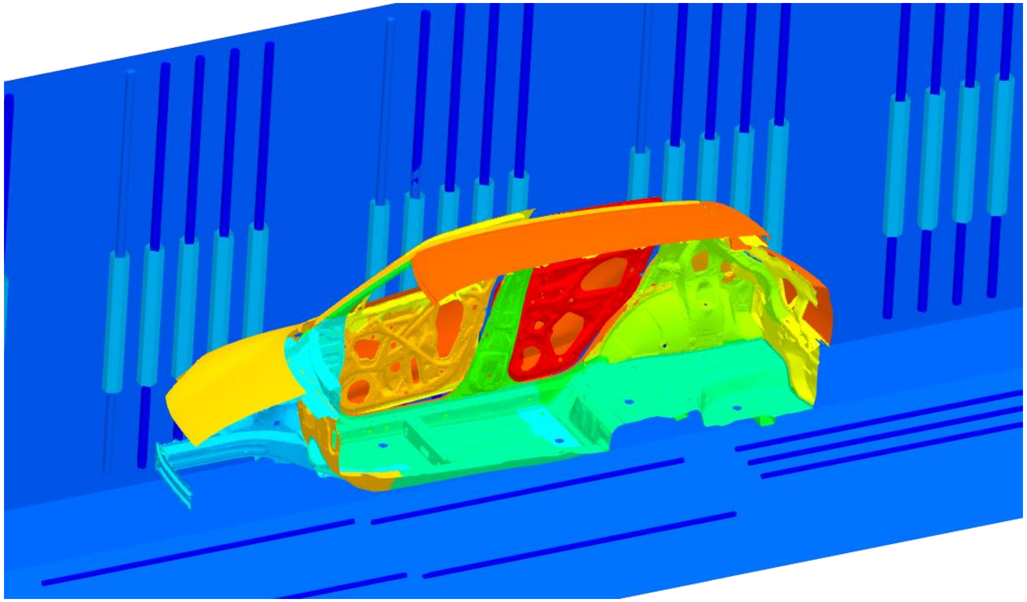
Application of Edge-based Smoothed Finite Element Method to Large-scale Electrodeposition Simulation for Automobile Manufacturing Lines



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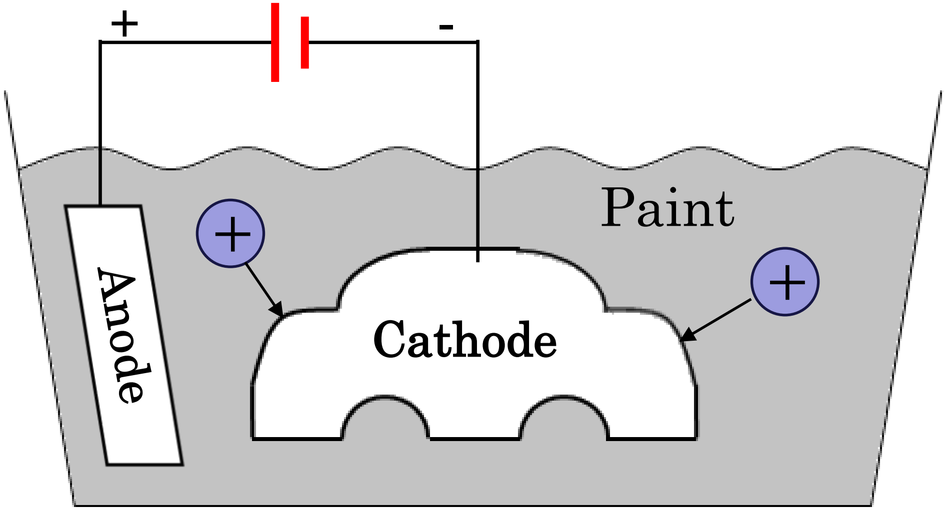
(Japan)

What is Electrodeposition (ED) ?

Outline


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



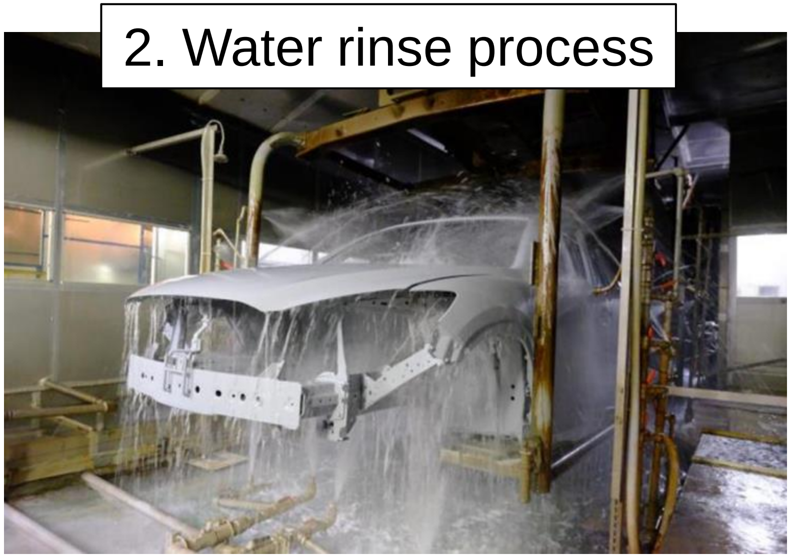
- Most widely-used **anti-rust basecoat** methods for various metal products including carbodies.
- Depositing coating film by applying **direct electric current** in a paint pool.
- Relatively good at depositing a **uniform film** on bodies in complex shape.

What is Electrodeposition (ED) ?

Photos of ED Process Line

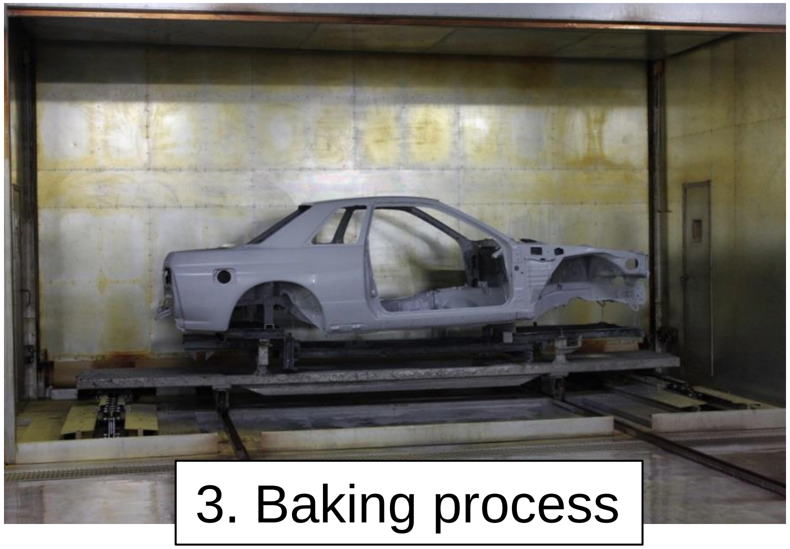
https://blog.mazda.com/archive/20160413_01.html

1. Deposition process



2. Water rinse process

We focus on this process.



3. Baking process

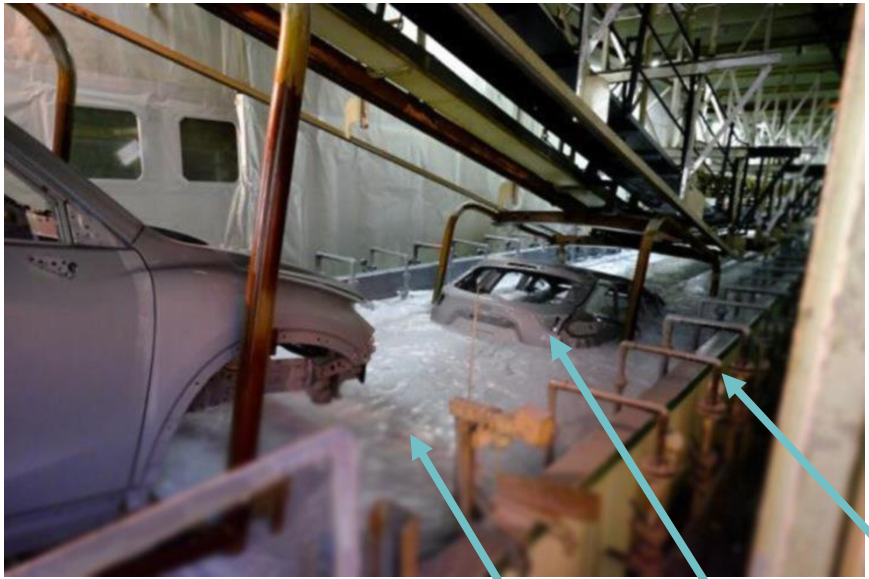
Difficulty in ED for Carbodies


https://www.goauto.ca/

- Undercarriages are exposed to severe corrosive environments, especially due to seawater or snow-melting chemicals.
- Some undercarriage parts (such as a **side sill**) have **bag-like complex structures** with many ED holes.
- It is not easy to deposit a required minimal thick film at the innermost faces of a bag-like structure, even for ED.
- Carbody design must consider the difficulty in ED process.

What is ED Simulation?

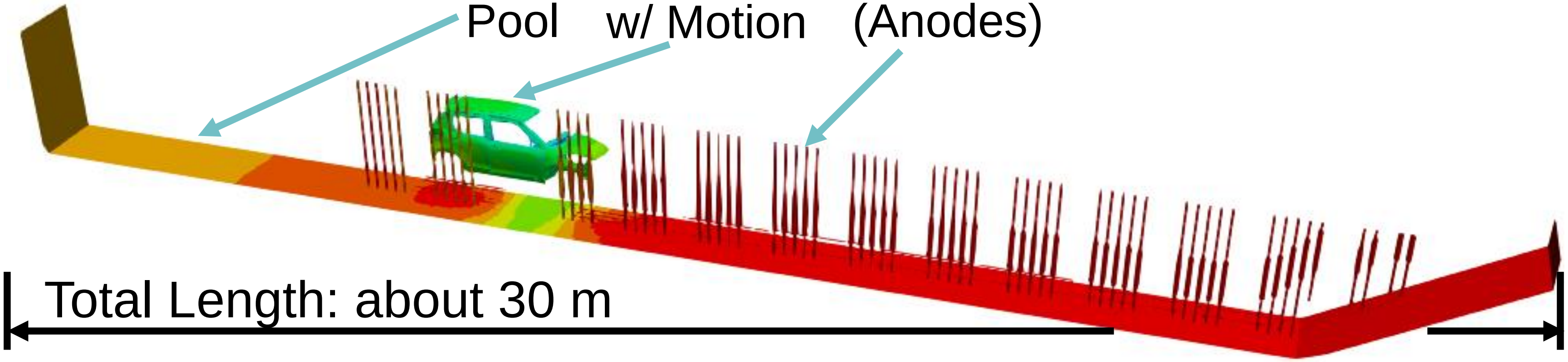
Actual ED Line



1. Paint Pool
2. Carbody with Motion
3. Electrodes (Anodes)

are reproduced in a computer.

ED Simulation



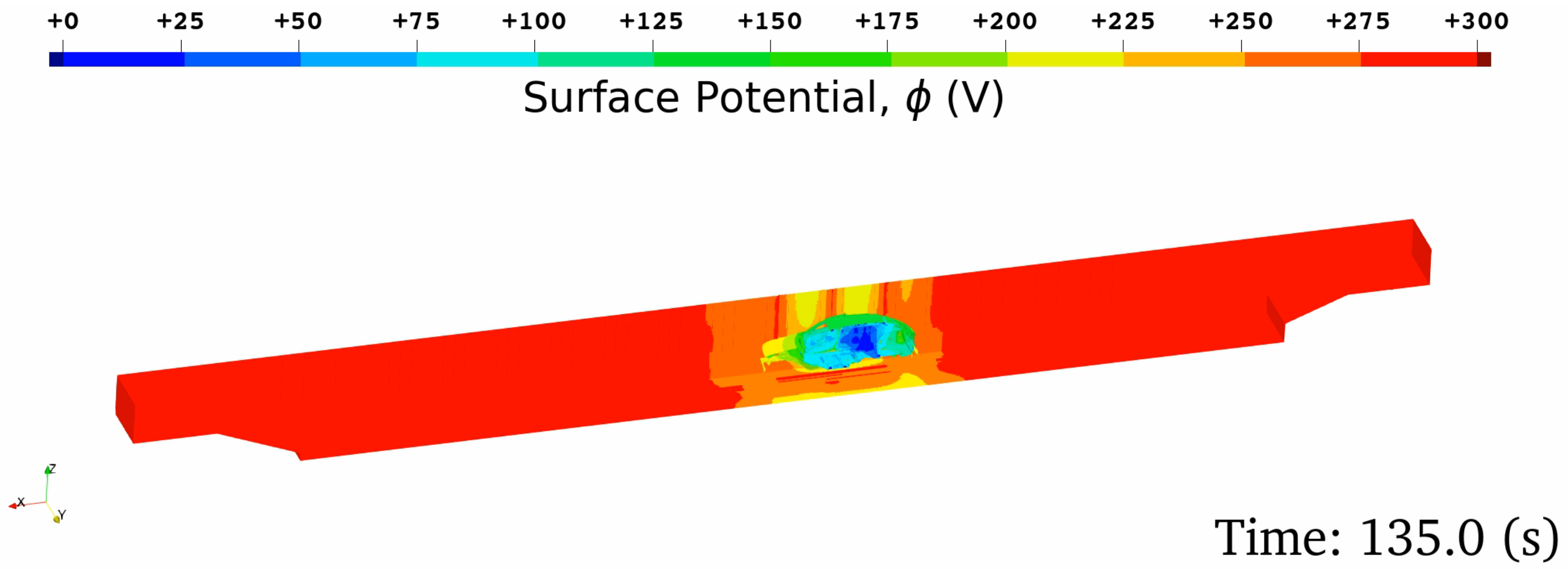
Paint Pool

Carbody w/ Motion

Electrodes (Anodes)

Total Length: about 30 m

What is ED Simulation?



- **Governing Equation:**

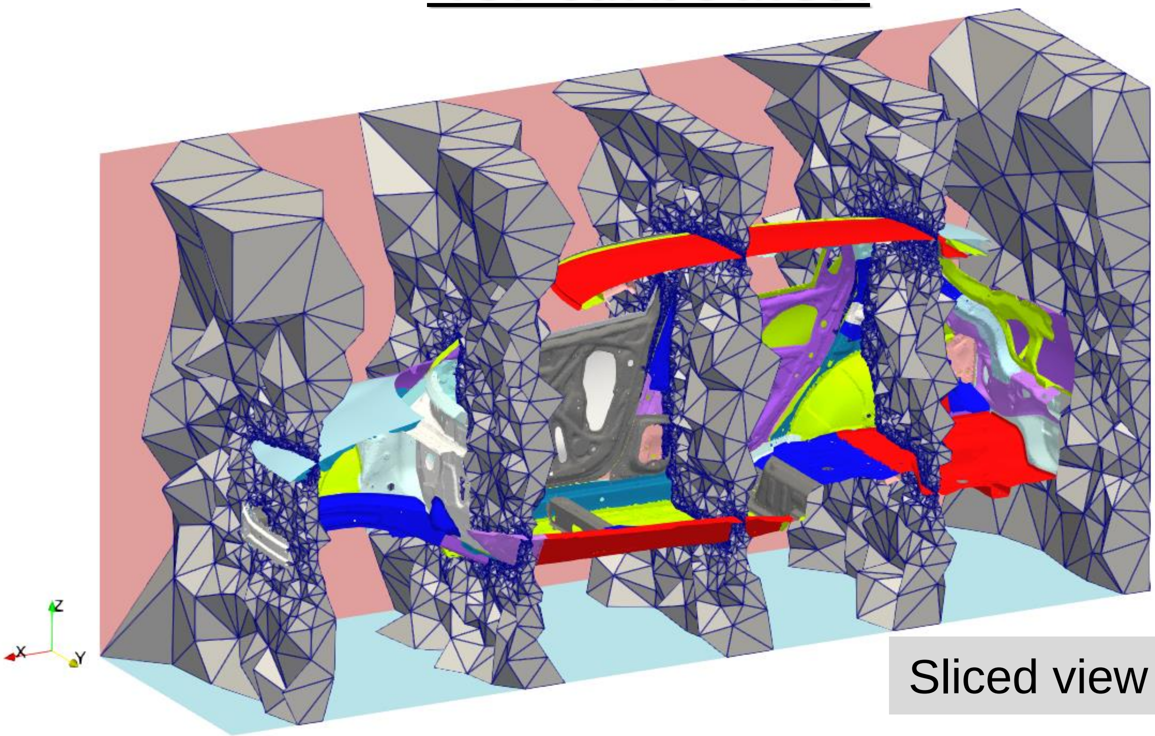
  Electrostatic Laplace equation ($\nabla^2\phi = 0$) in the paint pool domain.

- **Boundary Condition (BC):**
  1. Insulation BC,
  2. Anodic (electrode surface) BC,
  3. Cathodic (carbody surface) BC:
     Film resistance/growth constitutive model.

- **Outputs:**
  1. Surface potential,
  2. Current density,
  3. Coated film thickness.
     (main result)

Issue 1

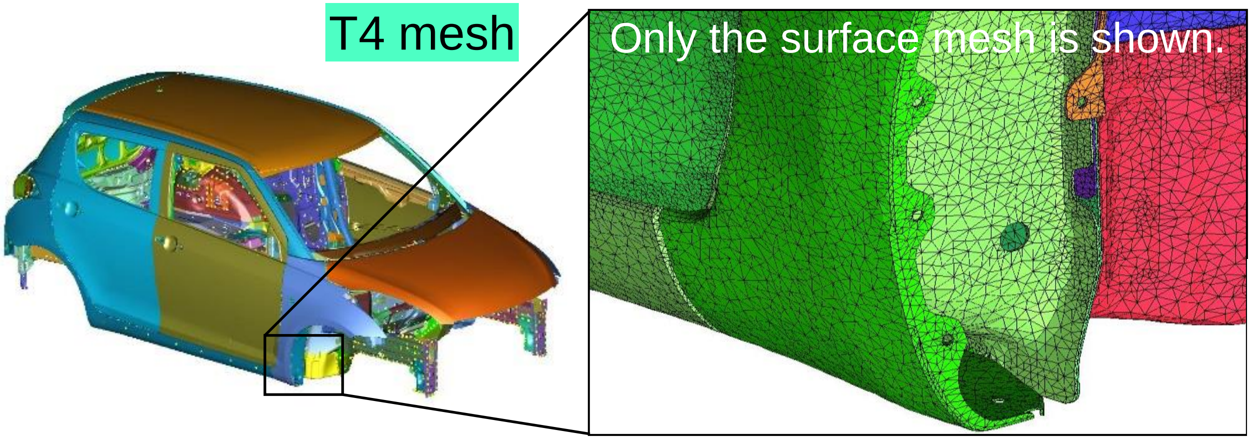
Issue 1: Impossible to make a good HEX mesh for carbodies.

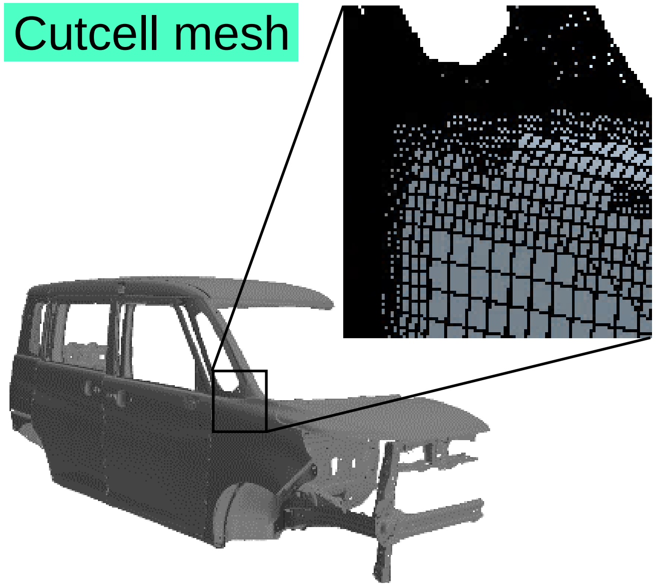


Sliced view of a carbody mesh

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

Issue 1 (cont.)





Zoom-in view
of a carbody mesh

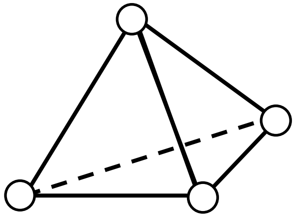
- The shape of a carbody is too complex to be discretized into a good HEX mesh.
- The Cartesian meshing (cutcell or snappy HEX meshing) is basically not suitable for the geometry with many holes.
  (∵ Massive increase in DOF, Linear mesh convergence rate, Presence of hanging nodes or polyhedral cells, Inapplicable to solid dynamics, etc.)

TET meshes are preferable in ED simulation.

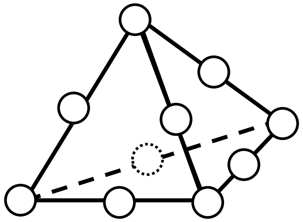
Issue 2

Issue 2: Both the standard 4-node and 10-node tetrahedral elements are inconvenient for carbodies.

- 4-node TET (**T4**) has poor accuracy with only a linear mesh convergence rate.
  ⟹ FEM-T4 and FVM-T4 require very fine meshes to obtain accurate results.

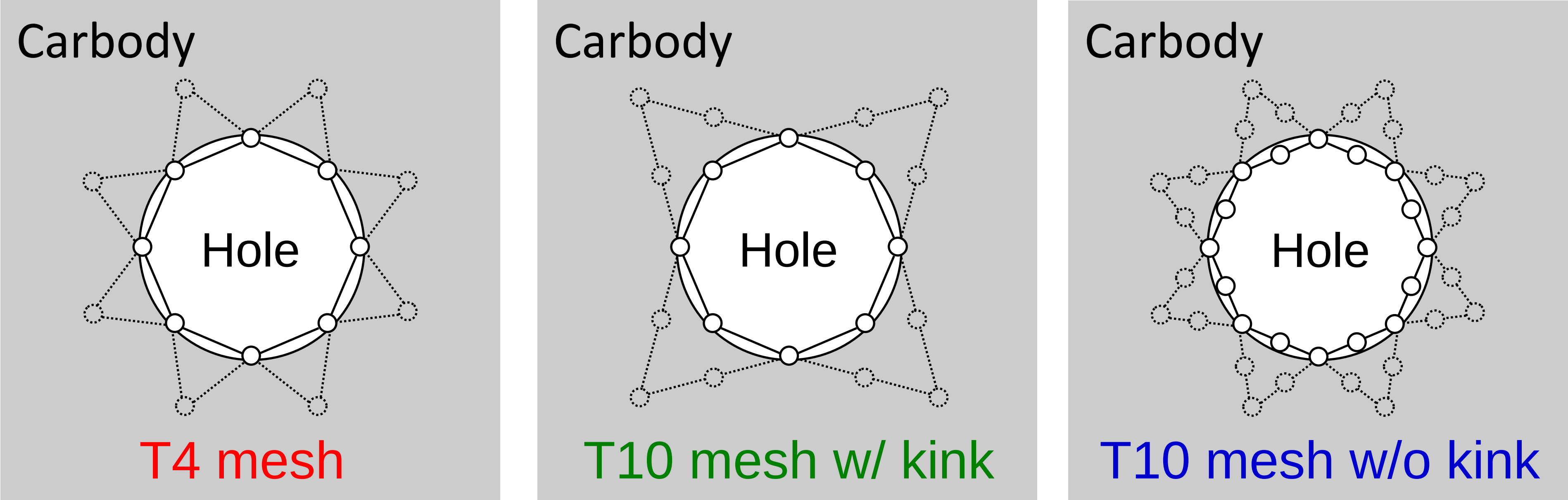


- 10-node TET (**T10**) has good accuracy with a quadratic mesh convergence rate; however, T10 mesh requires massively large DOF to represent complex shapes without any kink of element shapes.



Issue 2 (cont.)

For example, if there is a small **hole** on a carbody, the surface mesh around the hole looks like…



T4 mesh

T10 mesh w/ kink

T10 mesh w/o kink

✗ T10 w/ kink leads to severe accuracy loss.

✗ T10 w/o kink leads to a massive increase in DOF.

The standard T4 and T10 elements are both inconvenient for carbodies to achieve accurate simulation with minimal DOF.

Motivation

By the way, …

- The smoothed finite element method (S-FEM) has become popular in recent years as a next-generation high-performance FEM.
- Especially, the edge-based S-FEM using T4 mesh (ES-FEM-T4) is known to achieve a **superlinear mesh convergence rate even with T4 meshes**.

Therefore, we expect that…

ES-FEM-T4 could be a solution for the meshing issues
to achieve fast and accurate ED simulation.

Objective

Development of ED simulator using ES-FEM-T4
for large-scale ED simulations
of actual manufacturing lines.

Table of body contents:

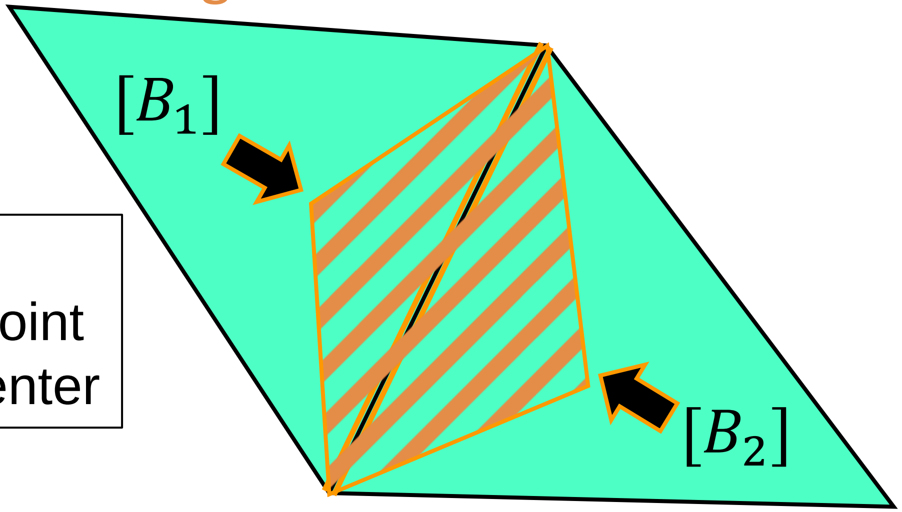
1. Brief of ED Formulation using ES-FEM-T4
2. Benchmark Analyses
3. Summary

Brief of ED Formulation using ES-FEM-T4

Brief Formulation of ES-FEM

Let us consider two 3-node triangular (T3) elements in 2D.

- Calculate $[B](= \mathrm{d}\boldsymbol{N}/\mathrm{d}\boldsymbol{x})$ at each element as usual.
- Distribute $[B]$ to each connecting edge with an area weight and build $[{}^{\mathrm{Edge}}B]$.
- Calculate current density ($\boldsymbol{J}$) and nodal internal current $\{i^{\mathrm{int}}\}$ in each edge smoothing domain.



As if putting
an integration point
on each edge center

$[{}^{\mathrm{Edge}}B]$

↳ ${}^{\mathrm{Edge}}\boldsymbol{J}, \{{}^{\mathrm{Edge}}i^{\mathrm{int}}\}$ etc.

Characteristics of ES-FEM-T4

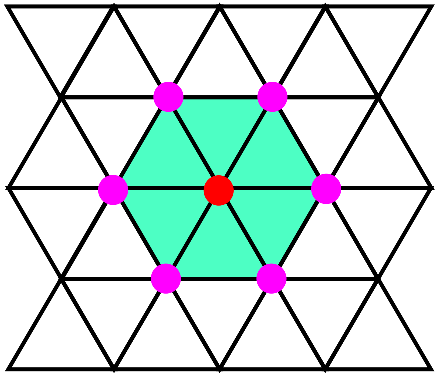
Advantage

- Superlinear mesh convergence (as fast as 2nd-order elems.).
- Same input file as FEM-T4.
- No increase in DOF (nodal potentials only; ∴ easy to code).

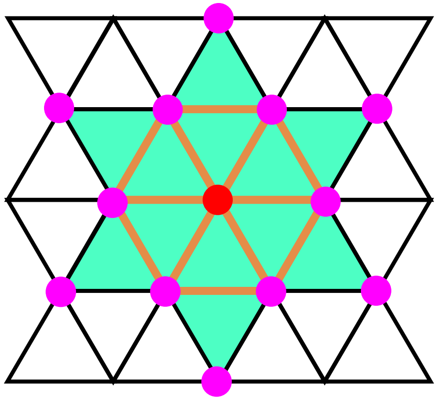
Disadvantage

- Longer assembling time of $[K]$ (~x2 of FEM-T4 w/ the same mesh).
- Wider bandwidth of $[K]$ (~x3 of FEM-T4 w/ the same mesh).
- No longer an independent T4 element.

A node is referred by 6 elements,
⇒ 7 nodes.



FEM-T3 (Bandwidth: 7)

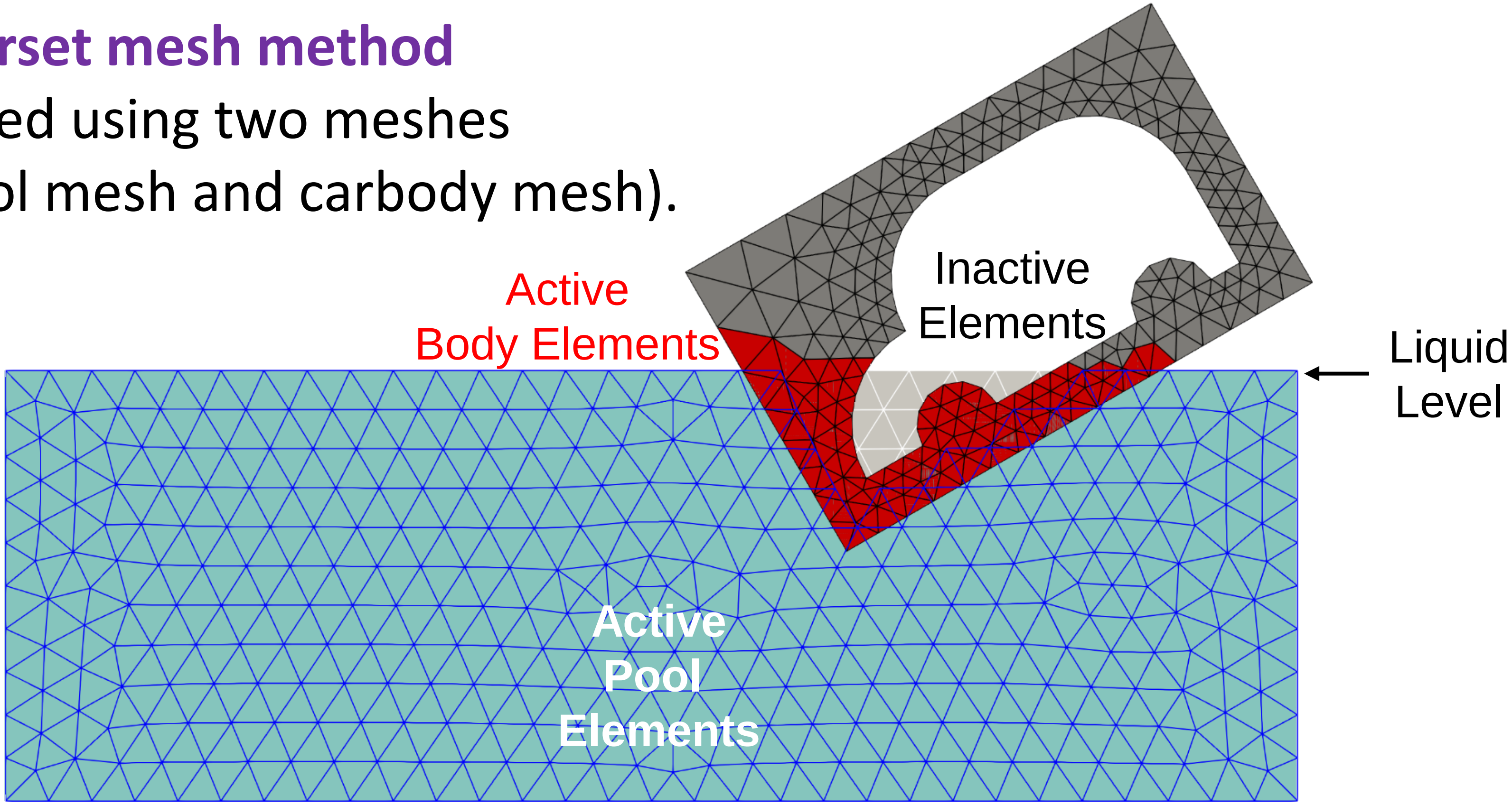


A node is referred by 12 edges,
⇒ 12 elements,
⇒ 13 nodes.

ES-FEM-T3 (Bandwidth: 13)

Handling of Moving Boundary

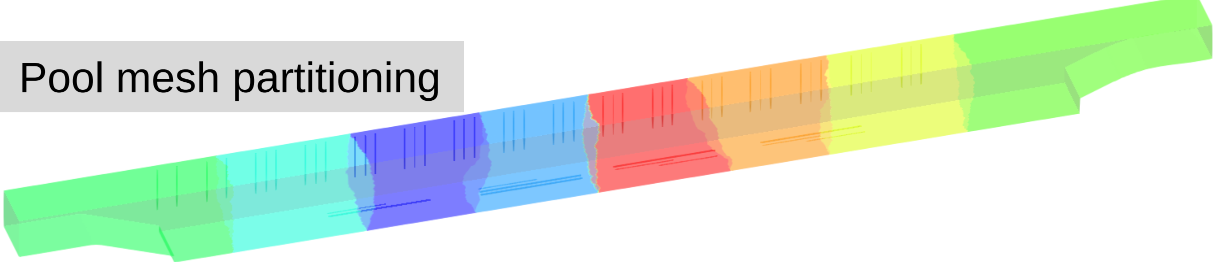
The **overset mesh method**
is adopted using two meshes
(i.e., pool mesh and carbody mesh).



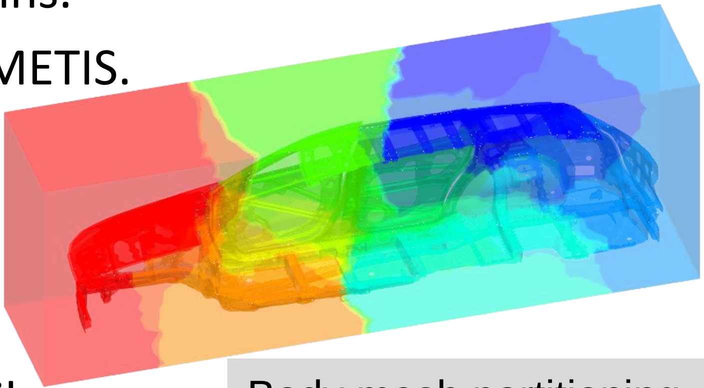
- Each interfacial node of the active pool elements is tied in the active body elements with the multi-point constraint (**MPC**).
- The classical **method of Lagrange multiplier** is used to satisfy the MPCs.

Parallelization of ES-FEM-T4

- There is no particular difference from FEM-T4 using MPI.
- The only difference is the number of overlapping nodes, which leads to a slight increase in communication cost.
- Calculation steps:
  1. Generating T4 mesh for pool and body domains.
  2. Partitioning and reordering each mesh with METIS.



Pool mesh partitioning



Body mesh partitioning

  3. Preparing an input file containing the mesh filenames, boundary conditions, motion path, etc..
  4. Executing the program. (e.g., in case of OpenMPI:

```
orterun –np N -bind-to socket -npersocket 1
 -x OMP_NUM_THREADS=8 -x numactl -l edesfem.bin input_file_name)
```

There is no difficulty in parallelization of ES-FEM-T4.

Benchmark Analyses

4-Plate BOX Simulation

Outline

- 4 Plates forms 3 bags.
- 3^{rd} bag is difficult to be deposited.

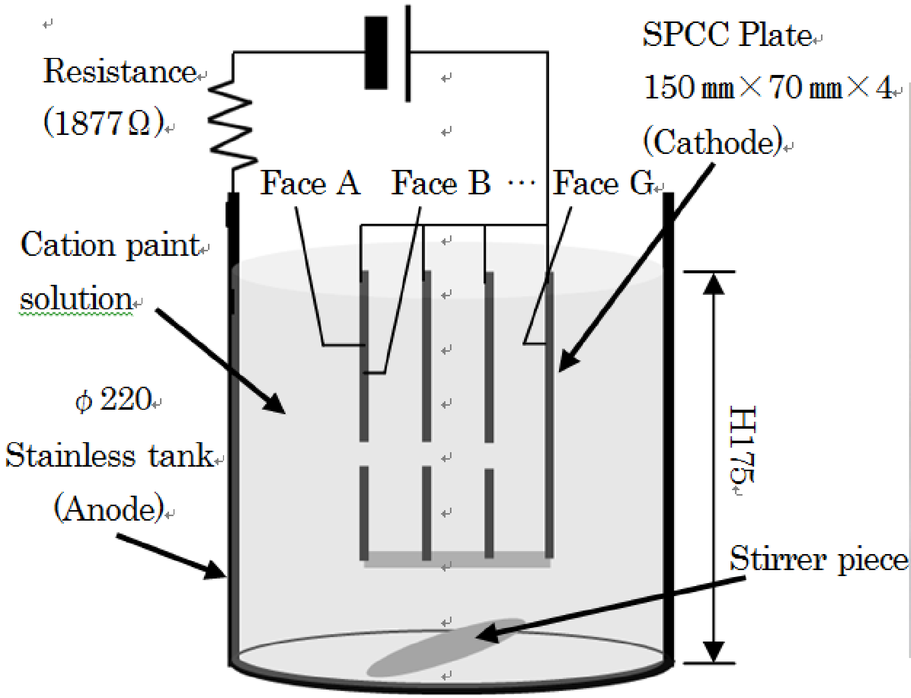
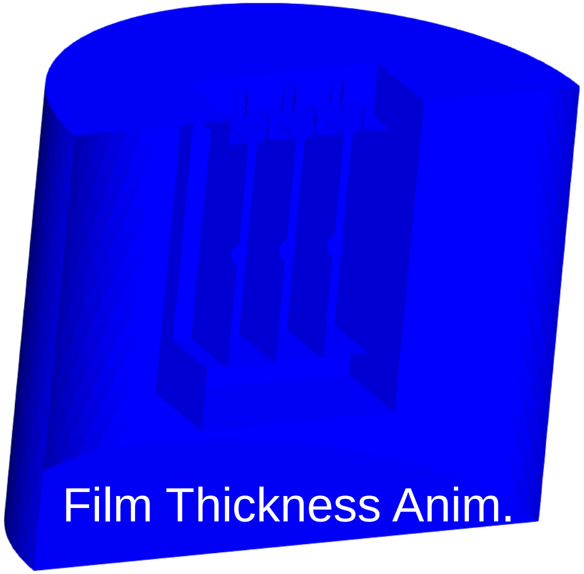


Photo of a BOX

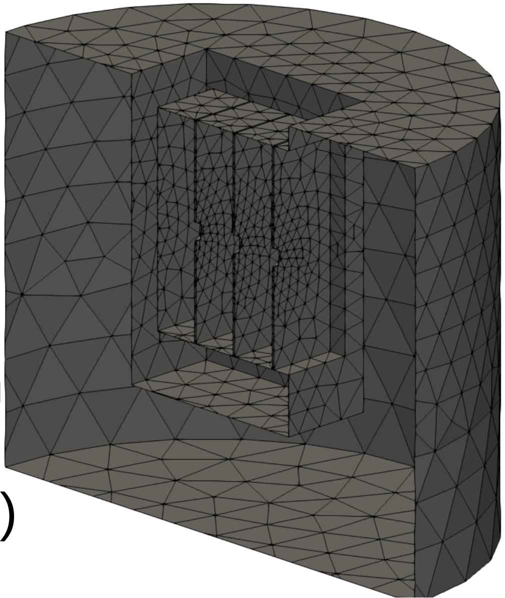


- Imitating a bag-like structure such as a side sill in a carbody.
- Film thickness on the **innermost surface** (Face G) is the most important so as to guarantee corrosion protection.
- The film thickness is evaluated with **4 different meshes for mesh validation using FEM-T4 and ES-FEM-T4.**

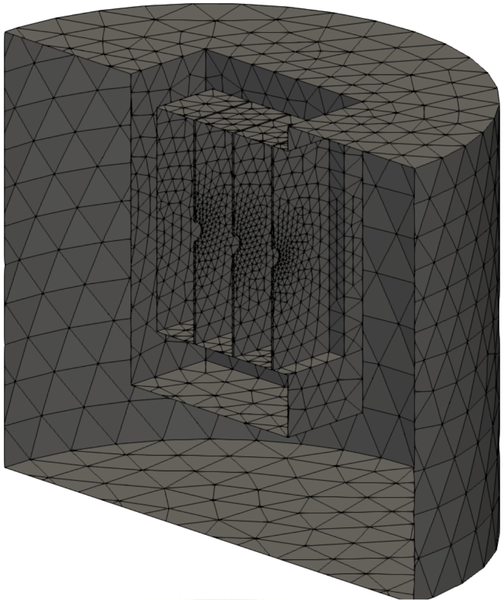
4-Plate BOX Simulation

Overview of Meshes

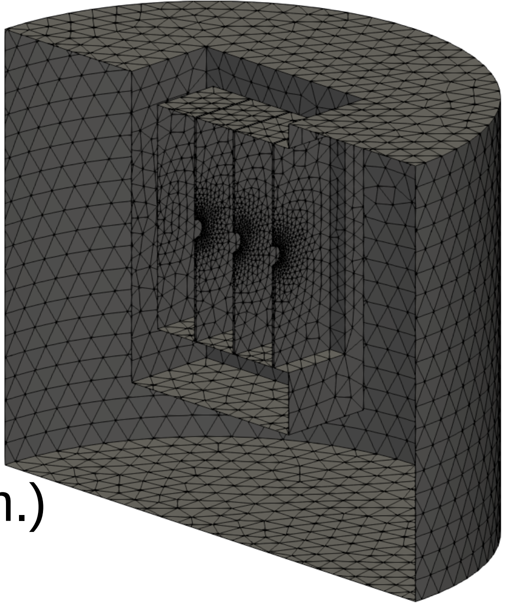
Only the surface meshes are shown.



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



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

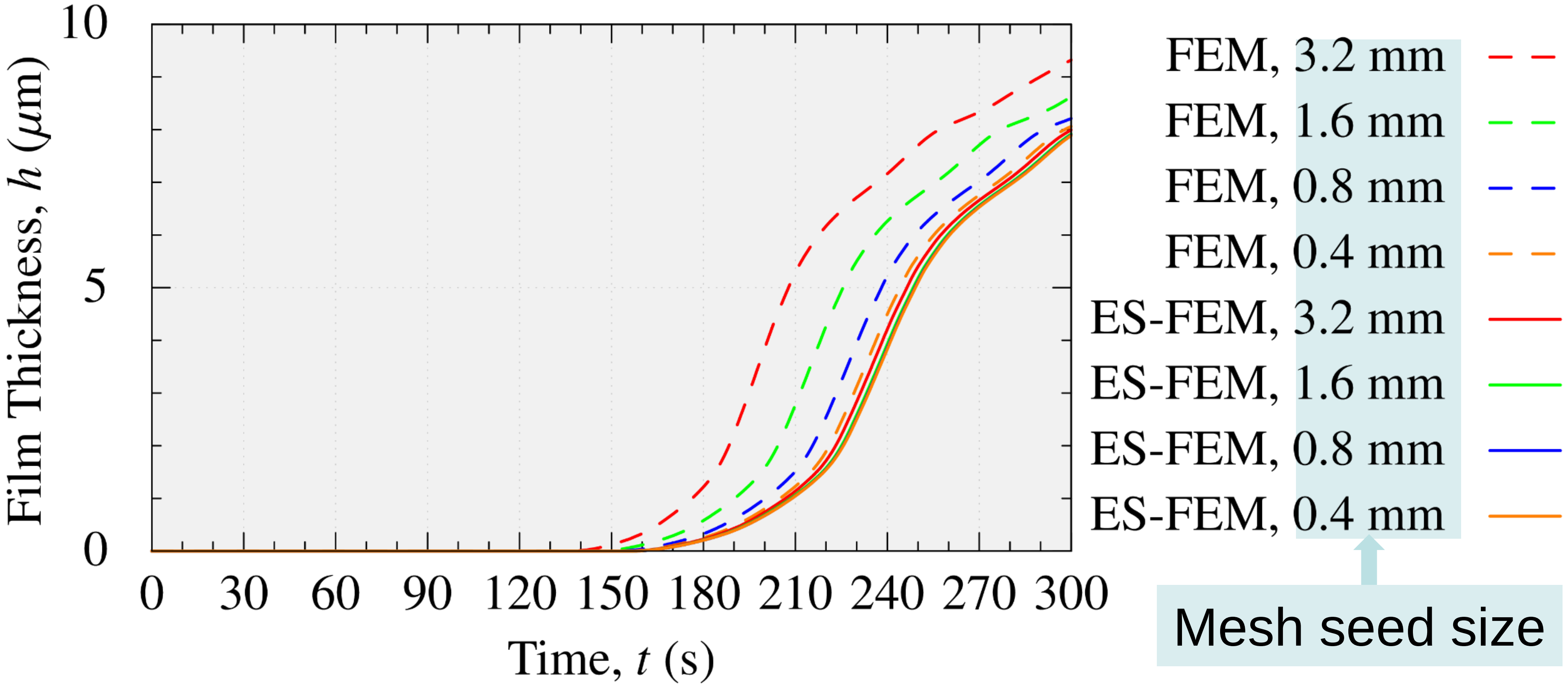


0.8 mm Mesh
Seed Size
(169k T4 elem.)

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

4-Plate BOX Simulation

Film Thickness on Face G (innermost surface)

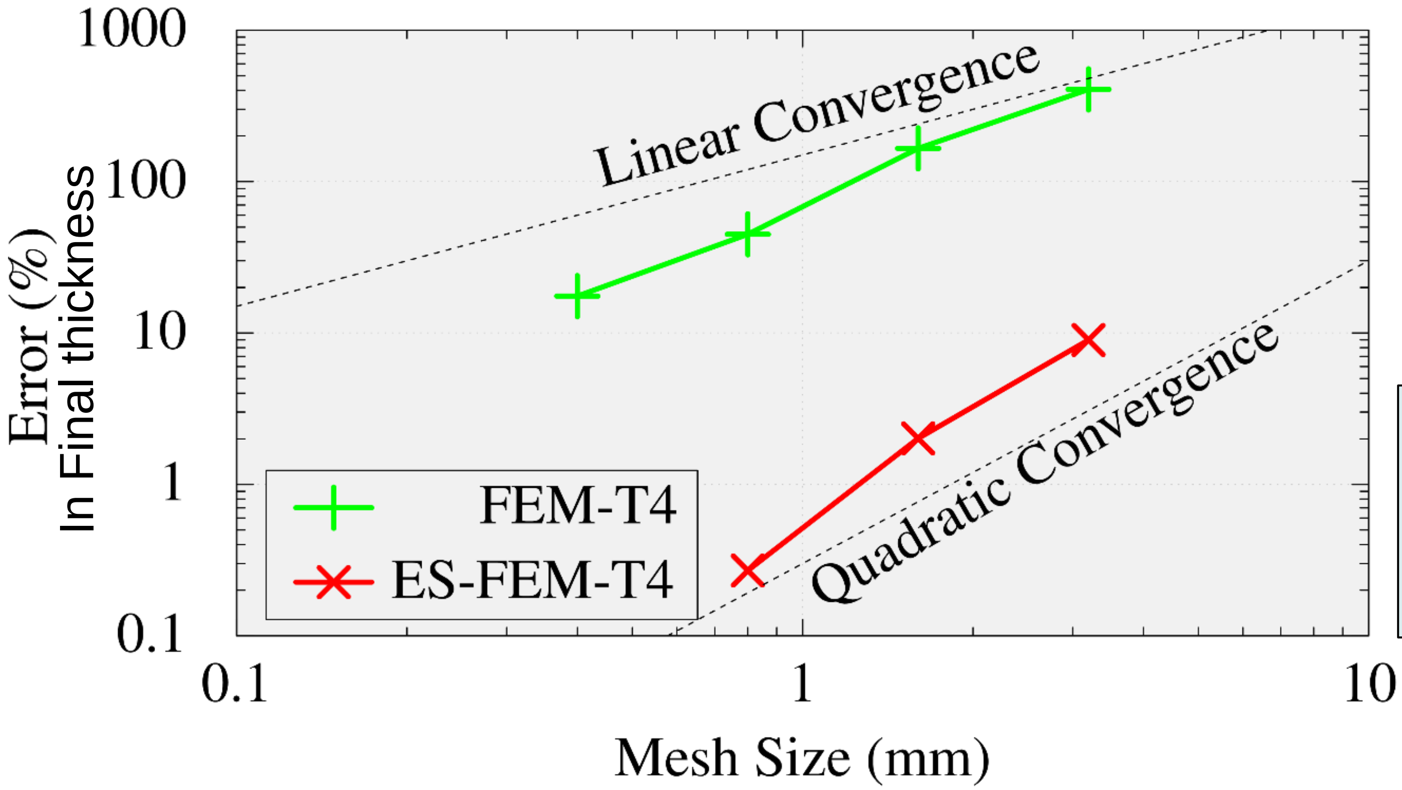


FEM results (dashed lines) have ***large*** errors.

Meanwhile, ES-FEM results (solid lines) have no such errors due to the fast mesh convergence rate.

4-Plate BOX Simulation

Comparison of Mesh Convergence Rate on Face G



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

- FEM-T4 shows a linear convergence.
- ES-FEM-T4 shows a quadratic convergence.

ES-FEM-T4 has much better mesh convergence rate than FEM-T4.

4-Plate BOX Simulation

Comparison of Calculation Time

on a PC (only 1 CPU: Intel i9-9960X)

Mesh Size	FEM-T4	ES-FEM-T4
3.2 mm	7 s	10 s
1.6 mm	8 s	14 s
0.8 mm	12 s	26 s
0.4 mm	41 s	125 s

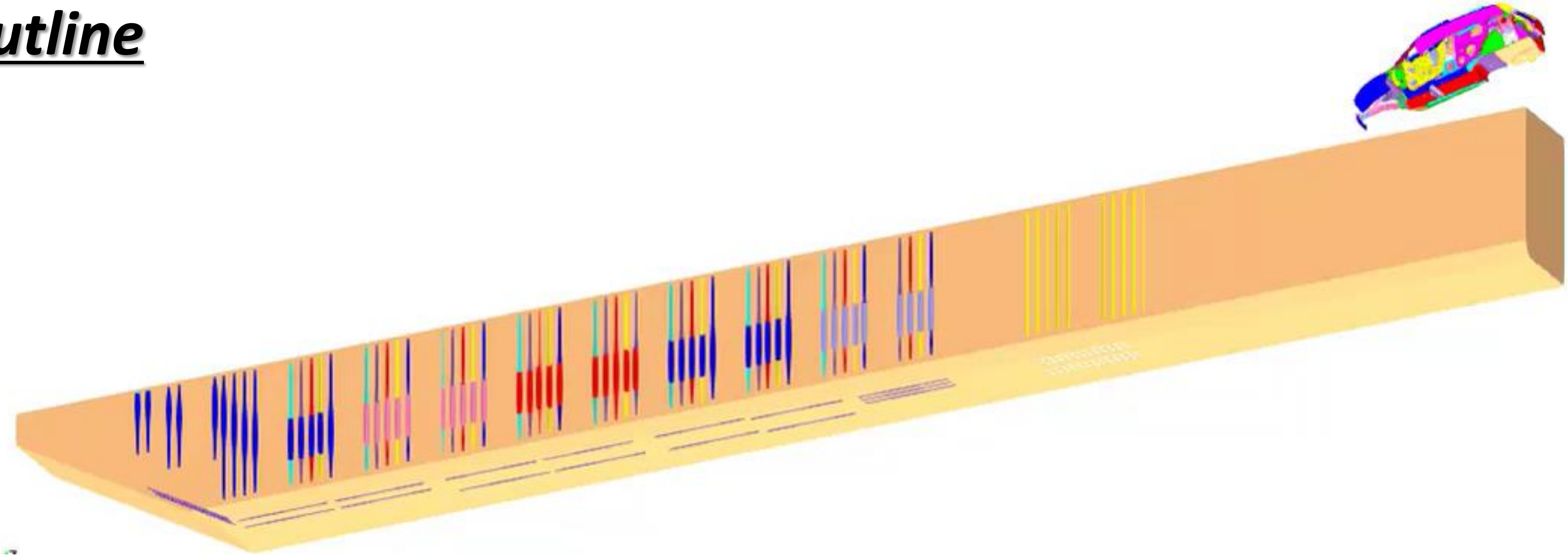
Comparable Accuracy

- With the same mesh, ES-FEM is slower than FEM by x2.
- For the same accuracy, ES-FEM is faster than FEM by x4.

ES-FEM-T4 is supremely efficient
in comparison to FEM-T4.

Actual Line Simulation

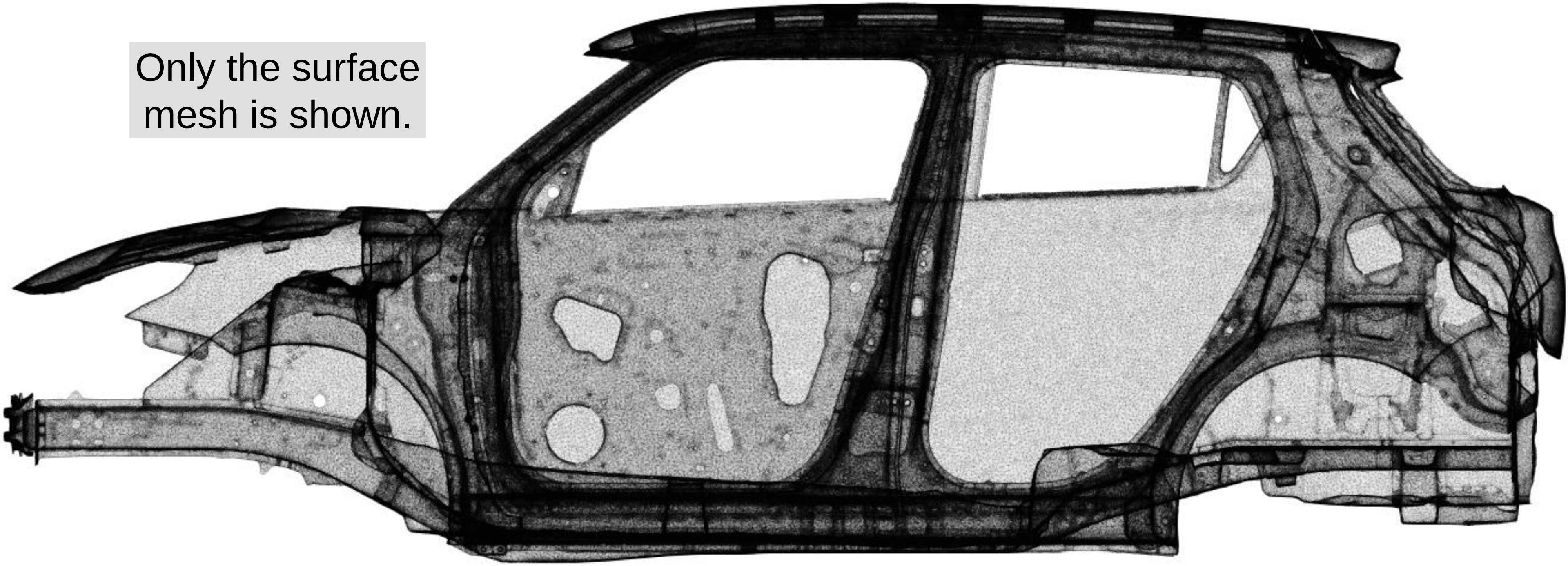
Outline



- **Half-body** analysis (only right-hand side).
- Entire line shape, carbody motion, and electrode conditions are faithfully reproduced.
- About 1000 timesteps for 300 s (i.e., average $\Delta t = 0.3$ s).
- The film thickness is evaluated with **3 different meshes for mesh validation using FEM-T4 and ES-FEM-T4.**

Actual Line Simulation

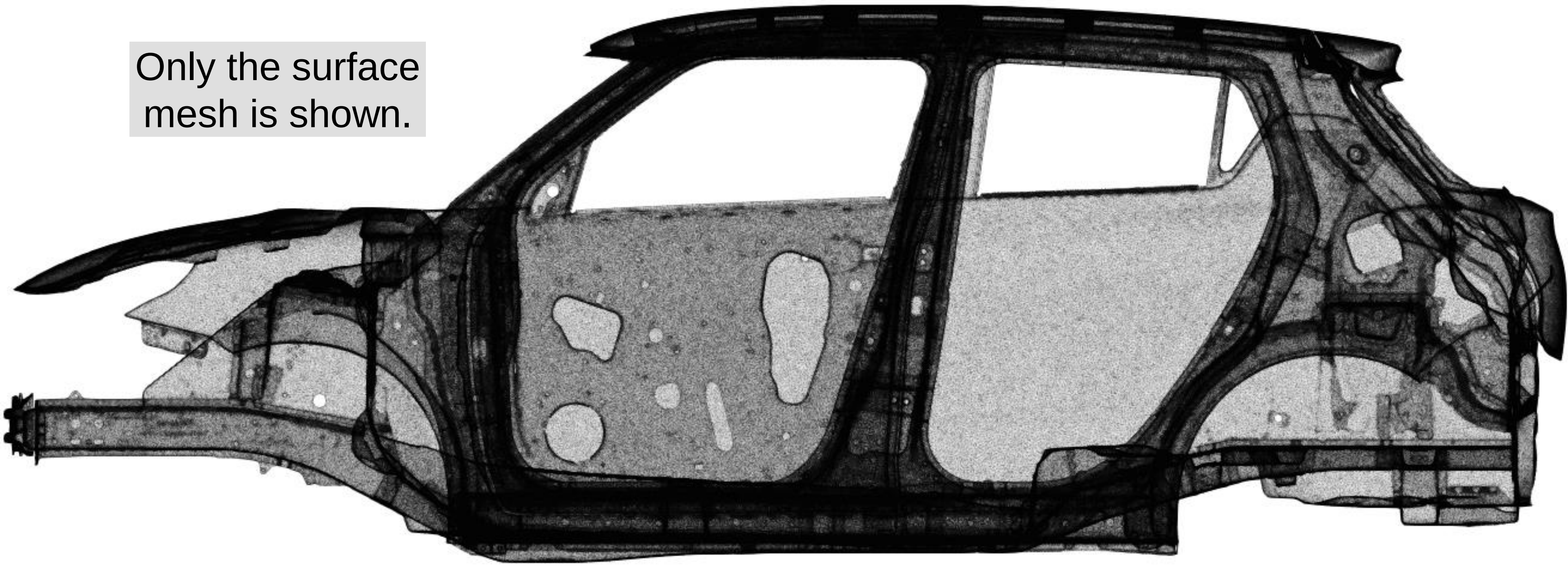
Overview of Surface Mesh of 10M Element Mesh


Only the surface mesh is shown.

- There are many ED holes around narrow spaces among plates.

Actual Line Simulation

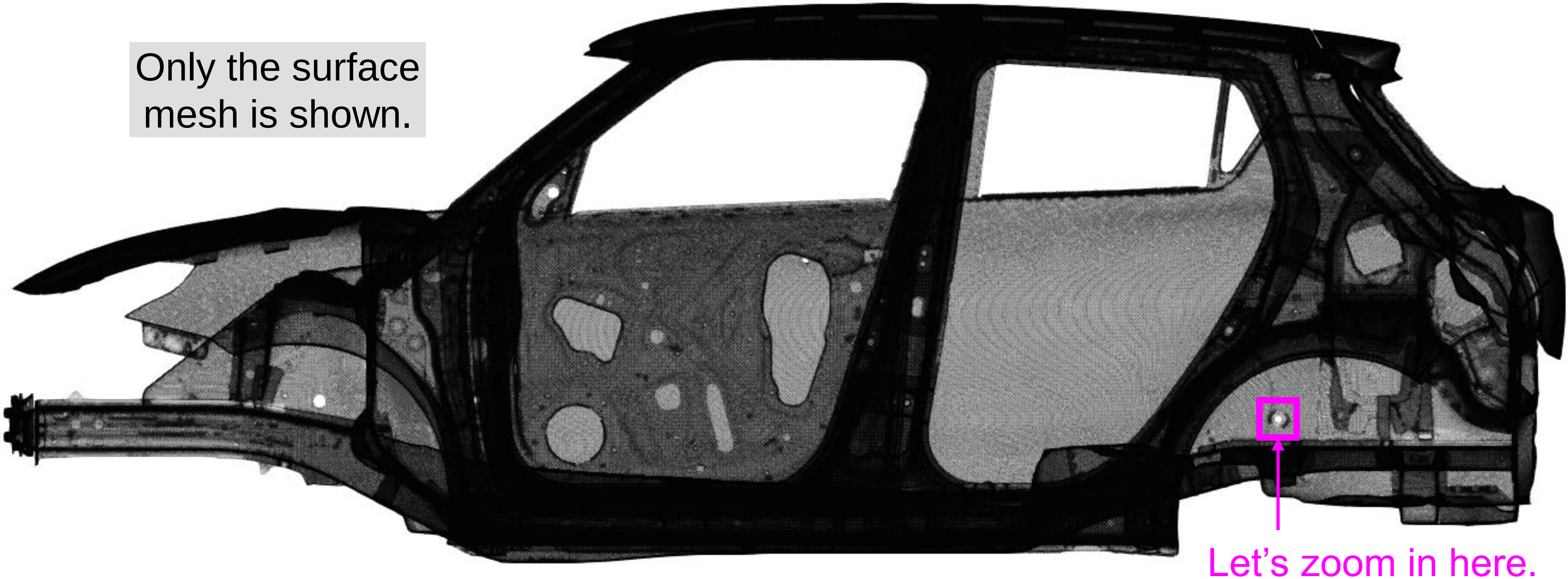
Overview of Surface Mesh of 16M Element Mesh


Only the surface mesh is shown.

- There are many ED holes around narrow spaces among plates.

Actual Line Simulation

Overview of Surface Mesh of 51M Element Mesh



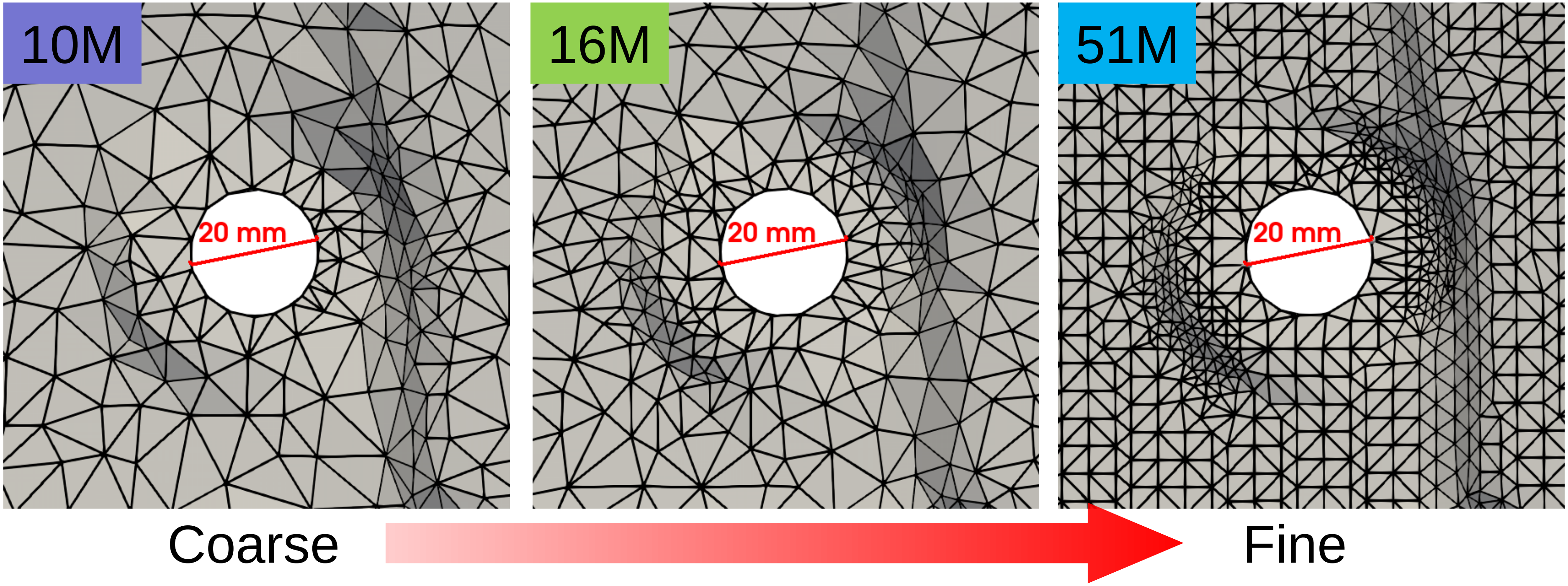
Only the surface mesh is shown.

Let's zoom in here.

- There are many ED holes around narrow spaces among plates.
- The difference in the mesh can be seen clearly by zooming in around a hole.

Actual Line Simulation

Zoom in View around a Hole on Carbody

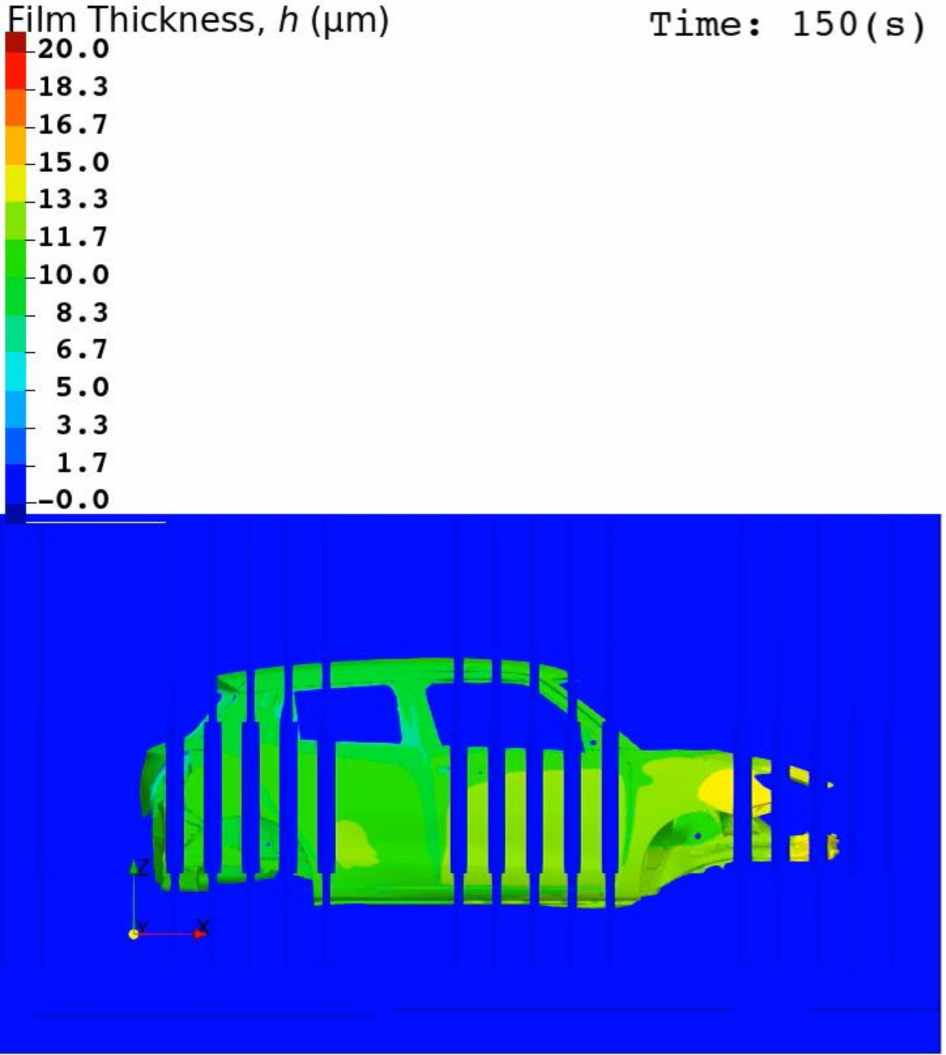


- There are many ED holes around narrow spaces among plates.
- The difference in the mesh can be seen clearly by zooming in around a hole.

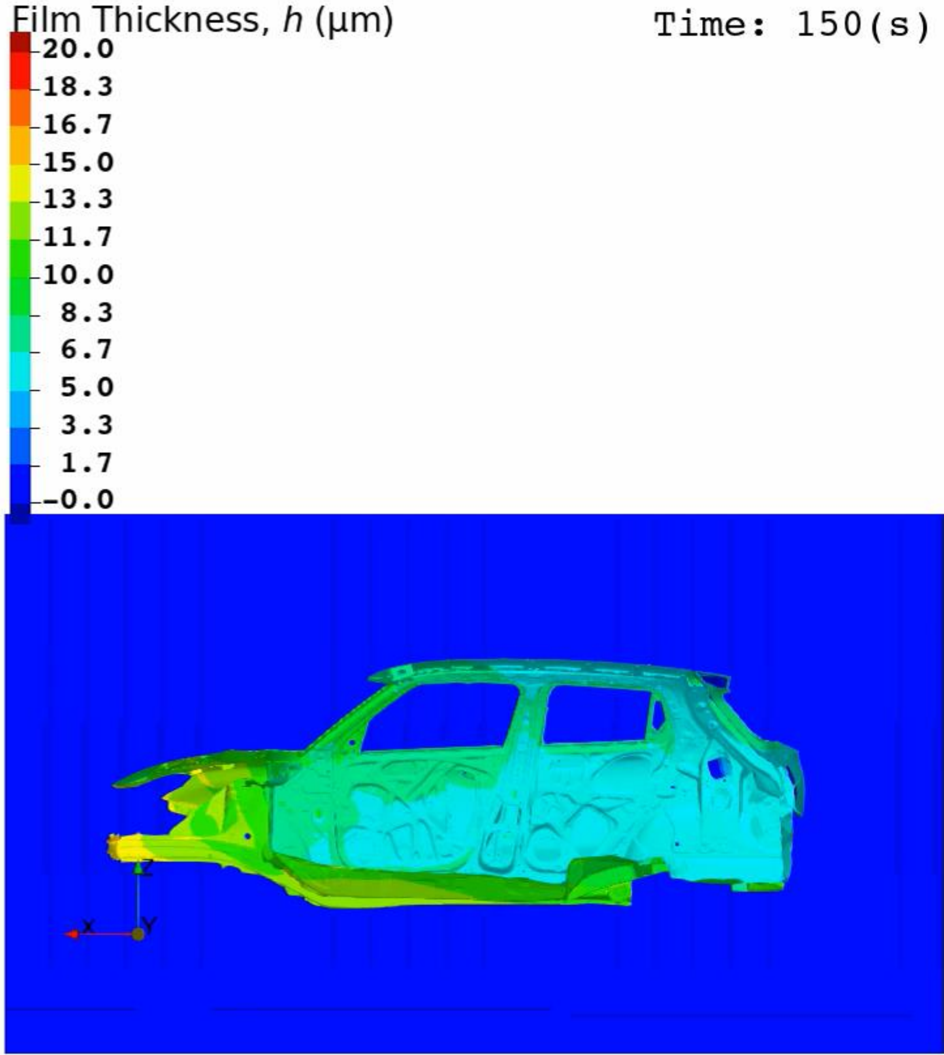
Actual Line Simulation

Animation of Film Thickness (ES-FEM with 51M Elems.)

Outer View



Inner View

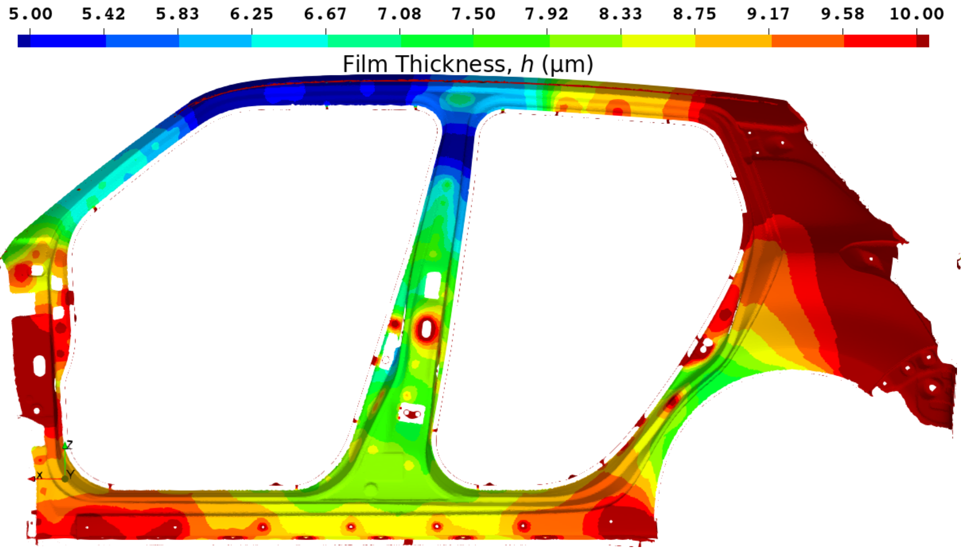


Actual Line Simulation

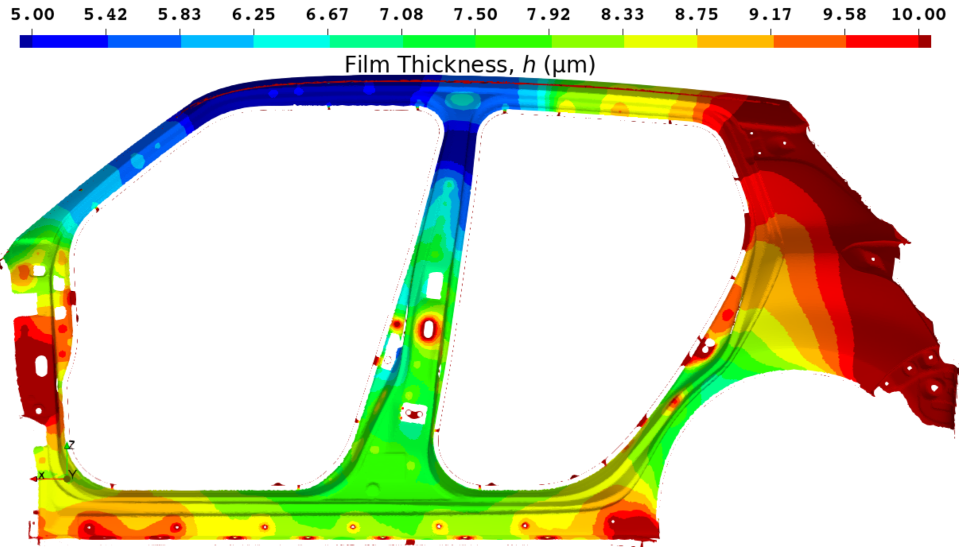
Film Thickness Distribution with 51M Elem. Mesh

(Clipped View on Side Sill)

FEM-T4



ES-FEM-T4



Reference Solution

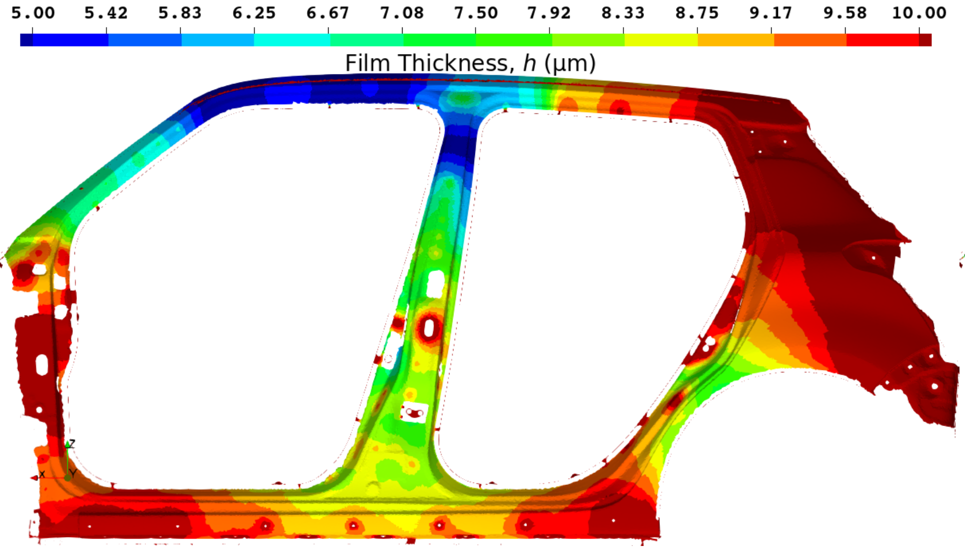
- FEM shows *a little thicker* result.
  (The center of the side sill is Yellow.)
- The ES-FEM result is regarded as a reference solution.
  (The center of the side sill is Green.)

Actual Line Simulation

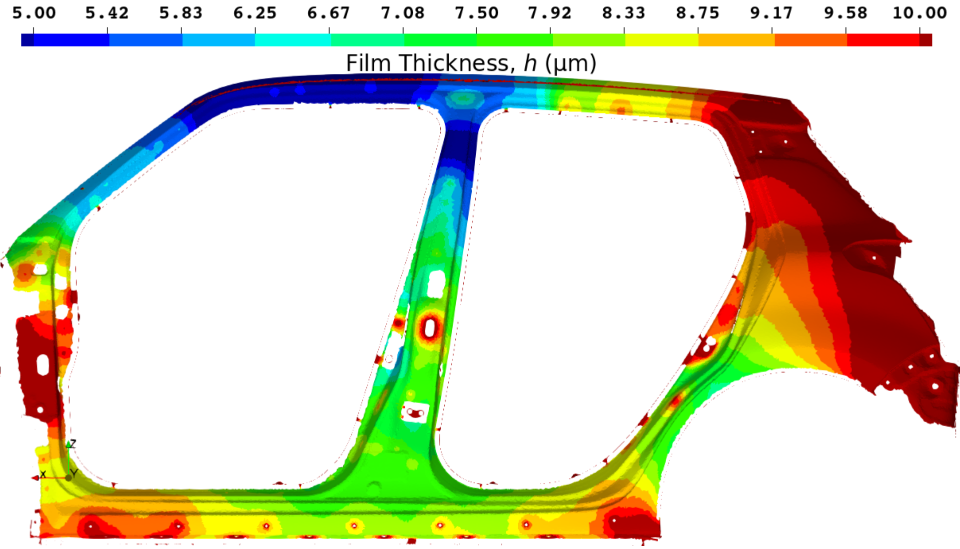
Film Thickness Distribution with 16M Elem. Mesh

(Clipped View on Side Sill)

FEM-T4



ES-FEM-T4

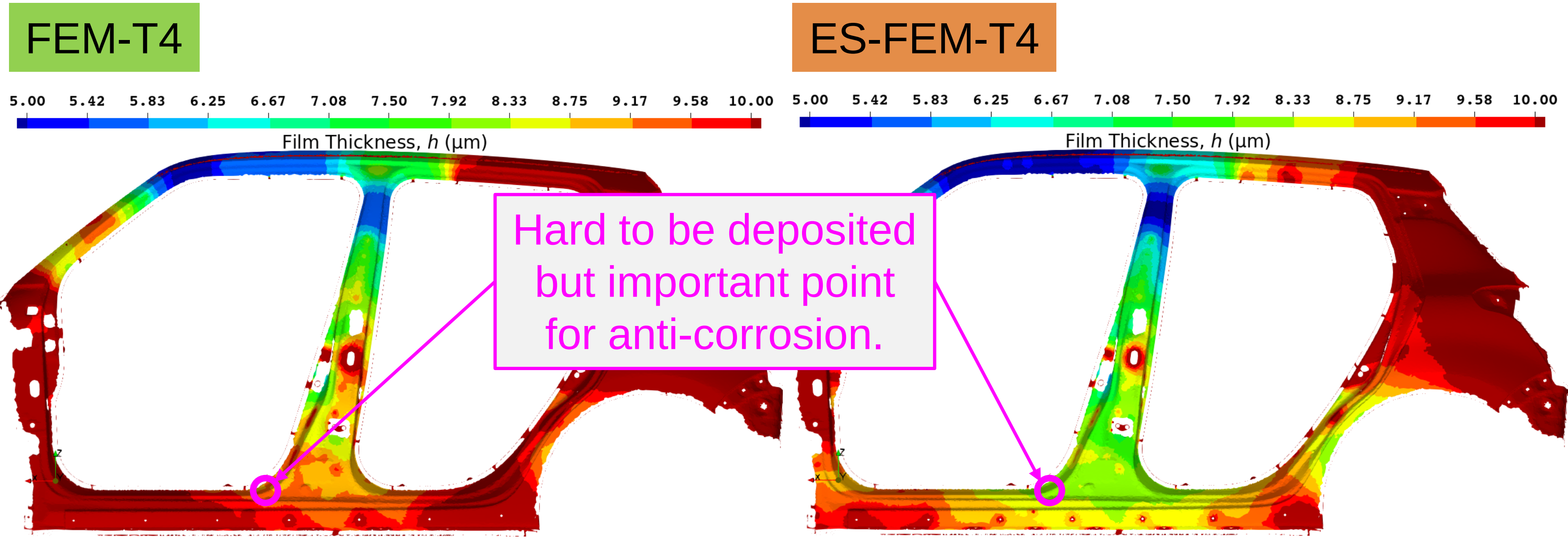


- FEM shows ***a much thicker*** result.
(The center of the side sill is Orange.)
- ES-FEM shows a similar result.
(The center of the side sill is Green.)

Actual Line Simulation

Film Thickness Distribution with 10M Elem. Mesh

(Clipped View on Side Sill)



FEM-T4

ES-FEM-T4

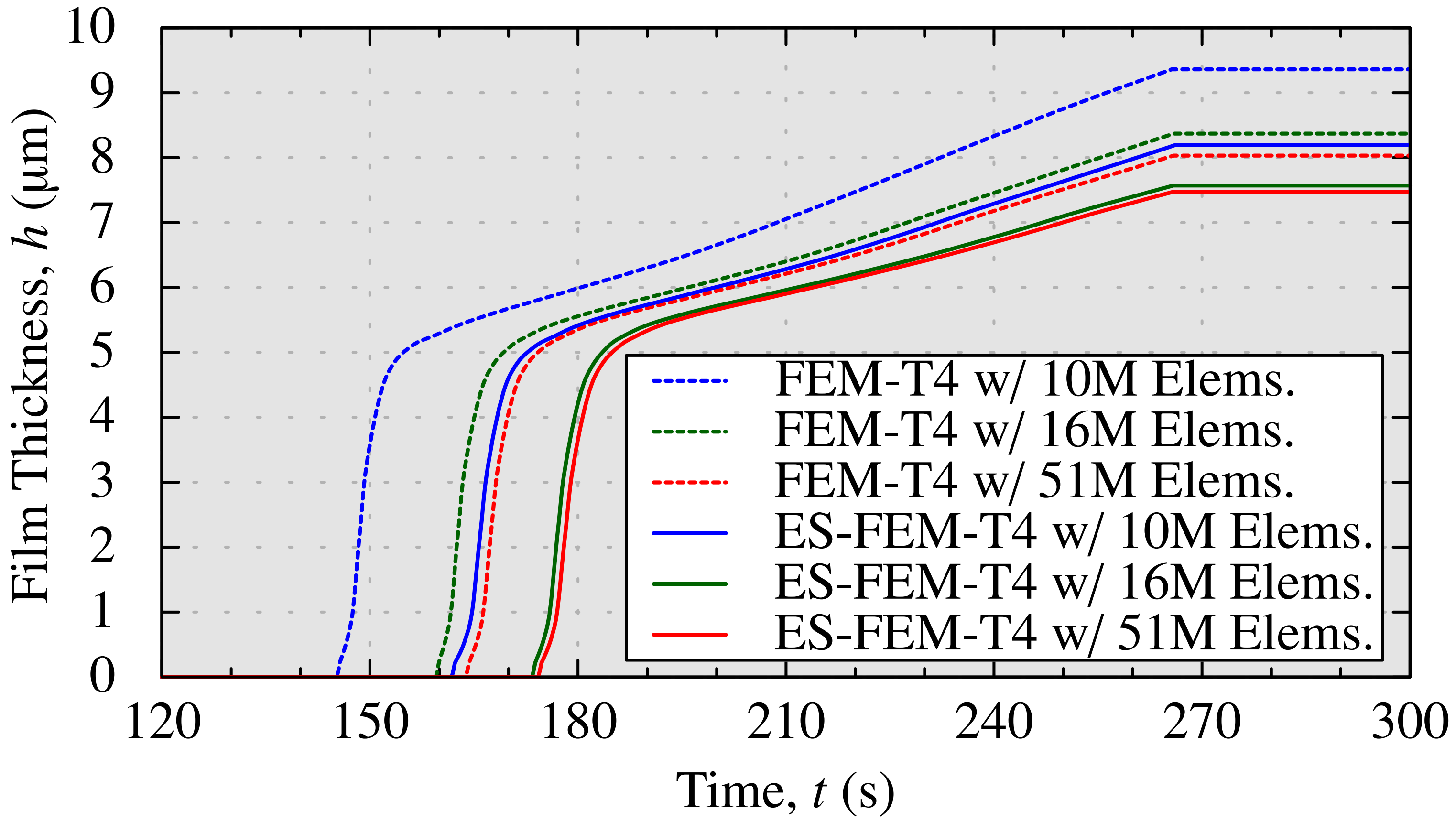
Hard to be deposited but important point for anti-corrosion.

- FEM shows ***a massively thicker*** result.
  (The center of the side sill is Red.)
- ES-FEM shows a little thicker result.
  (The center of the side sill is Yellow.)

Let's compare the time history of film thickness at a certain point.

Actual Line Simulation

Comparison of Time-histories of Film Thickness



- FEM-T4 with 51M elems. and ES-FEM-T4 with 10M elems. has almost comparable accuracy.
- ES-FEM-T4 with 16M elems. almost gets a converged result.

Actual Line Simulation

Comparison of Calculation Time

On a cluster (TSUBAME3.0: Intel Xeon E5-2680 v4, using 64 CPUs)

# of Elements	FEM-T4	ES-FEM-T4
10M	1.6 h	1.9 h
16M	2.3 h	3.4 h
51M	6.0 h	8.5 h

Comparable Accuracy

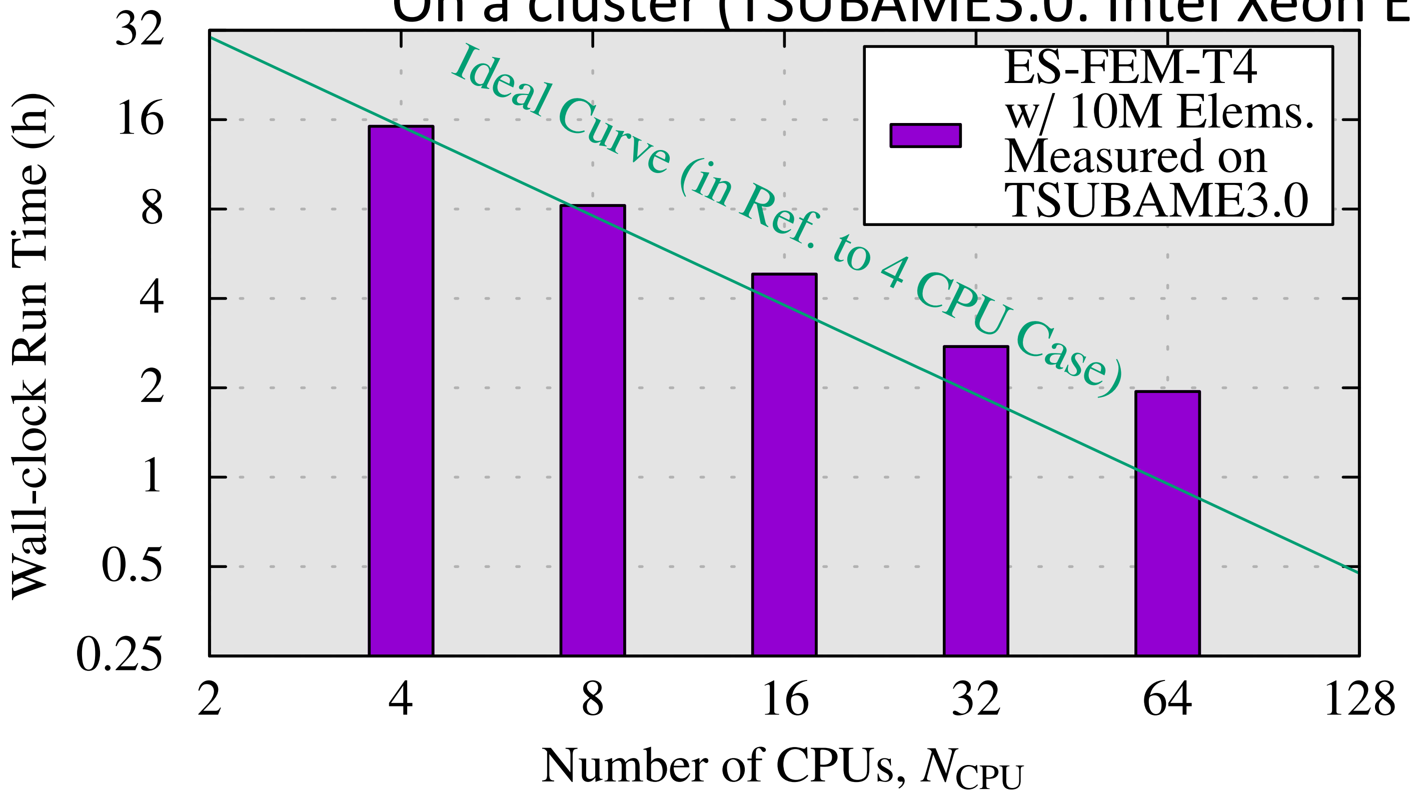
- With the same mesh, ES-FEM is slower than FEM by x1.5.
- For the same accuracy, ES-FEM is faster than FEM by x3.

For the accurate simulations of actual ED lines, ES-FEM-T4 is much better than FEM-T4.

Actual Line Simulation

Strong Scaling Test (with 10M Elem. Mesh)

On a cluster (TSUBAME3.0: Intel Xeon E5-2680 v4)



Our ES-FEM code scales to some extent up to 64 CPUs at least.

∵ Some tasks, including MPCs for the moving boundary, are not yet fully parallelized (our future work).

Summary

Summary

Conclusion

- ES-FEM-T4 was applied to large-scale practical ED simulations.
- The high accuracy of ES-FEM-T4, owing to its superlinear (almost quadratic) mesh convergence rate in ED simulation, was confirmed compared to the poor accuracy of FEM-T4.
- Our parallelized ES-FEM-T4 code enabled us to obtain mesh-converged accurate solutions of actual ED line simulations in reasonable time with relatively coarse meshes.
- Our code is already in use by automakers.

Summary

Acknowledgment

We appreciate the automakers below for supporting our project:

SUZUKI Motor Corp., SUBARU Corp., MAZDA Motor Corp..

Take-home Message

Why don't you use ES-FEM-T4?
It's supremely useful and easy to code!

Thank you for your kind attention.