Automotive Electrodeposition Coating Simulation using Edge-based Smoothed Finite Element Method

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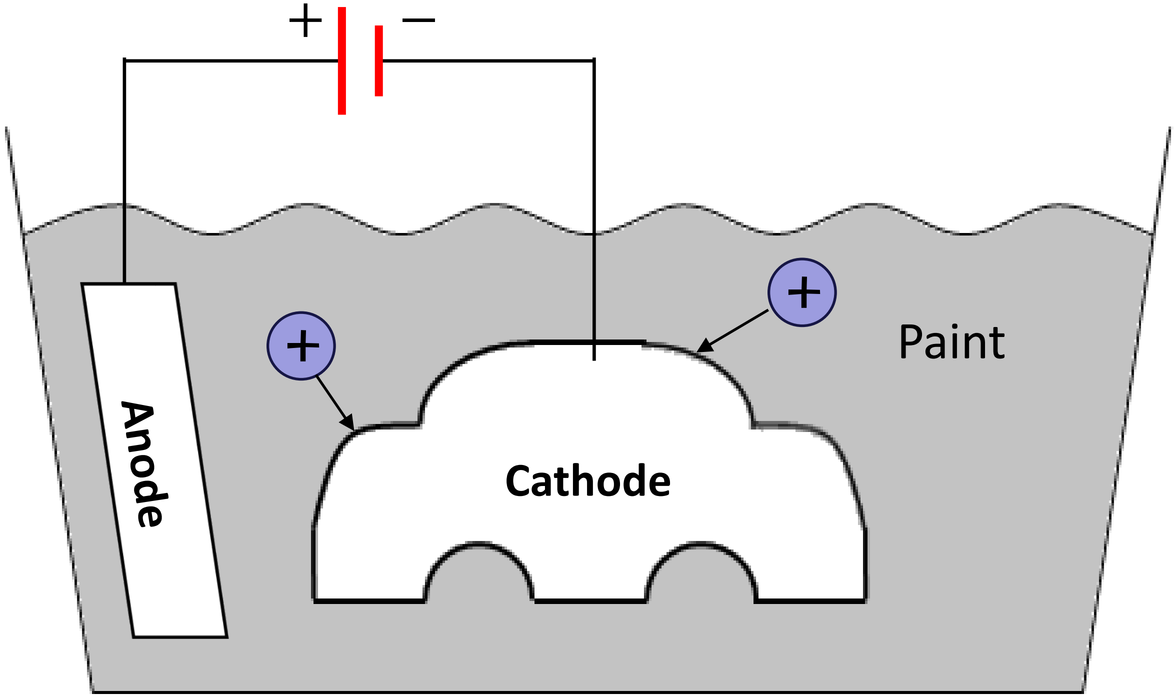
Relatively Long Introduction to Electrodeposition Simulation

What is Electrodeposition (ED) ?

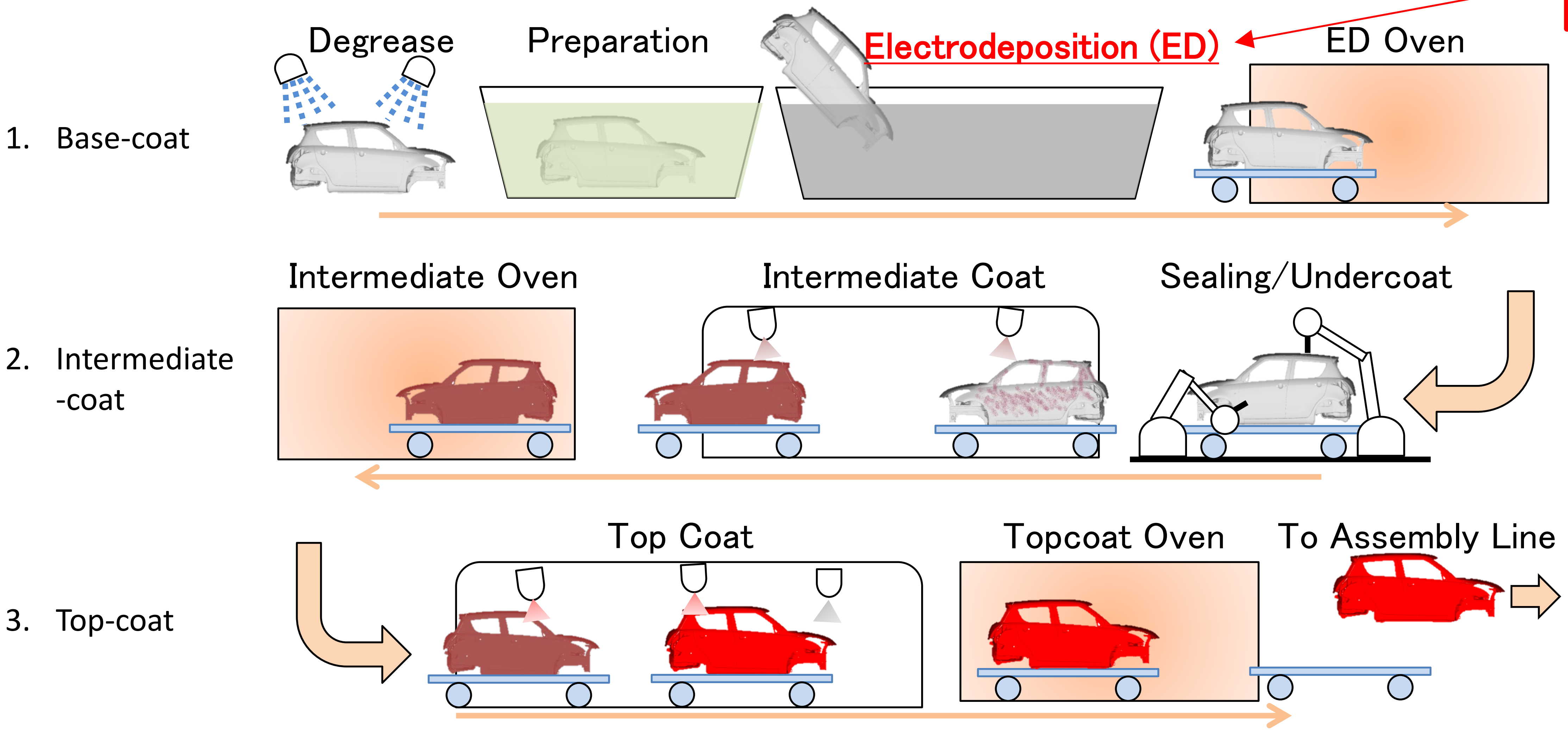


- Most widely-used **anti-rust base-coat** methods for various metal products including auto carbodies.
- Depositing coating film by applying **direct electric current** in a paint pool.
- In the actual car manufacturing line, the carbodies are moving in the paint pool.
- Relatively good at depositing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



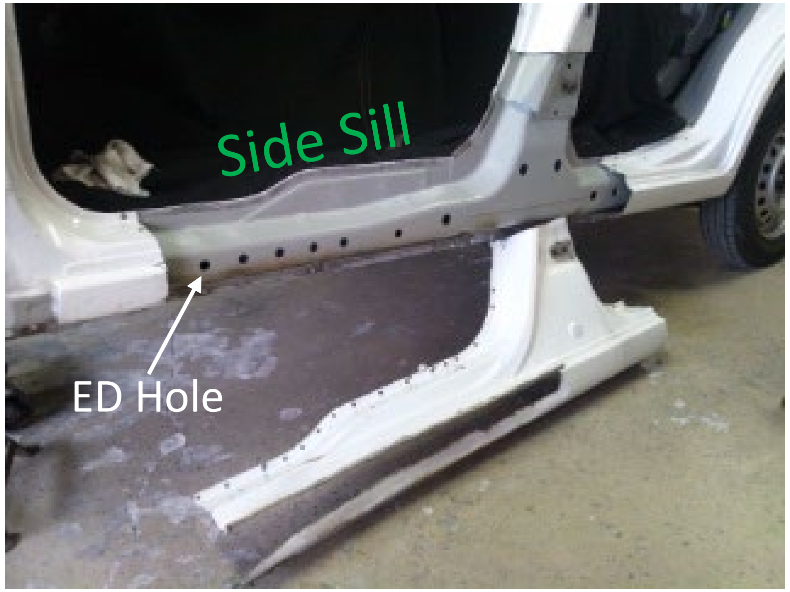
Importance of ED for safety

Quiz.)
Is this car safe
as when it was new?

- No, because corrosion significantly reduces the strength and stiffness of a car.
- As corrosion progresses, the initial strength and stiffness cannot be guaranteed.
- Nevertheless, the safety inspections of cars (e.g., crash tests) are usually performed with new cars without corrosion……

∴ ED is quite important for ensuring the long-term safety of carbodies.

Impact of ED process on carbody design

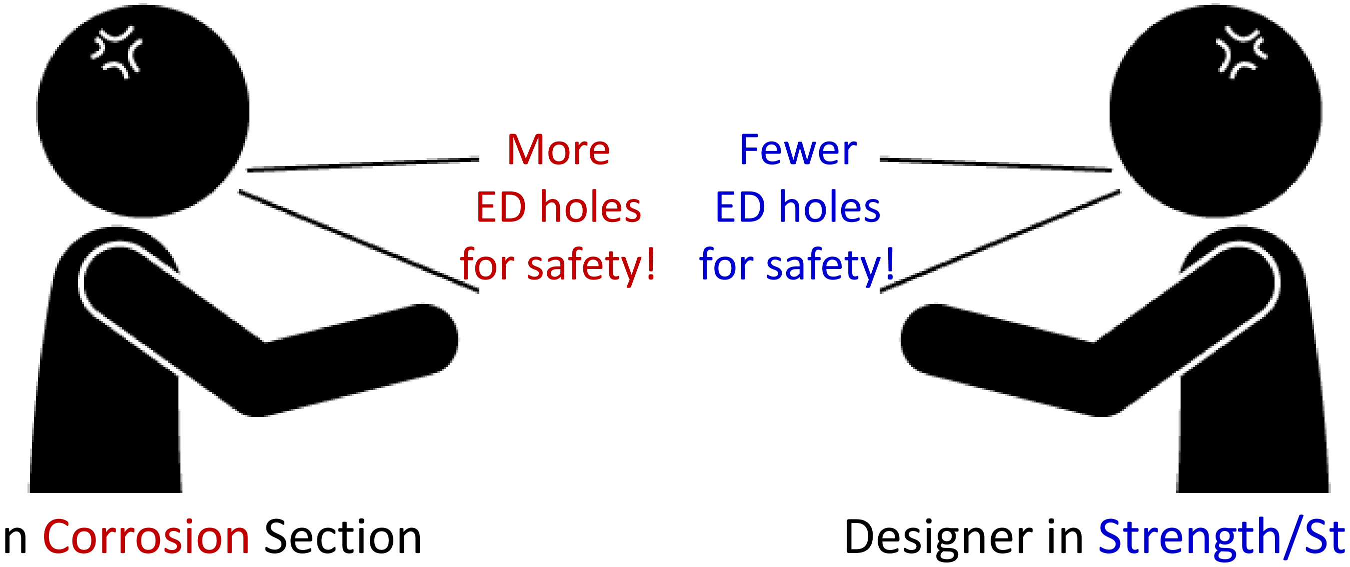


- Undercarriages are exposed to severe corrosive environments.
- ED film thickness must be above minimum over the entire surface of the undercarriages.
- Some undercarriage parts (e.g., side sills) have bag-like structures with multiple plates.
- It is necessary to drill **many ED holes** to allow the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

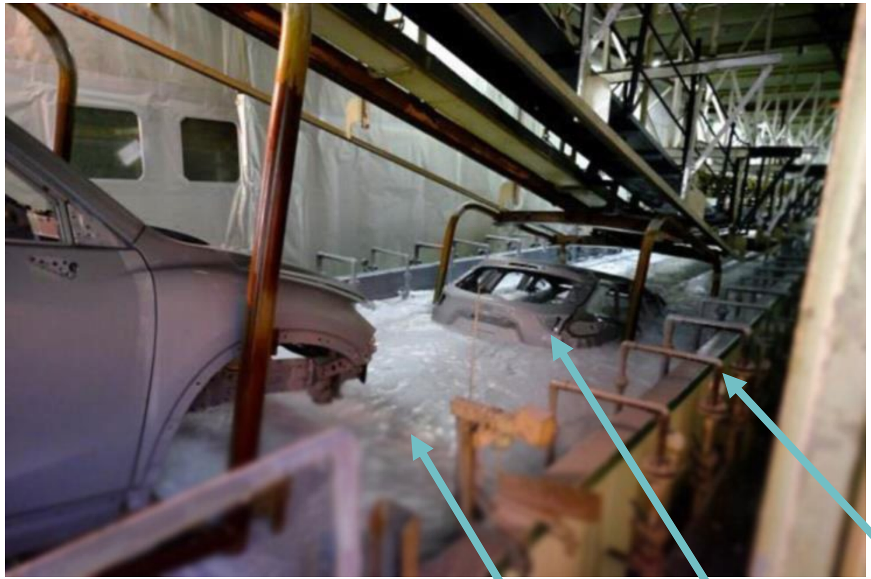
- ED holes are essential for corrosion protection,
  but they are NOT welcome for strength or stiffness.
- Thus, the following conflict always occurs between carbody designers.



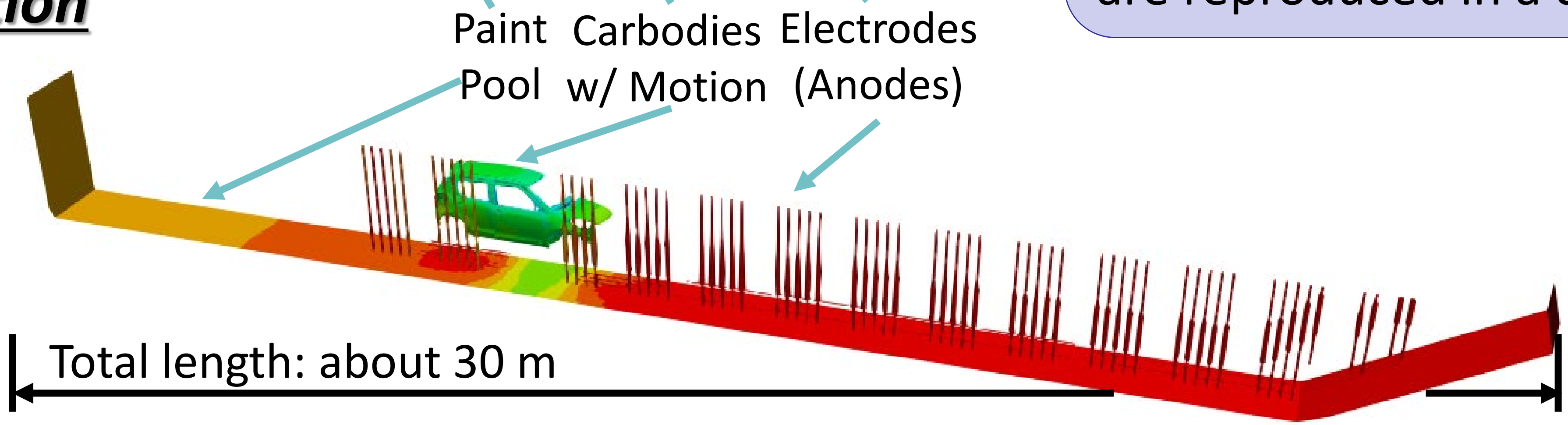
In such a case, **ED simulation** can resolve the conflict
based on quantitative evidence data and lead to the optimal carbody design.

What is ED Simulation?

Actual ED Line



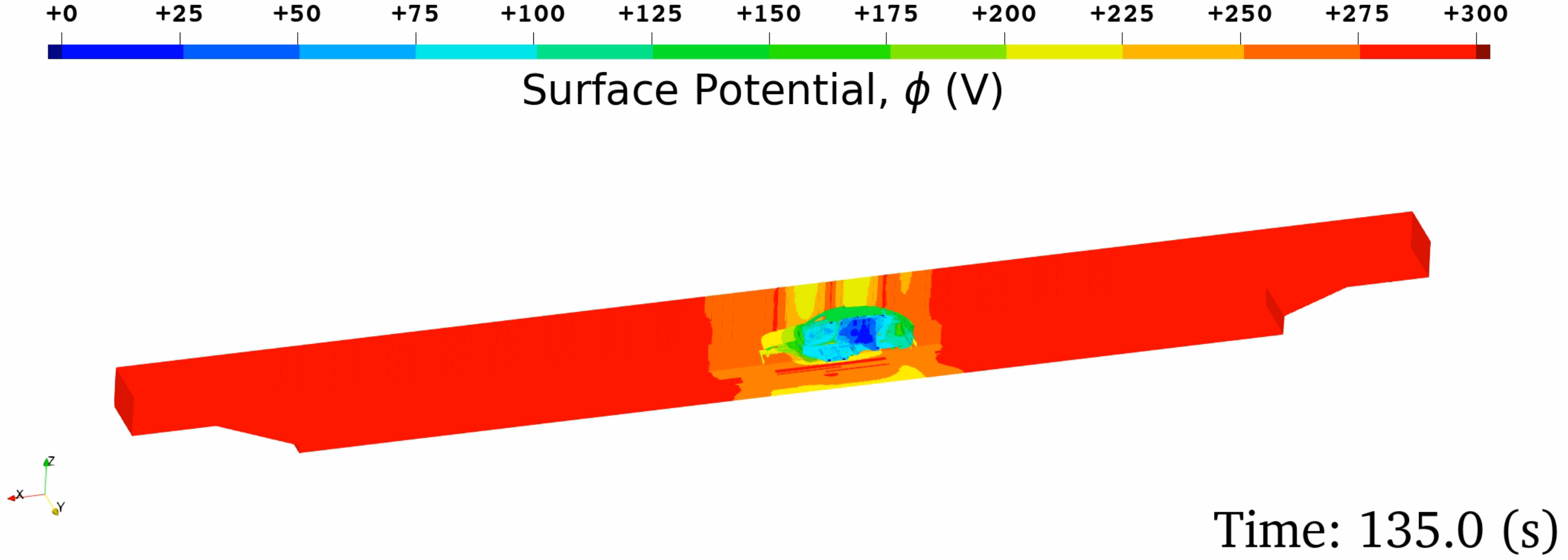
ED Simulation



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

are reproduced in a computer.

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:
     Film initiation/growth/resistance constitutive models.

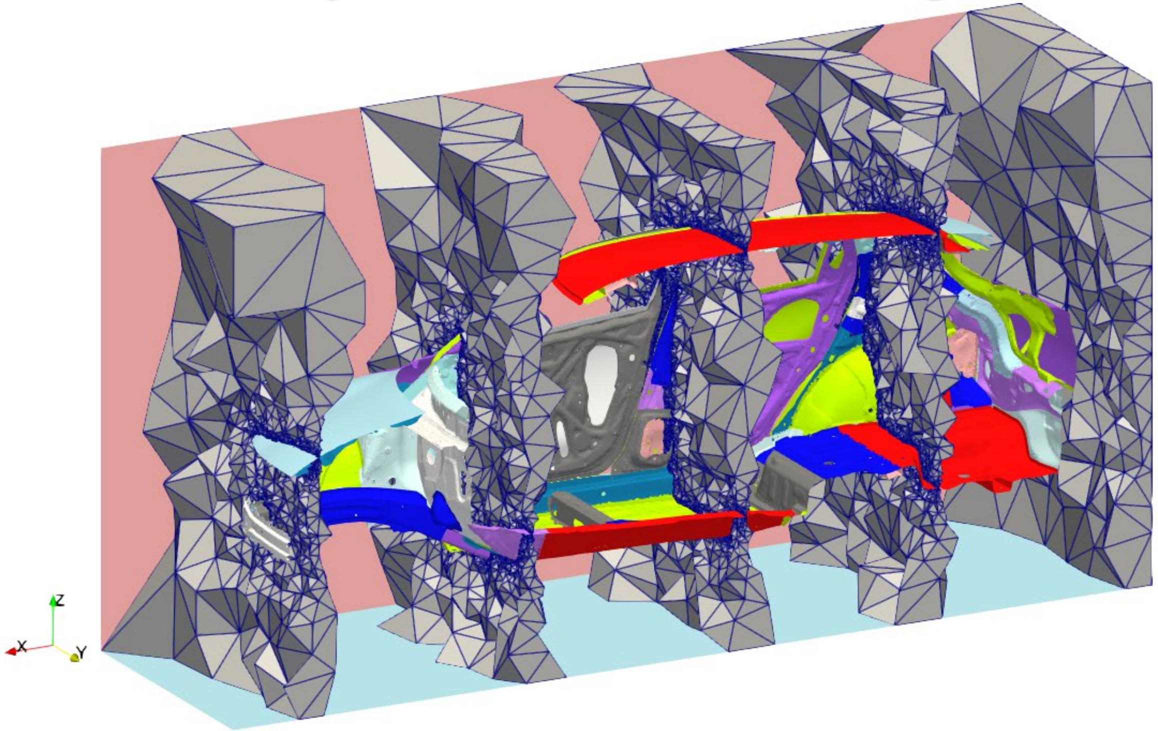
Identified via lab experiments. ↓

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

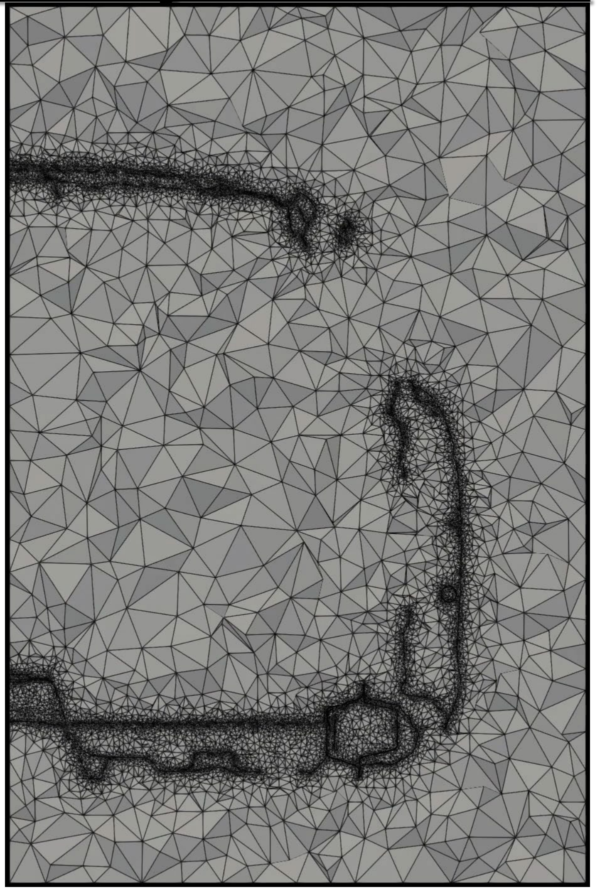
Final film thickness ← is the main output.

Two Issues in Meshing for ED Simulation

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



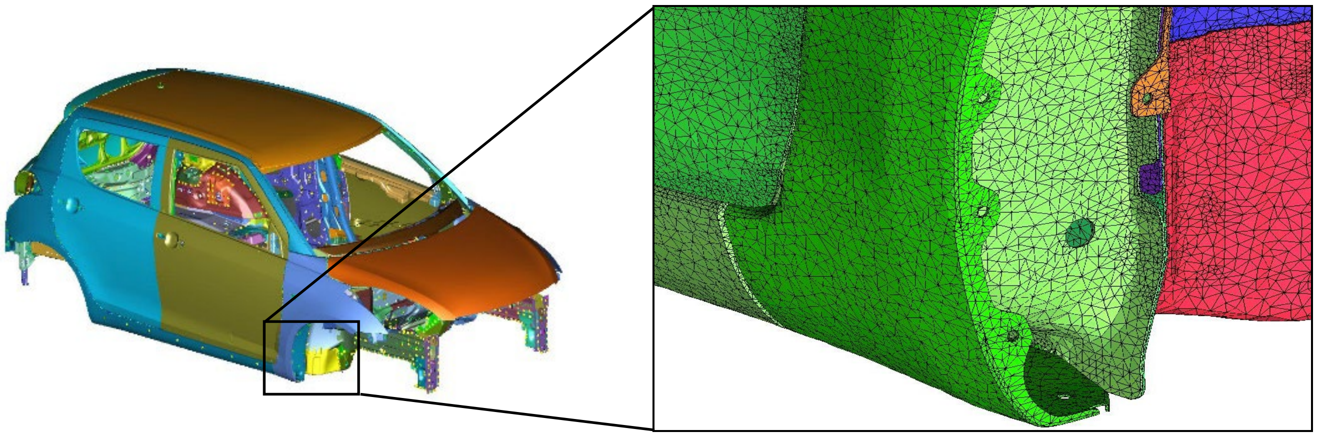
5 slices of a carbody mesh



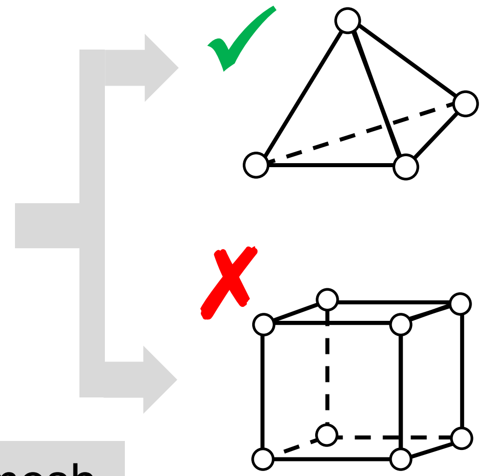
Animated slices of a carbody mesh from rear to front

- 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).

Two Issues in Meshing for ED Simulation



Zoom-in view of a carbody surface mesh



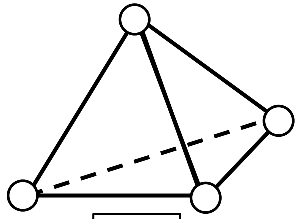
- The shape of a carbody is too complex to be discretized into a good HEX mesh.
- The Cartesian mesh (e.g., cutcell mesh, snappy hex mesh, cube mesh) is basically NOT suitable for the geometry with many holes.
  (∵ Massive increase in DOF, Linear mesh convergence rate of H8 element,
  Presence of hanging nodes or polyhedral cells)

TET meshes are preferable in ED simulation.

Two Issues in Meshing for ED Simulation

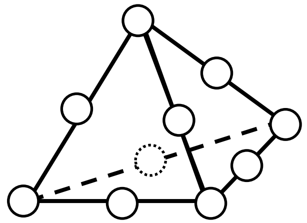
Issue #2: Both the standard 4-node and 10-node tetrahedral elements are inconvenient.

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



T4

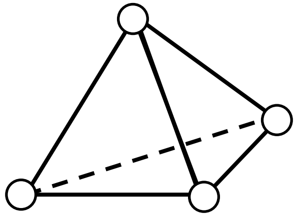
- 10-node TET (**T10**) has good accuracy with a quadratic mesh convergence rate; however, T10 mesh requires a massively large DOF to represent complex shapes without any kink in element shapes.



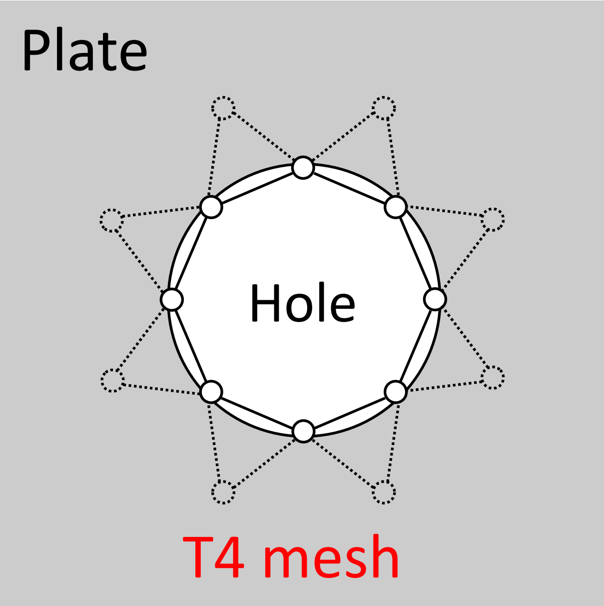
T10

Two Issues in Meshing for ED Simulation

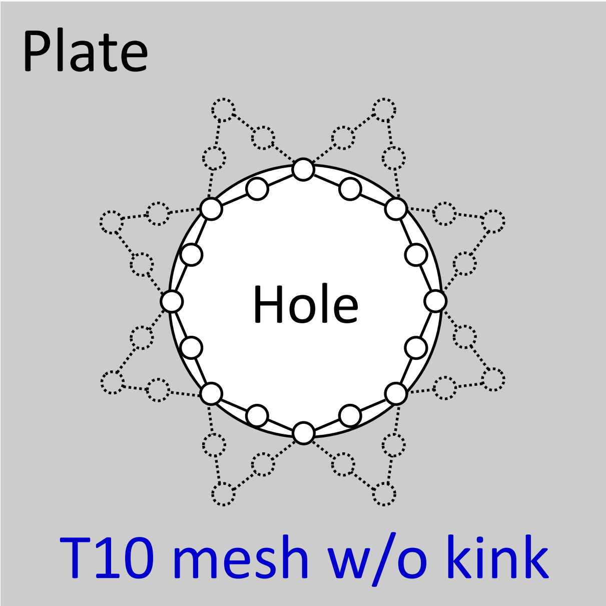
⟹ If there is a small **hole** on a carbody plate,
the surface mesh around the hole looks like…



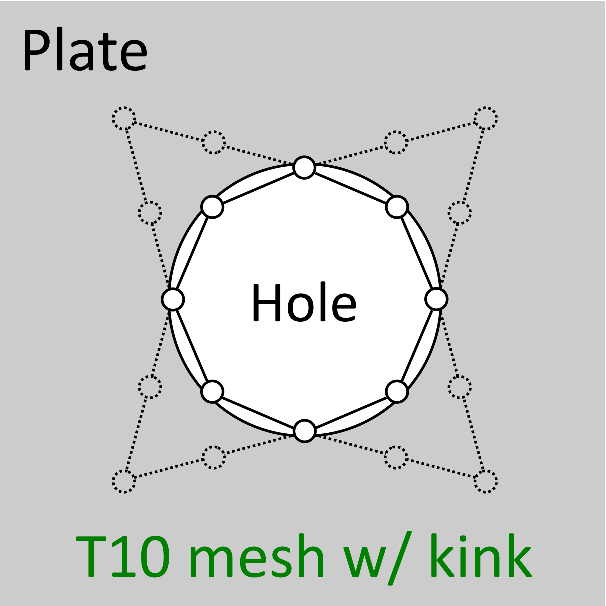
T4



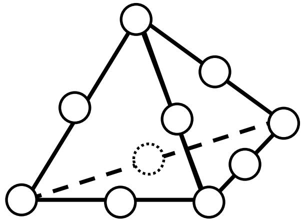
✗ leads to poor mesh convergence rate with FEM-T4.



✗ leads to a massive increase in DOF with mid-nodes.



✗ leads to severe accuracy loss in shape function with FEM-T10.



T10

Both the standard T4 and T10 elements are inconvenient as a carbody mesh to achieve accurate simulation with minimal DOF.

Motivation

By the way, …

- The smoothed finite element method (S-FEM) [detail later] 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 practical (fast & accurate) ED simulations.

Table of body contents:

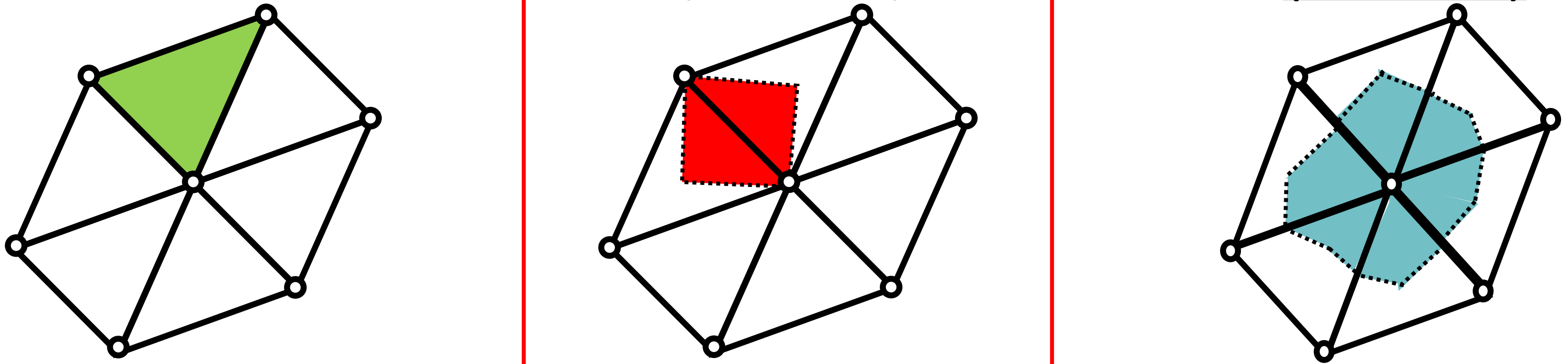
Quick Introduction to Smoothed Finite Element Method (S-FEM)

What is S-FEM?

- ***Smoothed*** finite element method (**S-FEM**) is a relatively new FE formulation proposed in 2006.
- S-FEM is one of the **gradient (strain) smoothing** techniques.
- **Many types of S-FEMs** have been developed with various smoothing schemes.
- There are a few *classical* S-FEMs depending on the smoothing domain.

For example, in a 2D triangular mesh:

Standard FEM | Edge-based S-FEM (ES-FEM) | Node-based S-FEM (NS-FEM)



Each colored area shows the domain for gradient smoothing.

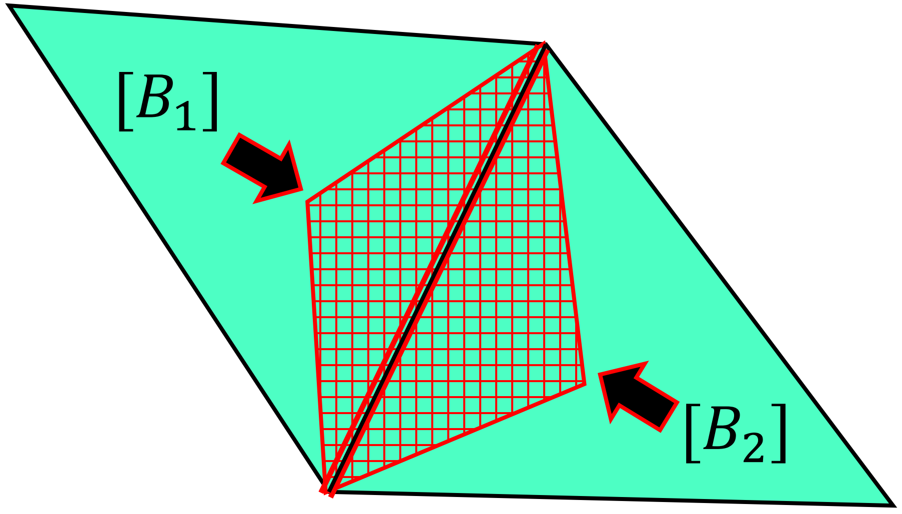
Brief of ES-FEM in Linear Elastic Analysis

Let us consider a mesh with only two 3-node triangular cells.

Let me explain in 2D for simplicity

- Make $[B](=\mathrm{d}\boldsymbol{N}/\mathrm{d}\boldsymbol{x})$ at each cell as usual.
- At each edge, gather $[B]$s of the connecting cells and average them with area weights to build $[{}^{\mathrm{Edge}}B]$.
- Calculate strain ($\boldsymbol{\varepsilon}$), stress ($\boldsymbol{\sigma}$) and nodal internal force $\{f^{\mathrm{int}}\}$ in each edge smoothing domain with $[{}^{\mathrm{Edge}}B]$.

As if putting a Gauss point at each edge center



No shear locking.

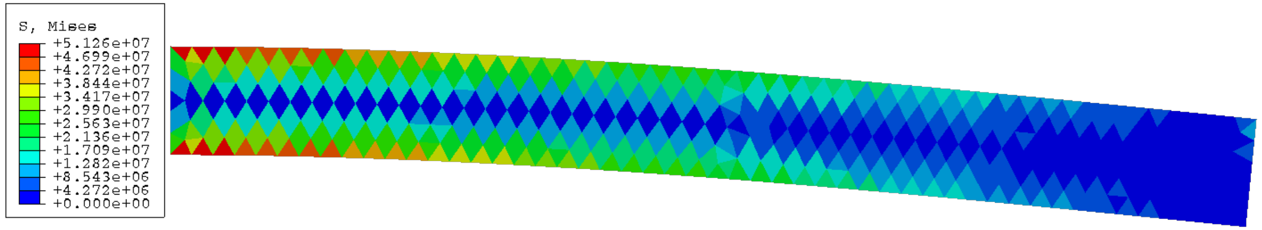
$[{}^{\mathrm{Edge}}B]$

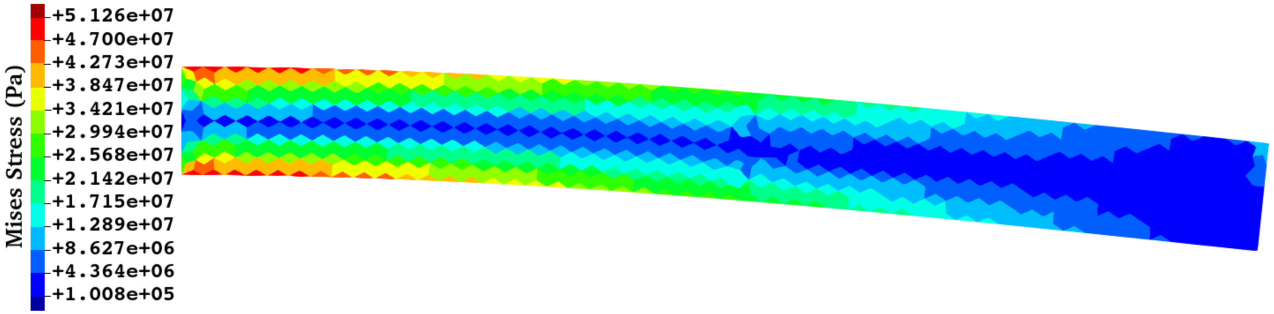
↳ ${}^{\mathrm{Edge}}\boldsymbol{\varepsilon}$, ${}^{\mathrm{Edge}}\boldsymbol{\sigma}$, $\{{}^{\mathrm{Edge}}f^{\mathrm{int}}\}$ etc.

Performance of ES-FEM in Linear Elastic Analysis

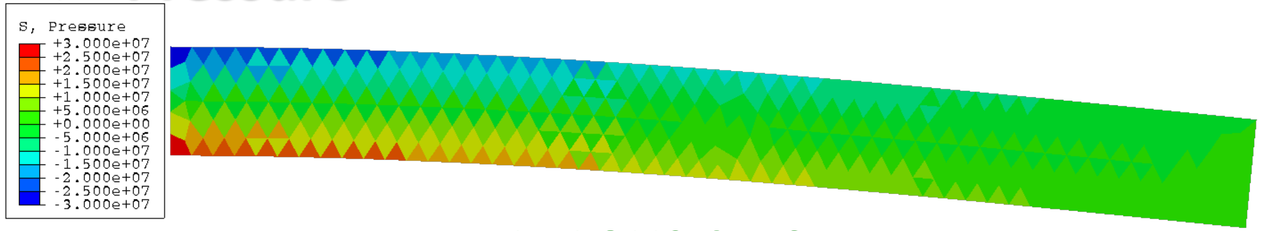
Cantilever Bending Analysis with Dead Load at the Tip Size:10x1 m, $\nu = 0.3$

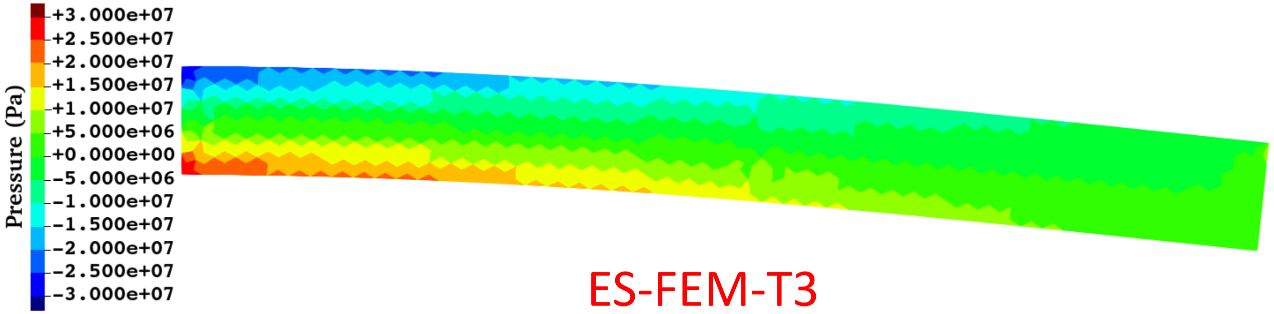
- **Mises stress**





- **Pressure**





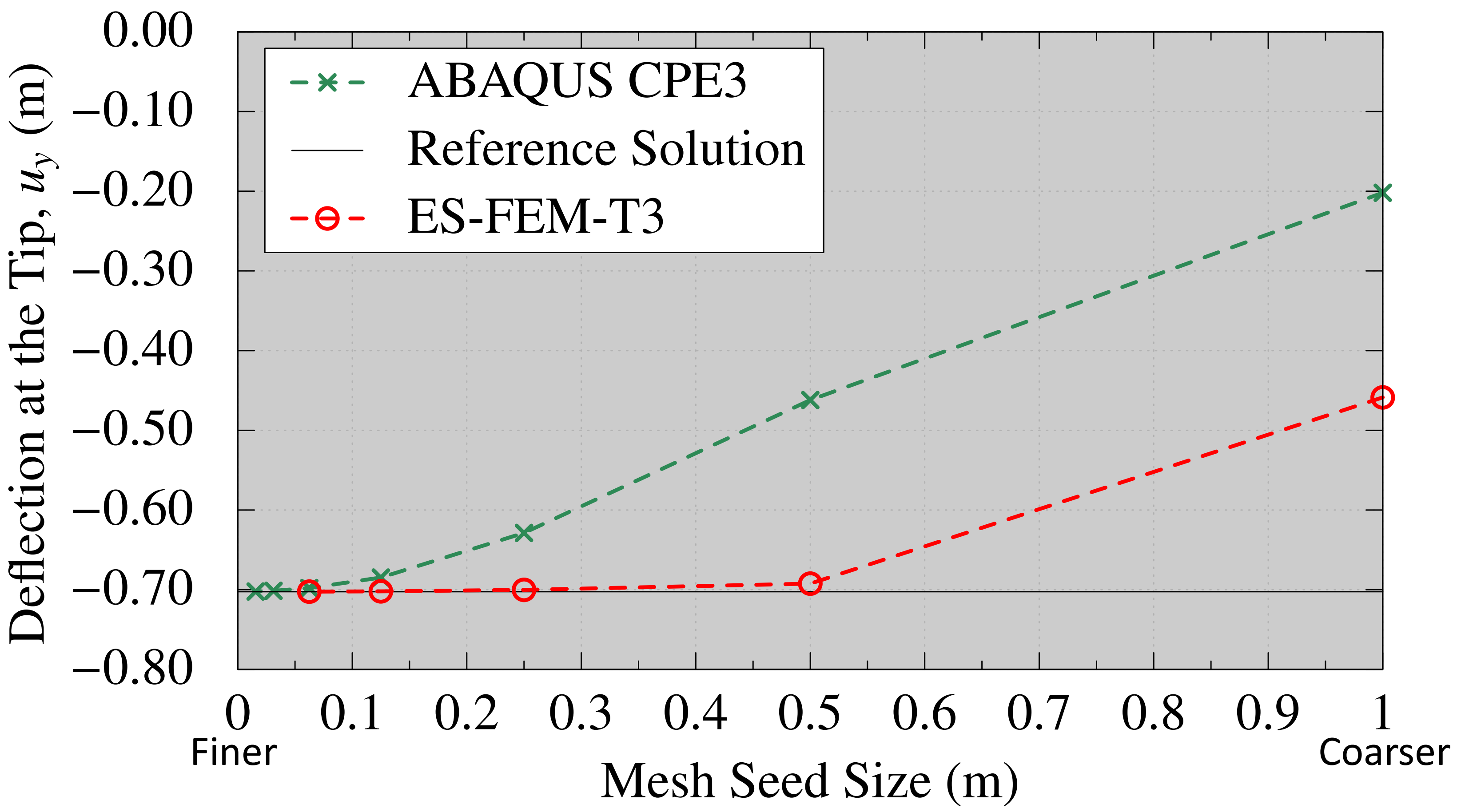
ABAQUS CPE3
(Standard FEM-T3)

ES-FEM-T3

ES-FEM-T3 gives more accurate stress/strain distributions than the standard FEM-T3 using the same mesh.

Performance of ES-FEM in Linear Elastic Analysis

➢ Mesh Convergence in Displacement



Mesh Seed Size (m)	The Number of Triangles
1	22
1/2	84 Converged
1/4	342
1/8	1,442
1/16	5,766 Converged
1/32	23,034
1/64	92,146

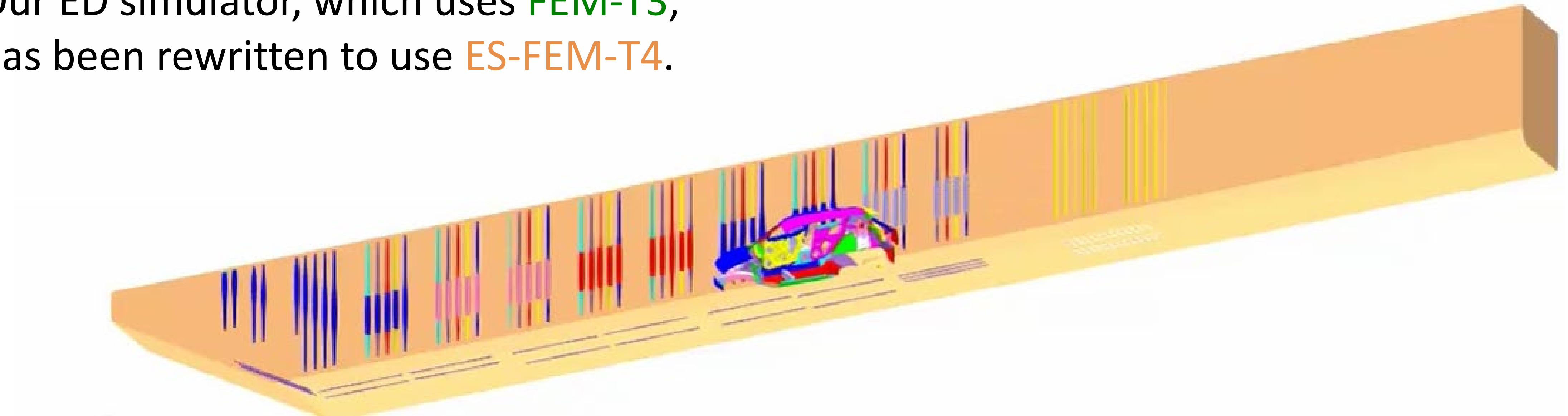
ES-FEM-T3 is shear locking free and thus the mesh convergence rate of displacement/force is much faster than the Standard FEM-T3.

➡ ES-FEM-T4 should also be excellent in electrostatic (ED) simulations.

Mesh Convergence Test

Outline

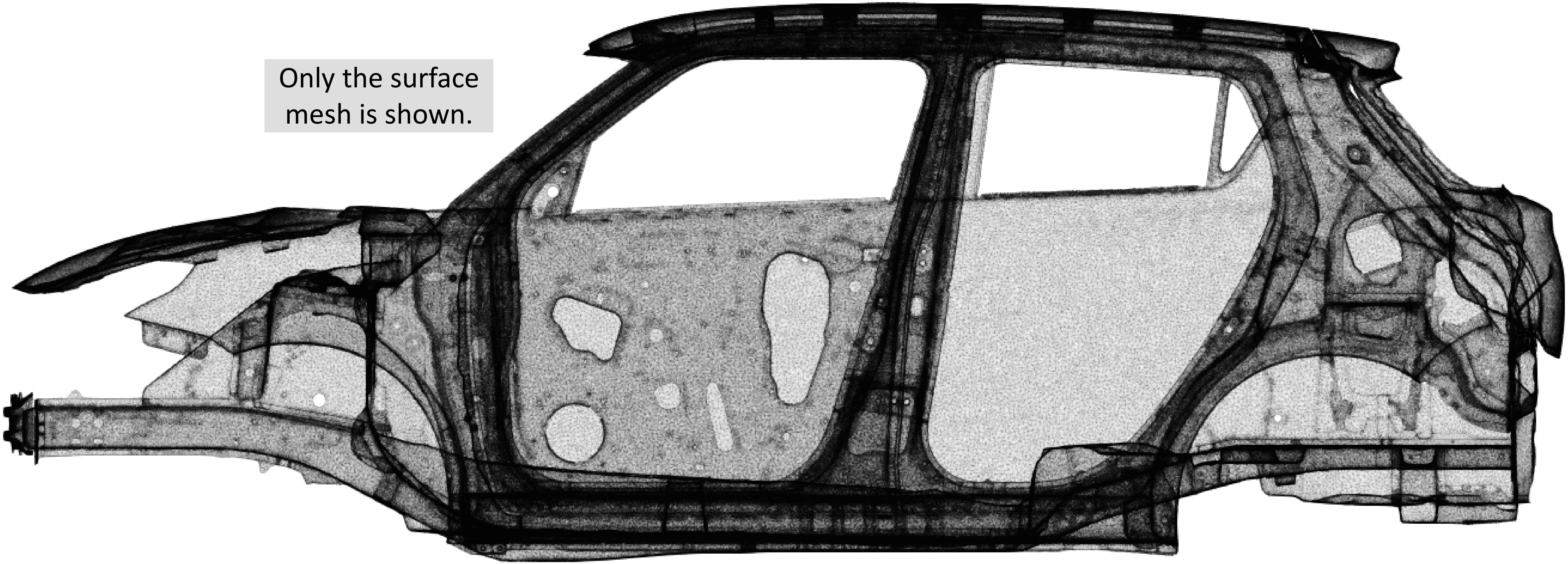
- Our ED simulator, which uses FEM-T3, has been rewritten to use ES-FEM-T4.



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

Mesh Convergence Test

Overview of Surface Mesh of 10M Element Mesh

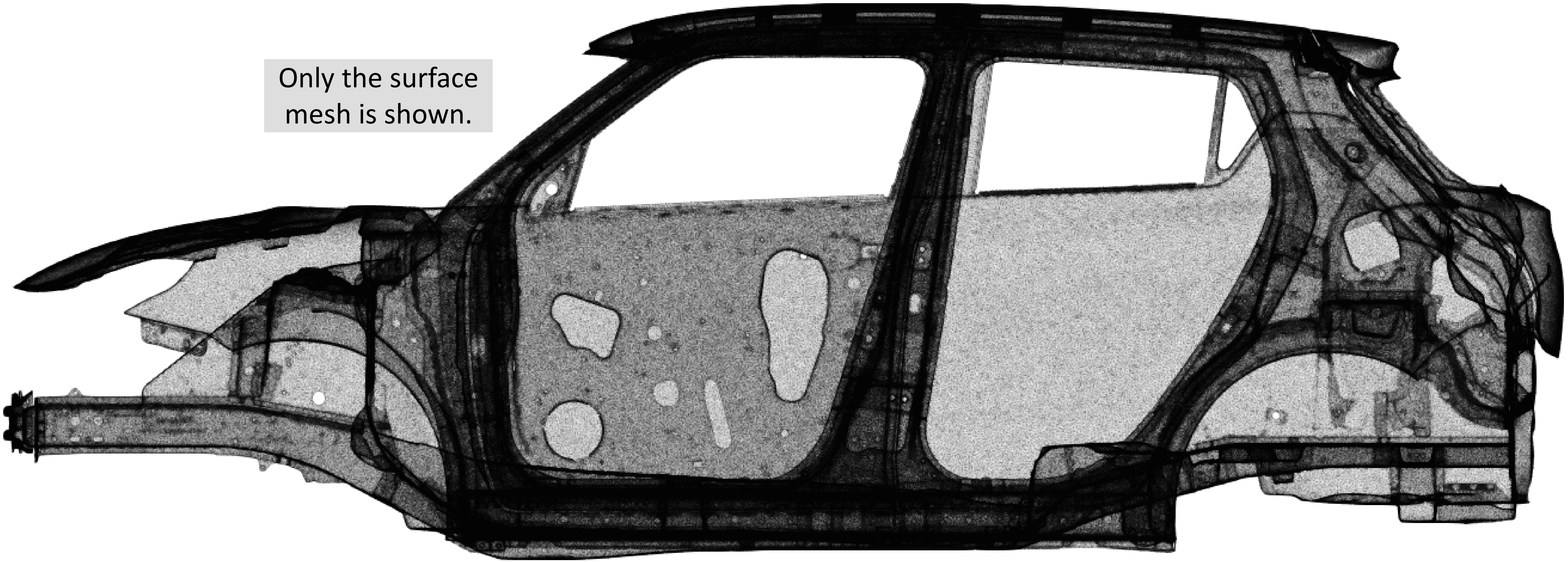


■ There are many **ED holes** around narrow spaces among plates.

Mesh Convergence Test

Overview of Surface Mesh of 16M Element Mesh

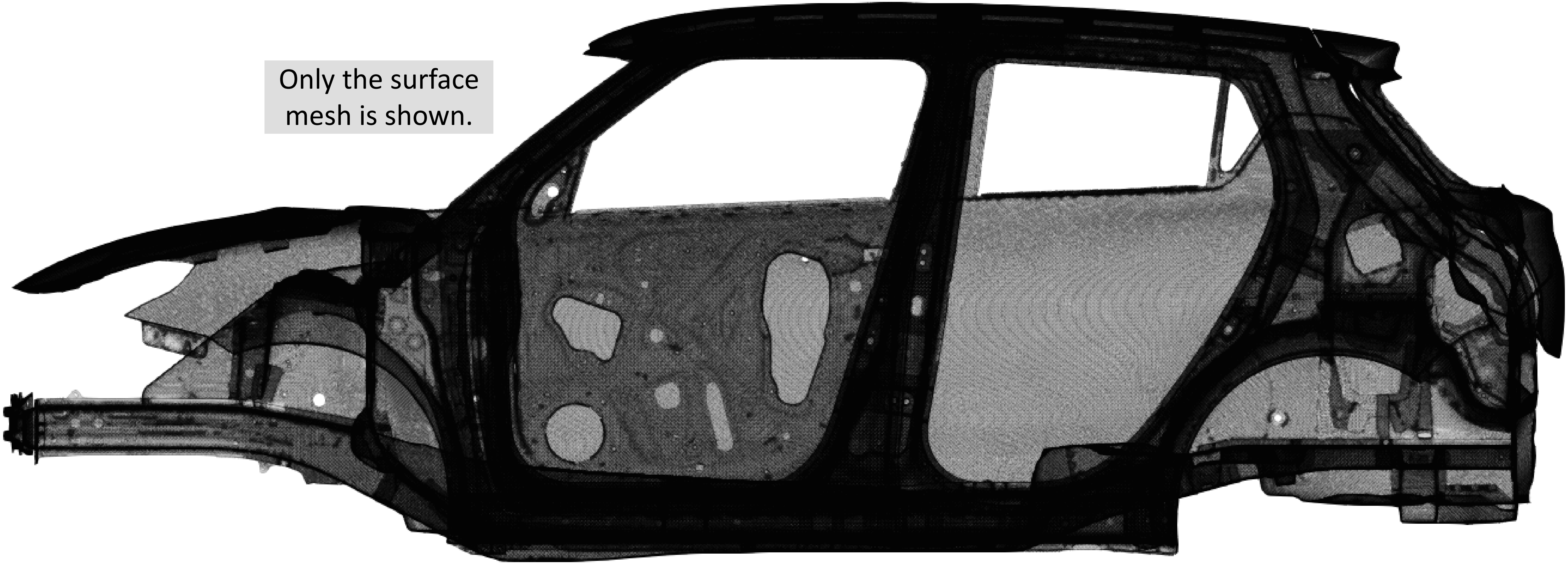
Only the surface mesh is shown.



■ There are many **ED holes** around narrow spaces among plates.

Mesh Convergence Test

Overview of Surface Mesh of 51M Element Mesh

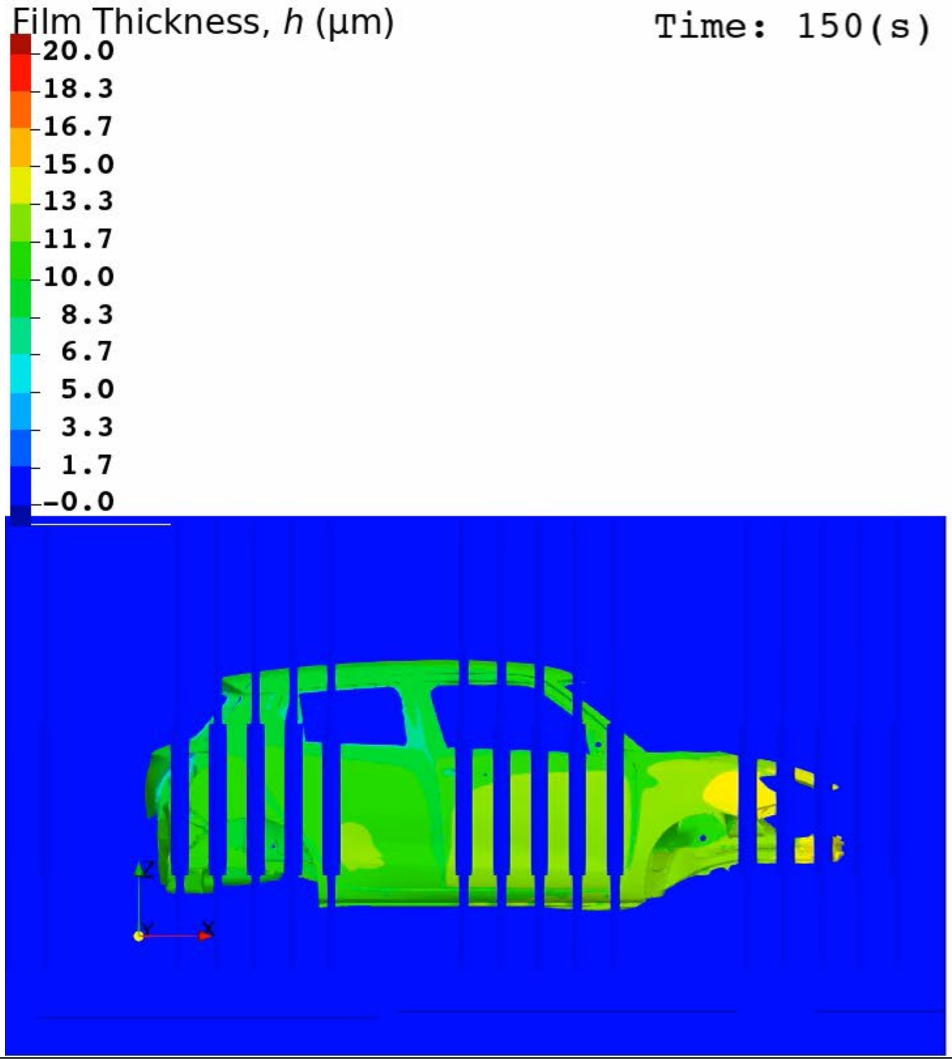


■ There are many **ED holes** around narrow spaces among plates.

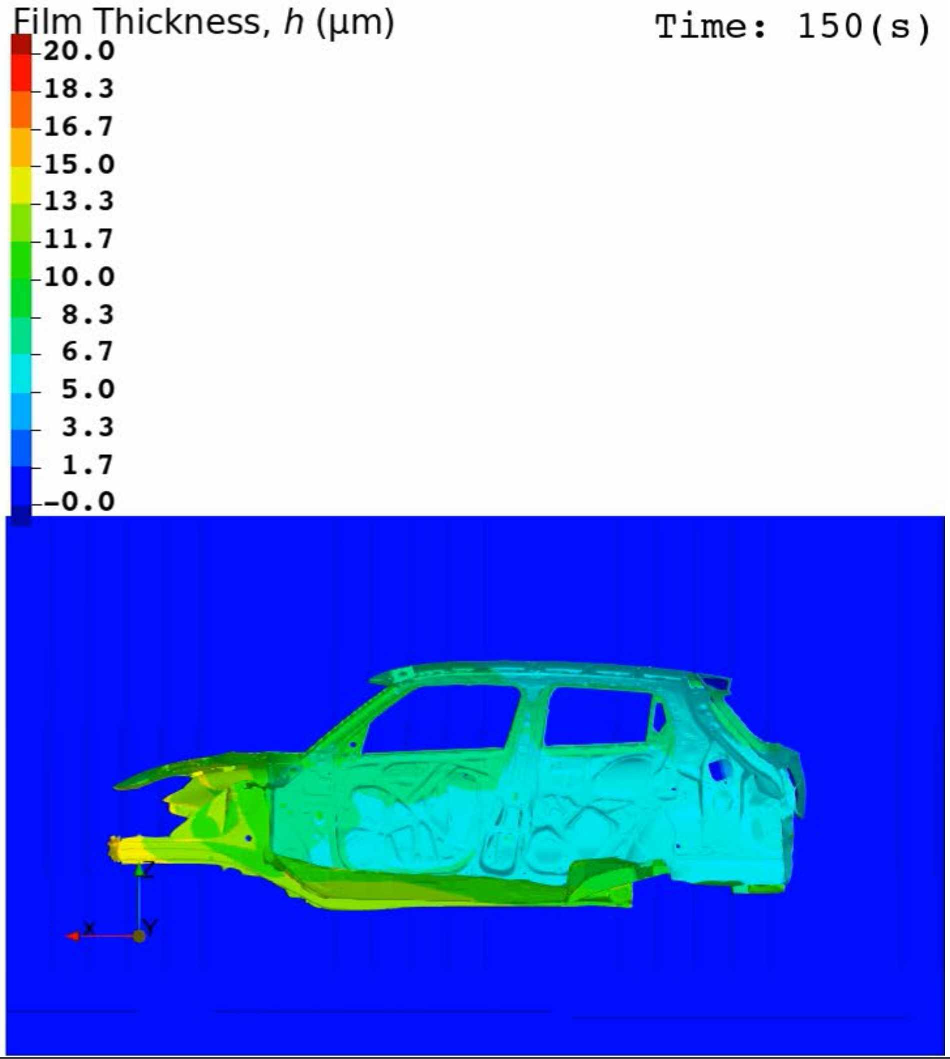
Mesh Convergence Test

Animation of Film Thickness (ES-FEM-T4 with 51M Element Mesh)

Outer View



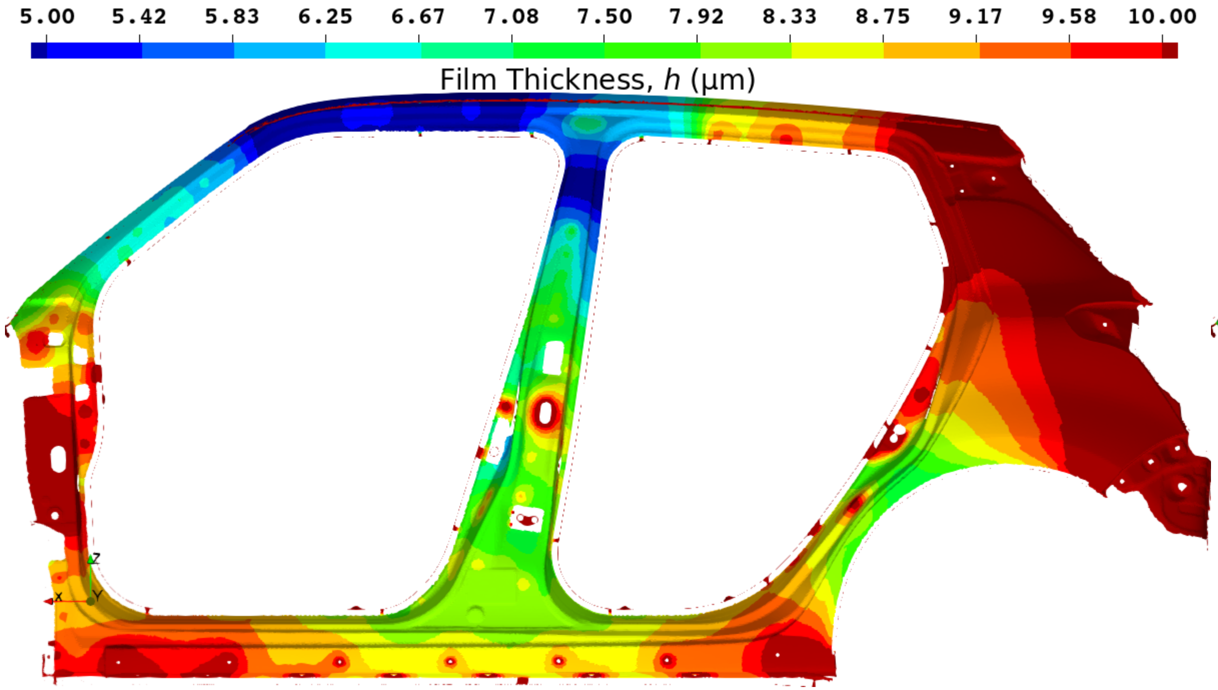
Inner View



Mesh Convergence Test

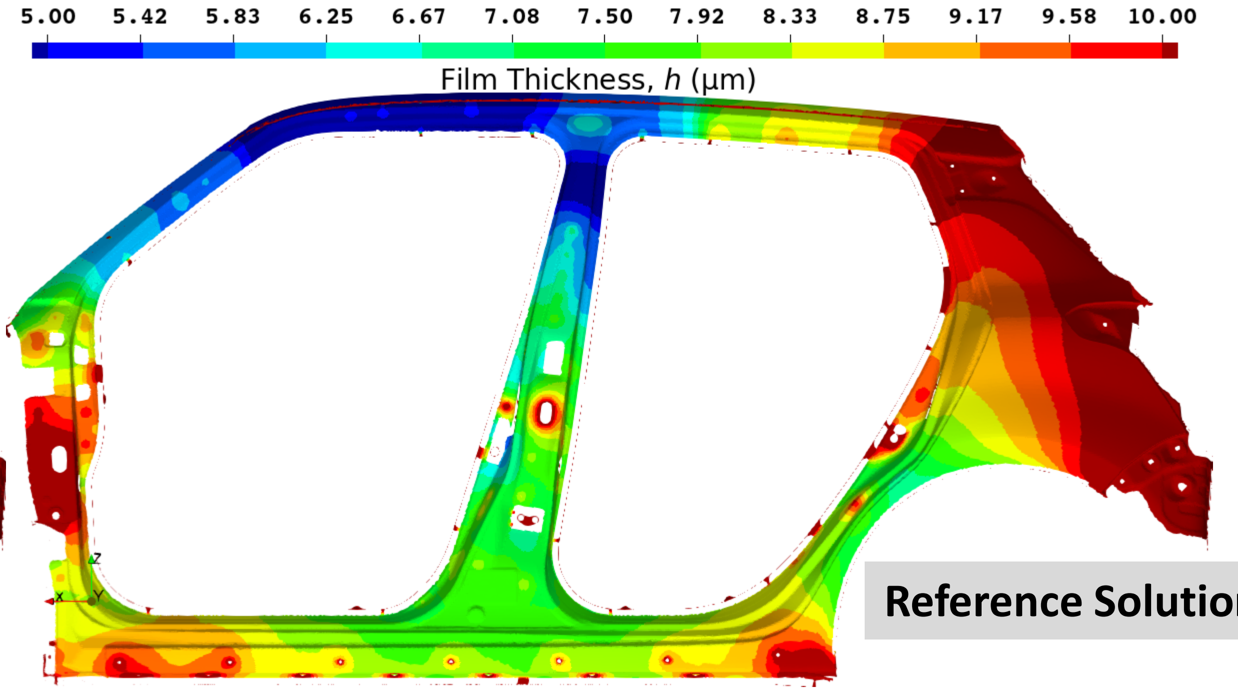
Final Film Thickness Distribution on the side sill part with 51M Element Mesh

Standard FEM (FEM-T4)



Standard FEM shows ***a little thicker*** result.
(The center of the side sill is Yellow.)

Present Method (ES-FEM-T4)



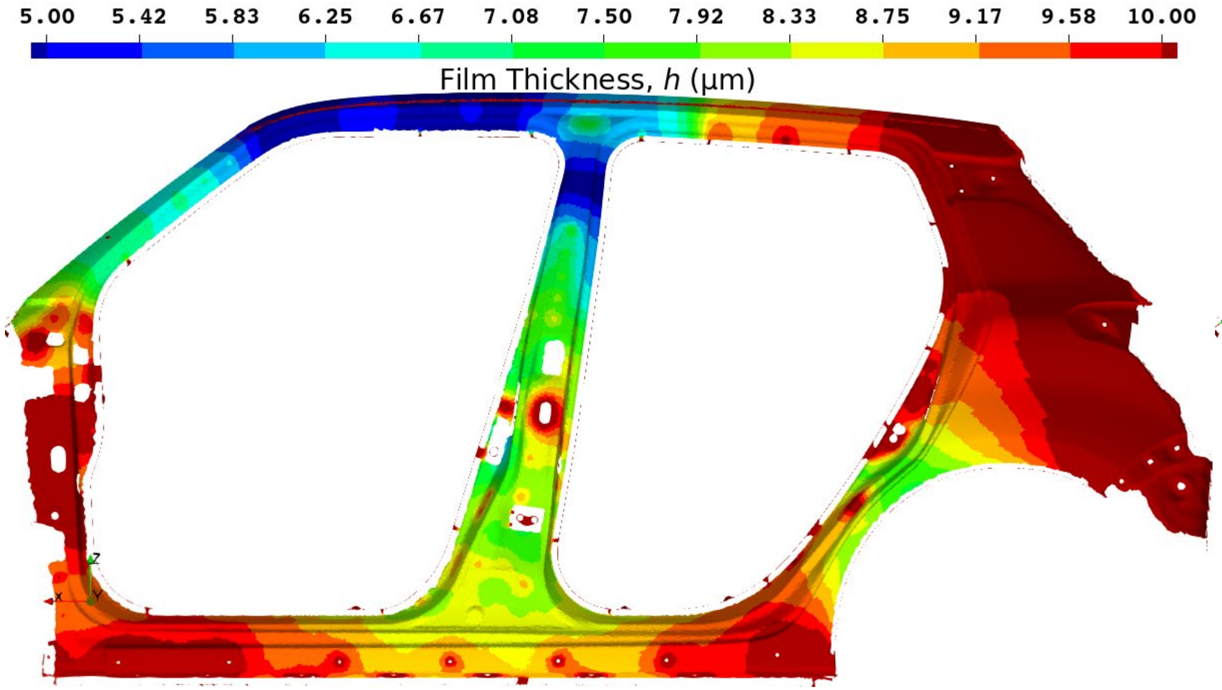
Reference Solution

This result is regarded as the ***reference*** solution.
(The center of the side sill is Green)

Mesh Convergence Test

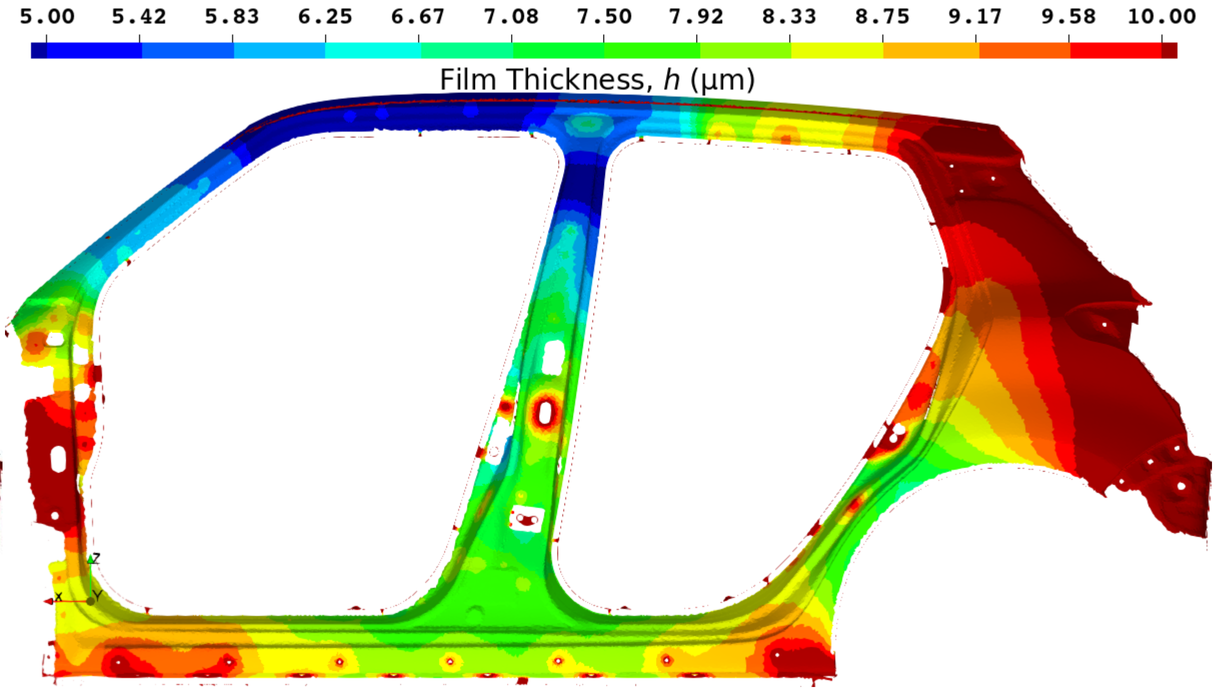
Final Film Thickness Distribution on the side sill part with 16M Element Mesh

Standard FEM (FEM-T4)



Standard FEM shows ***a much thicker*** result.
(The center of the side sill is Orange.)

Present Method (ES-FEM-T4)



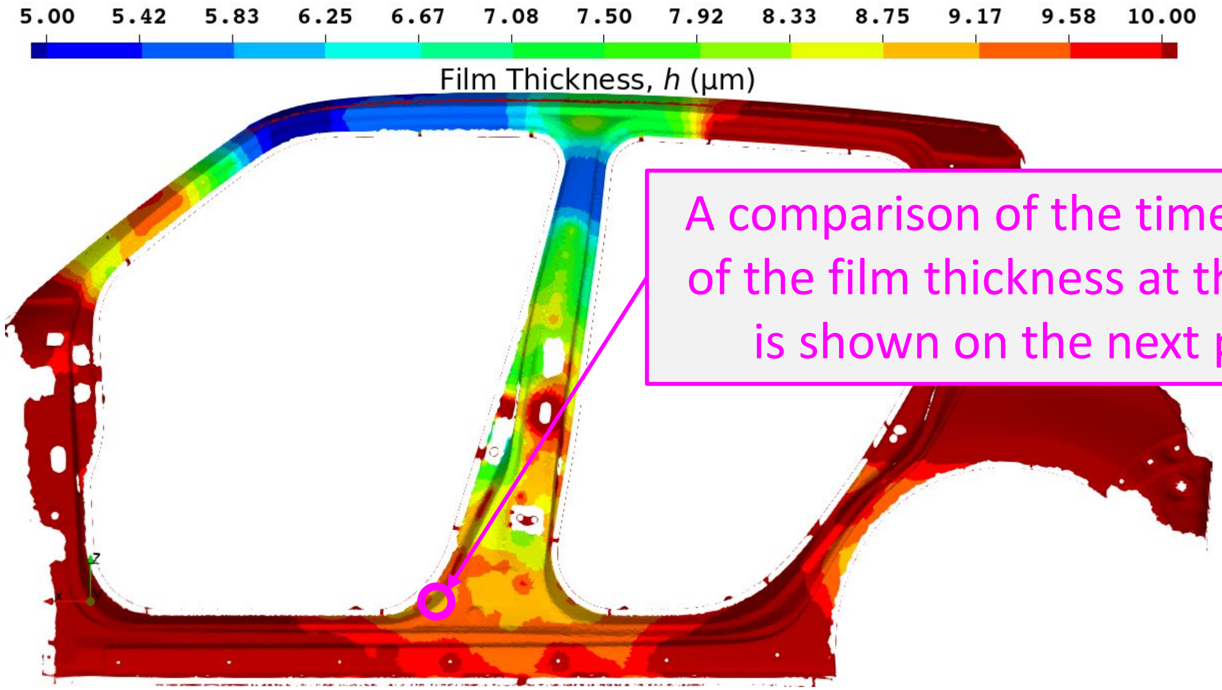
EDESFEM shows an ***accurate*** result.
(The center of the side sill is Green.)

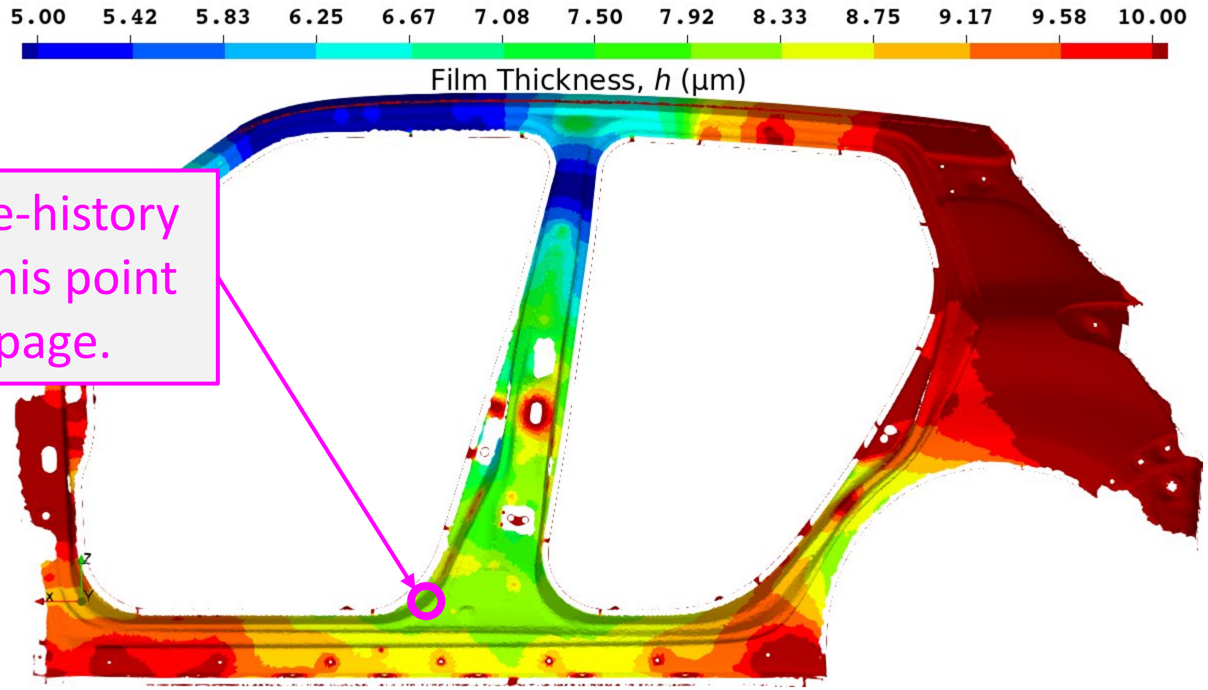
Mesh Convergence Test

Final Film Thickness Distribution on the side sill part with 10M Element Mesh

Standard FEM (FEM-T4)

Present Method (ES-FEM-T4)





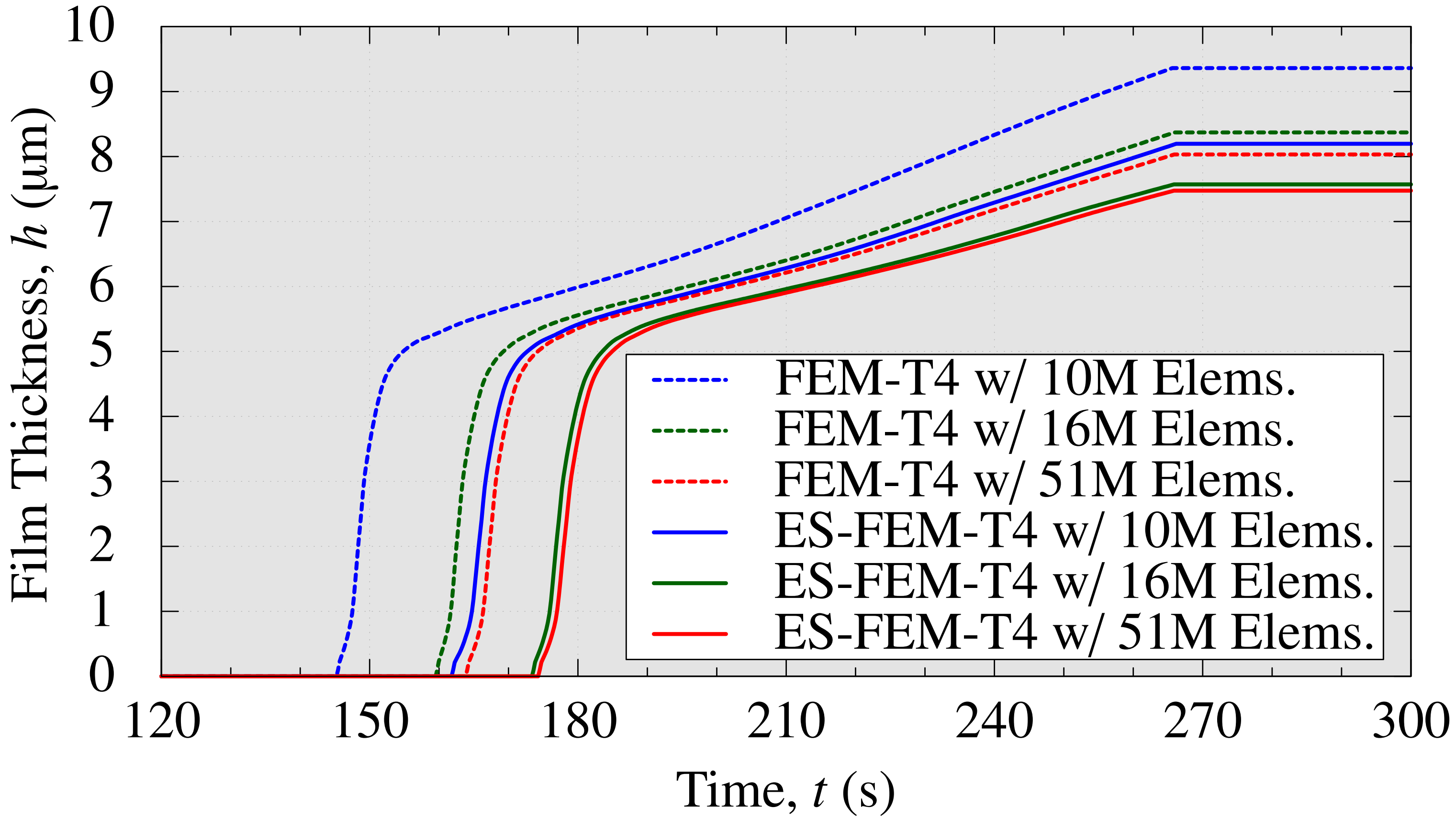
A comparison of the time-history of the film thickness at this point is shown on the next page.

Standard FEM shows ***a massively thicker*** result.
(The center of the side sill is Red.)

EDESFEM shows ***a little thicker*** result.
(The center of the side sill is Yellow.)

Mesh Convergence Test

Comparison of Time-histories of Film Thickness at a Sample Point on Side Sill



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

Mesh Convergence Test

Comparison of Calculation Time

On a cluster (64 CPUs: 896 cores of Intel Xeon E5-2680 v4 on TSUBAME3.0)

# of Elements	Standard FEM (FEM-T4)	Present Method (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

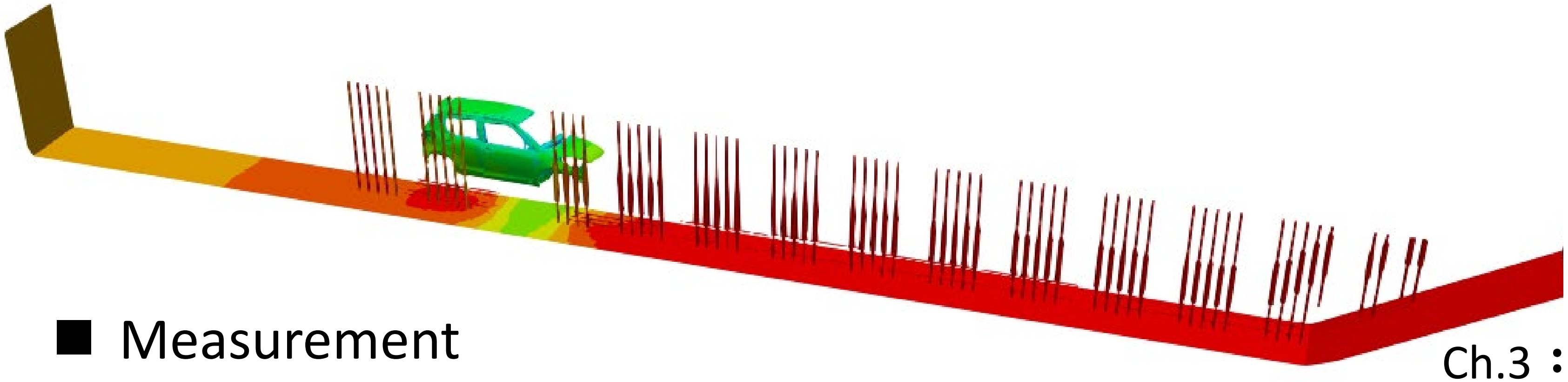
- With the same mesh, ES-FEM-T4 is slower than FEM by x1.5.
- For the same accuracy, ES-FEM-T4 is faster than FEM by x3.

For the simulations of actual ED lines,
ES-FEM-T4 is 3 times efficient than FEM-T4.

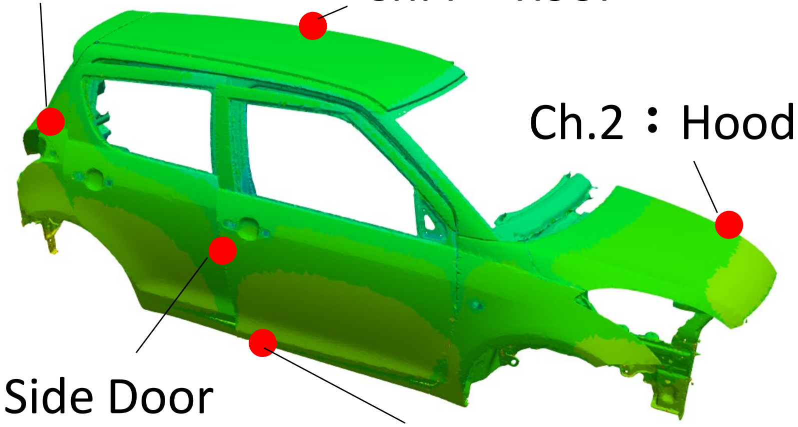
Validation Test

Validation Test

Outline



➤ Measured 6 Points (Ch.2 - 7):



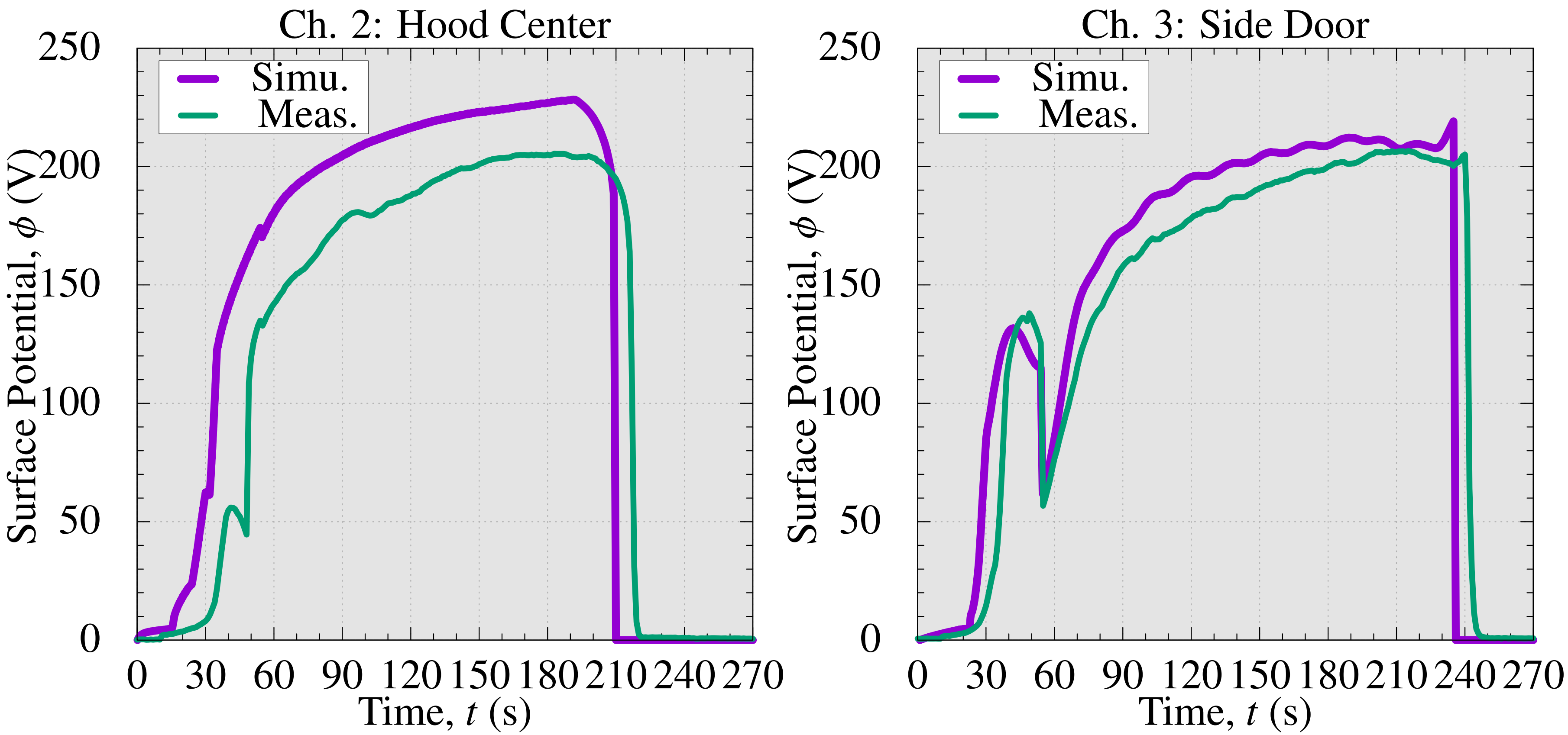
Ch.6 : Floor
(not visible on this Fig.)

- 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

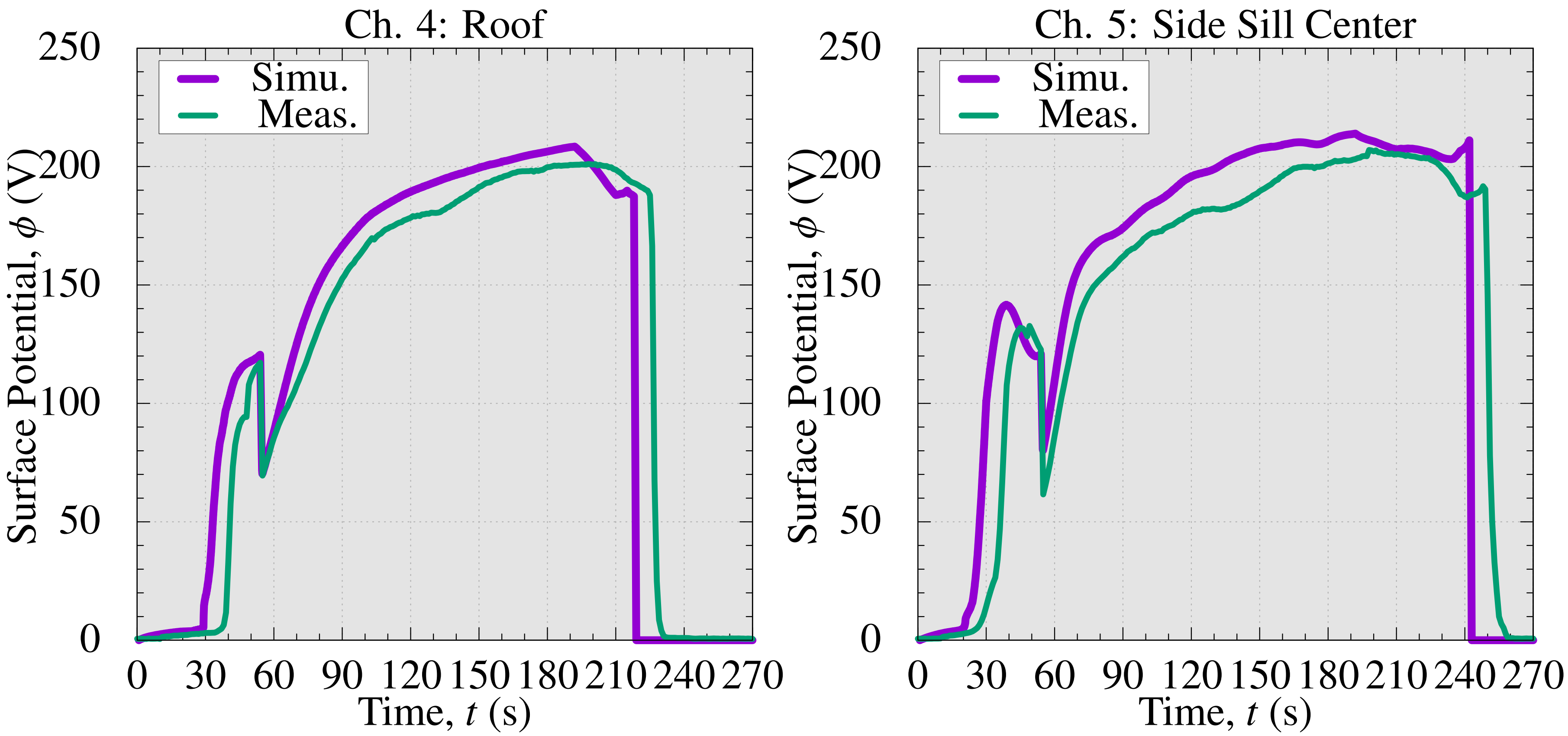
Validation of Surface Potential (Ch. 2 and 3)



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 practical accuracy.

Validation Test

Validation of Surface Potential (Ch. 4 and 5)

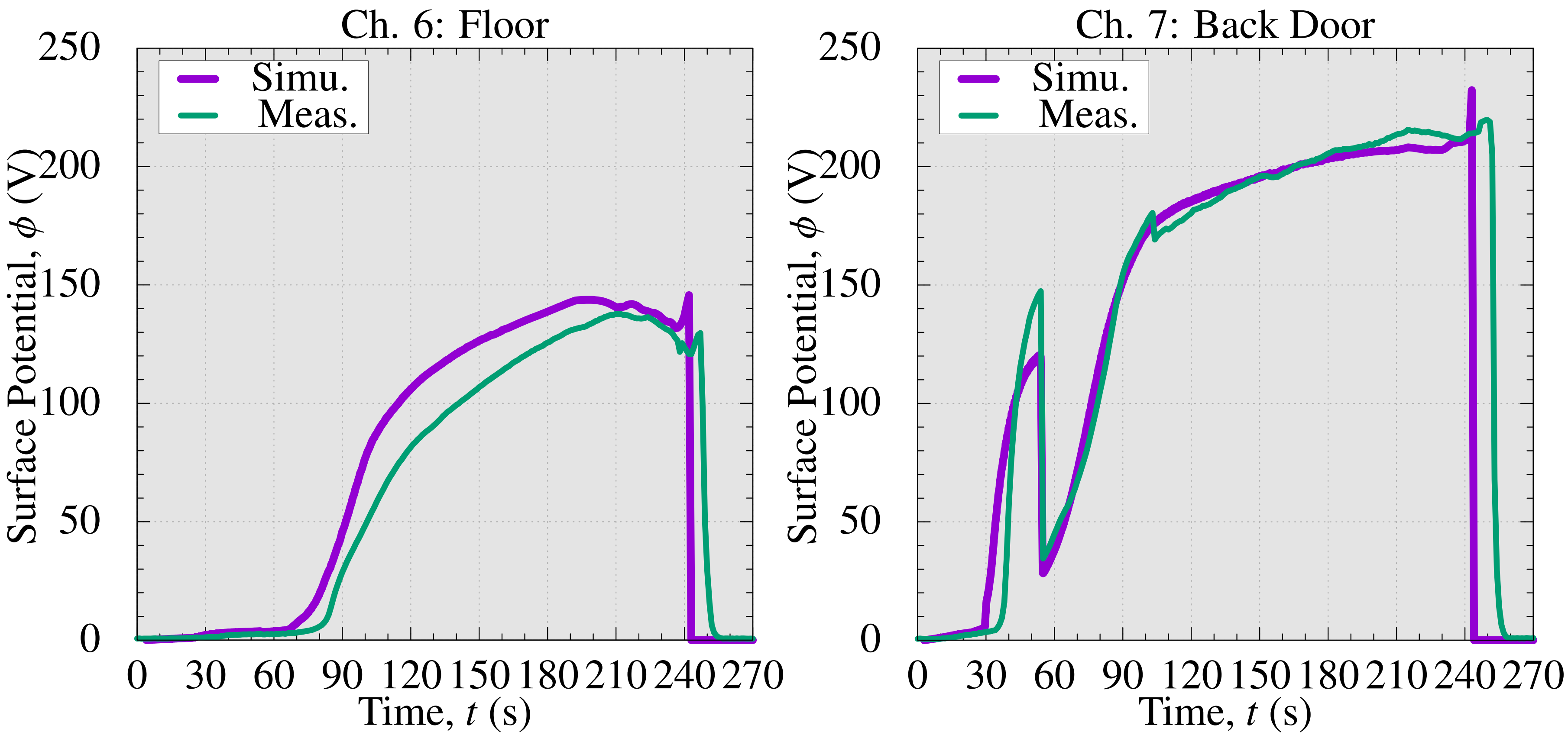


The simulated surface potential is a little high
because the degradation of the membranes of electrodes was not precisely simulated;
yet, the results generally agree with practical accuracy.

Validation Test

Validation 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 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.

Summary

Summary

- ■ Electrodeposition (ED) is important for automotive safety.
- ■ Tetrahedral meshes are preferable in ED Simulation.
- ■ ES-FEM-T4 has excellent accuracy for solving Laplace equation.
- ■ In the actual line ED simulations, ES-FEM-T4 is 3 times faster than the standard FEM-T4 to obtain the same accuracy result.
- ■ The effectiveness of our ED simulator was validated by several car companies.

- □ The application scope of ES-FEM-T4 and related FE formulations is now beginning to extend beyond Laplace simulations to solid, fluid, and acoustic simulations.
- □ If you are interested in our ED simulator, please check the website.

Search edesfem

Thank you for your kind attention!