Performance Evaluation of Edge-Based Smoothed Finite Element Method for 4-node Tetrahedral Meshes on Electrodeposition Simulation

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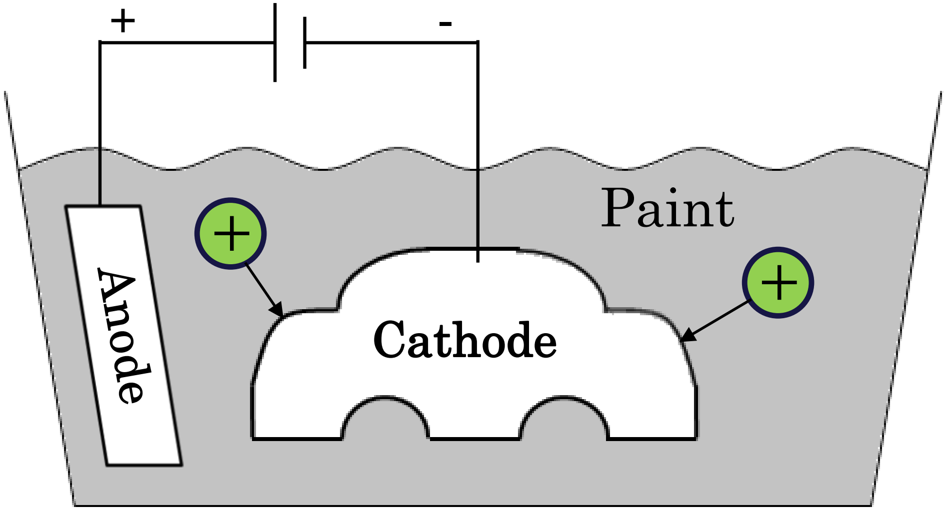
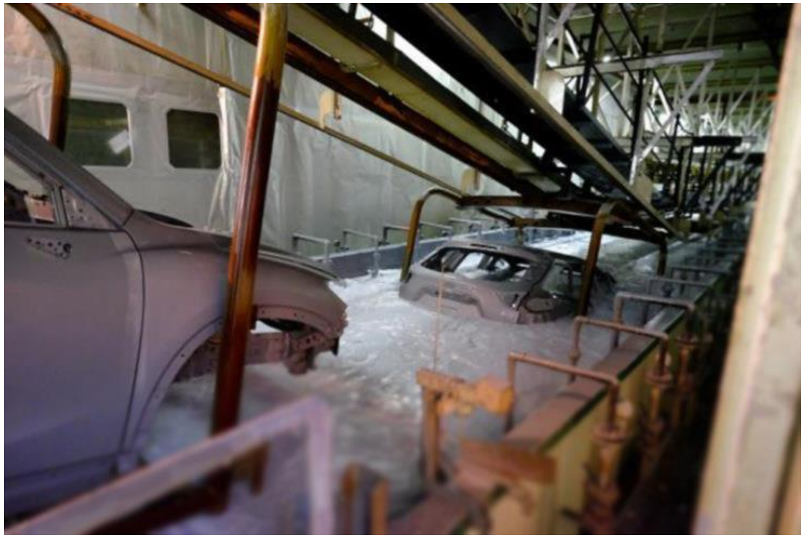
What is electrodeposition (ED) ?

http://n-link.nissan.co.jp/NOM/PLANT/



- 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 the optimization of carbody design and coating conditions in actual lines.

Photos of ED process line



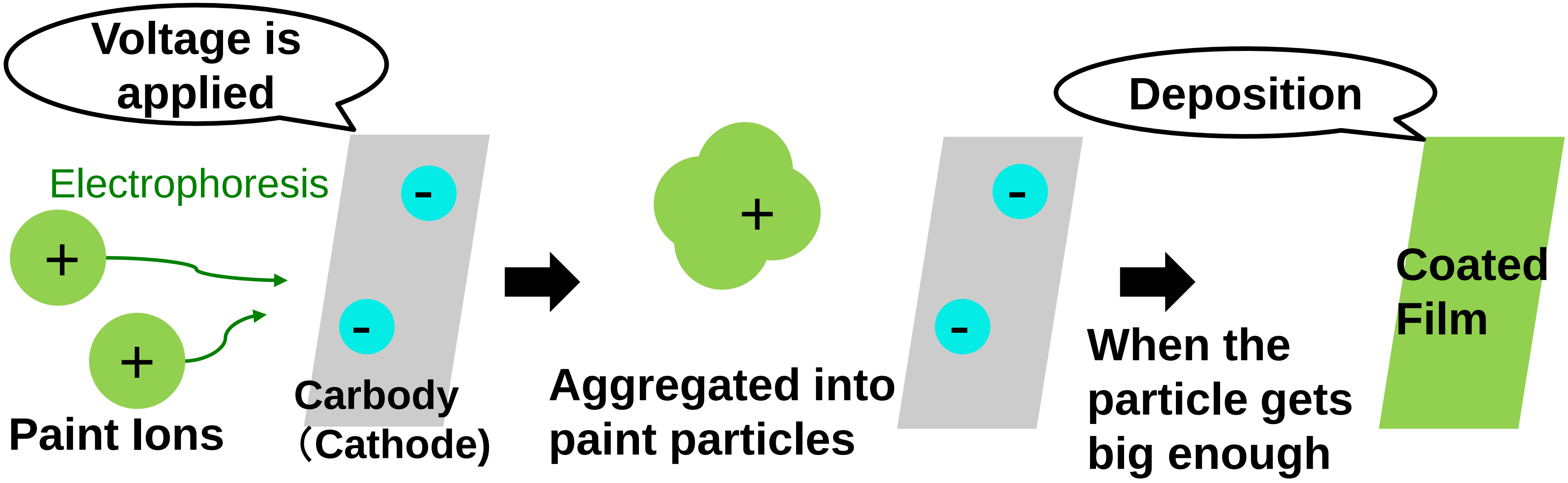
1. dipping and deposition process

2. water rinse process

We focus on this process.

3. baking process

Mechanism of Electrodeposition



Voltage is applied

Electrophoresis

Paint Ions

Carbody (Cathode)

Aggregated into paint particles

Deposition

When the particle gets big enough

Coated Film

- Positively charged paint ions are attracted to the cathode.
- Paint ions lose their electrical charge and are aggregated into paint particles.
- Some of the paint particles diffuse and dissolve.

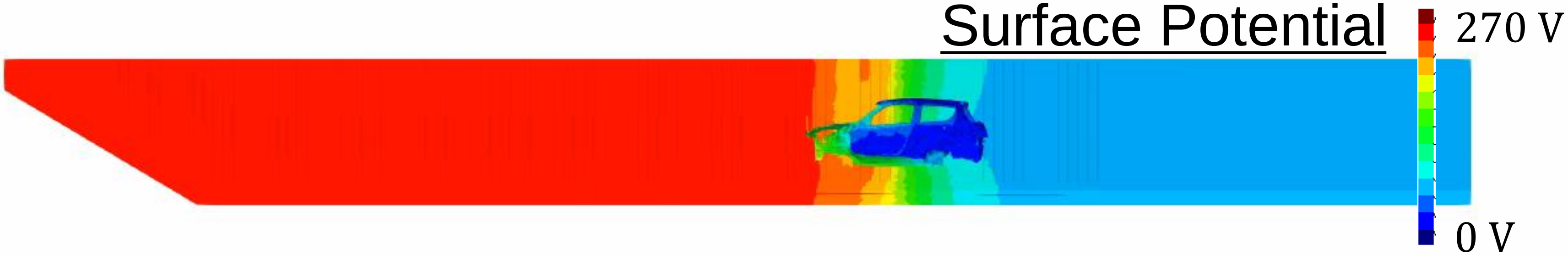
What is ED Simulation ?

ED simulation provides film thickness, surface potential, surface current density and so on.

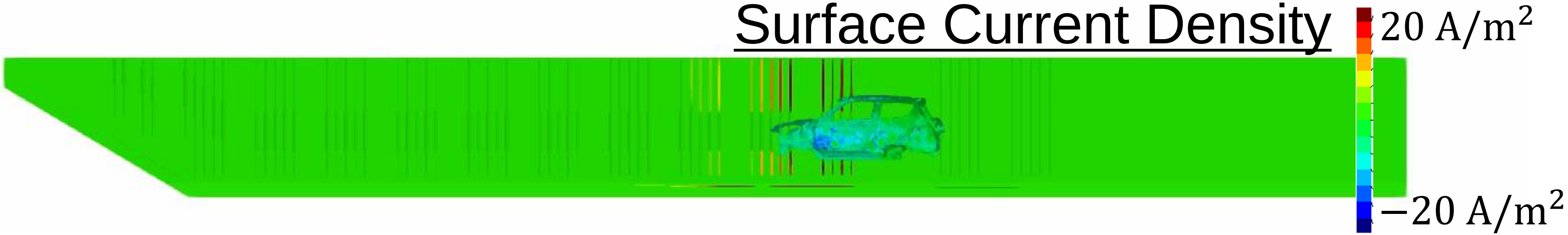
Film Thickness

You can see that the paint film starts to be deposited from the outside surface.

Surface Potential



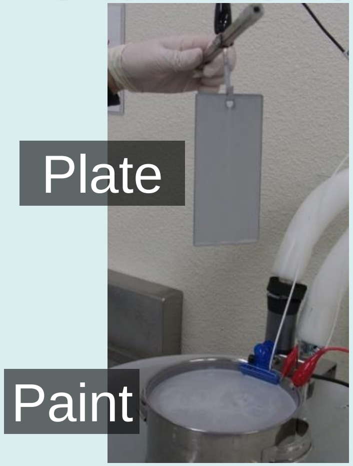
Surface Current Density

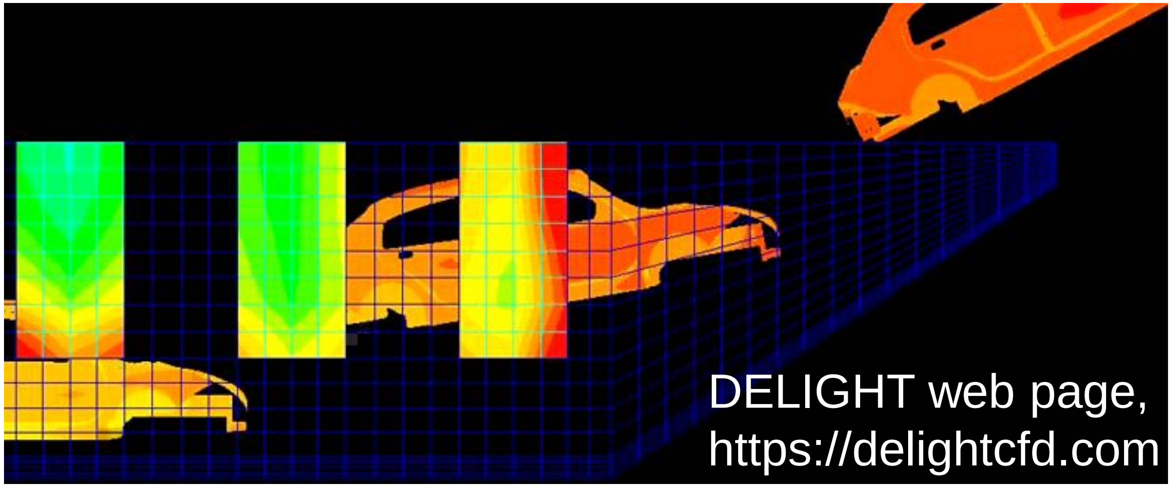


How to Develop an ED Simulator

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

One-Plate Test





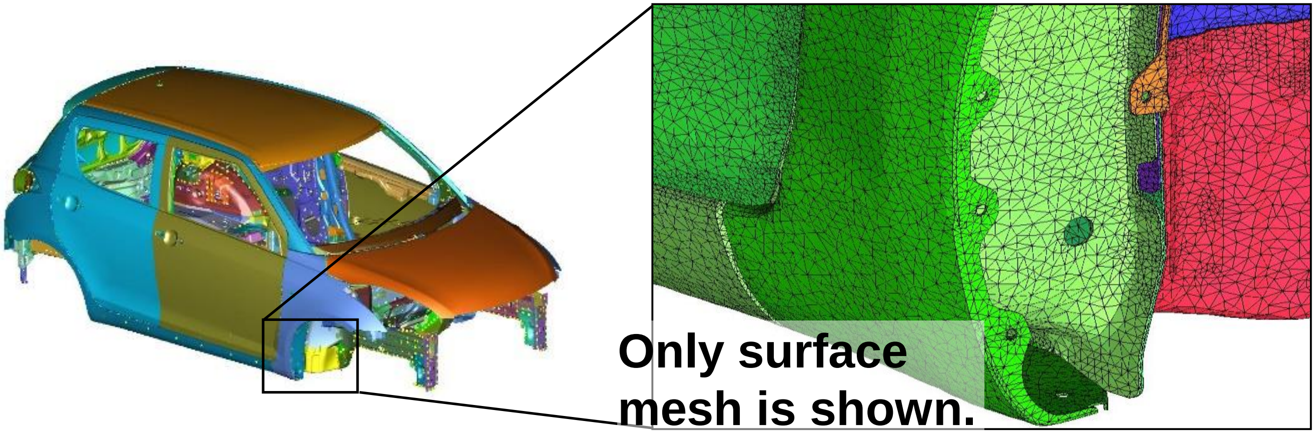
DELIGHT web page,
https://delightcfd.com

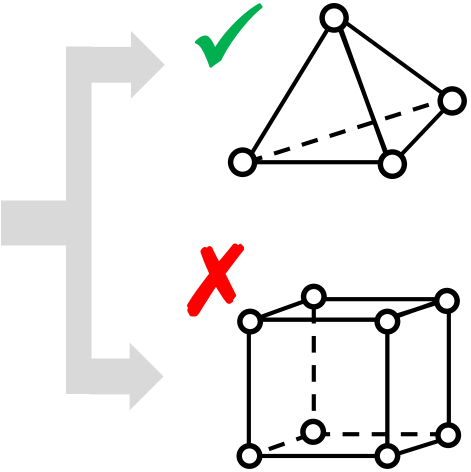
ED simulation for actual lines

On the analogy of solid mechanics,
Step 1: material tests with MTS,
Step 2: identification of elastoplastic model.

Issues in Meshing (1)

✗ It is difficult to discretize complex shapes such as car bodies with **hexahedral meshes**.





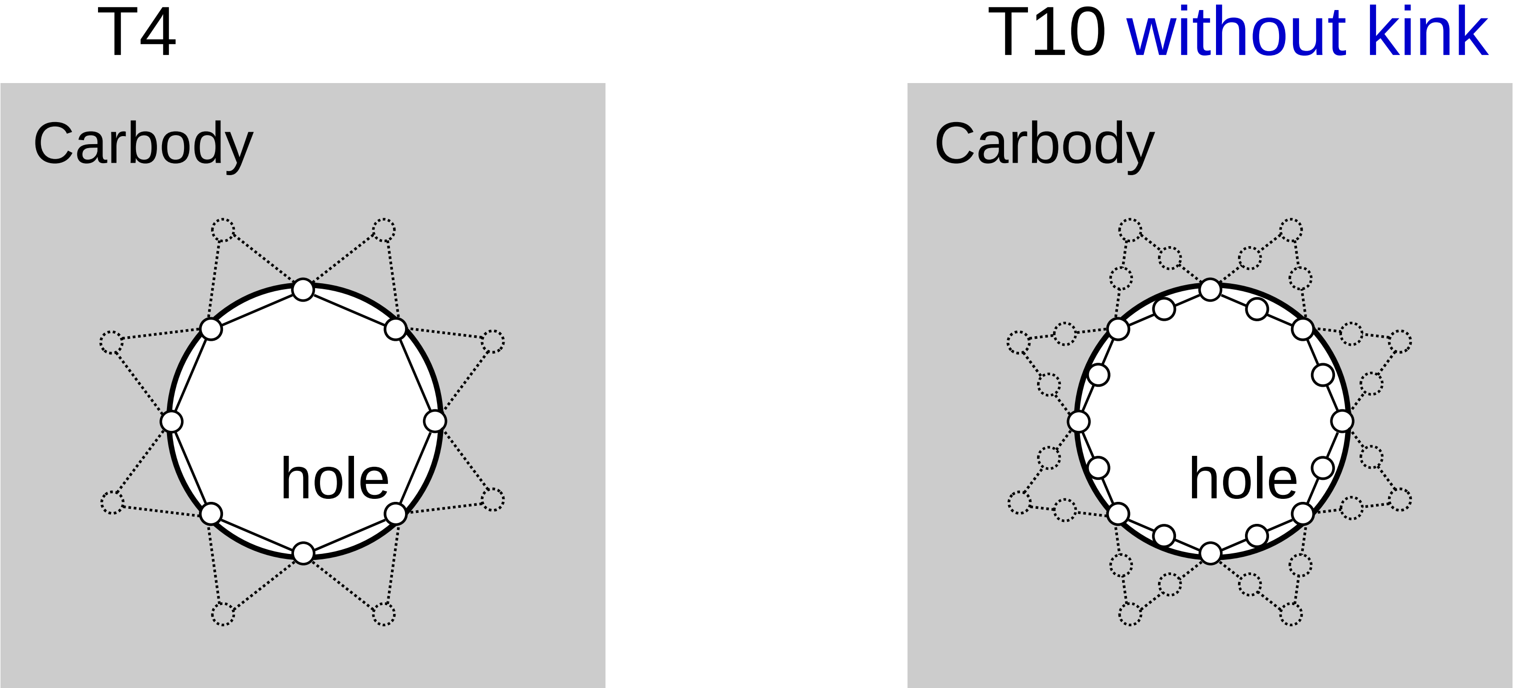
→ We have to use **tetrahedral meshes** in ED simulation.

However…

Accuracy of the standard FEM-T4 is insufficient in complex shapes.

Issues in Meshing (2)

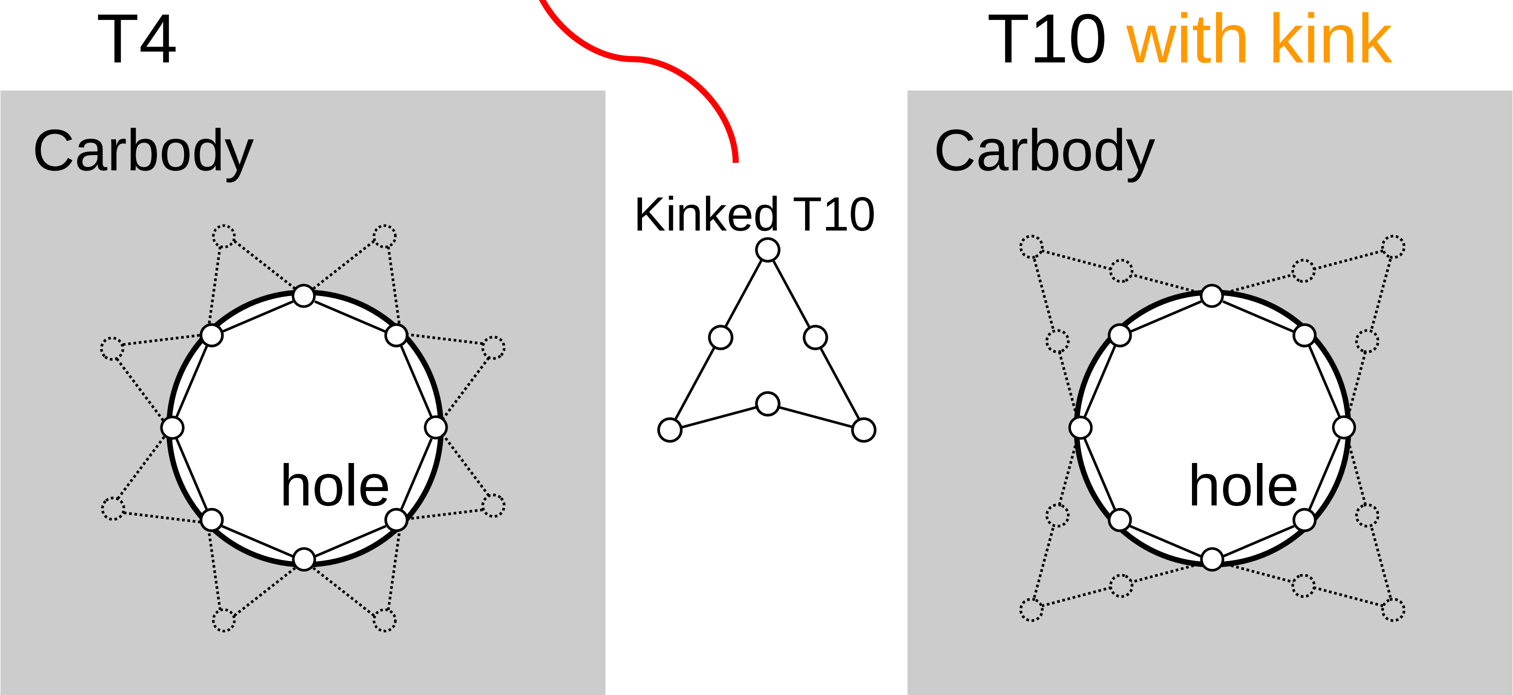
✗ **10-node tetrahedral** (T10) **mesh** without kink generally requires more large number of nodes than T4 mesh.



For the same shape representation, T10 mesh without kink leads to massive increase in DOF.

Issues in Meshing (2 Cont.)

✗ **10-node tetrahedral** (T10) **mesh** with kink causes severe accuracy loss.



T10 mesh with kink does not increase DOF
but induces severe accuracy loss.

Motivation

- Hexahedral elements:
  - ✗ It is difficult to discretize complex shapes.
- T10 elements without kink:
  - ✗ It leads to massive increase in DOF.
- T10 elements with kink:
  - ✗ It causes severe accuracy loss.

→ We want to realize high accuracy analysis with T4 mesh.

ES-FEM-T4 could be a solution to these issues.

Objective

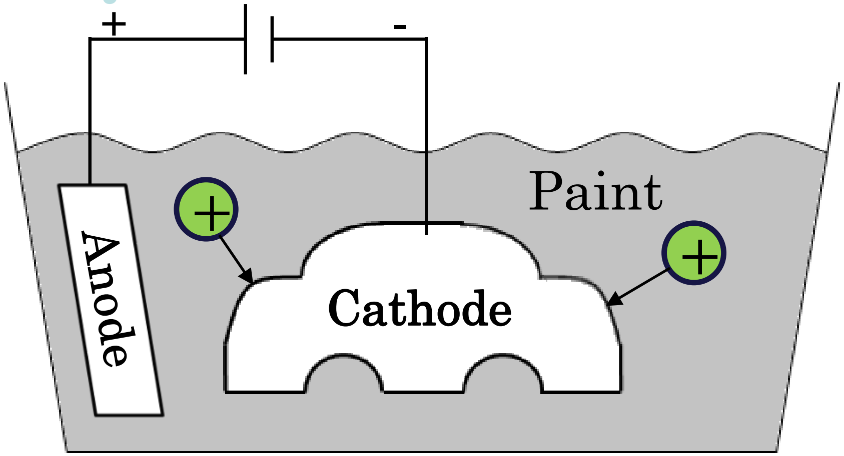
Development of ED simulator using ES-FEM-T4
and its performance evaluation
by comparing with FEM-T4.

Table of body contents:

1. Outline of ED Simulation
2. Formulation of ES-FEM for ED Simulation
3. Analysis Results

Outline of ED Simulation

Fundamental Equations



Governing equation

The electrostatic Laplace equation

$\nabla^2\phi = 0$, in the paint pool domain

Boundary conditions (BCs)

1. Insulation BC
2. Anodic (Electrode surface) BC
3. Cathodic (Carbody surface) BC

ED boundary models are identified with experimental data at a laboratory.

Solving the Laplace equation for potential, the current density distribution on a carbody is determined and then the film thickness distribution is time-evolutionally calculated.

Two Complexities of ED Phenomena

Two nonlinearities in ED boundary model

Our ED boundary model consists of 2 sub-models:

1. Film resistance model

   Film resistance R is NOT linear to film thickness h:

   $$R \neq \alpha\, h$$

   R: resistance, α: const., h: film thickness.

2. Film growth model

   Film growth rate $\dot{h}$ is NOT linear to current density j:

   $$\dot{h} \neq \beta\, j$$

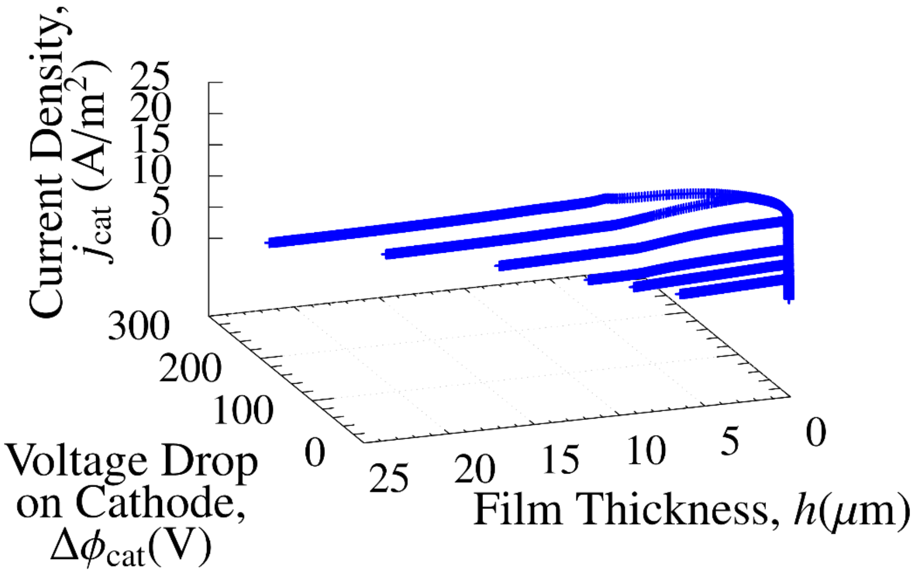
   $\dot{h}$: film growth rate, β: const., j: current density.

Procedure to Identify Film Resistance Model

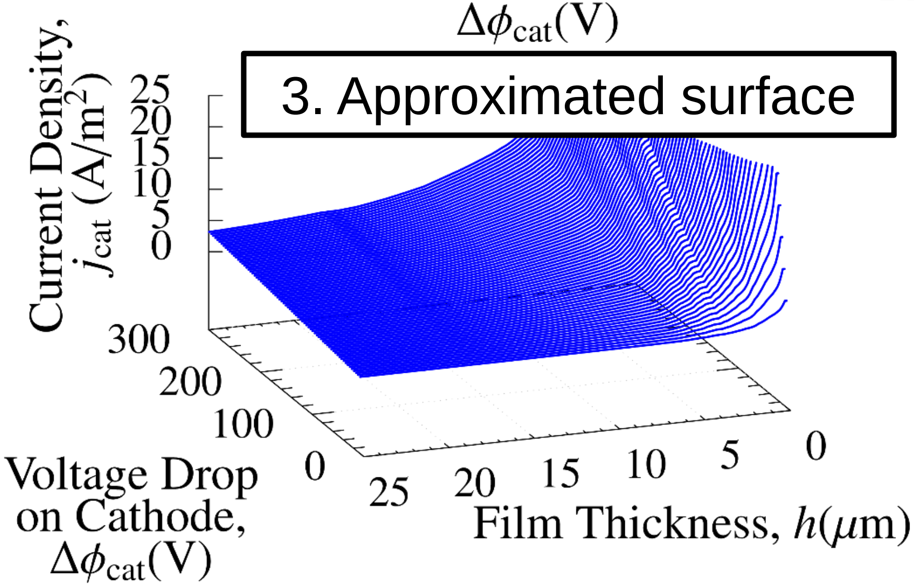
1. One-plate tests

Plot

2. Scatter diagram of $\Delta\phi_{\mathrm{cat}}, j_{\mathrm{cat}}$ and h



3. Approximated surface



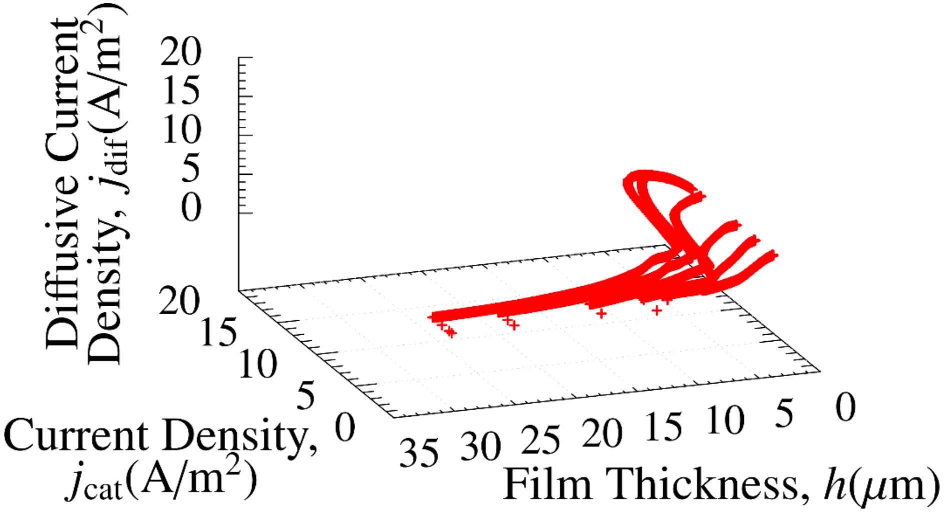
Data fitting

Procedure to Identify Film Growth Model

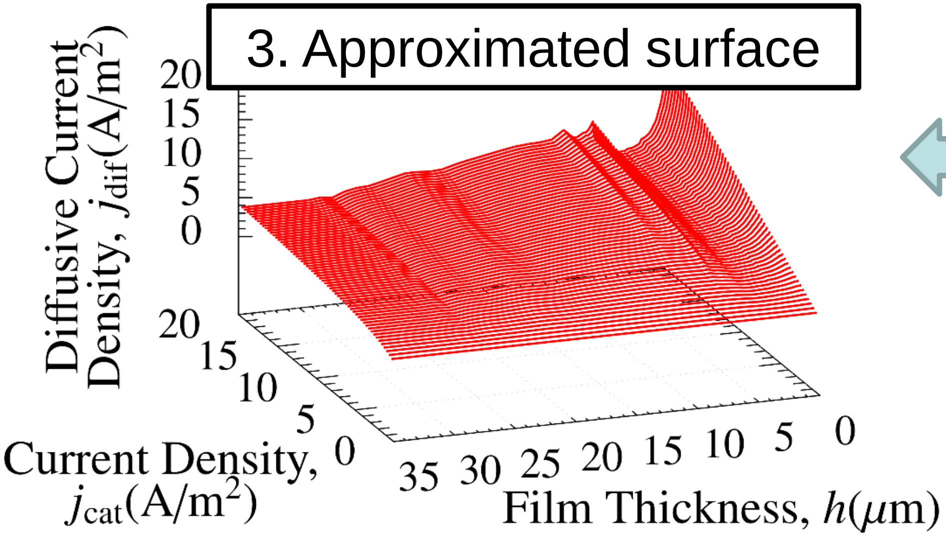
1. One-plate tests

Plot

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



3. Approximated surface



Data fitting

Diffusive current density represents the amount of electricity consumed for the electrolysis of water, not used for the deposition of the coating film.

Formulation of ES-FEM for ED Simulation

Outline of ES-FEM

What is ES-FEM-T4?

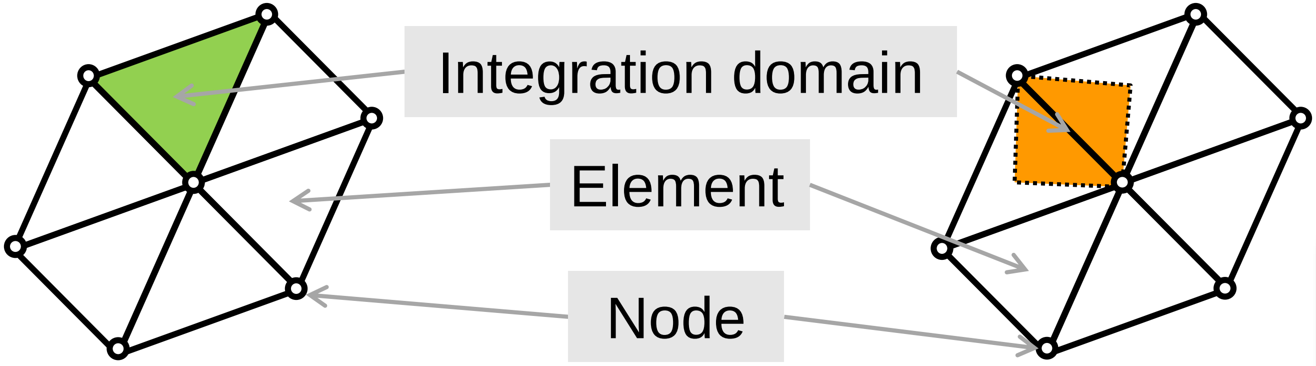
- A kind of strain smoothing method.
- Using element edges as Gauss points.
- Robust against element skew.
- Super-linear mesh convergence rate with T4 mesh.

Standard FEM

FEM assembles
each element's value.

ES-FEM

ES-FEM assembles
each edge's value.



Integration
domain is
different !!

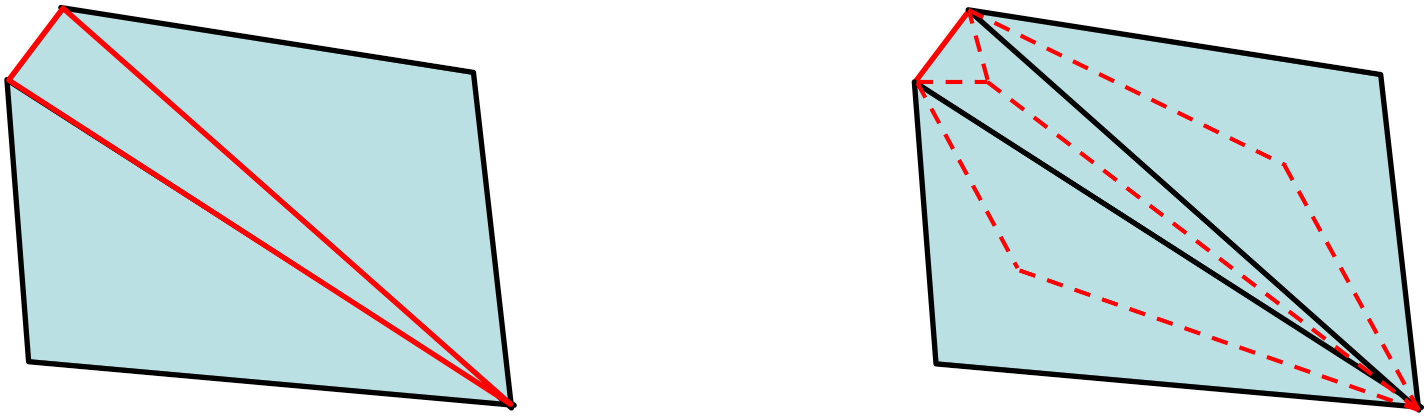
Outline of ES-FEM

Short edges

- When meshing complex shape, the generation of short edges is inevitable.
- Short edges lead to accuracy loss in standard FEM-T4.

Conventional FEM

ES-FEM

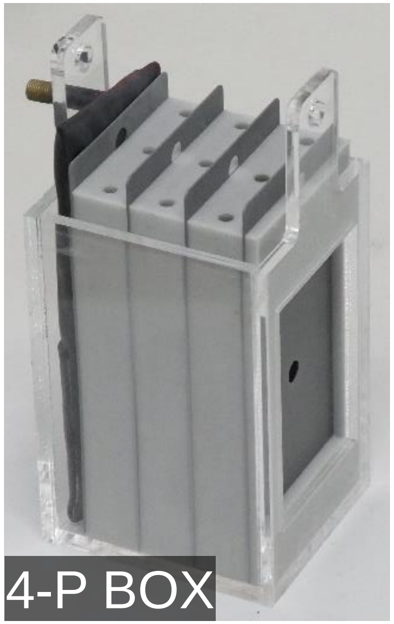


ES-FEM can suppress the accuracy loss by smoothing.

Analysis Results

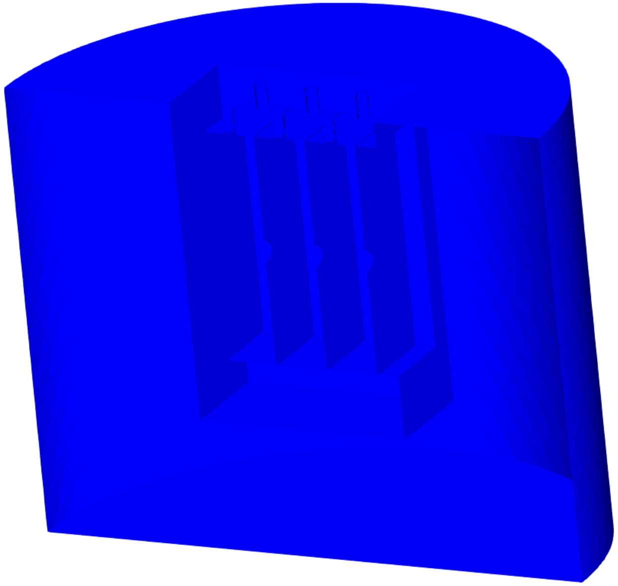
4-Plate BOX Simulation

Outline



(http://plaza.rakuten.co.jp/heroc)

Film Thickness

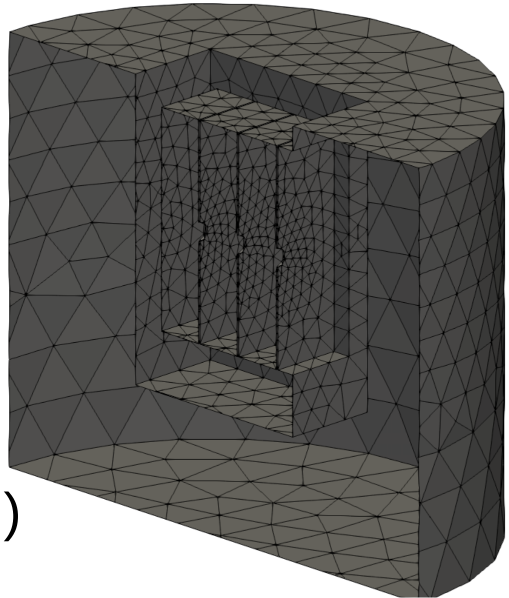


- Imitating a bag-like structure such as side sill in a carbody.
- Accuracy on the innermost surface (leftmost plate surface) is the most important; i.e., “maximize the minimum”.
- Film thickness is calculated with 4 different mesh seed sizes and compared between FEM-T4 and ES-FEM-T4.

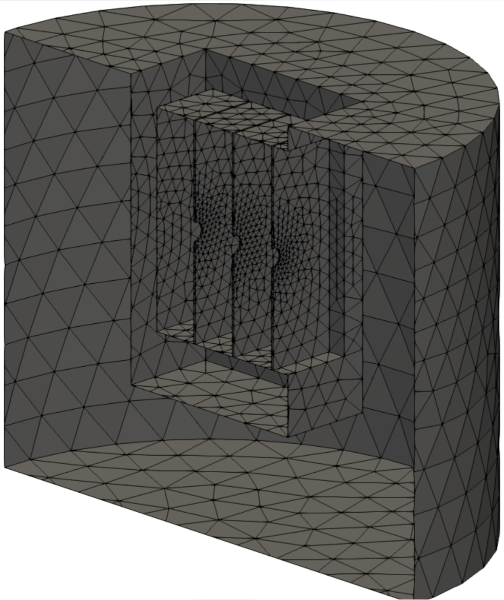
4-Plate BOX Simulation

Overview of Meshes

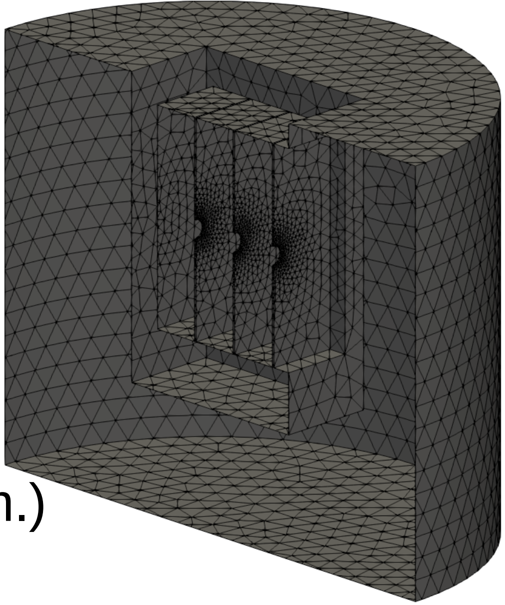
Only the surface meshes are shown.



3.2 mm Mesh
Seed Size
(31k T4 elem.)



1.6 mm Mesh
Seed Size
(65k T4 elem.)

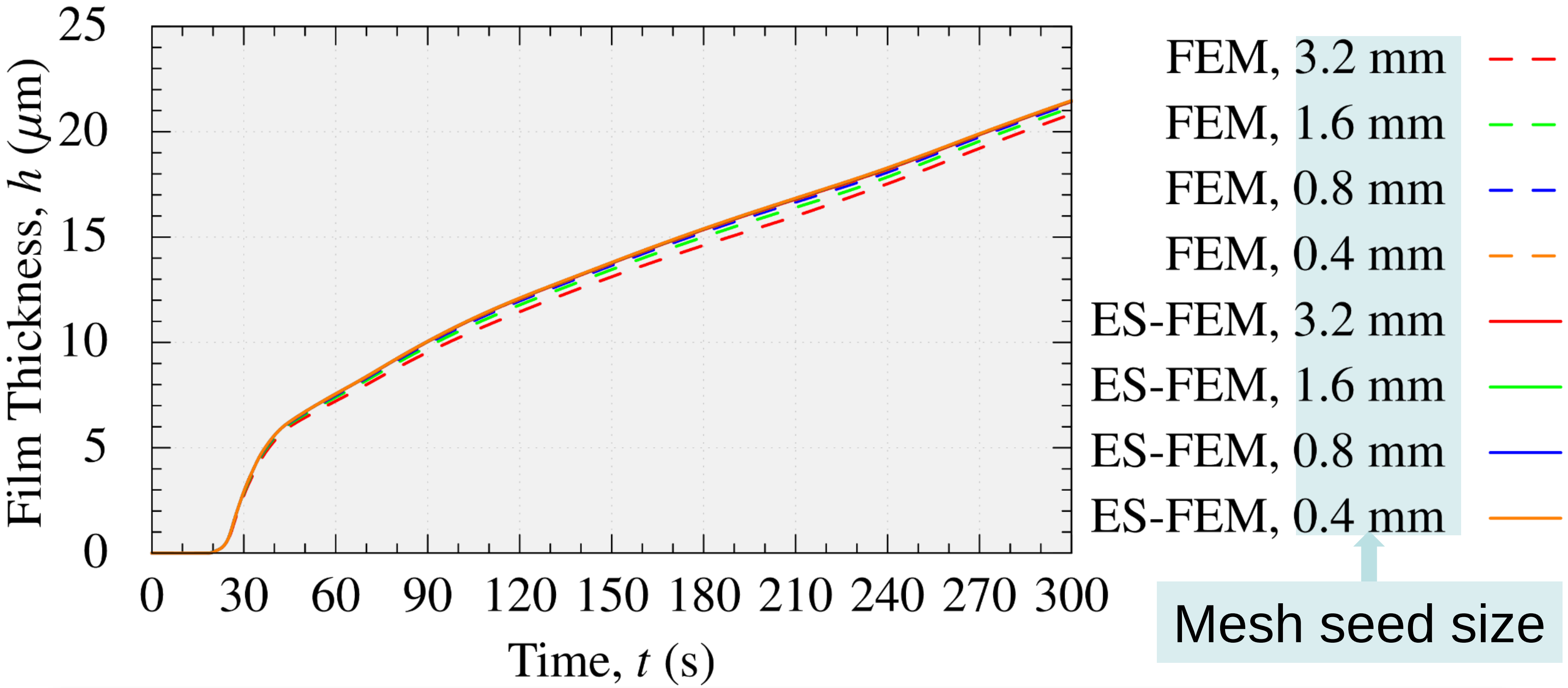


0.8 mm Mesh
Seed Size
(169k T4 elem.)

0.4 mm Mesh
Seed Size
(716k T4 elem.)

4-Plate BOX Simulation

Film Thickness of A-Plate (outermost surface)

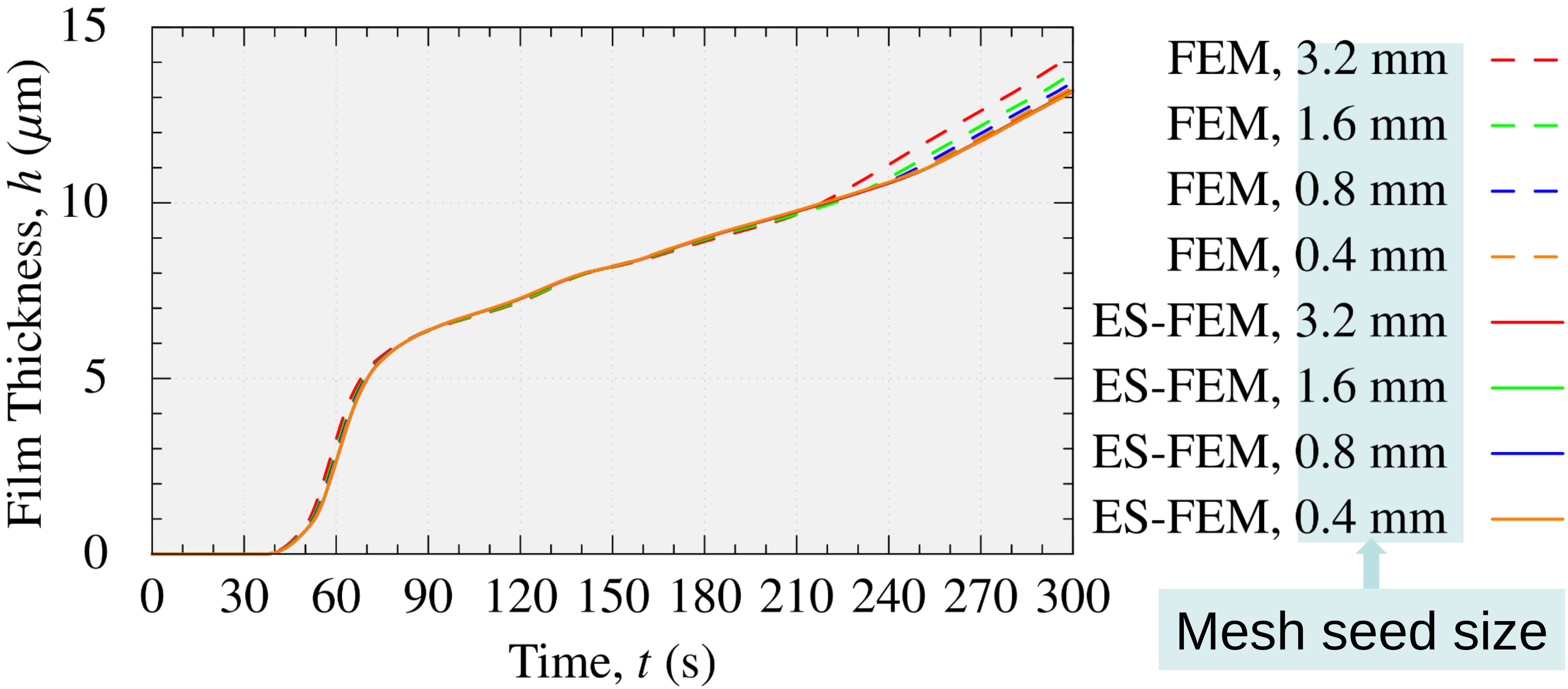


Mesh seed size

FEM results (dashed lines) have ***tiny*** errors due to mesh coarseness. Meanwhile, ES-FEM (solid lines) results have no such errors.

4-Plate BOX Simulation

Film Thickness of C-Plate (surface in the 1st bag)

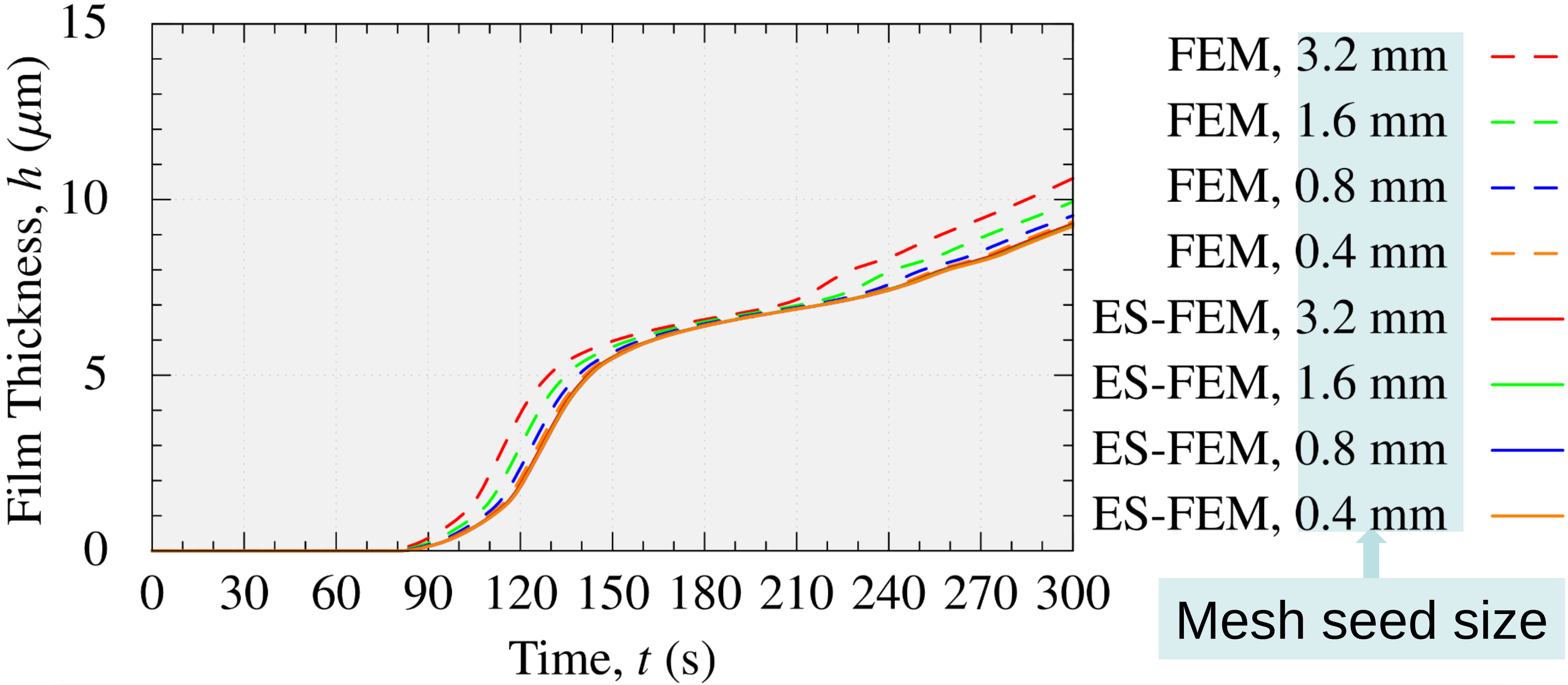


Mesh seed size

FEM results (dashed lines) have ***small*** errors
due to mesh coarseness.
Meanwhile, ES-FEM (solid lines) results have no such errors.

4-Plate BOX Simulation

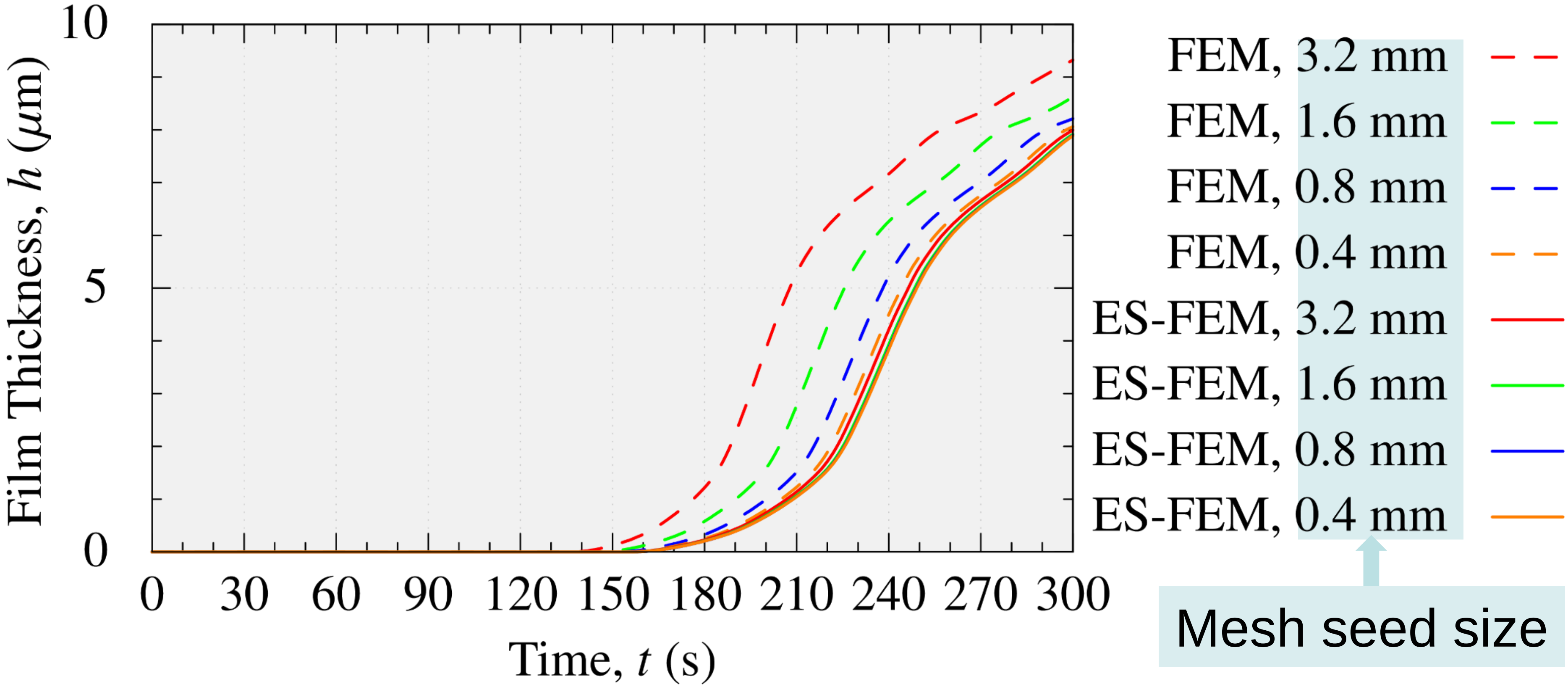
Film Thickness of E-Plate (surface in the 2nd bag)



FEM results (dashed lines) have ***medium*** errors due to mesh coarseness.
Meanwhile, ES-FEM (solid lines) results have no such errors.

4-Plate BOX Simulation

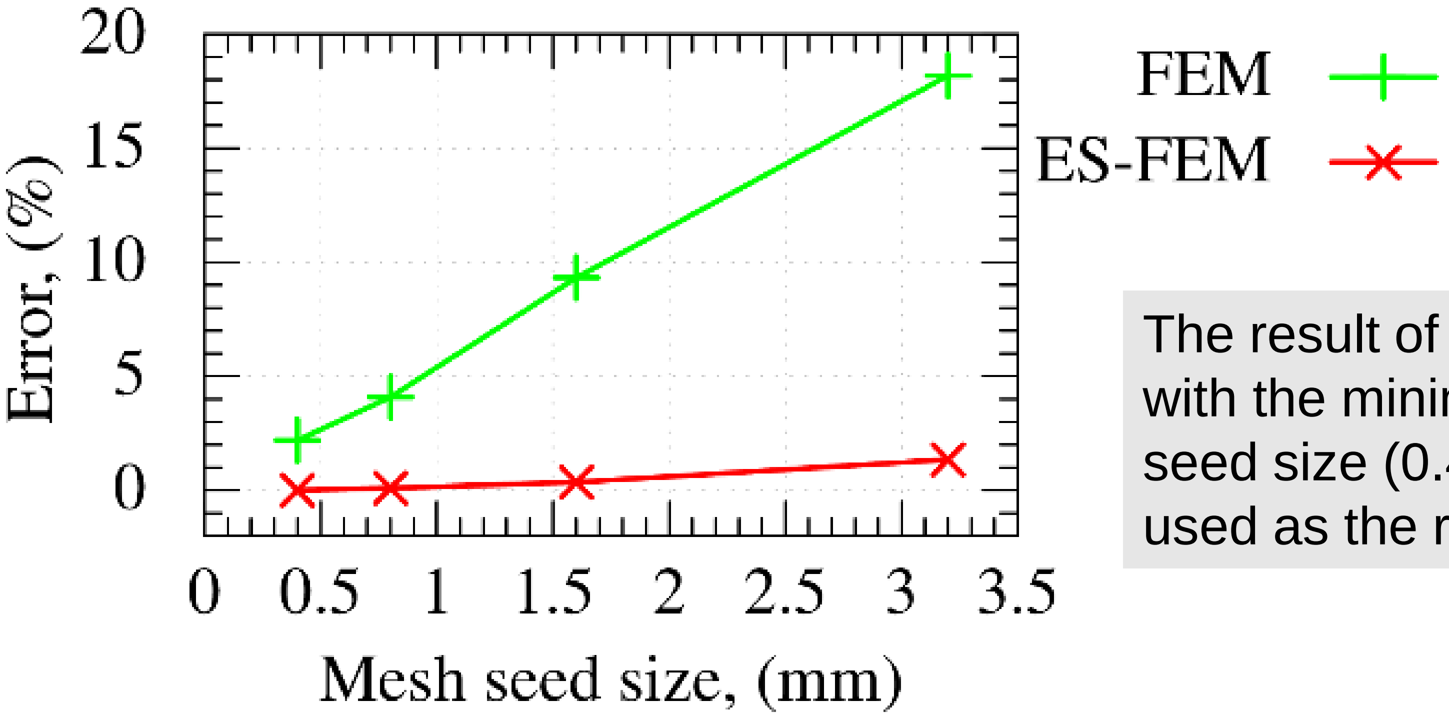
Film Thickness of G-Plate (innermost surface)



FEM results (dashed lines) have ***large*** errors
due to mesh coarseness.
Meanwhile, ES-FEM (solid lines) results have no such errors.

4-Plate BOX Simulation

Error of Final Film Thickness on G-Plate

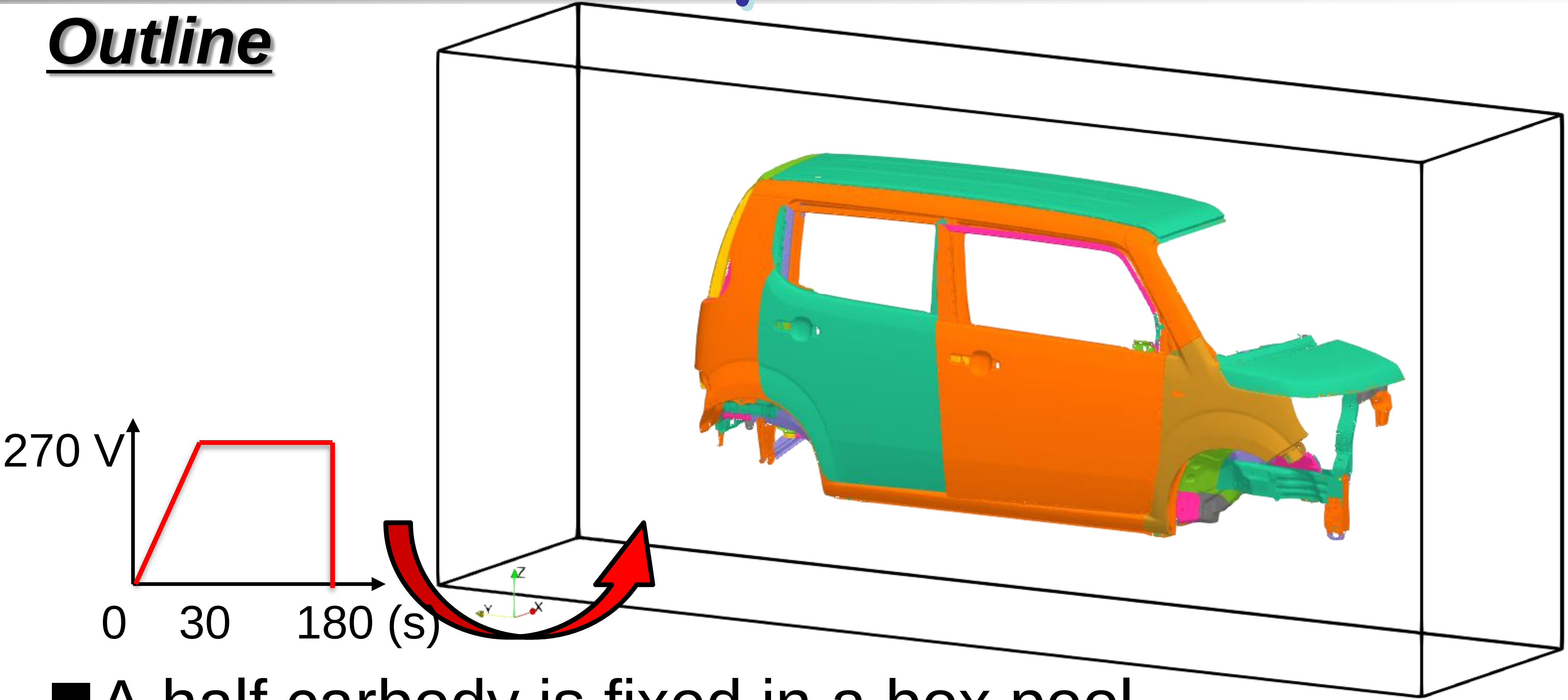


The result of ES-FEM with the minimum mesh seed size (0.4 mm) is used as the reference.

ES-FEM-T4 has far better mesh convergence rate than FEM-T4 !!

Carbody Simulation

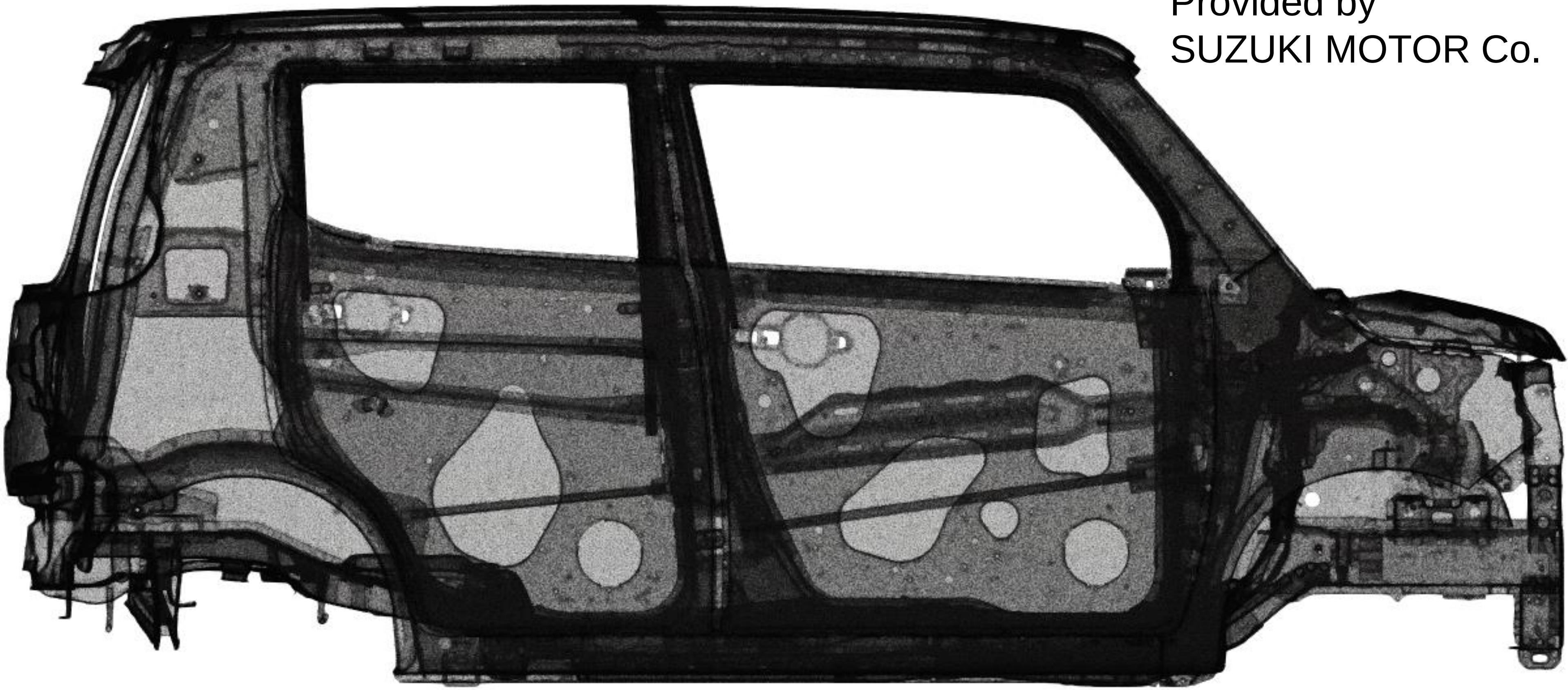
Outline



- A half carbody is fixed in a box pool.
- The side wall is treated as an anode surface.
- Compare the time-developed film thickness between FEM-T4 and ES-FEM-T4 with a same mesh.

Carbody Simulation

Overview of Surface Mesh

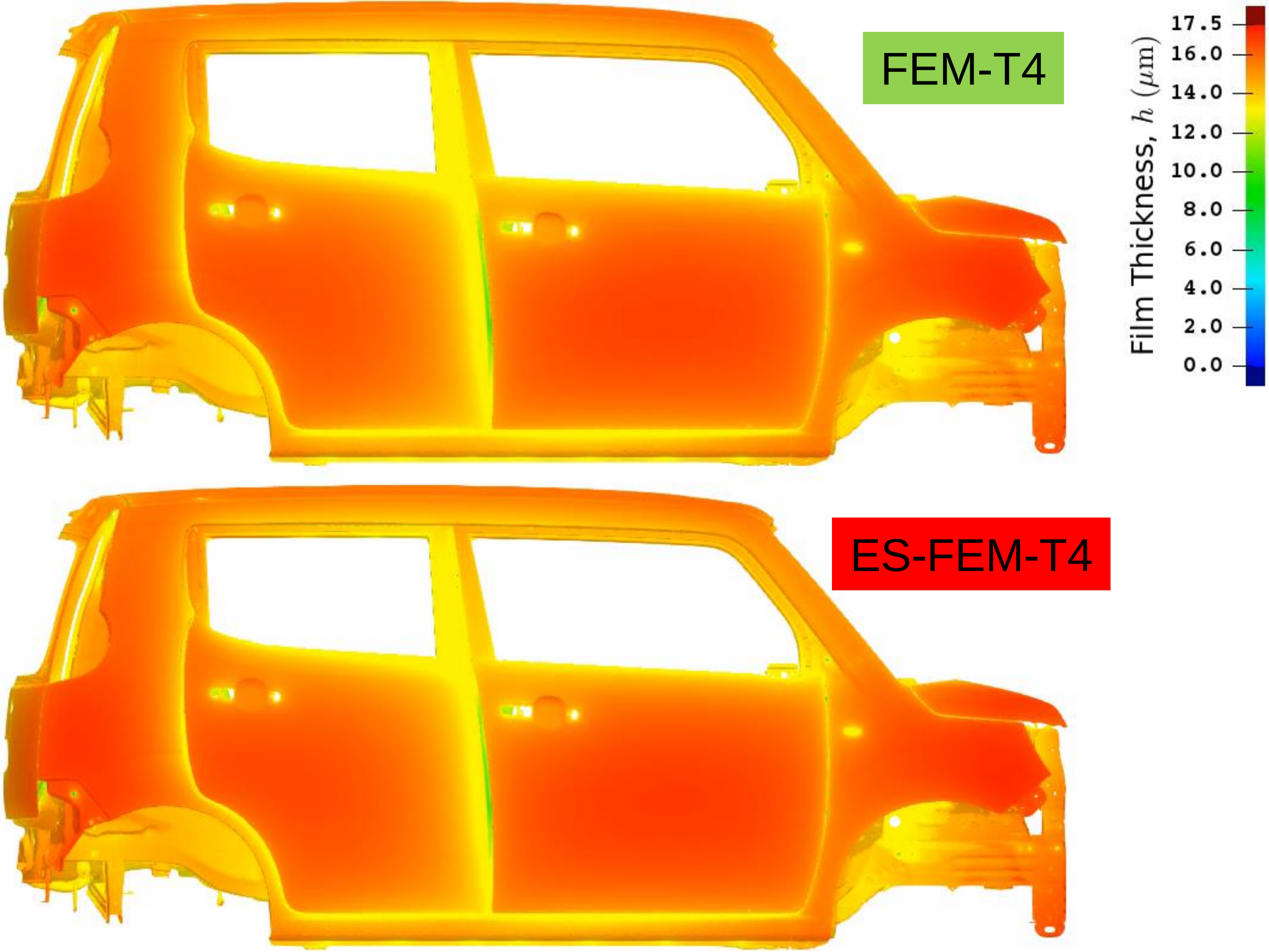


Provided by
SUZUKI MOTOR Co.

- 13M T4 elements (3M nodes & 18M edges) in total in the pool.

Carbody Simulation

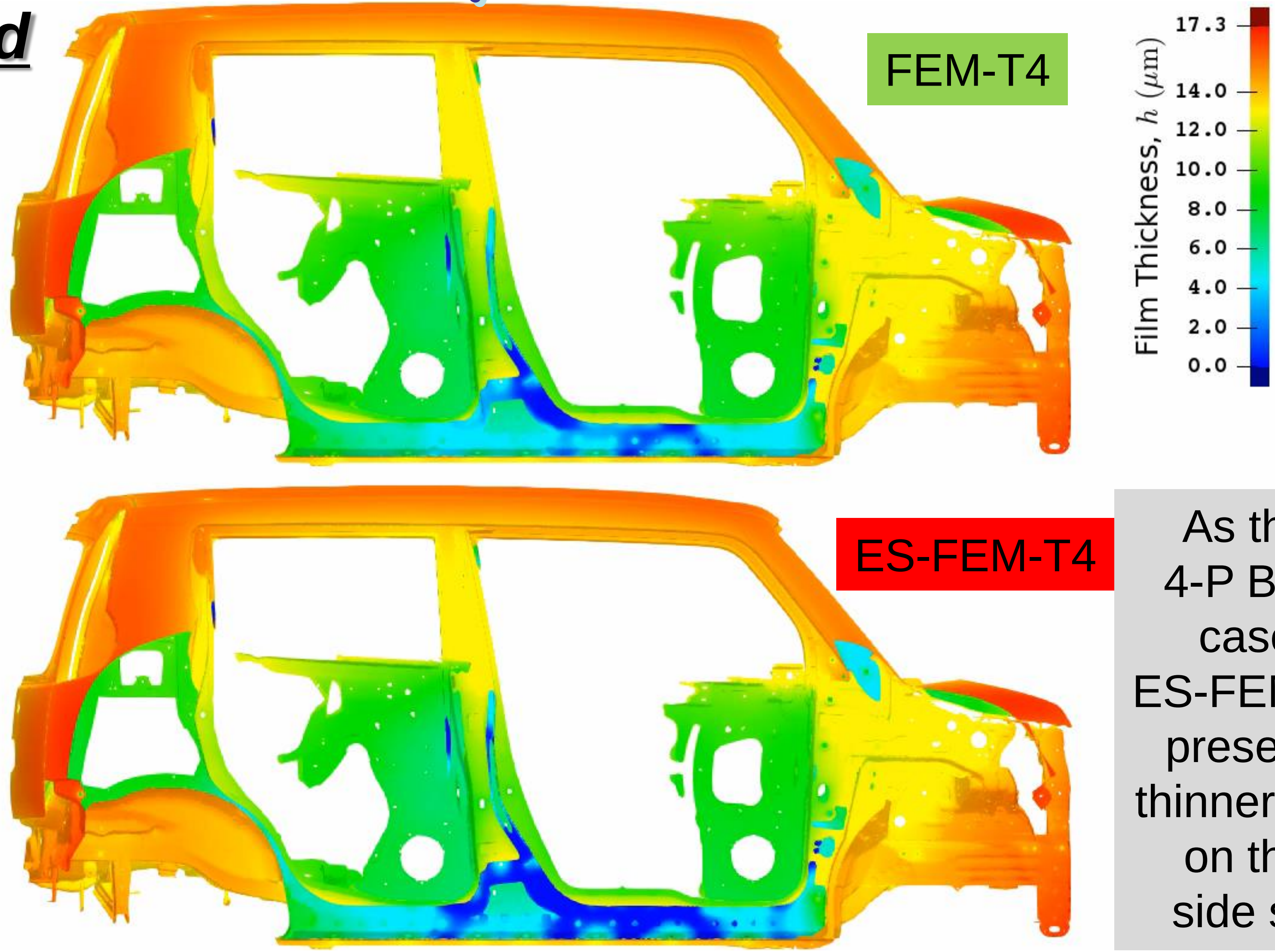
Outer View



There is no mush difference on the outer surfaces.

Carbody Simulation

Clipped View on Side Sill



As the 4-P BOX case, ES-FEM-T4 presents thinner dist. on the side sill.

Big difference appears on the inner surfaces.

Comparison of Computational Costs

Calculation Time

on a PC with Intel i9-9960X using 10 cores

	FEM-T4	ES-FEM-T4
4-P BOX with 3.2 mm mesh	0.02 h	0.02 h
4-P BOX with 1.6 mm mesh	0.04 h	0.05 h
4-P BOX with 0.8 mm mesh	0.45 h	0.45 h
4-P BOX with 0.4 mm mesh	9.5 h	9.0 h
Carbody	67 h	125 h

Same Accuracy

There is no big difference in calculation time although the accuracy of ES-FEM-T4 is much better.

Summary

Summary

Conclusion

- ES-FEM-T4 was applied to ED simulations.
- High accuracy of ES-FEM-T4 because of its super-linear mesh convergence rate was confirmed in comparison to the poor accuracy of FEM-T4.

Future Works

- Validation of the ED models on the actual manufacturing lines.
- Calculation speed-up with distributed memory parallelization.

Thank you for your kind attention.

Appendix

ED Boundary Models

Film Resistance Model

- It represents the relation between $\mathrm{h}, \Delta\phi_{\mathrm{cat}}$ and j_{cat}.
- Used to decide film resistance.
- Flow rate dependency is considered.

$$j_{\mathrm{cat}}(\Delta\phi_{\mathrm{cat}}, h) = \begin{cases} c_1(h)\Delta\phi_{\mathrm{cat}} & : \text{With stirring} \\ c_1(h)\left(e^{c_2(h)\Delta\phi_{\mathrm{cat}}} - e^{-c_2(h)\Delta\phi_{\mathrm{cat}}}\right) & : \text{Without stirring} \end{cases}$$

Film Growth Model

- It represents the relation between $\mathrm{h}, j_{\mathrm{cat}}$ and j_{dif}.
- Used to decide film growth rate.

After deposition : $j_{\mathrm{difA}}(j_{\mathrm{cat}}, h) = \dfrac{(j_{\mathrm{cat}}+d_1(h))^{d_2(h)}}{d_1^{d_2(h)-1} d_2(h)} - \dfrac{d_1(h)}{d_2(h)}$

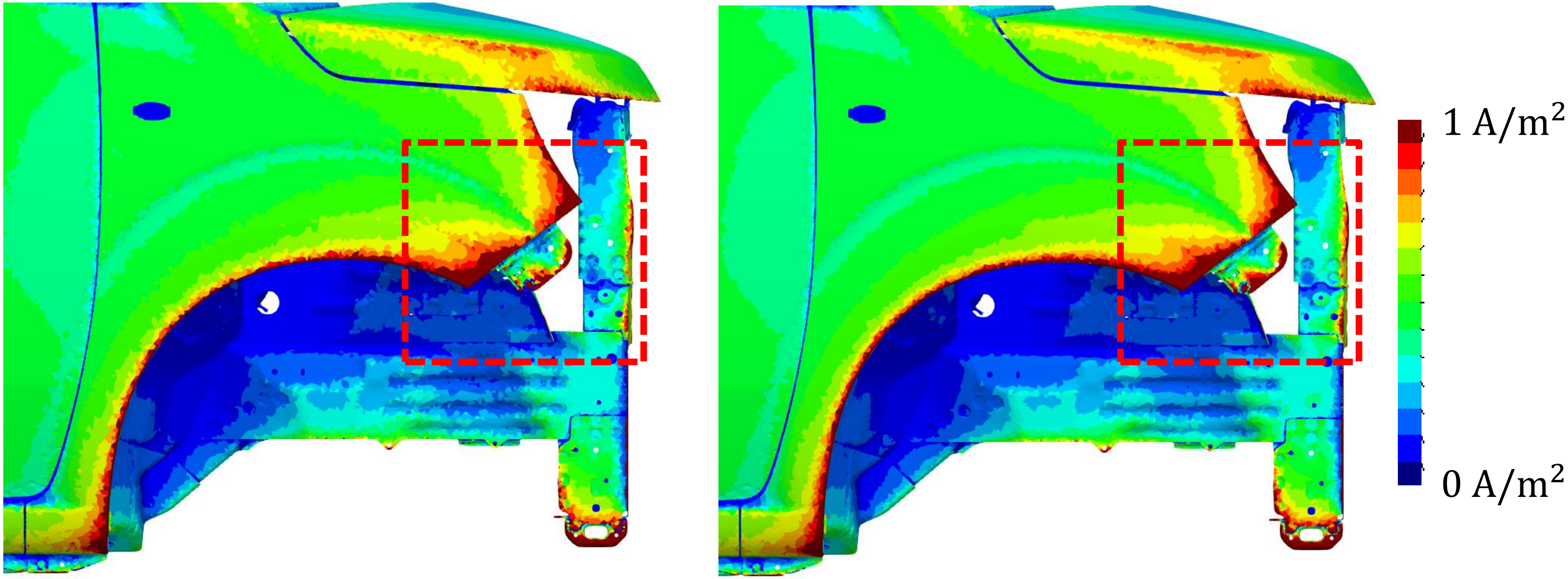
Comparison of Computational Costs

This is because …

- Most of the calculation time is consumed by the iterative matrix solver (MINRES with Jacobi preconditioner).
- The matrix band width of ES-FEM-T4 is 3 times wider than that of FEM-T4; i.e., ES-FEM-T4 requires 3 times larger memory size.
- However, the iteration count of MINRES in ES-FEM-T4 is about 1/3 or 2/3 of that in FEM-T4 thanks to the well-posedness of the matrix.

Carbody Simulation

Surface Current Density



FEM-T4

ES-FEM-T4

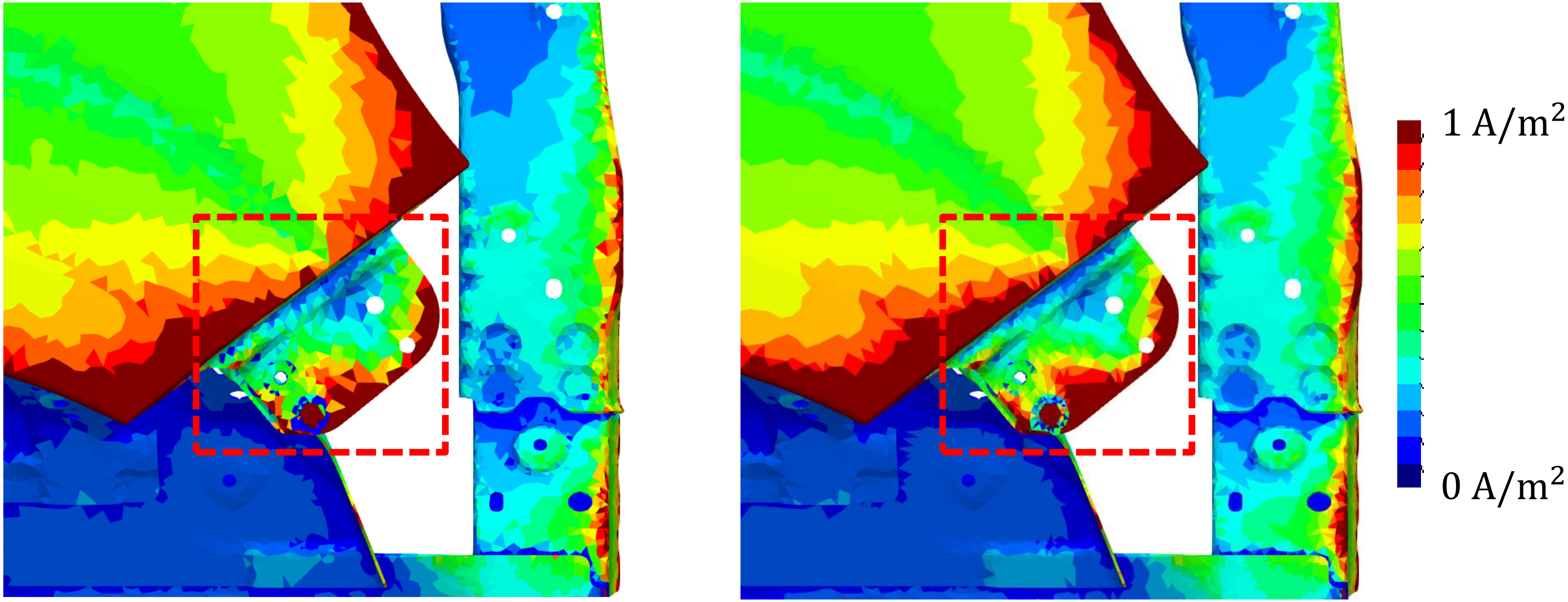
ES-FEM suppresses the spike error
of surface current density appearing in FEM.

Carbody Simulation

Surface Current Density

FEM-T4

ES-FEM-T4



ES-FEM suppresses the spike error
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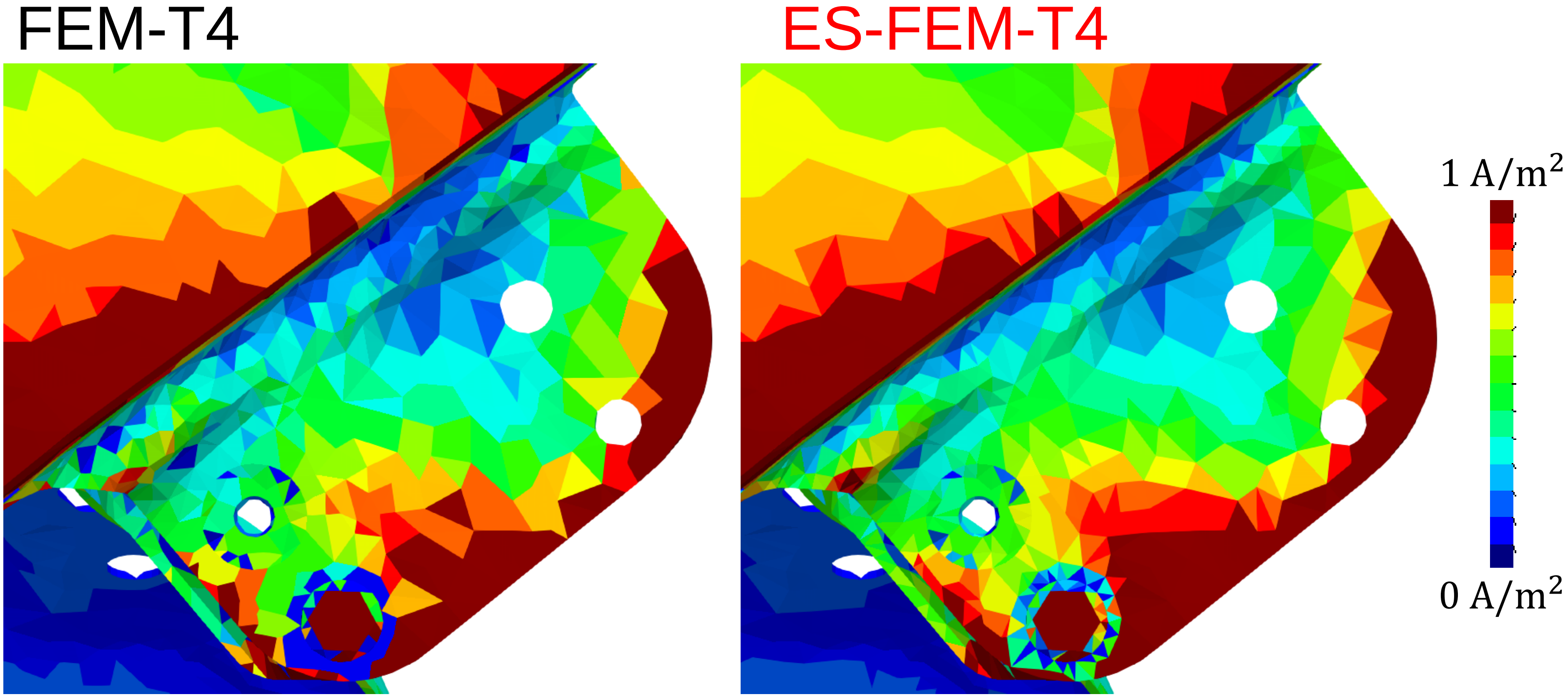
Carbody Simulation

Surface Current Density



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