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

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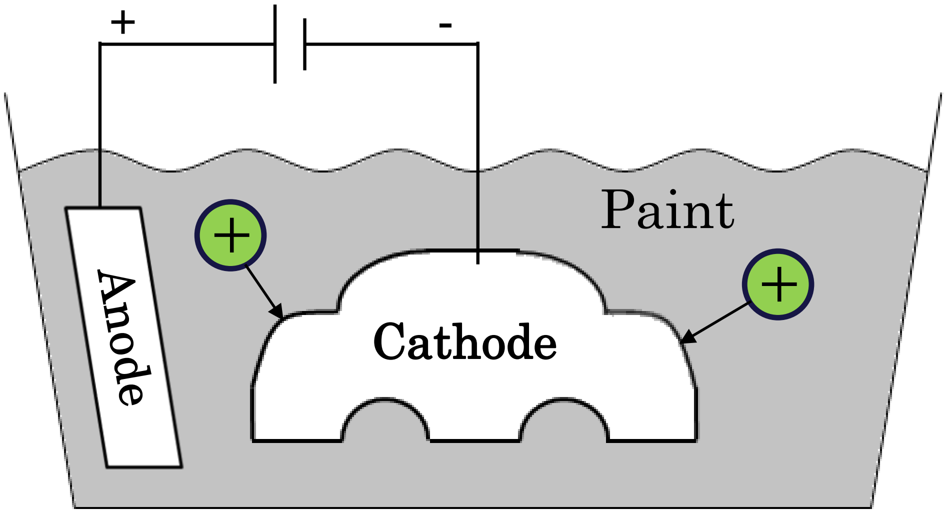
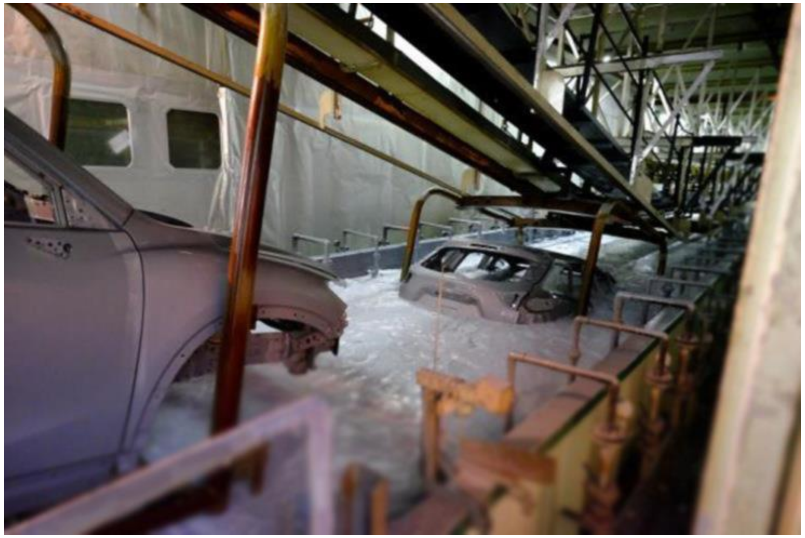
What is electrodeposition (ED) ?



- Most widely-used basecoat methods for car bodies.
- Making coating 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



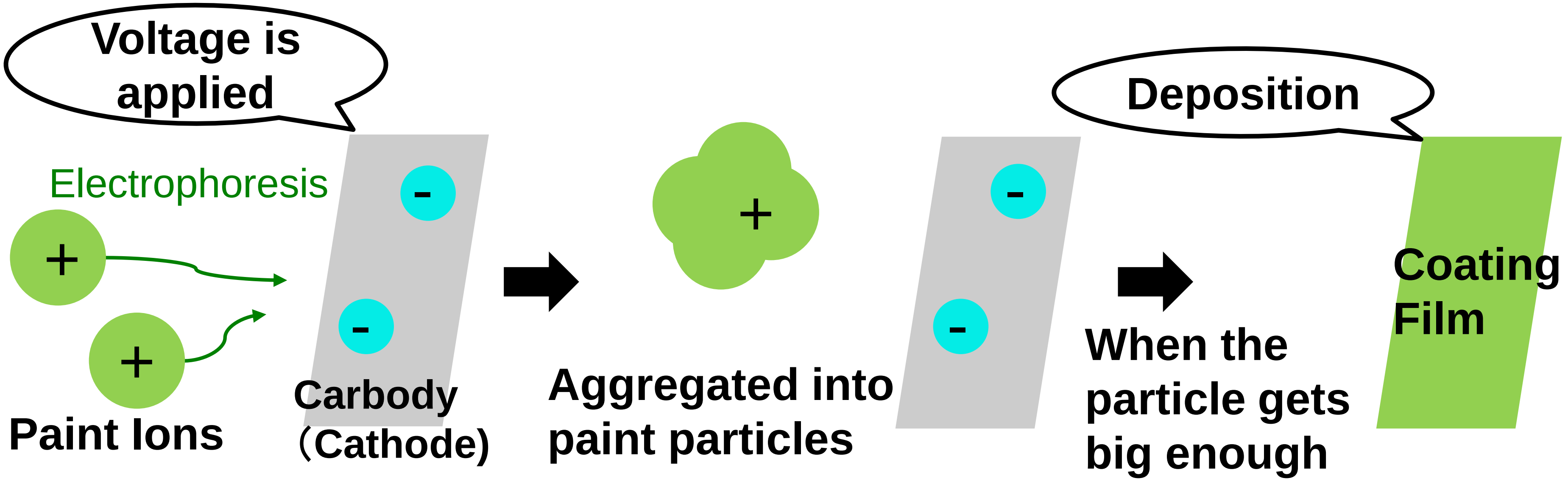
1. dipping and deposition process

2. water rinse process

We focus on this process.

3. baking process

Mechanism of Electrodeposition

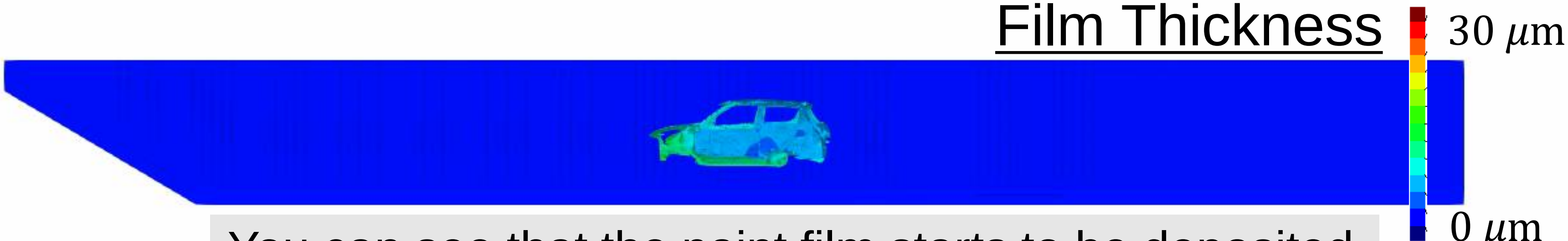


- **Positively charged** paint ions are attracted to the cathode.
- Paint ions gradually lose their electrical charge and **are aggregated into paint particles**.
- Some of the paint particles **diffuse and dissolve**.

What is ED Simulation ?

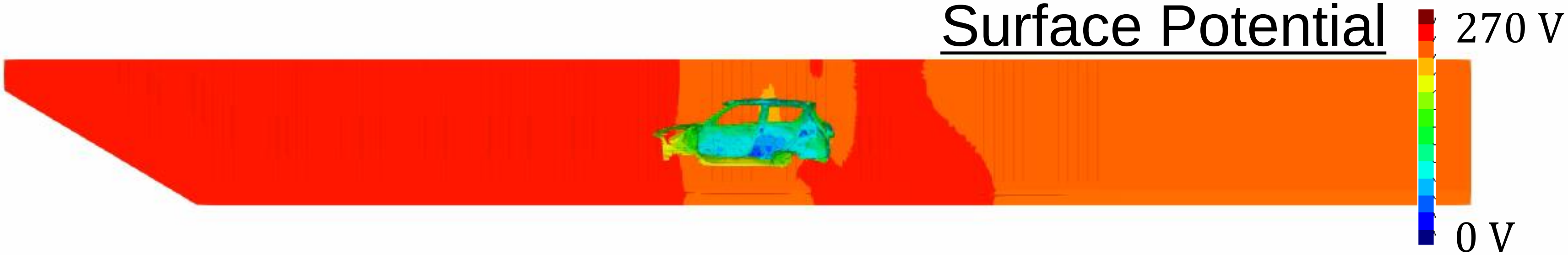
ED simulation provides film thickness, surface potential, surface current density and so on.

Film Thickness

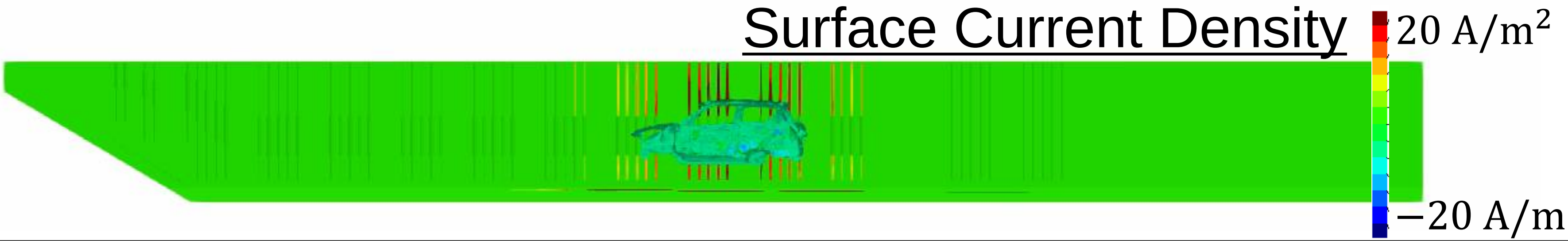


You can see that the paint film starts to be deposited from the outside surface.

Surface Potential



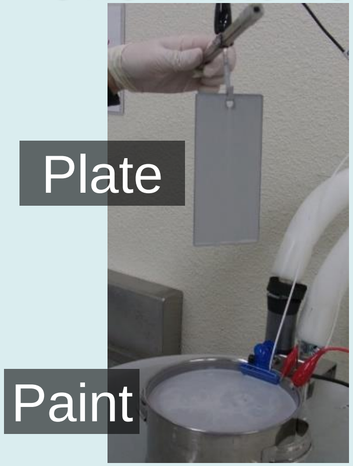
Surface Current Density

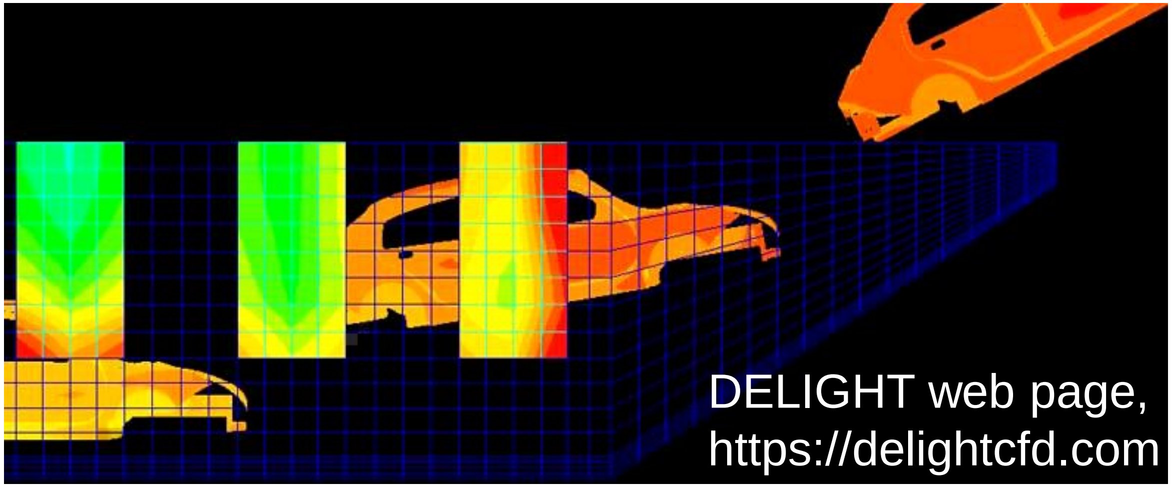


How to Develop an ED Simulator

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



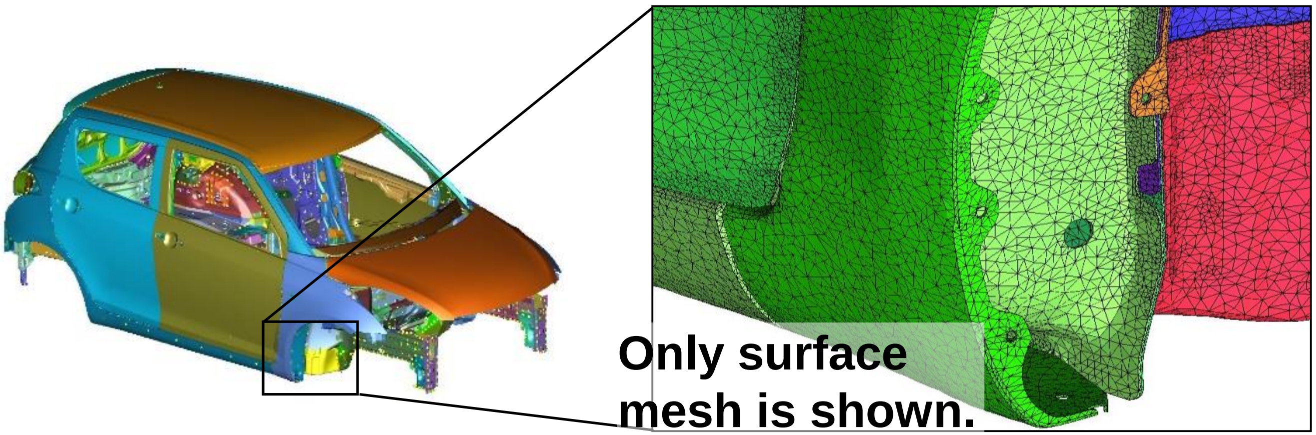


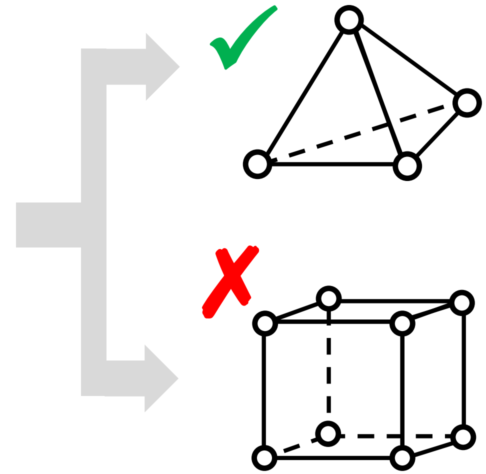
ED simulation for actual lines

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.

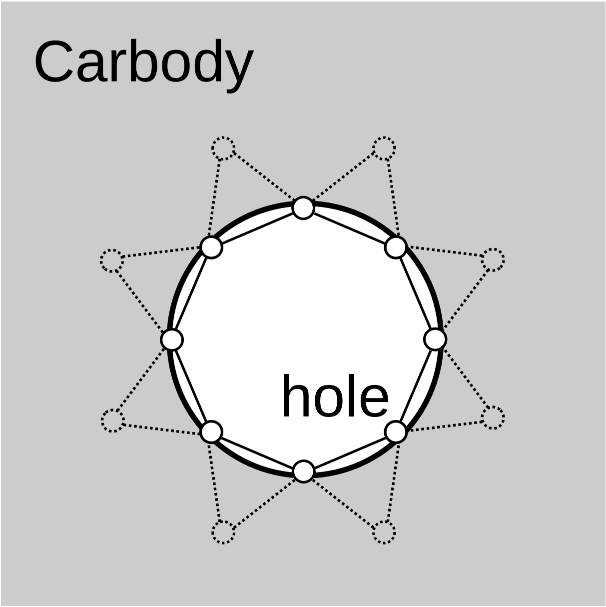
However…

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

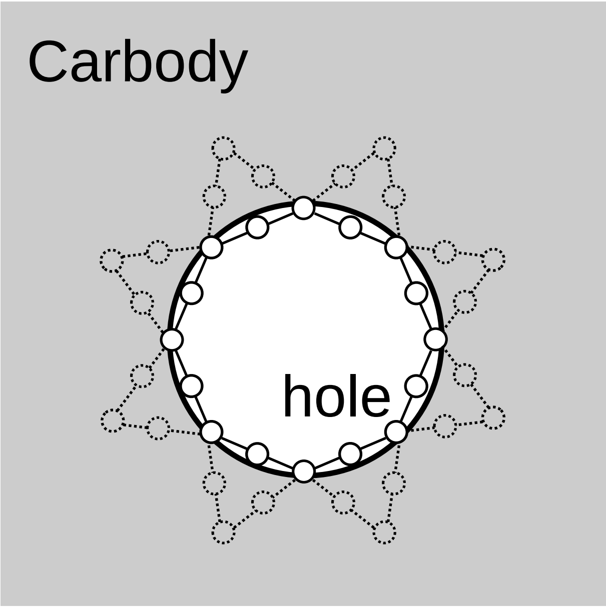
Issues in Meshing (2)

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

T4



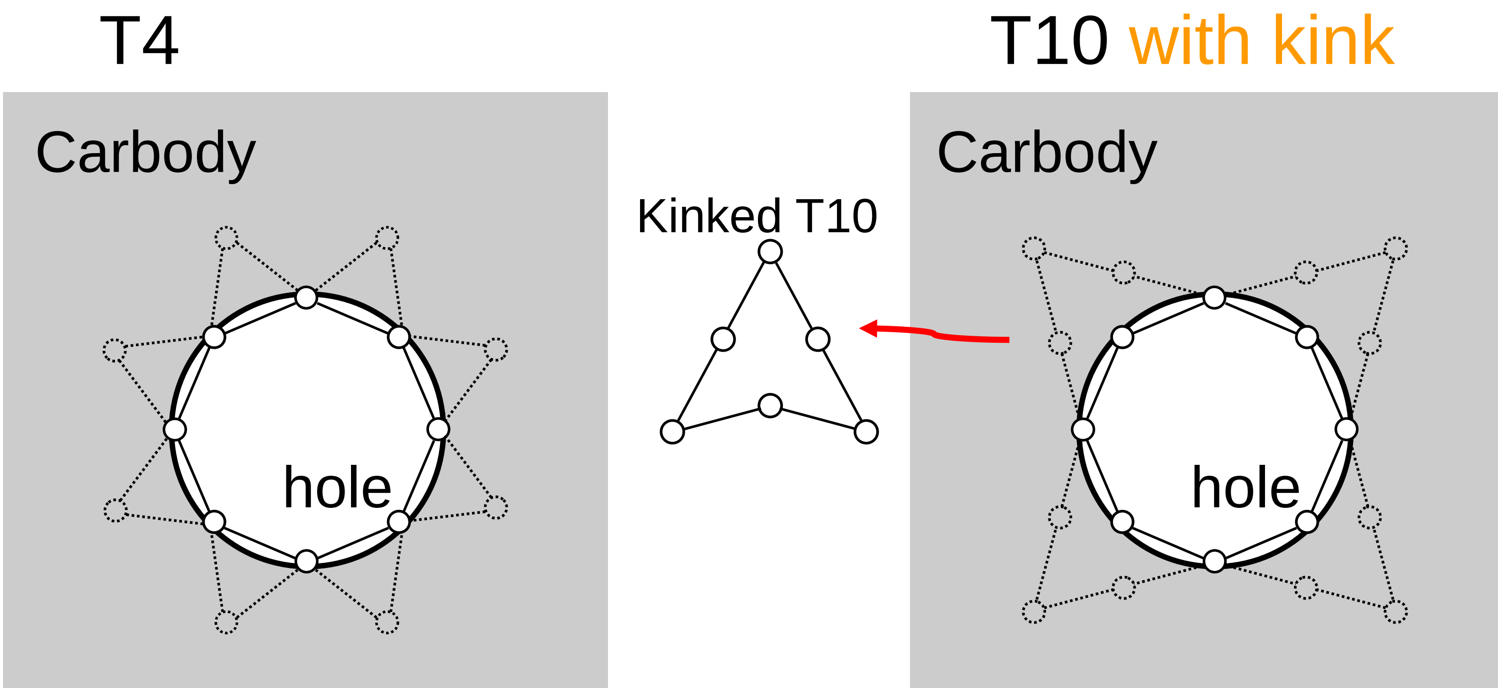
T10 without kink



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

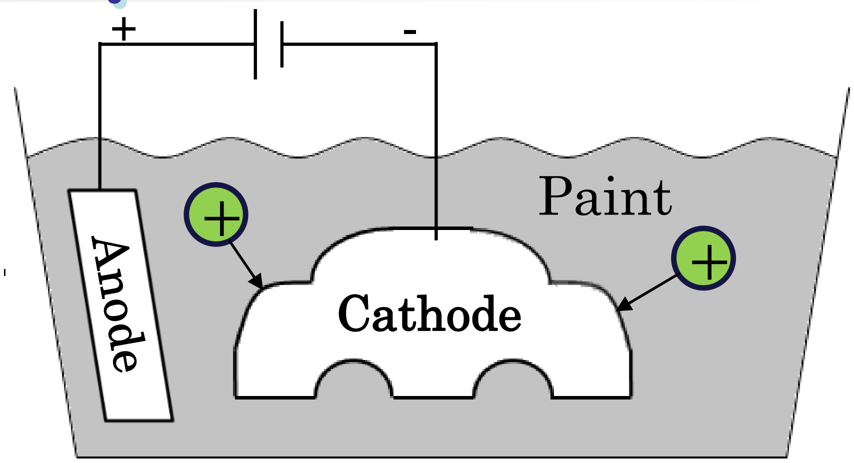
Development of ED simulator using ES-FEM-T4
and its performance evaluation
by comparing with FEM-T4.

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.

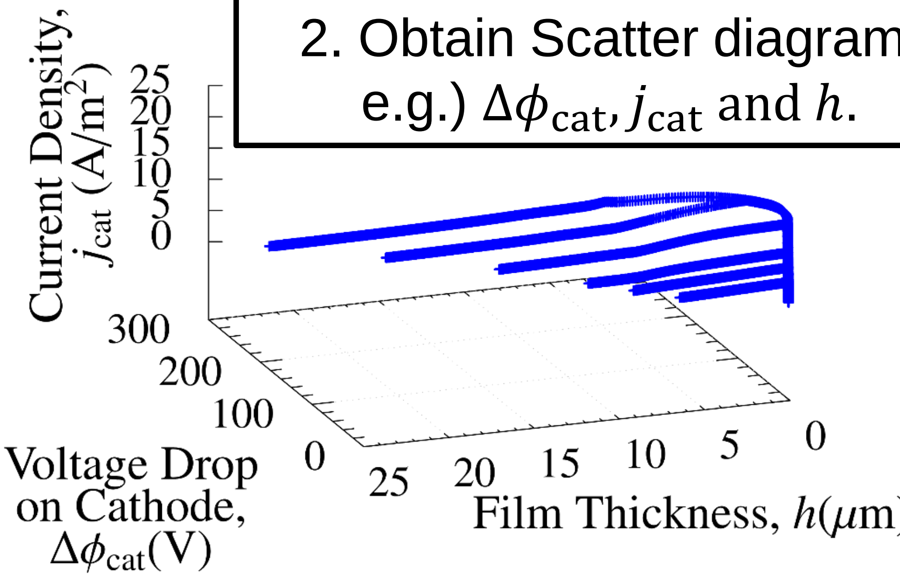
Solving the Laplace equation for potential, the current density distribution on a carbody is determined and then the film thickness distribution is time-evolutionally calculated.

How to Identify ED Boundary Models

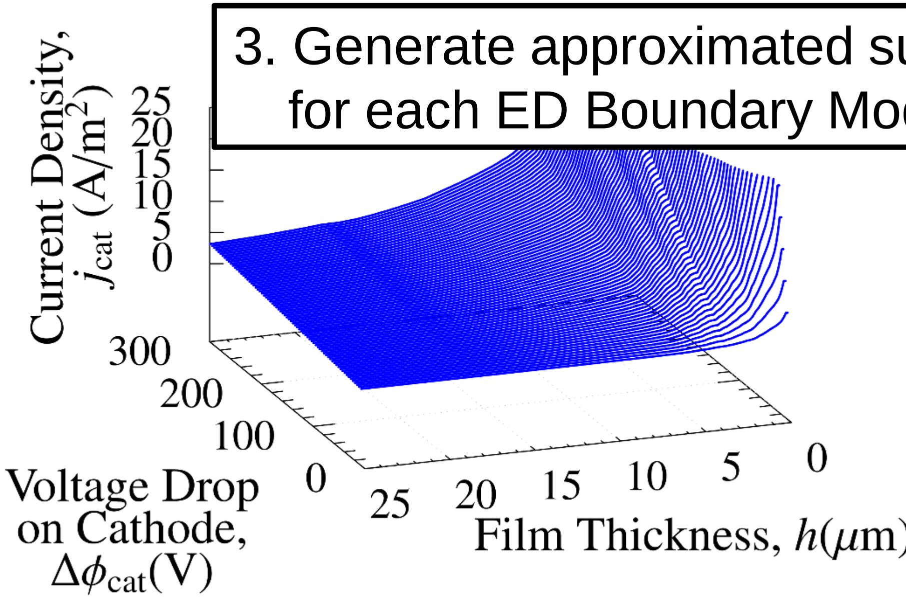
1. Conduct a lab experiment called one-plate tests.

Plot

2. Obtain Scatter diagram. e.g.) $\Delta\phi_{cat}, j_{cat}$ and h.



3. Generate approximated surface for each ED Boundary Model.



Data fitting

Formulation of ES-FEM for ED Simulation

Outline of ES-FEM

What is ES-FEM-T4?

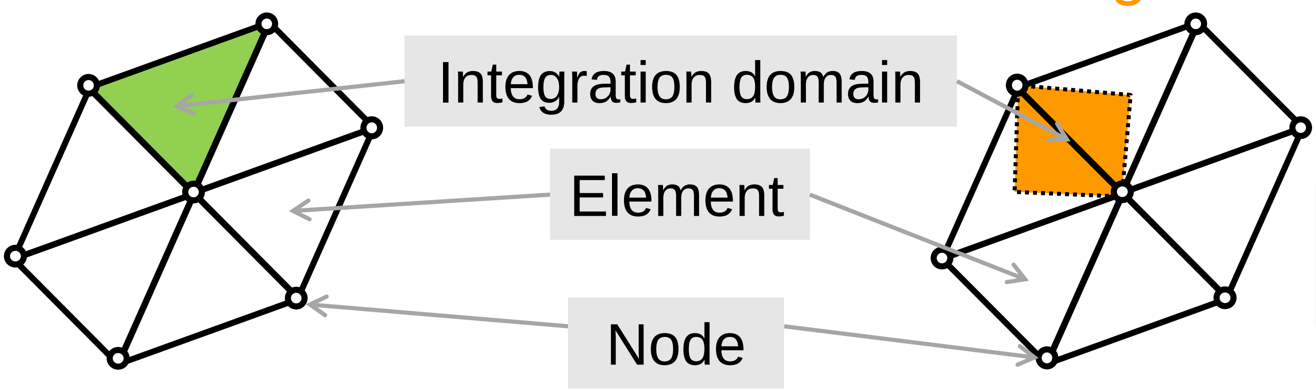
- A kind of strain smoothing method.
- Using element edges as Gauss points.
- Robust against element skew.
- Super-linear mesh convergence rate with T4 mesh.
- ES-FEM can suppress the accuracy loss by smoothing.

Standard FEM

FEM assembles each element's value.

ES-FEM

ES-FEM assembles each edge's value.

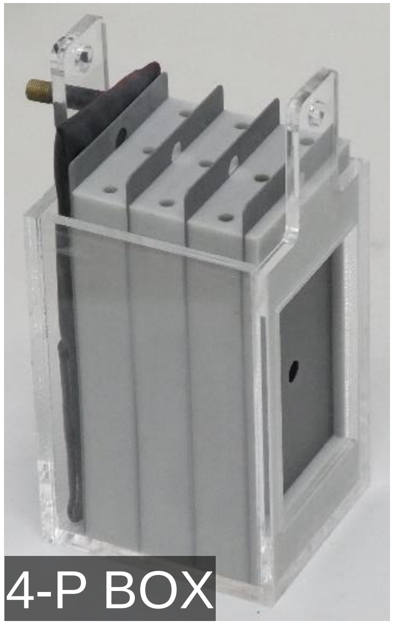


Integration domain is different !!

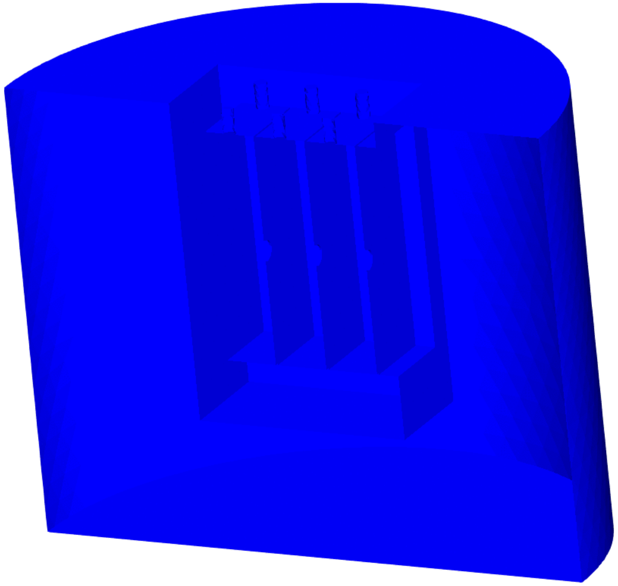
Analysis Results

4-Plate BOX Simulation

Outline



Film Thickness

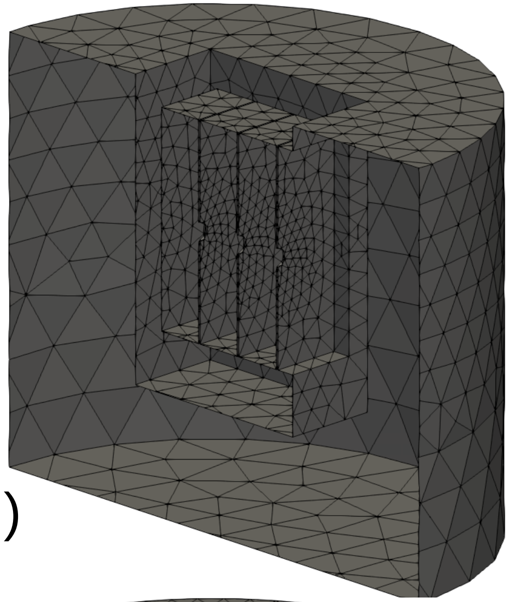


- Imitating a bag-like structure such as side sill in a carbody.
- Accuracy on the innermost surface (leftmost plate surface) is the most important; i.e., “maximize the minimum”.
- Film thickness is calculated with 4 different mesh seed sizes and compared between FEM-T4 and ES-FEM-T4.

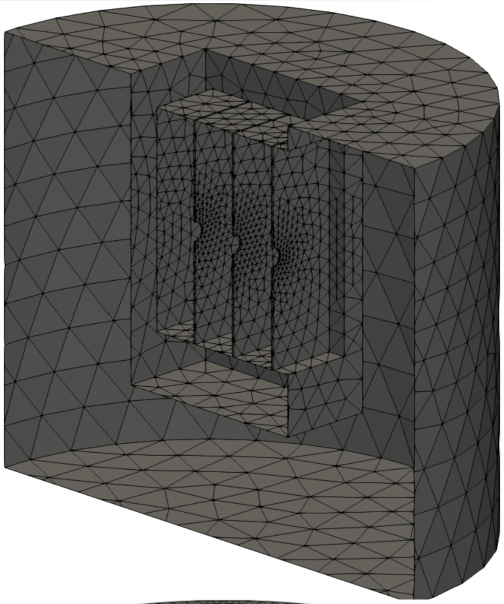
4-Plate BOX Simulation

Overview of Meshes

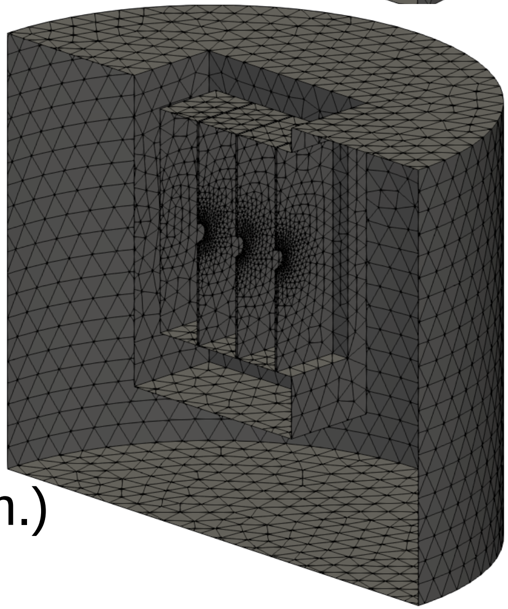
Only the surface meshes are shown.



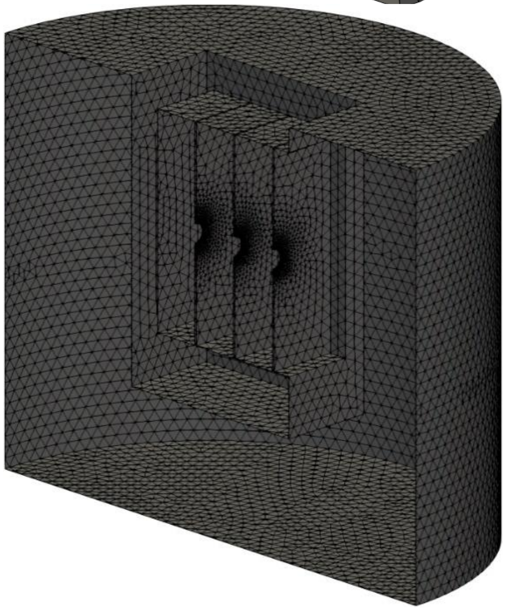
3.2 mm Mesh
Seed Size
(31k T4 elem.)



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



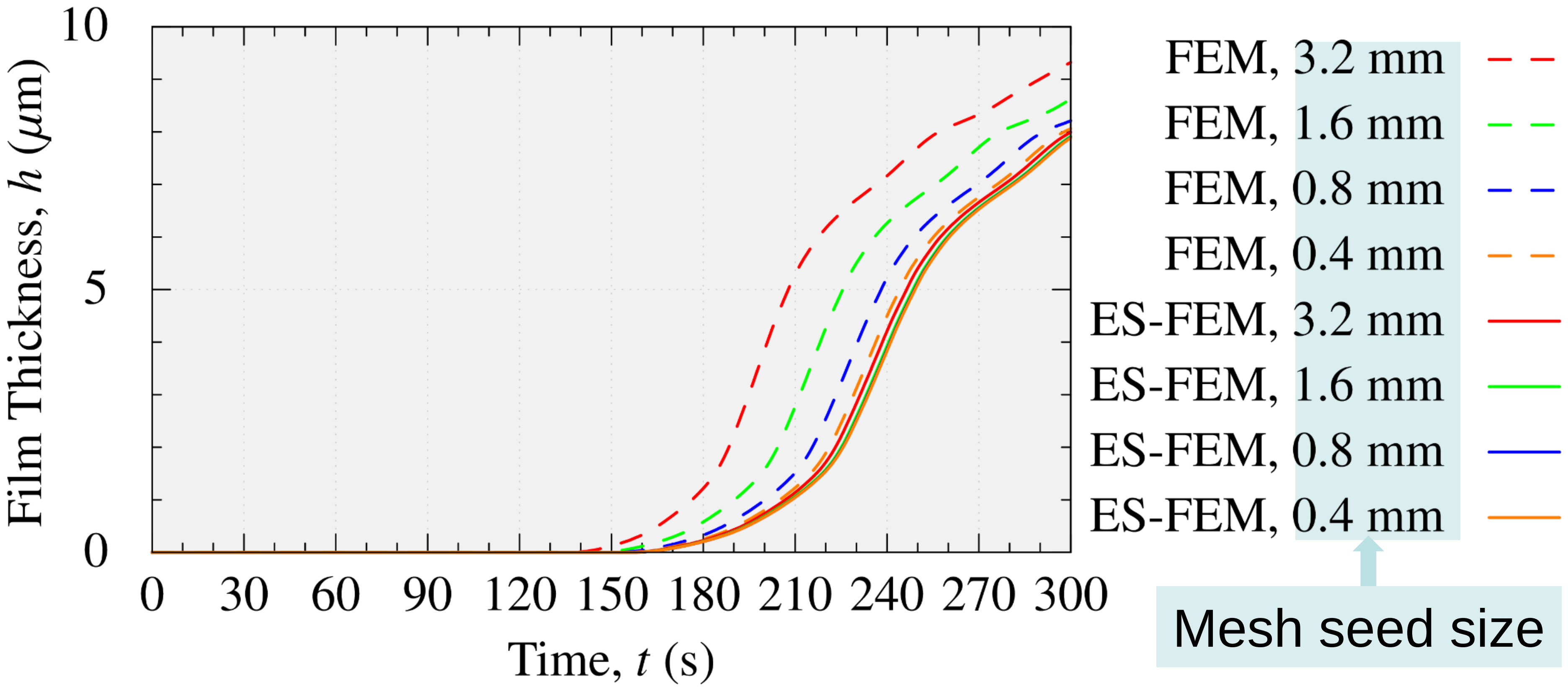
0.8 mm Mesh
Seed Size
(169k T4 elem.)



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

4-Plate BOX Simulation

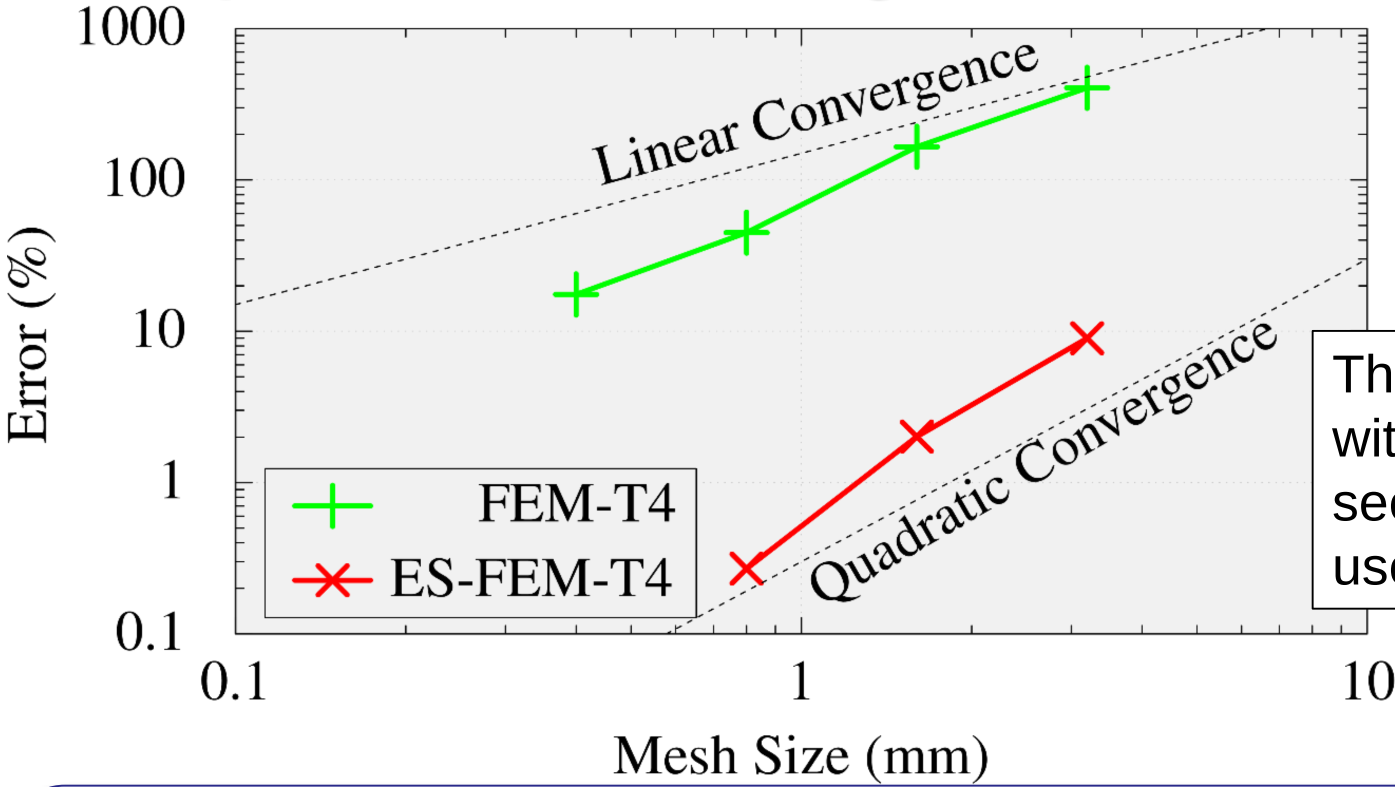
Film Thickness on G-Plate (innermost surface)



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

Comparison of Convergence Rate on G-Plate



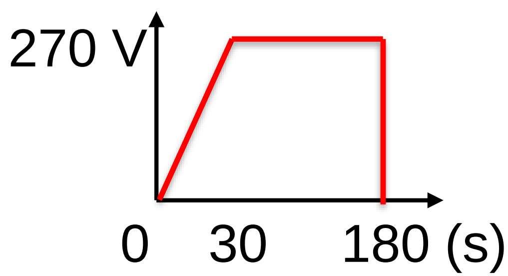
The result of ES-FEM with the minimum mesh seed size (0.4 mm) is used as the reference.

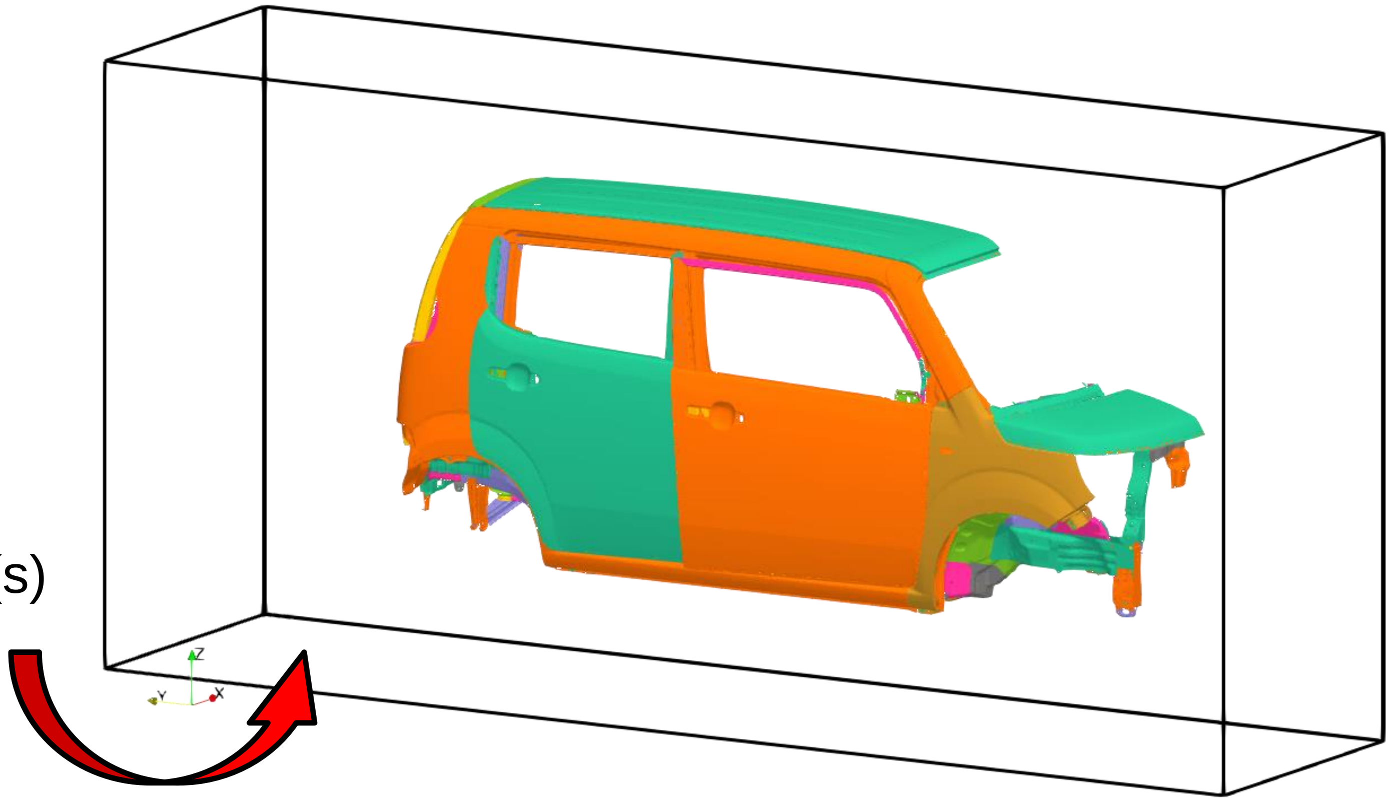
FEM-T4 shows a linear convergence.
Meanwhile, ES-FEM-T4 almost shows a quadratic convergence.
ES-FEM-T4 has much better mesh convergence rate than FEM-T4.

Carbody Simulation

Outline

Applied Voltage

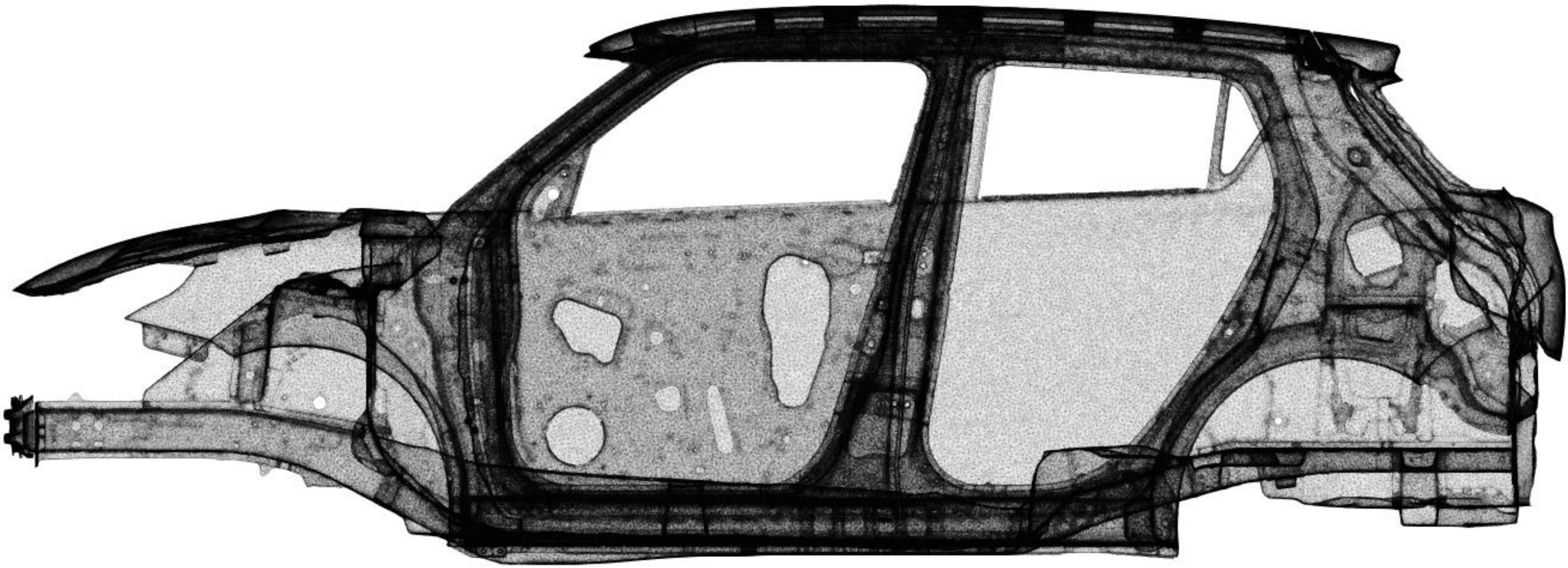




- A half carbody is fixed in a box pool.
- The side wall is treated as an anode surface.

Carbody Simulation

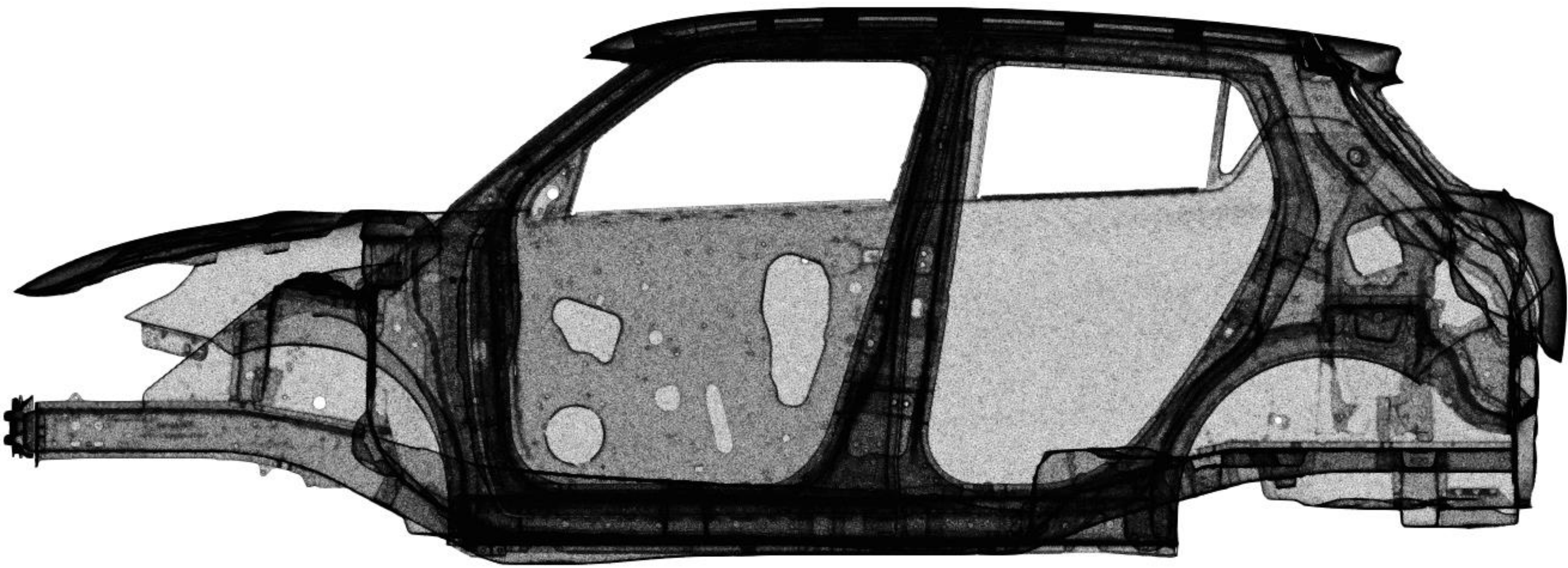
Overview of Surface Mesh with 10M Elems.



- Compare the time-developed film thickness between FEM-T4 and ES-FEM-T4 with 3 different size meshes.
- Each mesh has 10M, 16M and 50M T4 elements.

Carbody Simulation

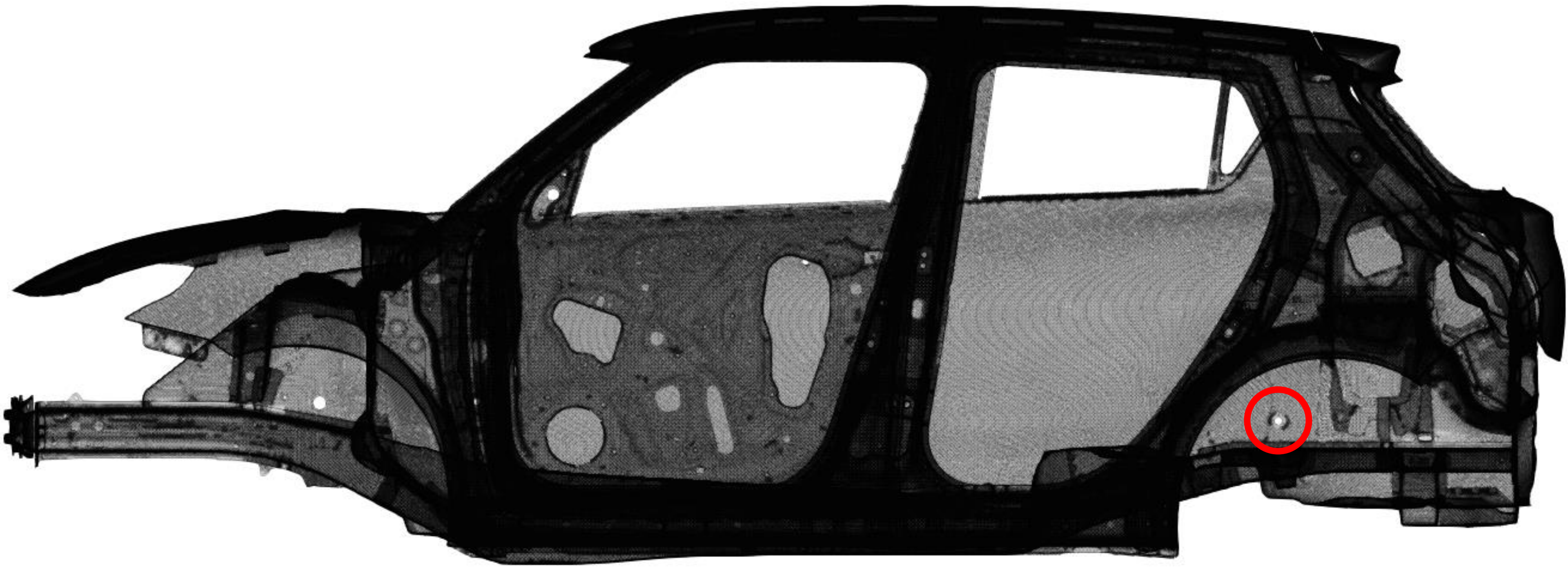
Overview of Surface Mesh with 16M Elems.



- Compare the time-developed film thickness between FEM-T4 and ES-FEM-T4 with 3 different size meshes.
- Each mesh has 10M, 16M and 50M T4 elements.

Carbody Simulation

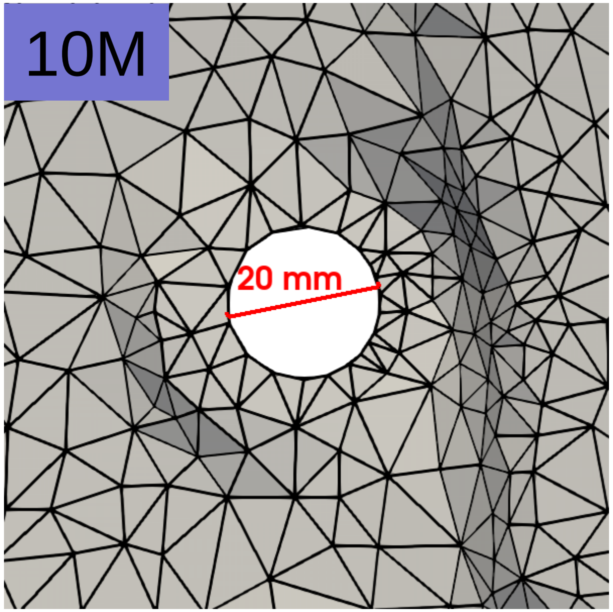
Overview of Surface Mesh with 50M Elems.

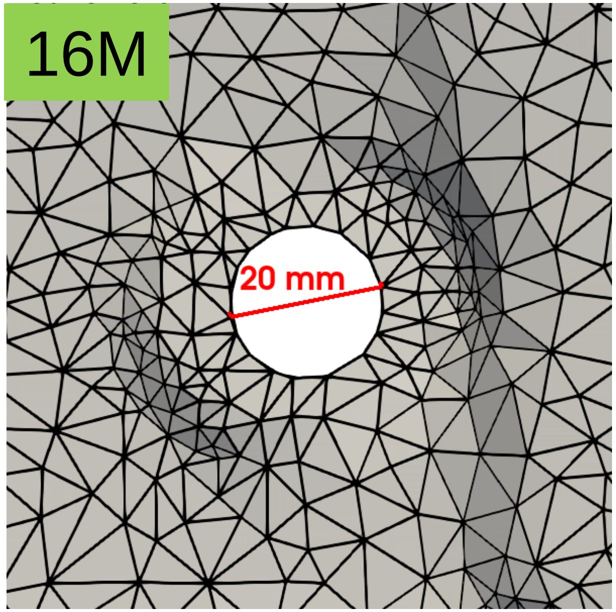


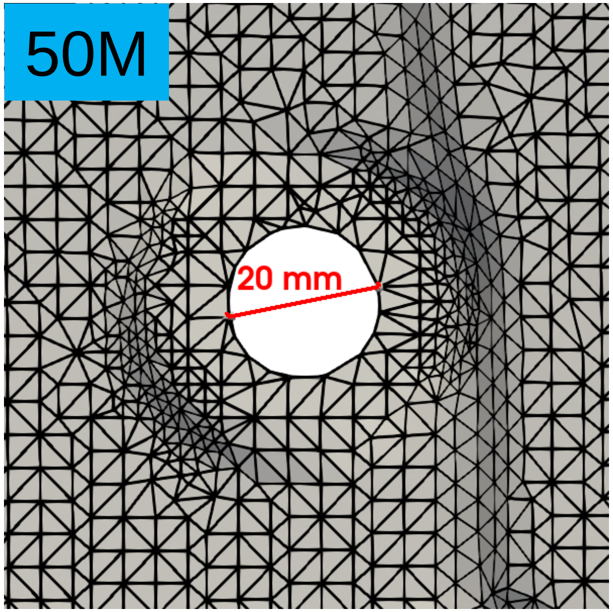
- Compare the time-developed film thickness between FEM-T4 and ES-FEM-T4 with 3 different size meshes.
- Each mesh has 10M, 16M and 50M T4 elements.

Carbody Simulation

Zoom in View around a Hole on Carbody





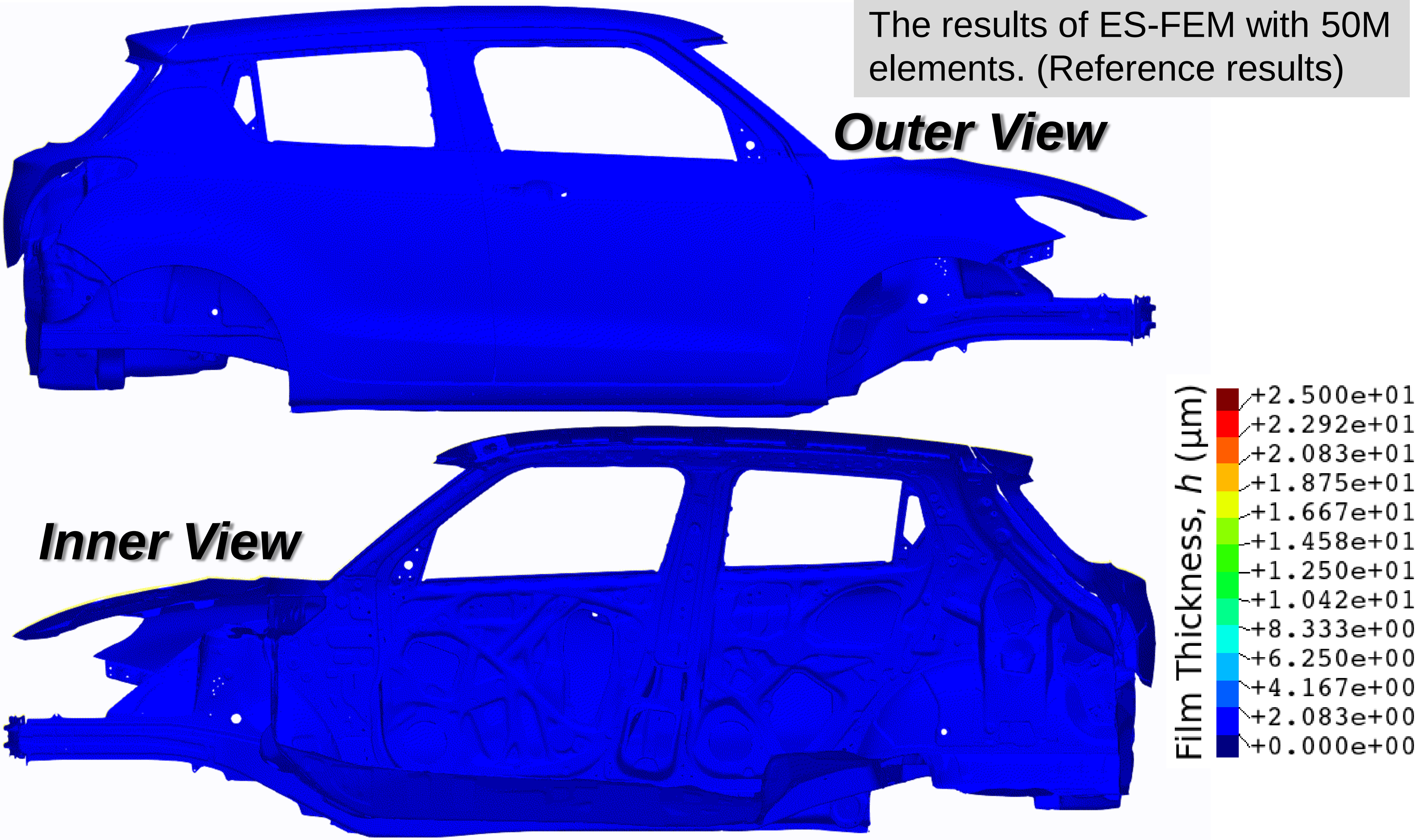


- Compare the time-developed film thickness between FEM-T4 and ES-FEM-T4 with 3 different size meshes.
- Each mesh has 10M, 16M and 50M T4 elements.

Carbody Simulation

Overview results of Film Thickness Distribution

The results of ES-FEM with 50M elements. (Reference results)

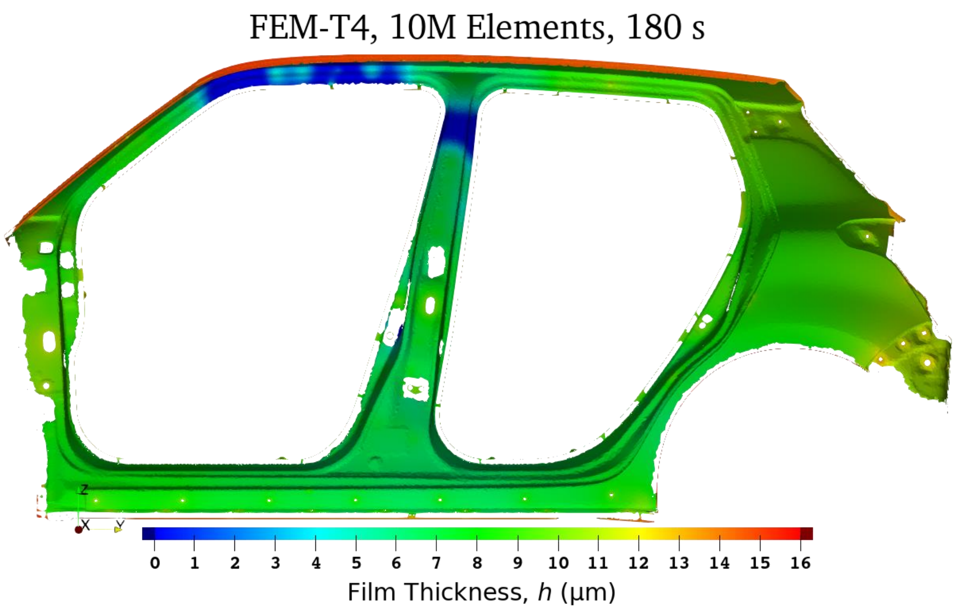


Carbody Simulation

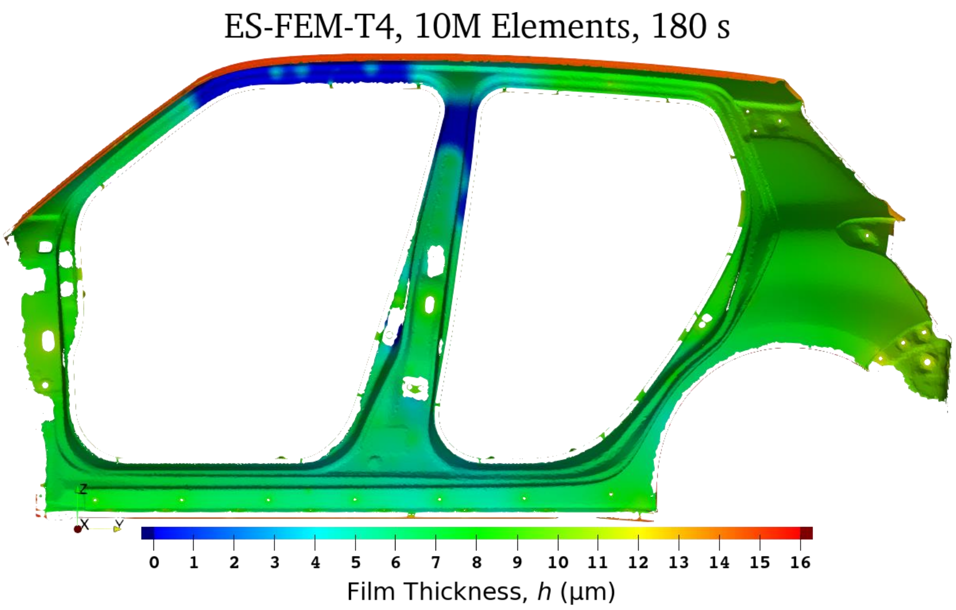
Film Thickness Distribution with 10M Elems. Mesh

(Clipped View on Side Sill)

FEM-T4



ES-FEM-T4



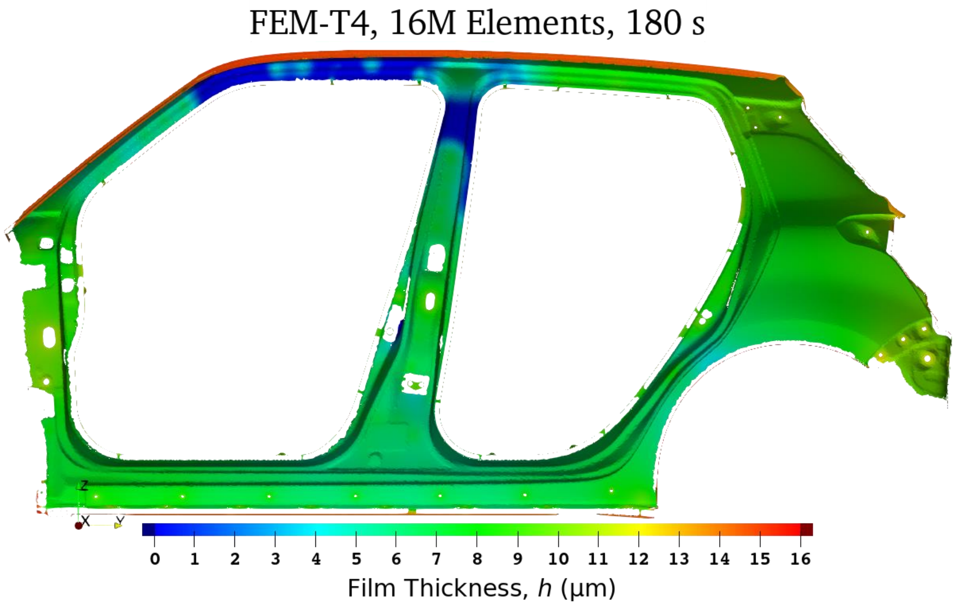
FEM-T4 requires 50M elements to obtain the converged solution. Meanwhile, ES-FEM-T4 requires only 16M elements.

Carbody Simulation

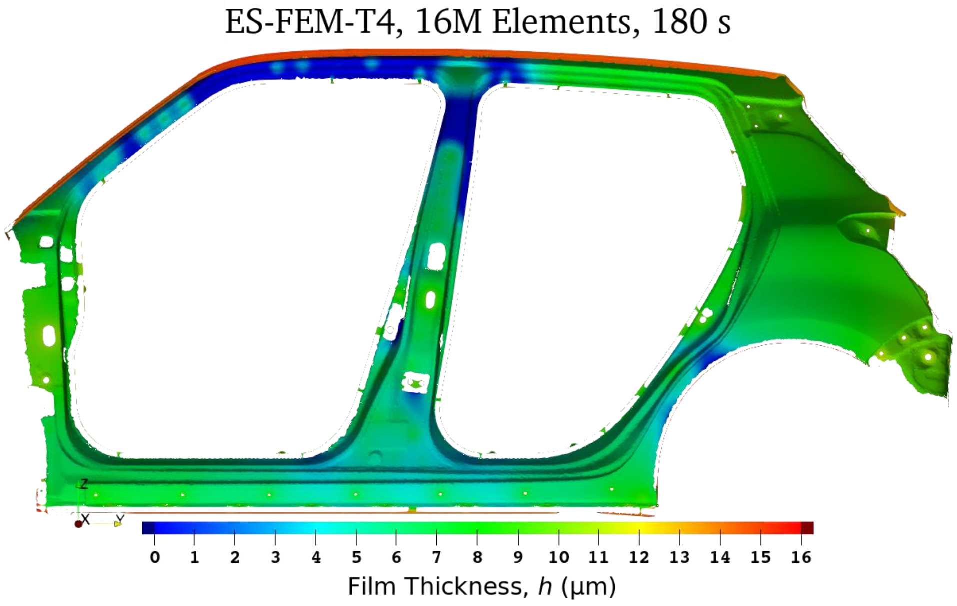
Film Thickness Distribution with 16M Elems. Mesh

(Clipped View on Side Sill)

FEM-T4



ES-FEM-T4



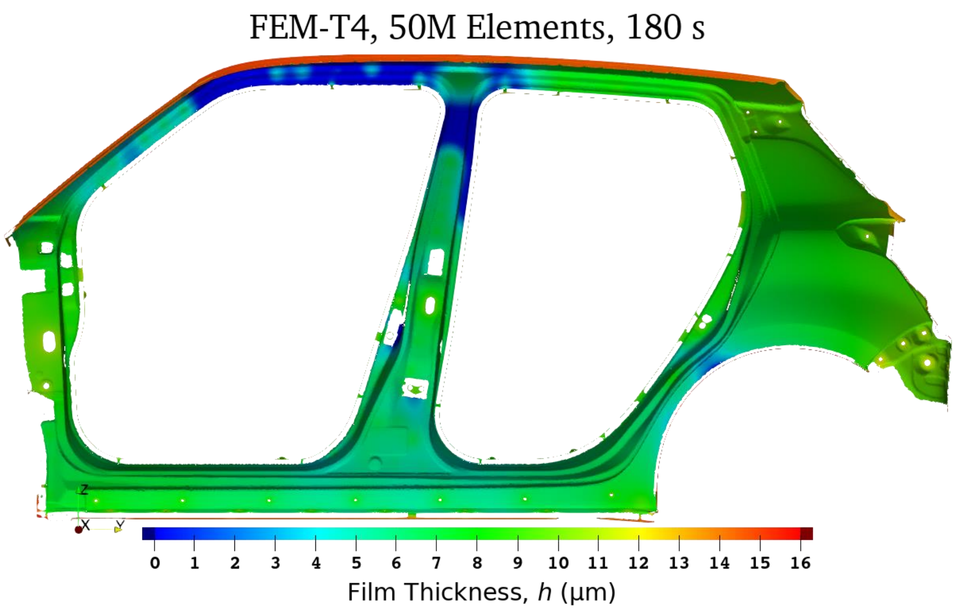
FEM-T4 requires 50M elements to obtain the converged solution. Meanwhile, ES-FEM-T4 requires only 16M elements.

Carbody Simulation

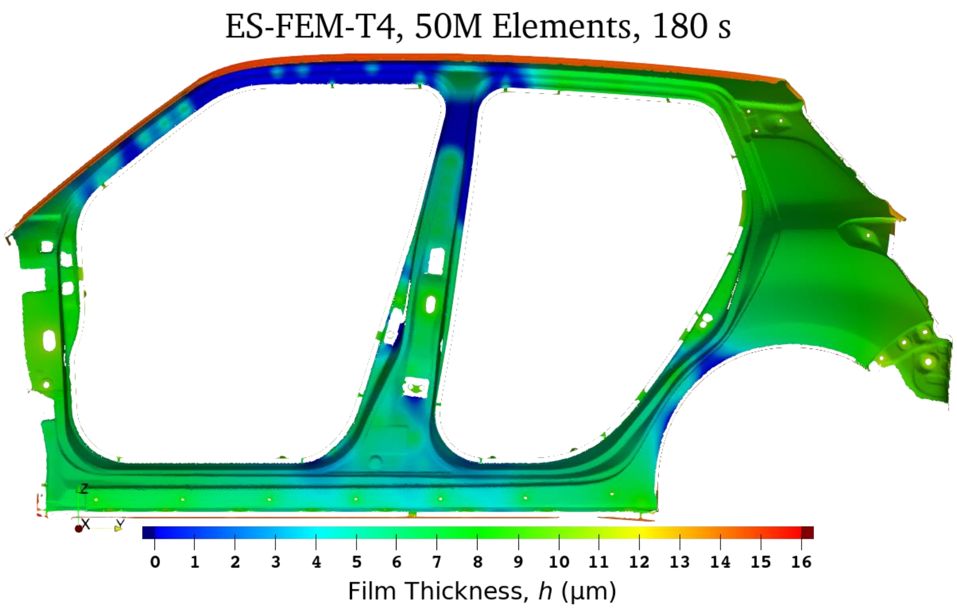
Film Thickness Distribution with 50M Elems. Mesh

(Clipped View on Side Sill)

FEM-T4



ES-FEM-T4



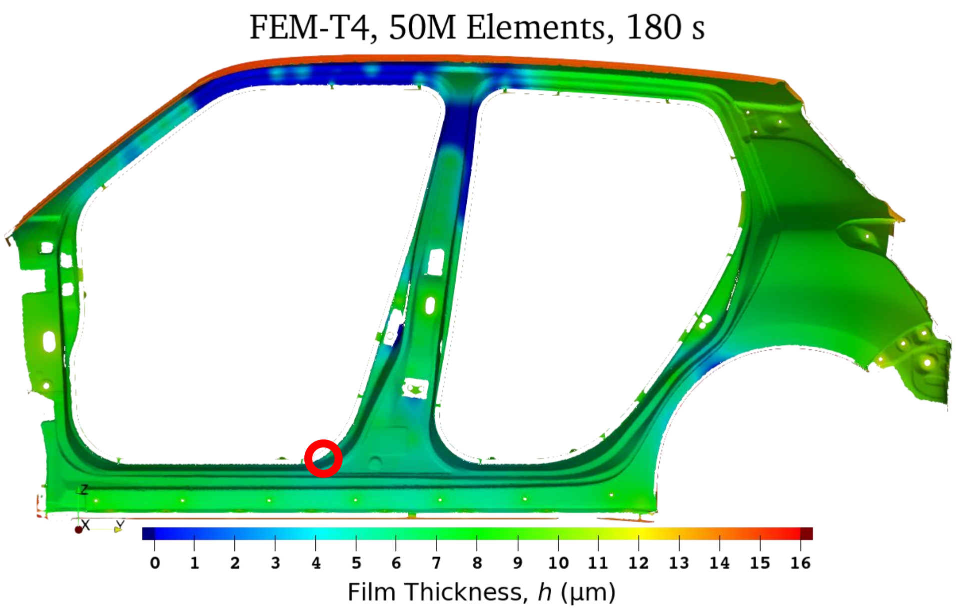
FEM-T4 requires 50M elements to obtain the converged solution. Meanwhile, ES-FEM-T4 requires only 16M elements.

Carbody Simulation

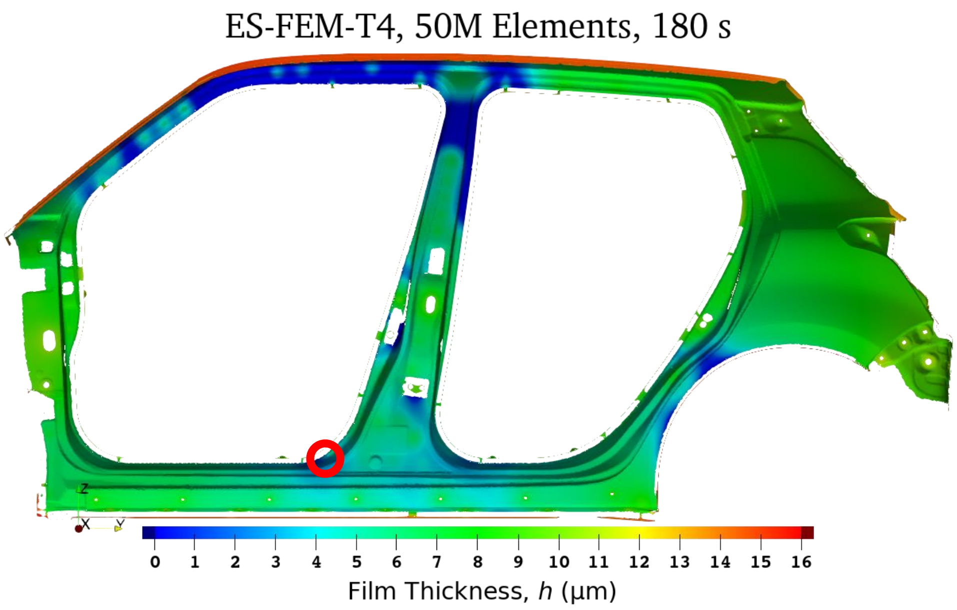
Film Thickness Distribution with 50M Elems. Mesh

(Clipped View on Side Sill)

FEM-T4



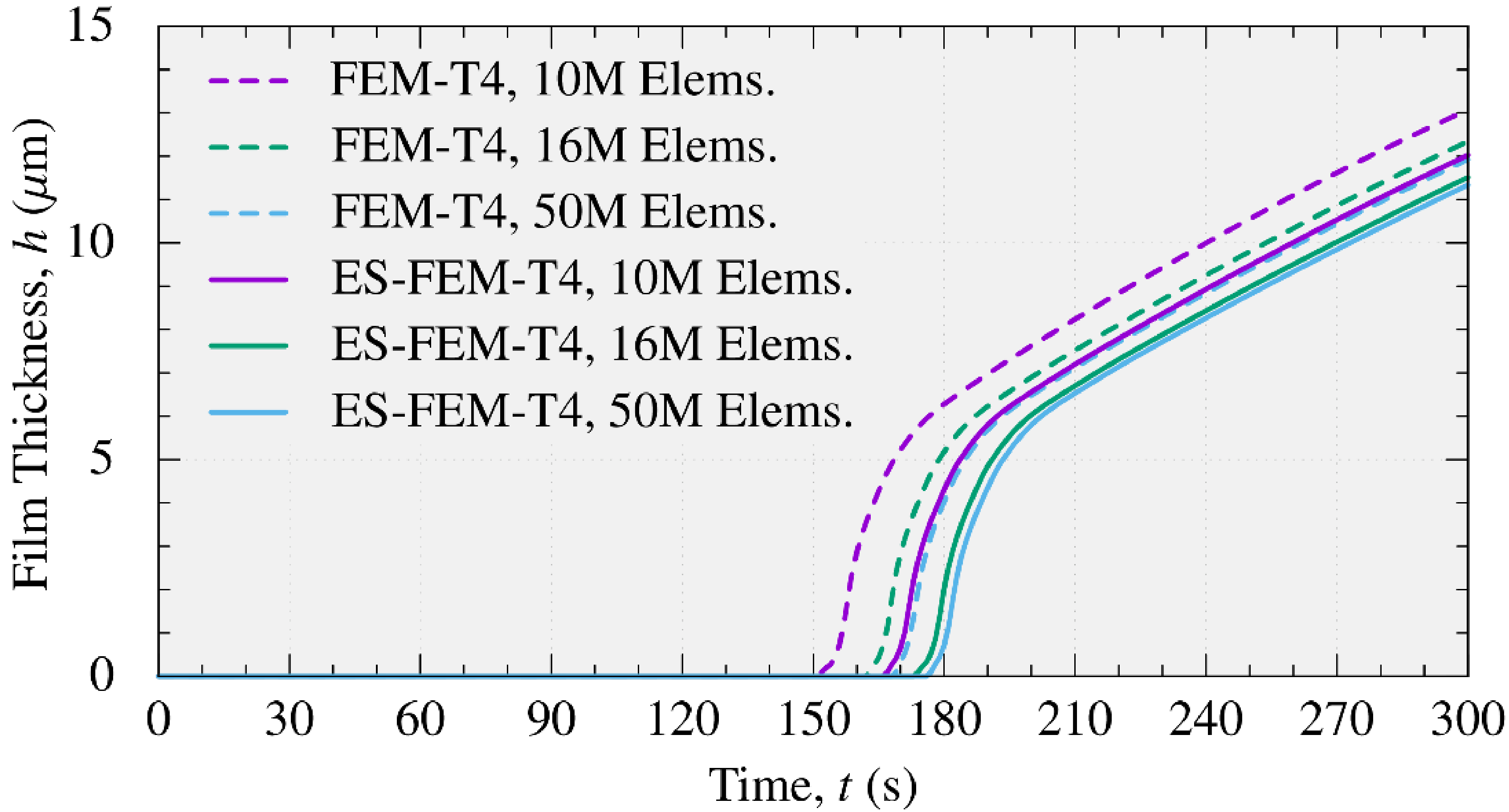
ES-FEM-T4



FEM-T4 requires 50M elements to obtain the converged solution. Meanwhile, ES-FEM-T4 requires only 16M elements.

Carbody Simulation

Comparison of Time-histories of Film Thickness



FEM-T4 with 50M elems. and ES-FEM-T4 with 10M elems. show almost the same results.

Comparison of Computational Costs

Calculation Time

on a PC with Intel i9-9960X using 8 cores

	Mesh / Elements	FEM-T4	ES-FEM-T4
4-P BOX	3.2 mm	0.3 min	0.5 min
	1.6 mm	0.5 min	0.9 min
	0.8 mm	1.2 min	2.4 min
	0.4 mm	6.3 min	12.2 min
Carbody	10M Elements	1.5 h	3.0 h
	16M Elements	2.4 h	4.7 h
	50M Elements	6.9 h	15.4 h

Same Accuracy

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 actual ED simulations.
- High accuracy of ES-FEM-T4 because of its super-linear (almost quadratic) 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.