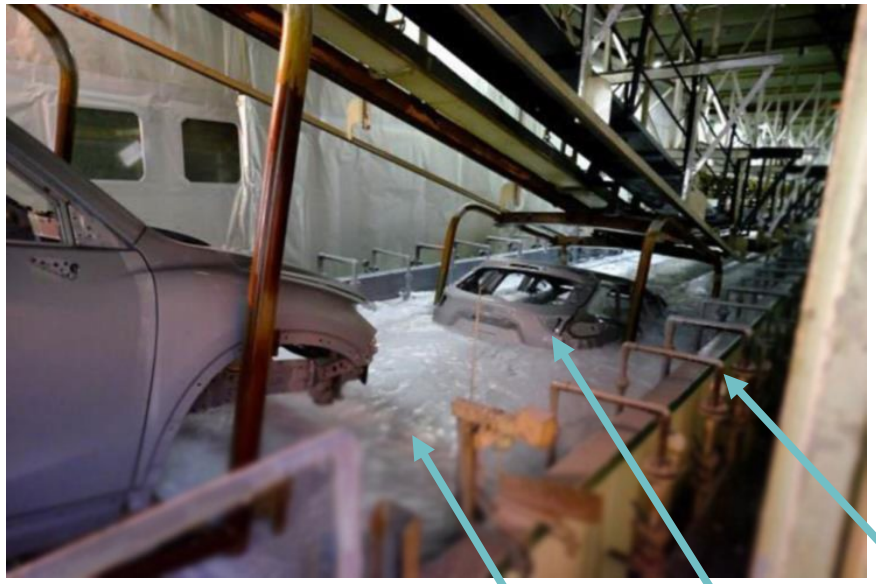
Designer in Corrosion Section

Designer in Strength/Stiffness Section

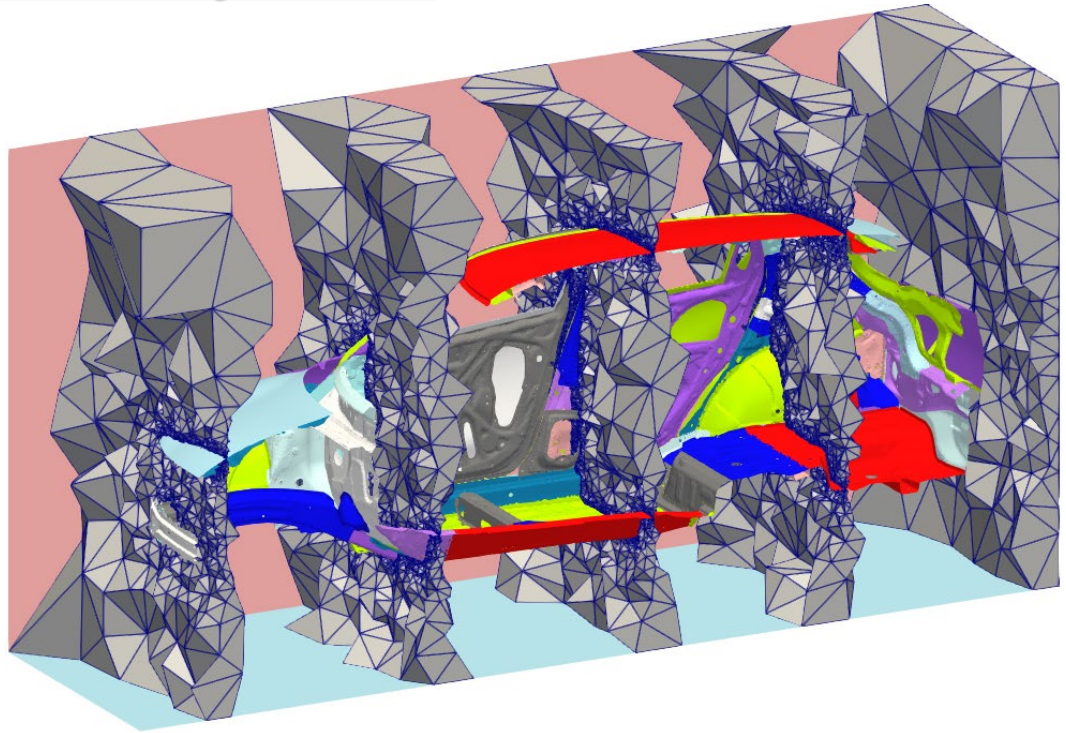
In such a case, **ED simulation** can resolve the conflict
based on quantitative evidence data and lead to the optimal carbody design.

What is ED Simulation?

Actual ED Line

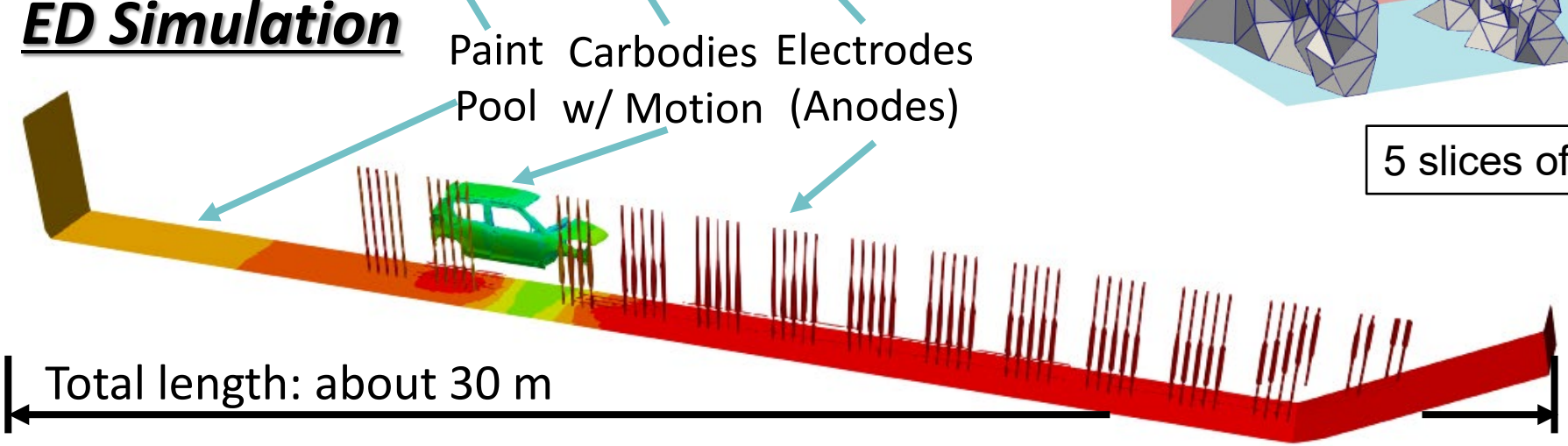


Carbody Mesh

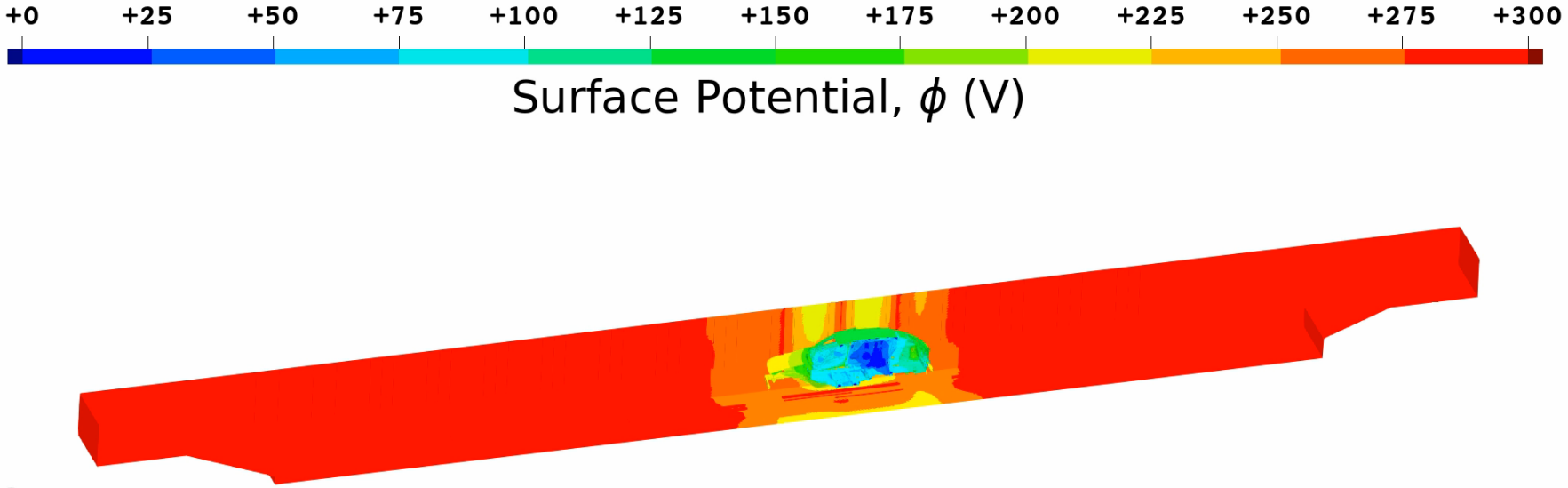


5 slices of a carbody mesh

ED Simulation



What is ED Simulation?



- Governing equation:
  Electrostatic Laplace equation ($\nabla^2\phi = 0$) in the paint pool domain.
- Boundary conditions:
  1. Wall (insulation) BC,
  2. Anodic (electrode surface) BC,
  3. Cathodic (carbody surface) BC: ED constitutive models for film initiation / resistance / growth.

Need to identify them via lab experiments

- Mesh: 4-node tet (T4) mesh for complex carbody shape.

Need for accurate FEM-T4

- Motion: Overset mesh method
- Outputs: Time-histories of
  - Surface potential,
  - Current density,
  - Film thickness.

Need for validation before deployment

Objective

Development of a practical ED simulator
using the next-gen FE formulation (ES-FEM)
with the ED constitutive models based on lab experiments
and its validation for actual manufacturing.

Table of body contents:

- Methods: ES-FEM, Lab Experiment, Actual Line Measurement
- Results: Validation at an Actual Manufacturing Line
- Summary

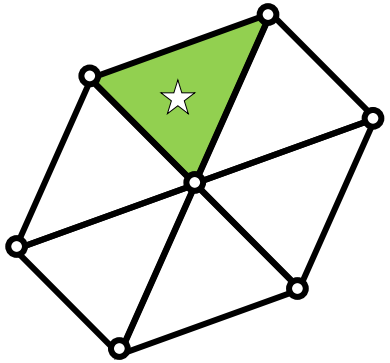
Methods:
ES-FEM, Lab Experiment, and Actual Line Measurement

The next-gen FE formulation: ES-FEM

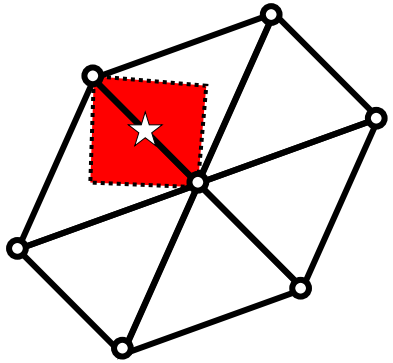
- **Edge-based Smoothed Finite Element Method (ES-FEM)** is a relatively new FE formulation proposed in 2006 by Prof. G. R. Liu (the 1st plenary speaker of APCOM2025).
- S-FEM is one the gradient/strain smoothing techniques.
- ES-FEM is a method as if putting a Gauss point at each edge center.

For example, in a 2D triangular mesh:

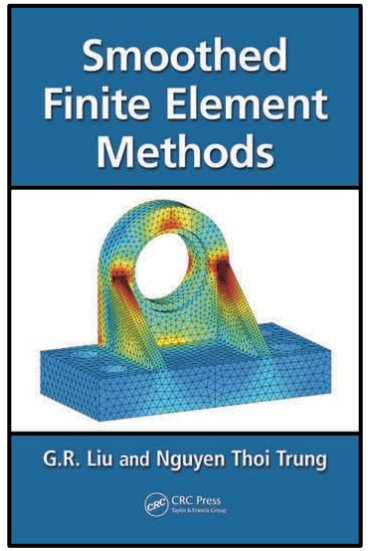
Standard FEM



Edge-based S-FEM (ES-FEM)



The red area shows the domain for gradient smoothing.

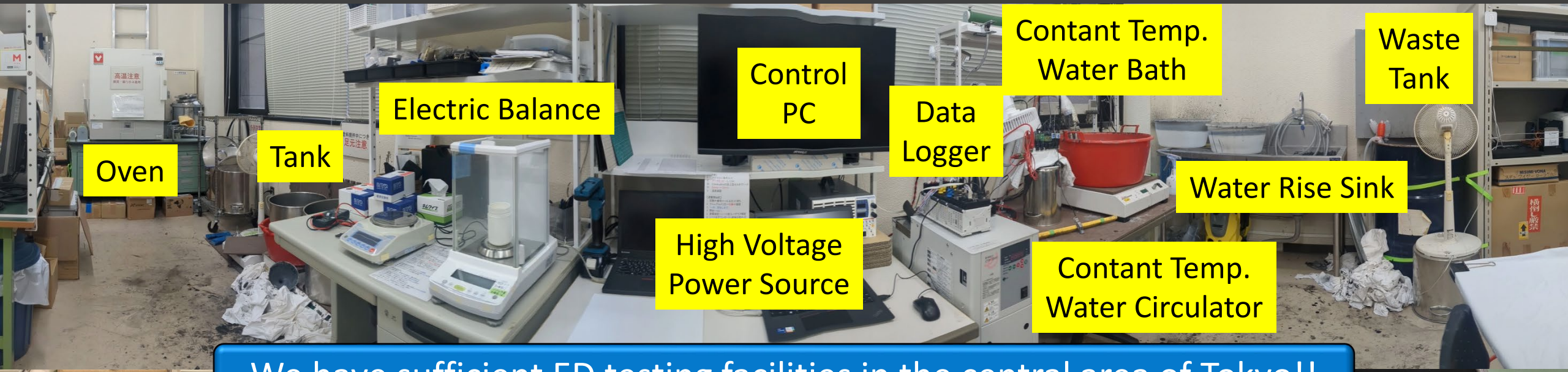


G.R. Liu *et al.*, CRC Press

Search | S-FEM wiki

Using ES-FEM-T4, a super-linear mesh convergence rate in electrostatic analyses is expected.

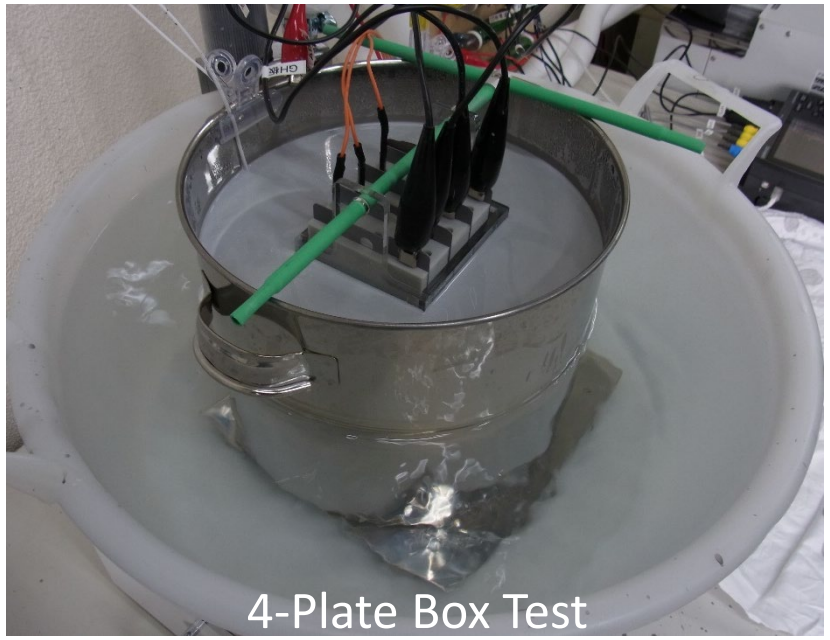
Overview of Our ED Experiment Lab

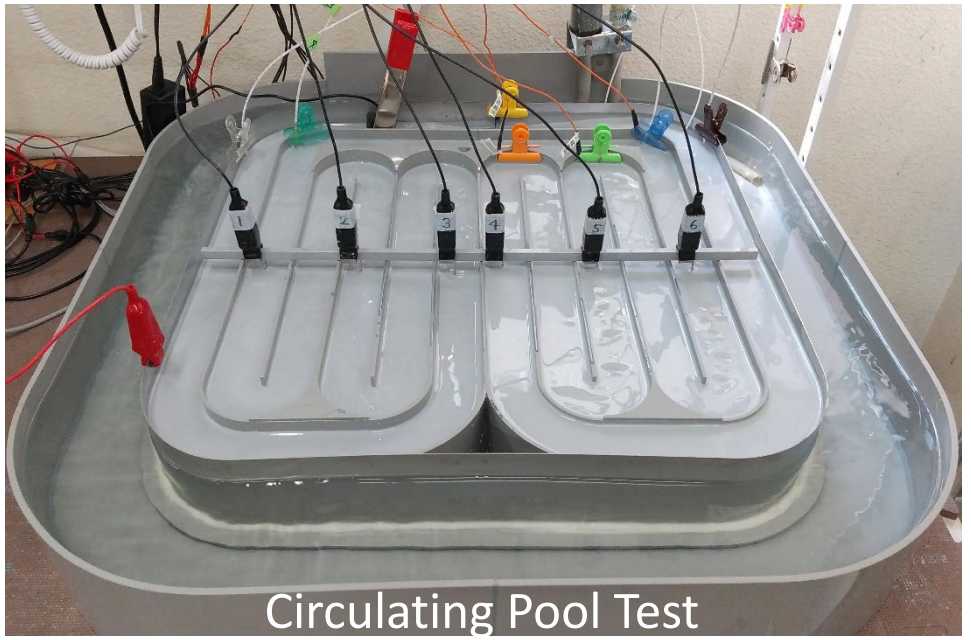


We have sufficient ED testing facilities in the central area of Tokyo!!

3 Major Lab Tests


One-Plate Test


4-Plate Box Test


Circulating Pool Test

- The one-plate test is used to identify the numerical ED constitutive models:
  - Film initiation model,
  - Film resistance model,
  - Film growth model.

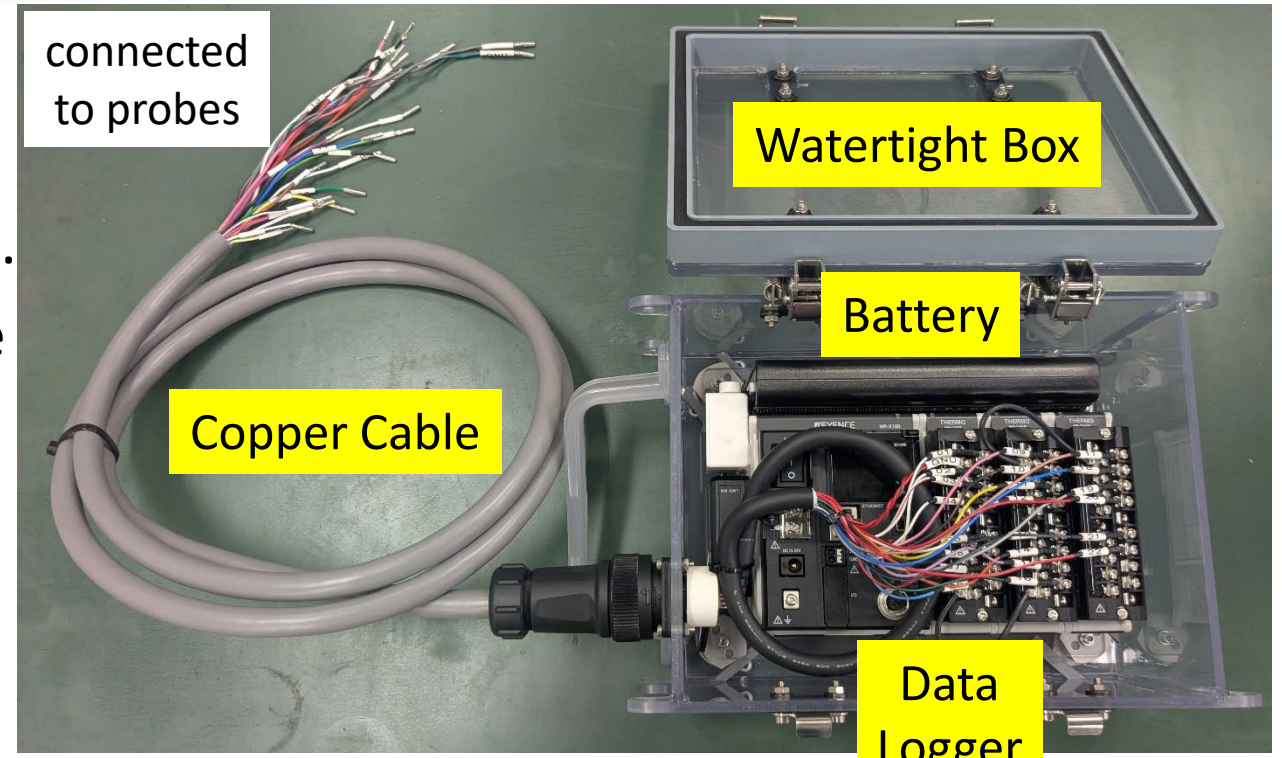
  } All strongly non-linear models… It takes 200 tests at least.
- The other tests are used for the validation of the identified ED constitutive models.

One of the Actual Line Monitoring Devices

Carbody Surface Potential Measurement Device

1. Hang this device in the middle of carbody.
2. Put electric probes on the carbody surface.
3. Let is sink in the paint pool to measure the electric potential during the ED process.

⟹ We can obtain the time-histories of electric potential on the carbody surface.



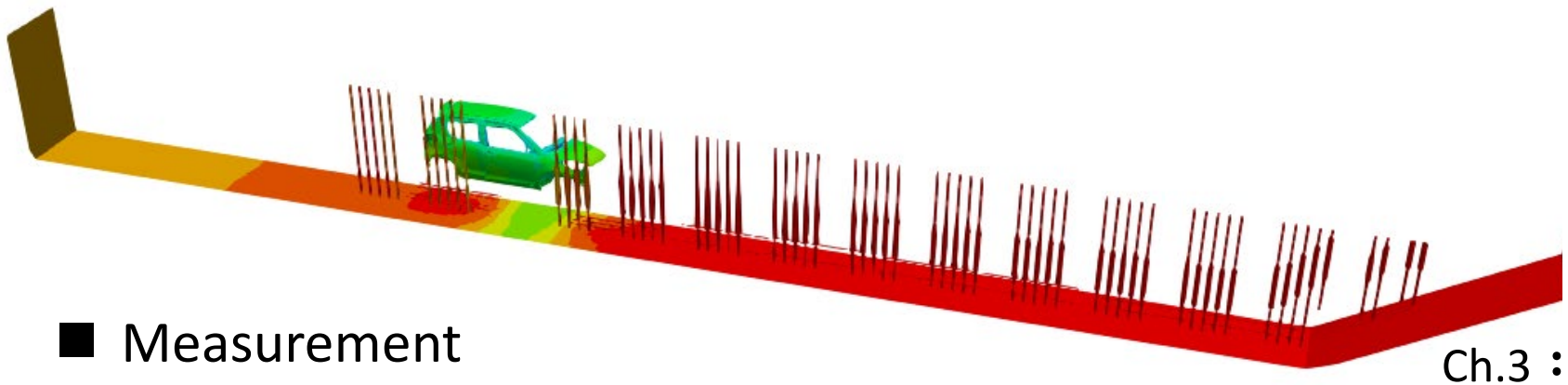
Getting time-history monitoring data is very important
for the validation of a line simulator, in addition to the final state data.

Making real devices by yourself for actual manufacturing line is sometimes necessary to motivate factory engineers, even though you are a computational engineer.

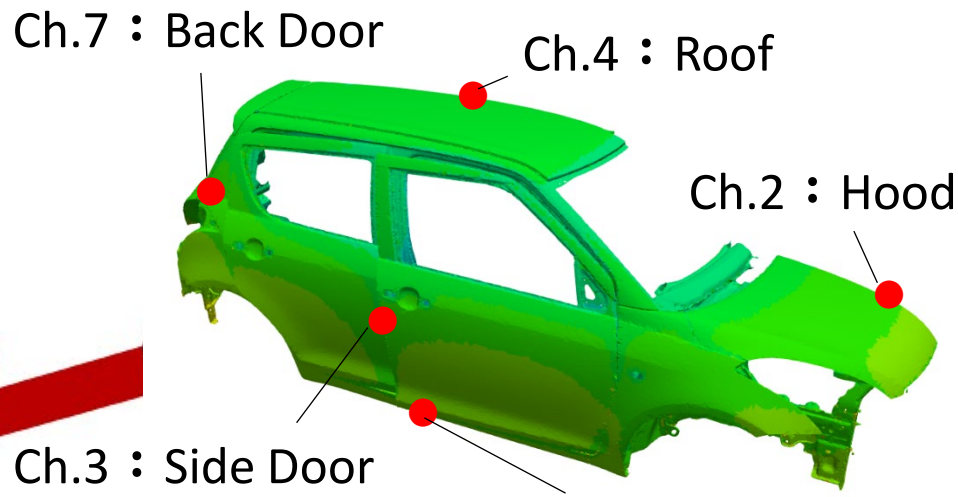
Result:
Validation Test at an Actual Manufacturing Line

Validation Test

Outline



- Measured 6 Points (Ch.2 - 7):



Ch.6：Floor
(not visible on this Fig.)

■ Measurement

- A **surface potential logging device** with 6 probes was mounted on a car running on an actual ED line.
- After baking, the film thickness was measured at the probe points.

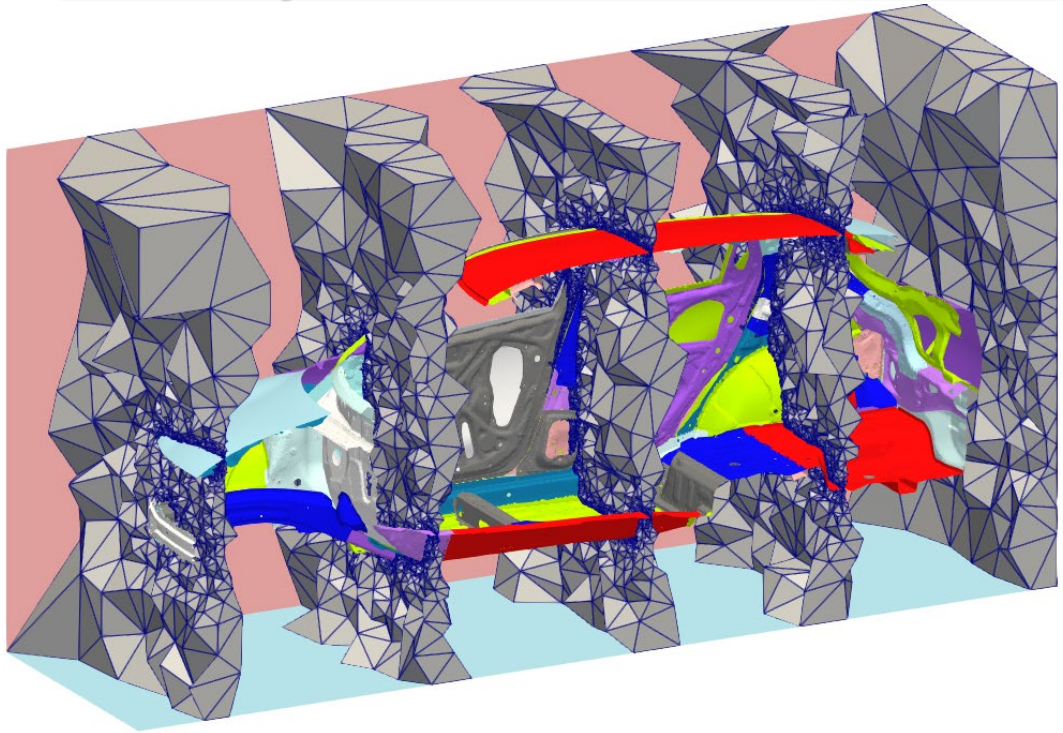
■ Simulation (Same as the mesh convergence test.)

- Half-body analysis (only right-hand side).
- The entire line shape, carbody motion, and standard electrode conditions are input.

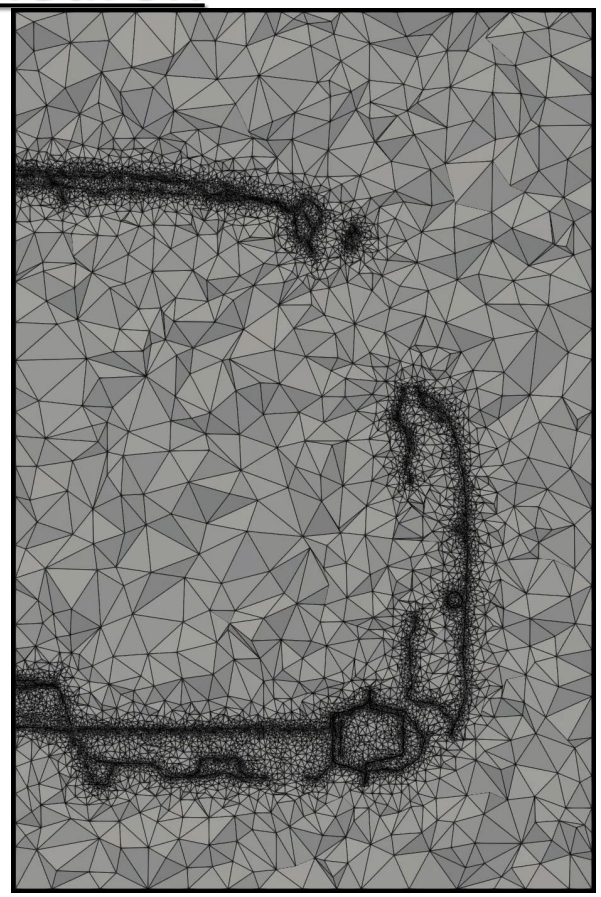
Surface potential time history and final film thickness at the 6 points are compared.

Validation Test

Carbody Mesh with 4-node Tetrahedron



5 slices of a carbody mesh



Animated slices of a carbody mesh from rear to front

# of Elements

- 25M for carbody
- 7M for pool

(32M in total)

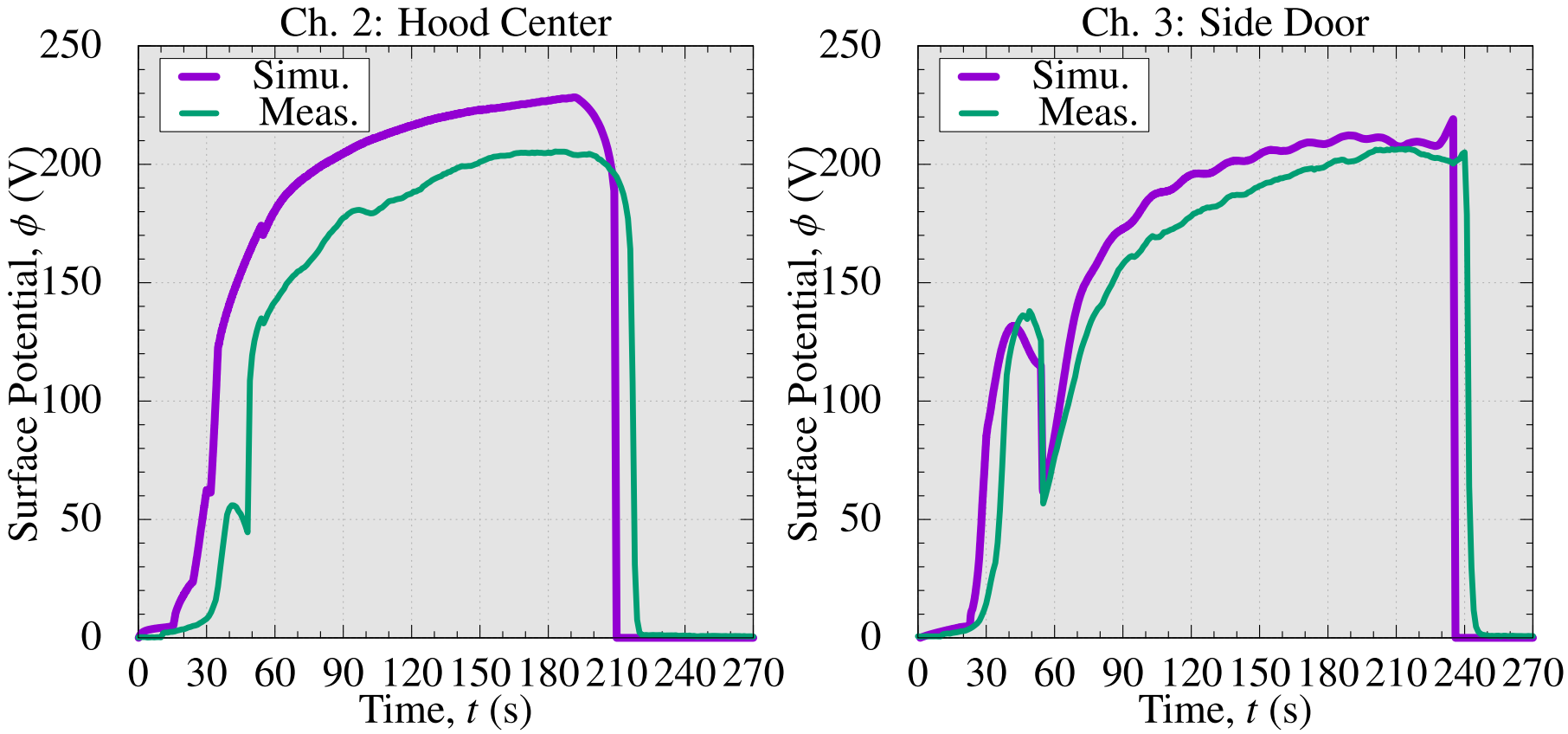
CPU Cost

7 hours with AMD EPYC 9274F x 1, MPI/OpenMP Hybrid.

- An ED simulation requires a mesh for the space around the carbody like CFD.
- In contrast to CFD, an ED mesh should include the room space and many narrow spaces among plates (such as inside of the side sill).

Validation Test

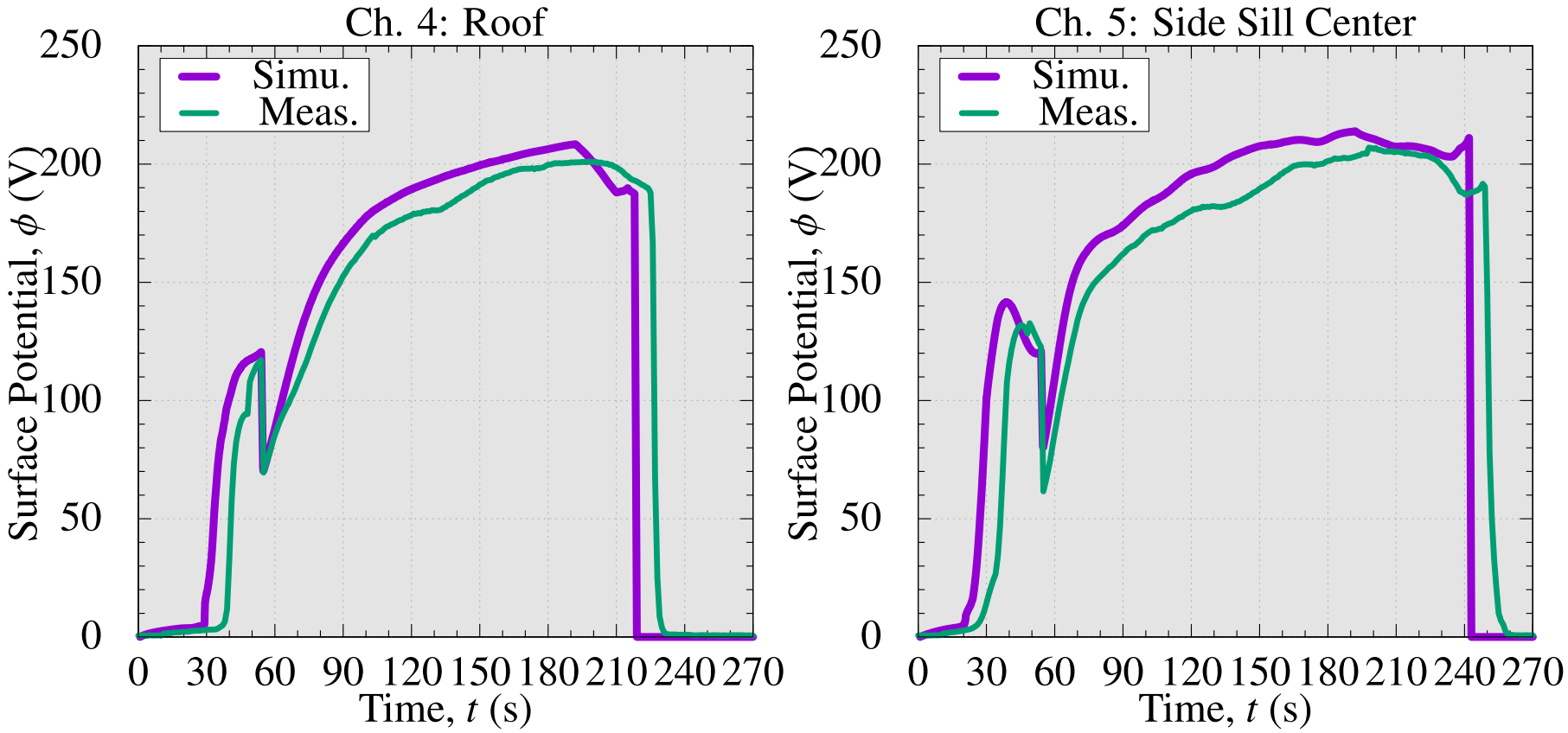
Validation of Time-history of Surface Potential (Ch. 2 and 3)



The simulated surface potential is a little high
because the degradation of the membranes of electrodes was not precisely simulated;
yet, the results generally agree with measured data in practical accuracy.

Validation Test

Validation of Time-history of Surface Potential (Ch. 4 and 5)



The simulated surface potential is a little high
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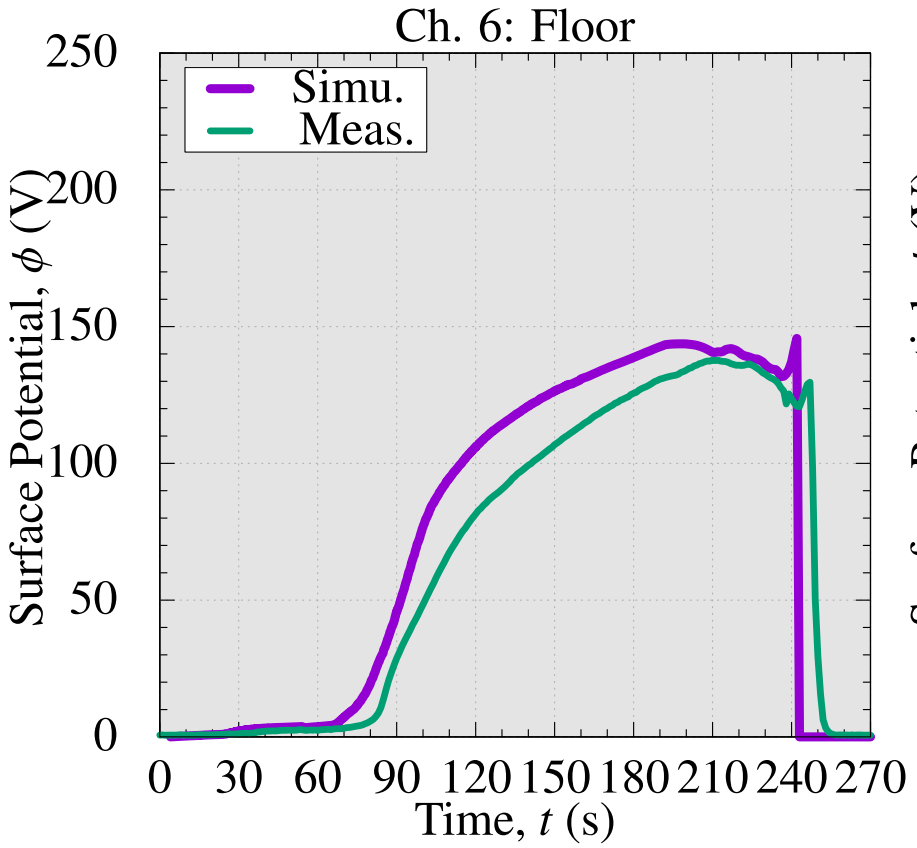
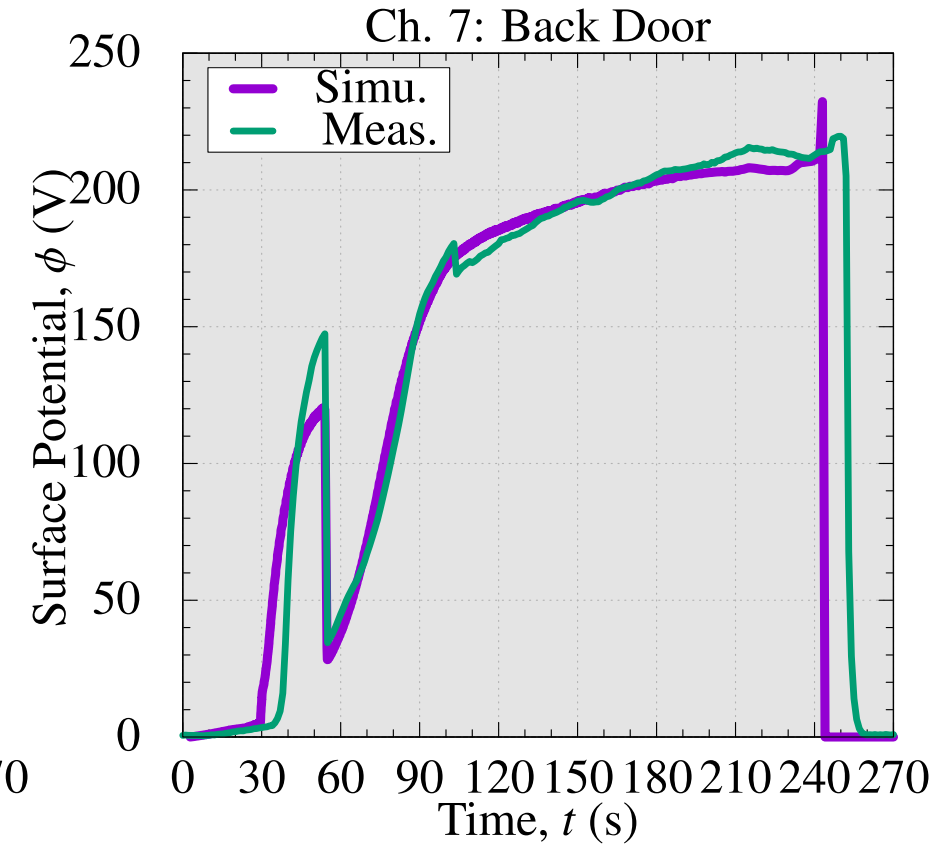
Validation Test

Validation of Time-history of Surface Potential (Ch. 6 and 7)

The deposition delay at the floor, an inner part, is reproduced successfully.





The simulated surface potential is a little high
because the degradation of the membranes of electrodes was not precisely simulated;
yet, the results generally agree with measured data in practical accuracy.

Validation Test

Validation of Final Film Thickness

Point	Measured (μm)	Simulated (μm)	Error (μm)
Ch.2: Hood	20.1	21.4	$+1.3$ $(+6.5\%)$
Ch.3: Side Door	19.0	21.0	$+2.0$ $(+10.5\%)$
Ch.4: Roof	17.0	19.3	$+2.3$ $(+13.5\%)$
Ch.5: Side Sill	20.0	21.6	$+1.6$ $(+8.0\%)$
Ch.6: Floor	–	14.5	–
Ch.7: Back Door	23.0	20.3	-2.7 (-11.7%)

Although there is still room for improvement in accuracy,
the maximum error in film thickness is less than 3 μm,
which is accurate enough for practical use.

The validation example presented here is from about 10 years ago.
Due to confidentiality reasons, we cannot disclose the latest results.

Summary

Summary

- An electrodeposition (ED) simulator was developed.
- The simulator adopts the next-gen FE formulation (ES-FEM) with 4-node tetrahedral meshes for complex carbody shapes.
- A series of lab experiments are conducted to identify the ED constitutive models.
- A novel device to measure the time-histories of electric potential on the carbody surface was developed and utilized in actual manufacturing lines.
- A test on an actual manufacturing line validated the effectiveness of our ED simulator.

- Our commercial ED simulator is already in practical use in major Japanese car companies.
- If you are interested in our ED simulator, please check the website. Search edesfem

Thank you for your kind attention!