Application of Edge-based Smoothed Finite Element Method to Electrodeposition Simulation aiming for Super-linear Mesh Convergence in Film Thickness Accuracy

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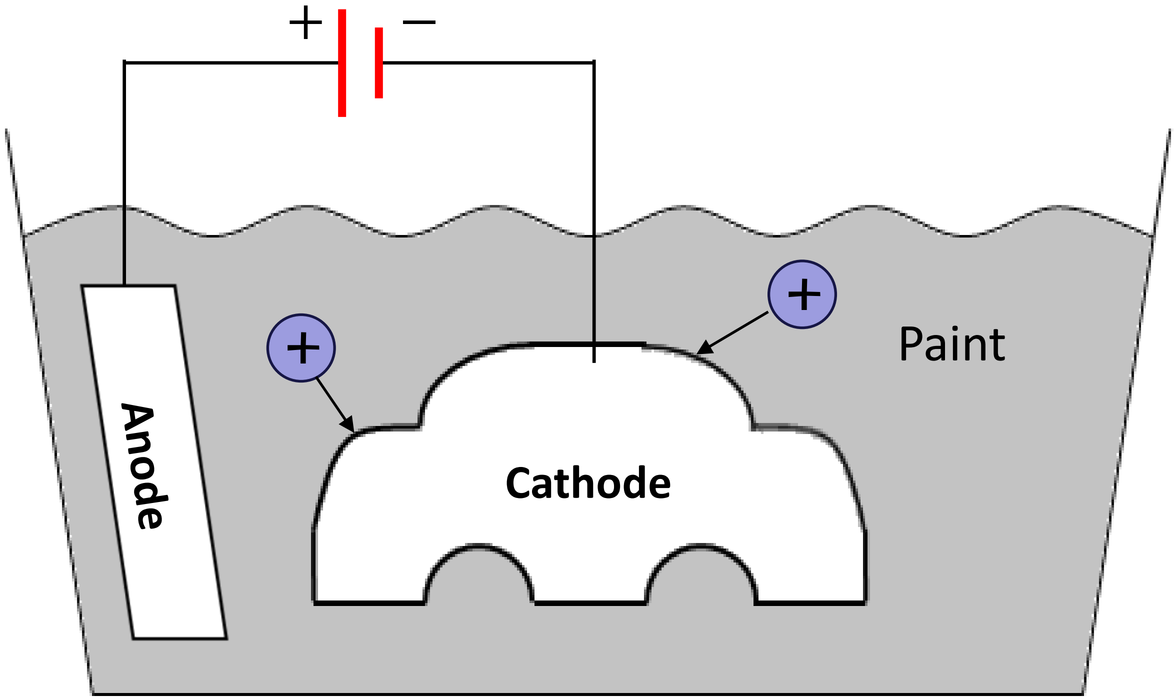
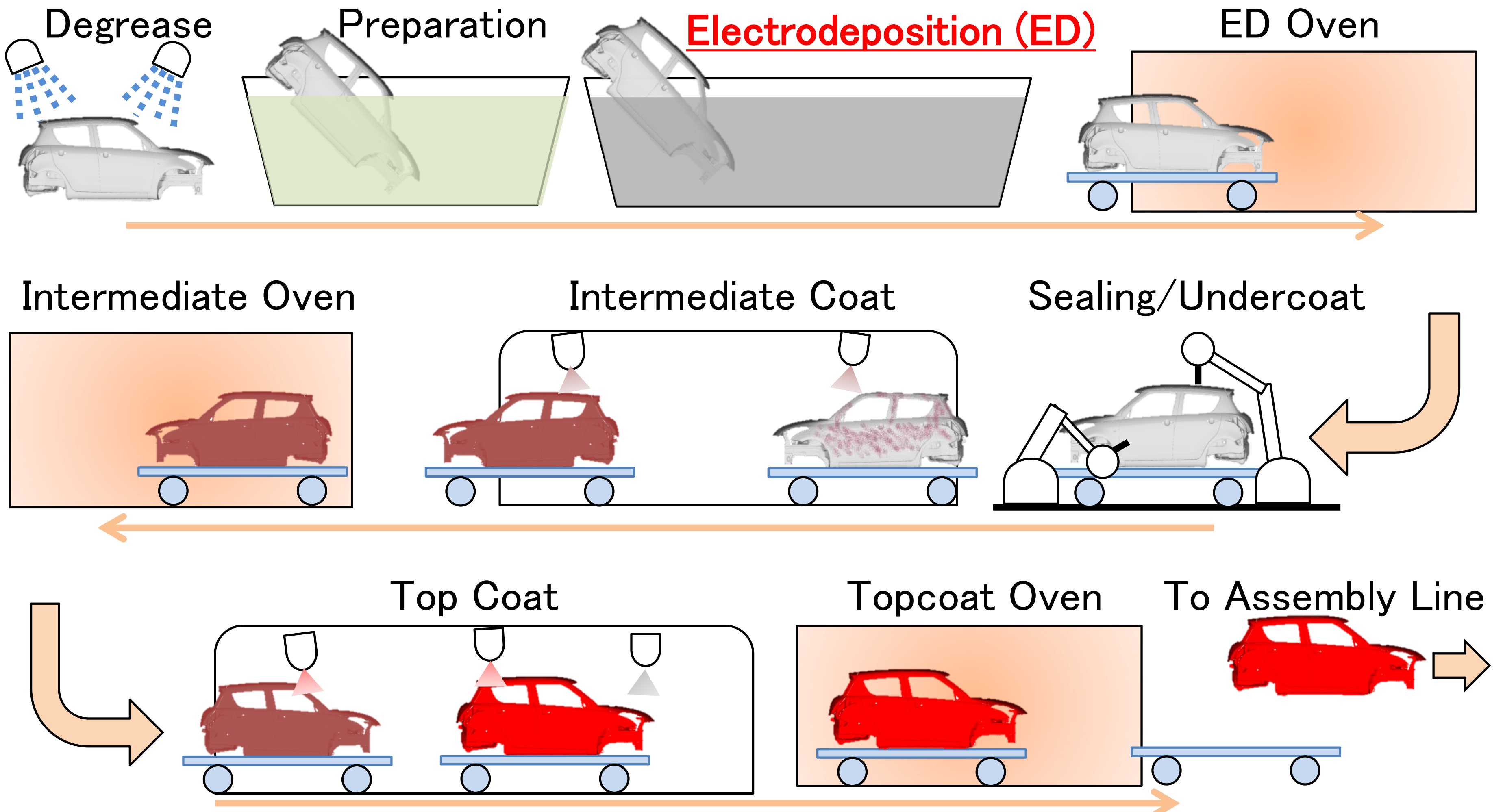
What is Electrodeposition (ED) ?



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

What is Electrodeposition (ED) ?

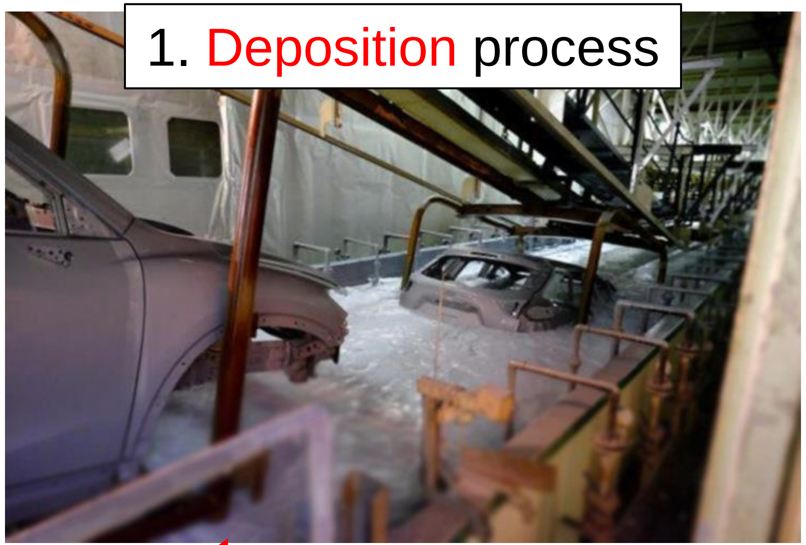
Overview of the Carbody Paint Shop



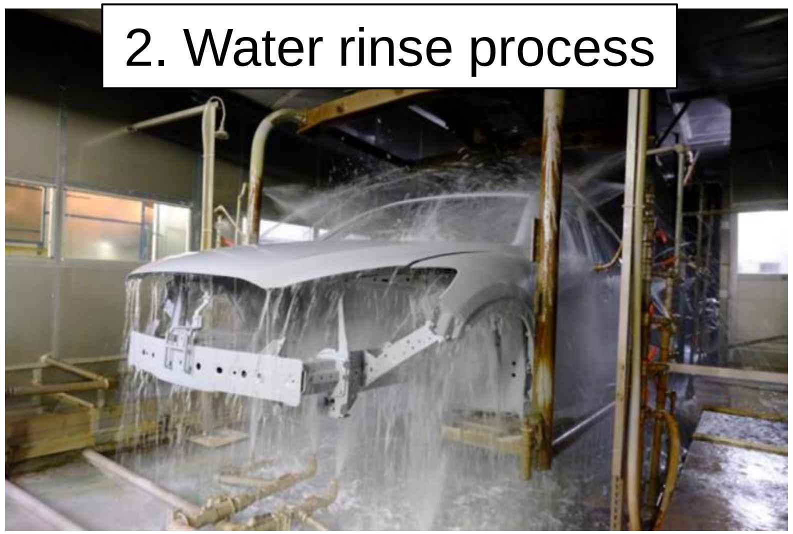
ED is responsible for the basecoat of a carbody.

What is Electrodeposition (ED) ?

Photos of ED Process Line

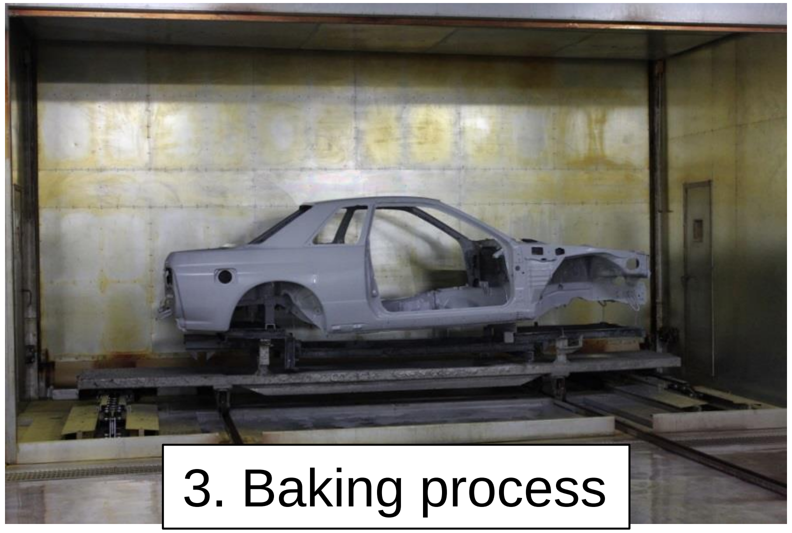


1. Deposition process



2. Water rinse process

We focus on this process.



3. Baking process

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

What is ED Simulation?

Actual ED Line

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

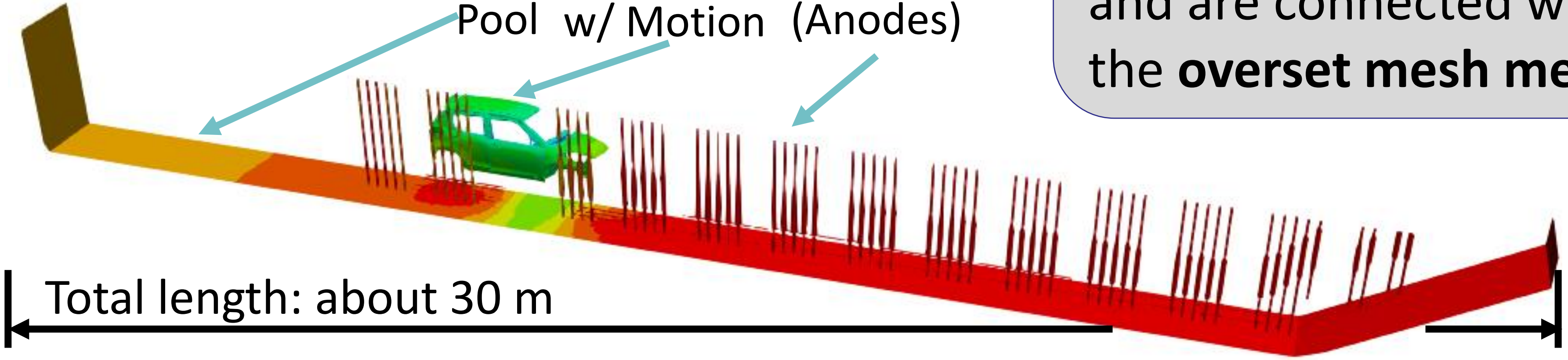
are reproduced in a computer.

ED Simulation

Paint Pool

Carbody w/ Motion

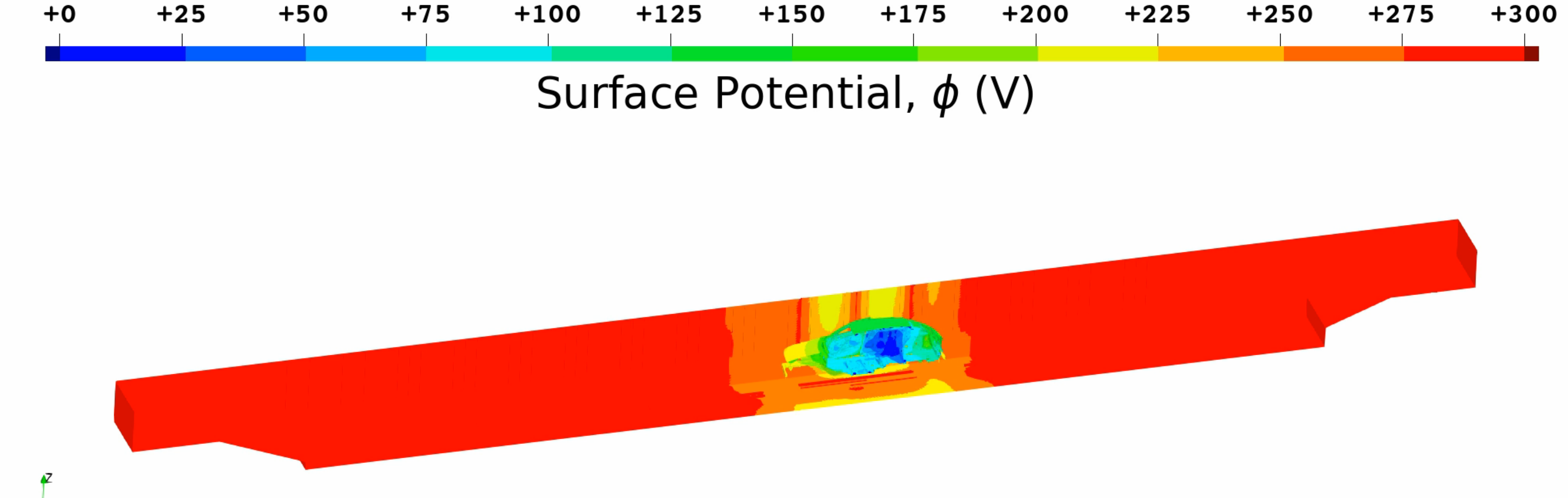
Electrodes (Anodes)



i. Paint Pool Mesh
ii. Carbody Mesh

are separately prepared and are connected with the **overset mesh method**.

What is ED Simulation?



Time: 135.0 (s)

- Governing equation:
  Electrostatic Laplace equation ($\nabla^2 \phi = 0$) in the paint pool domain.
- A paint pool mesh and carbody meshes are connected with the **overset mesh method**.
- Boundary conditions:
  1. Wall (insulation) BC,
  2. Anodic (electrode surface) BC,
  3. Cathodic (carbody surface) BC:
     Film resistance/growth constitutive model (Strongly non-linear).

Identified via lab experiments. ↓

- Outputs: time-histories of
  - Surface potential,
  - Current density,
  - Film thickness

Final film thickness ← is the main output.

Motivation

- The actual ED line simulations cost high due to the large number of meshes.
  E.g., a typical actual ED line simulation for 3 carbodies sank in a paint pool at the same time requires about **100 million elements** in total.
- The standard FEM with 4-node tetrahedral elements (FEM-T4) is known as a poor formulation due to the *slow (linear)* mesh convergence rate.
- The edge-based smoothed FEM using T4 meshes (ES-FEM-T4) is known as a next-generation high-performance formulation achieving a **super-linear mesh convergence rate even with T4 meshes**.

Therefore, we expect that...

Parallelized ES-FEM-T4 would be the best choice
for the actual ED line simulations for automakers.

Objective

Development of an ED simulator using the parallelized ES-FEM-T4
for large-scale practical ED simulations
to achieve super-linear mesh convergence.

Table of body contents:

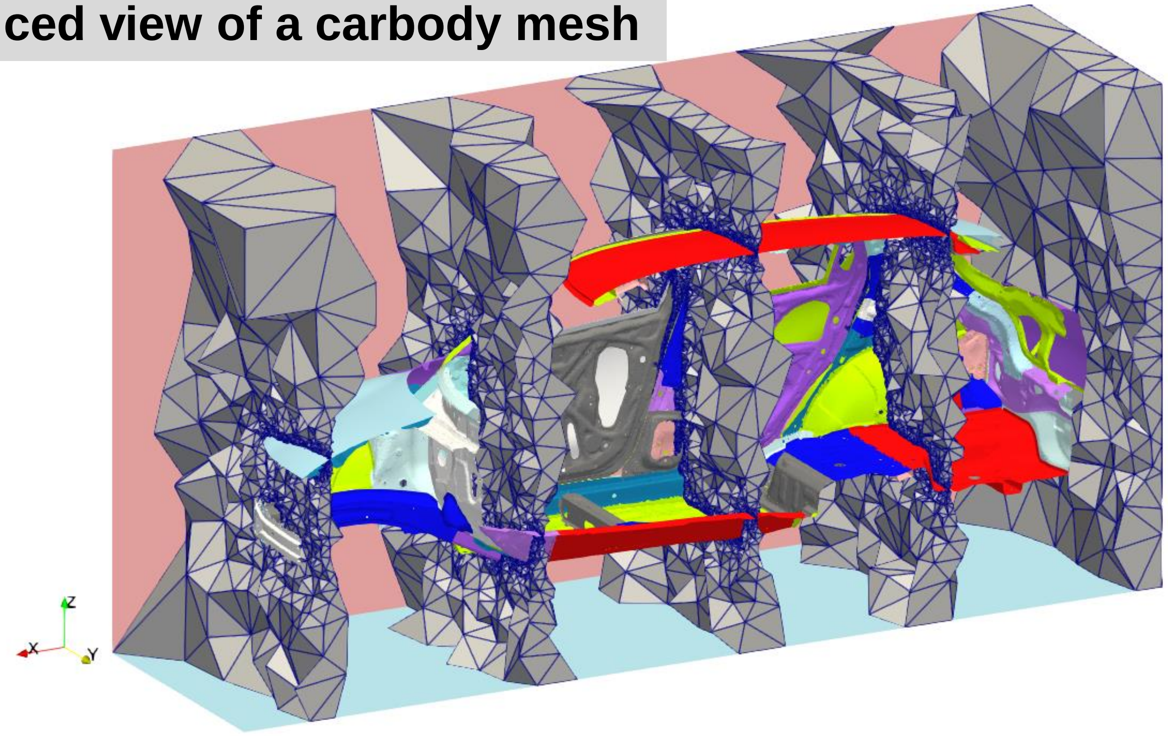
1. Two Major Reasons for "Why did we choose ES-FEM-T4?"
2. Implementation of Parallelized ES-FEM-T4
3. Benchmark Tests
4. Summary

Two Major Reasons for
“Why did we choose ES-FEM-T4?”

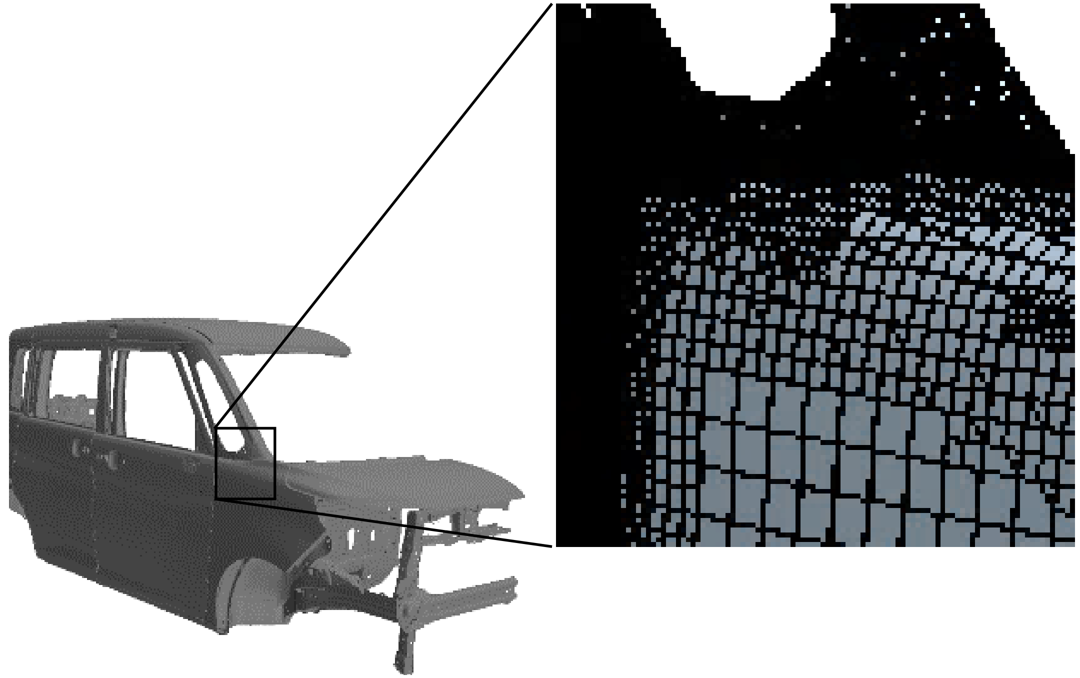
Why did we choose ES-FEM-T4?

Reason 1: It is impossible to make good HEX meshes for carbodies.

Sliced view of a carbody mesh



A CutCell mesh of a carbody

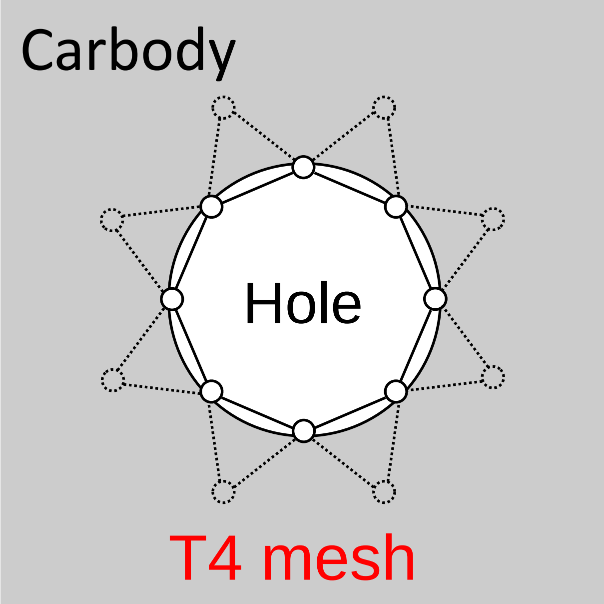


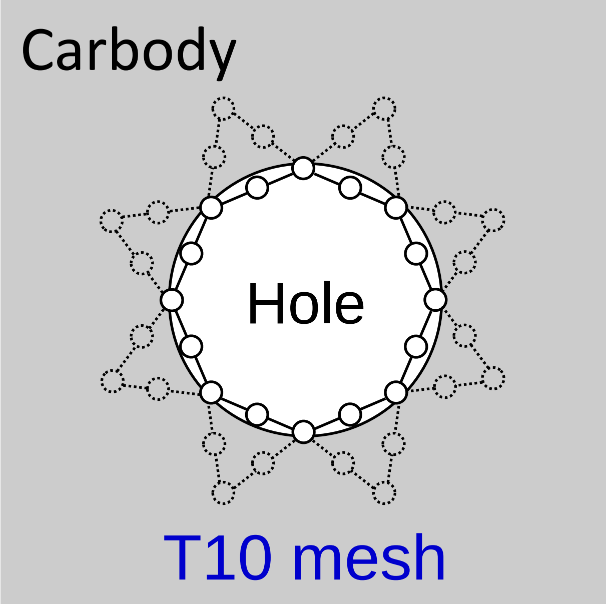
- An ED simulation requires a mesh for the complex spaces around the carbody.
- The Cartesian meshing generates unnecessarily fine meshes on curved surfaces.

TET meshes are preferable in ED simulation.

Why did we choose ES-FEM-T4?

Reason 2: There are many small holes on the carbody plates.





- ED simulations need 3D meshes around **many ED holes**.
- The 10-node TET meshing for the standard 2nd –order TET elements leads to a massive increase in nodes and DOF around ED holes.

The 4-node TET (T4) meshing is preferable.

→ ES-FEM-T4 would be the best choice.

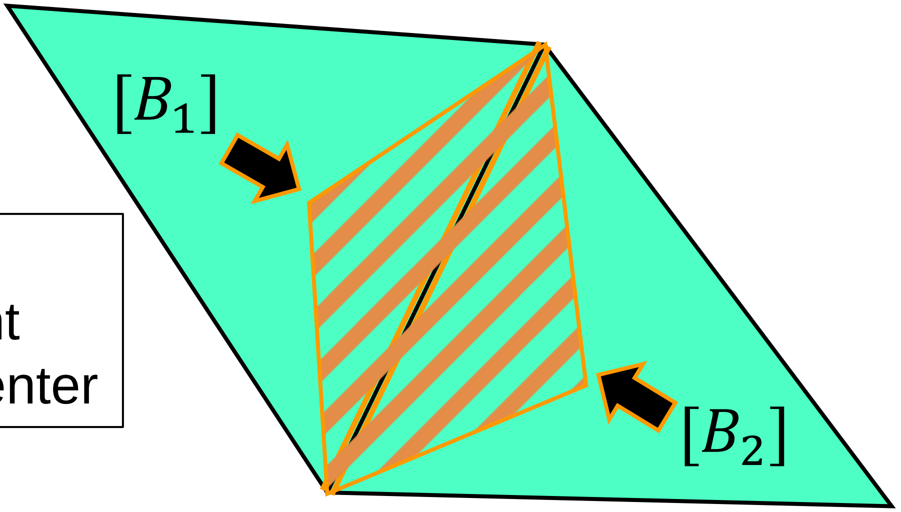
Implementation of Parallelized ES-FEM-T4

Brief Formulation of ES-FEM

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

- 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
a Gauss point
on each edge center



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

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

Characteristics of ES-FEM-T4

Advantages

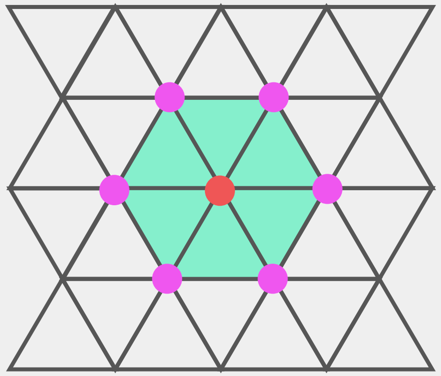
- Super-linear mesh convergence rate (as fast as 2nd-order elements).
- No increase in DOF (Unknowns are nodal potentials only).
- Same input file as FEM-T4.

Disadvantages All these disadvantages are cleared by developing parallelized in-house code.

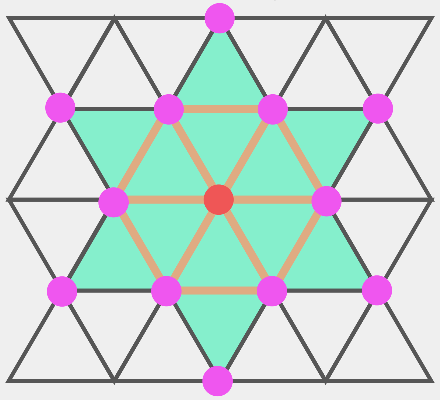
- Longer assembling time of $[K]$ (~x2 of FEM-T4 w/ the same mesh) ∵ES-FEM uses edges.
- Wider bandwidth of $[K]$ (~x3 of FEM-T4 w/ the same mesh).

In 2D case:

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



FEM-T3 (Bandwidth: 7)



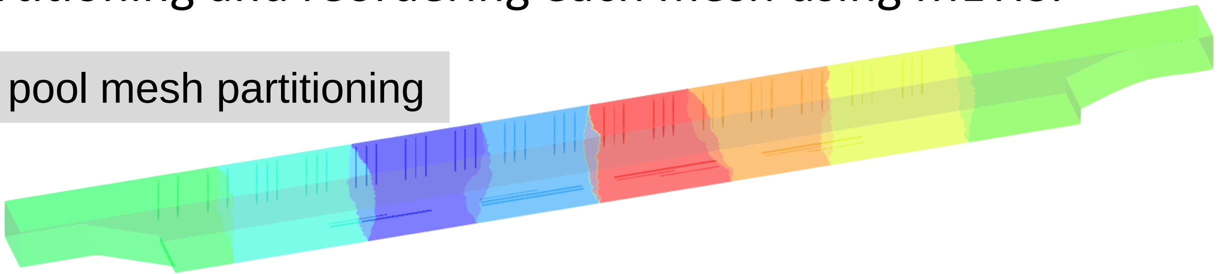
A node is used by 12 edges, ⇒ 12 elements, ⇒ 13 nodes.

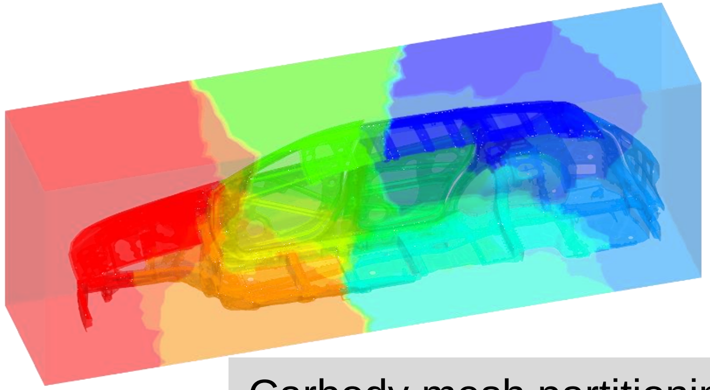
ES-FEM-T3 (Bandwidth: 13)

- No longer an independent T4 element (No good way to implement in standard FE codes).

Parallelization of ES-FEM-T4

- Our code adopts MPI/OpenMP hybrid parallelization for multi-core CPUs in multi-node HPC environments.
- In the MPI/OpenMP coding, there is no particular difference from that of FEM-T4.
- Execution steps:
  1. Generating T4 mesh for paint pool and carbody domains.
  2. Partitioning and reordering each mesh using METIS.





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

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

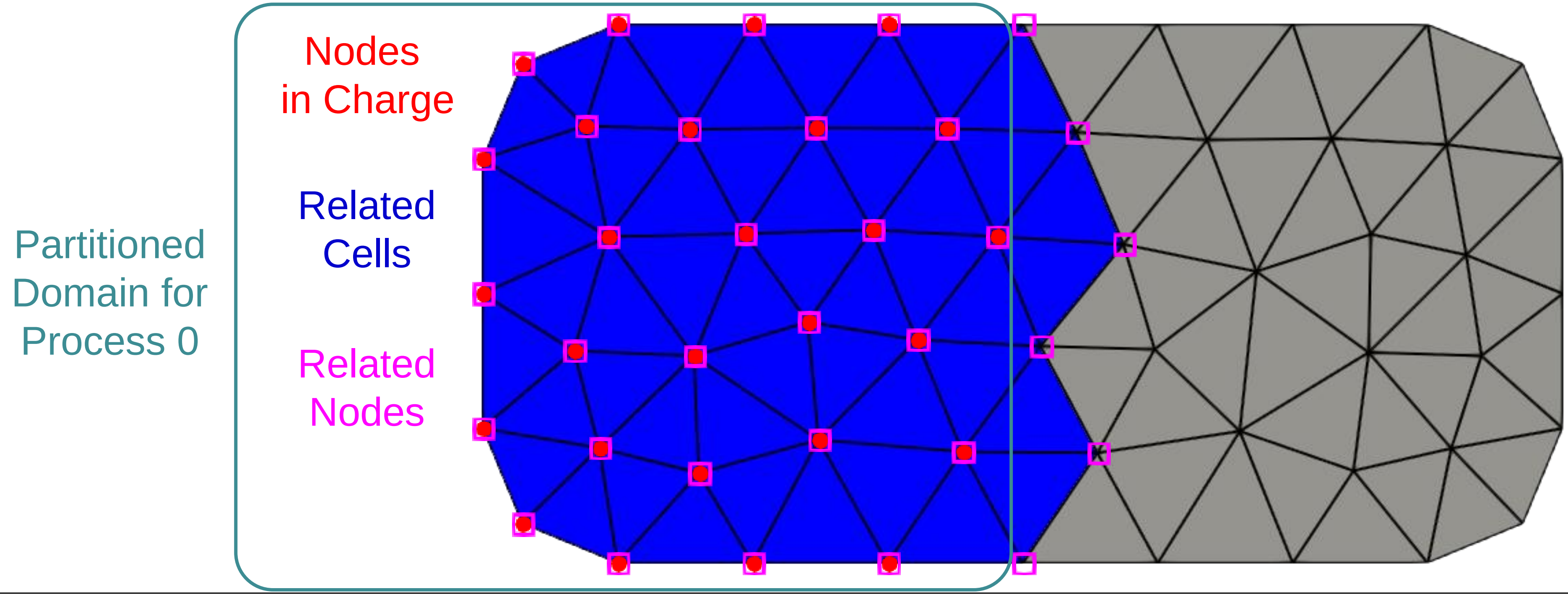
There is no difficulty in parallelization of ES-FEM-T4.

Parallelization of ES-FEM-T4

Review of a Typical Processing Flow in the Parallelized FEM-T3

2D explanation for simplicity

- Partitioning assigns "nodes in charge" to each MPI process.
- Each MPI process extracts "related cells", which use the nodes in charge.
- Each MPI process extracts "related nodes", which are used by the related cells.
- Each OpenMP thread in an MPI process calculates the contributions of related cells and makes $\{i^{\mathrm{int}}\}$ and $[K]$ for the rows of nodes in charge.

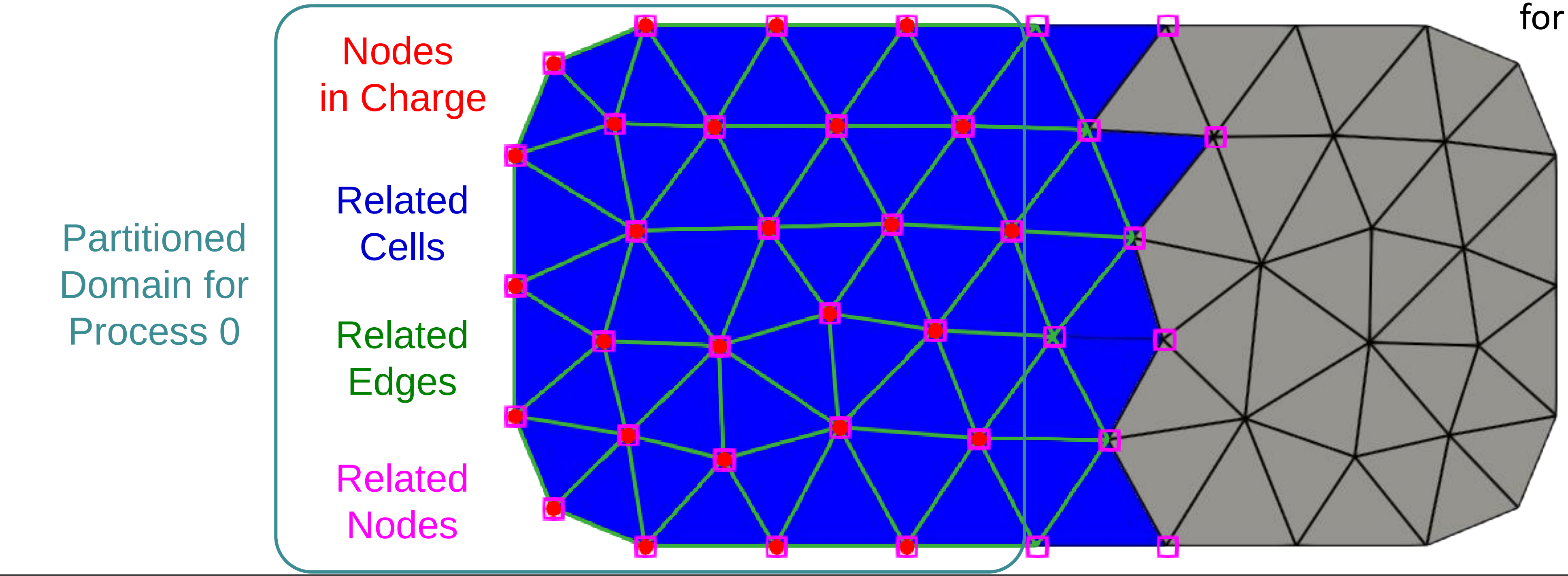


Parallelization of ES-FEM-T4

Brief of the Processing Flow in Our Parallelized ES-FEM-T3

2D explanation for simplicity

- Partitioning assigns "nodes in charge" to each MPI process.
- Each MPI process extracts "related cells", which use the nodes in charge.
- Each MPI process extracts "related edges", which compose the related cells.
- Each MPI process ***updates*** "related cells", which use the related edges.
- Each MPI process extracts "related nodes", which are used by the related cells.
- Each OpenMP thread in an MPI process calculates the contributions of related edges and makes $\{i^{\mathrm{int}}\}$ and $[K]$ for the rows of nodes in charge.



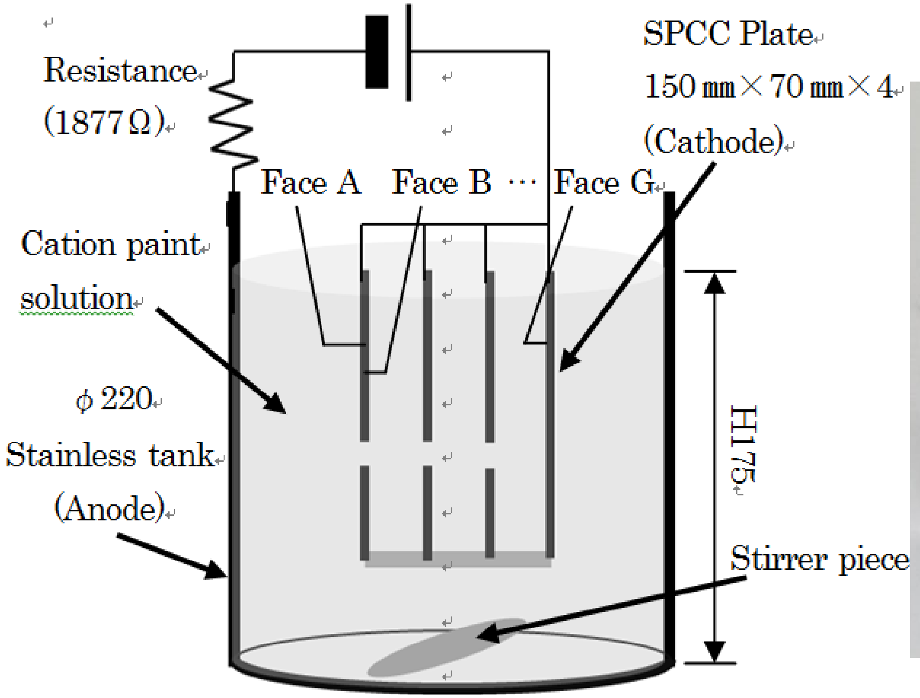
The number of overlapping nodes has increased compared to FEM, which leads to a ***slight*** increase in calculation and communication costs.

Benchmark Tests

4-Plate BOX Analysis

Outline

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



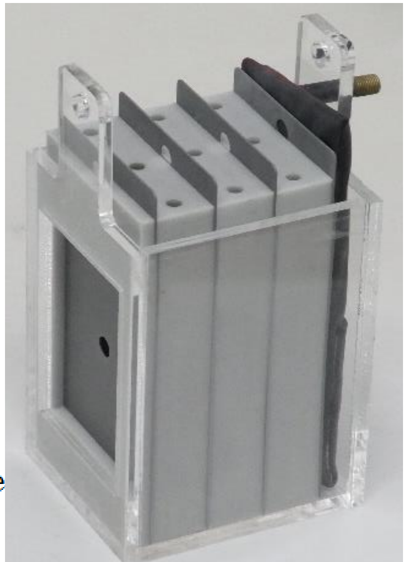
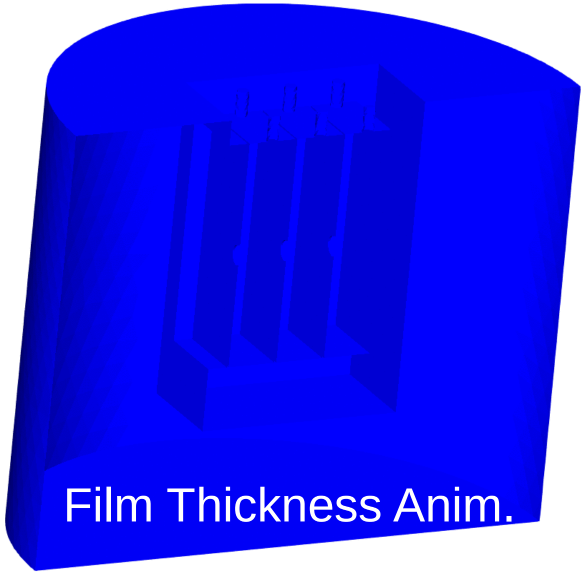


Photo of a BOX

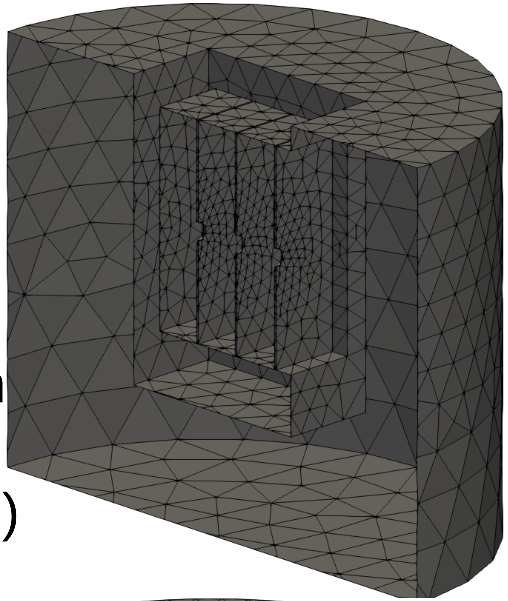


- Imitating a bag-like structure such as a side sill in a carbody.
- Film thickness on the **innermost face** (Face G) is the most important so as to guarantee corrosion protection.
- The film thickness is evaluated with **4 different meshes for using FEM-T4 and ES-FEM-T4** to compare the mesh convergence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

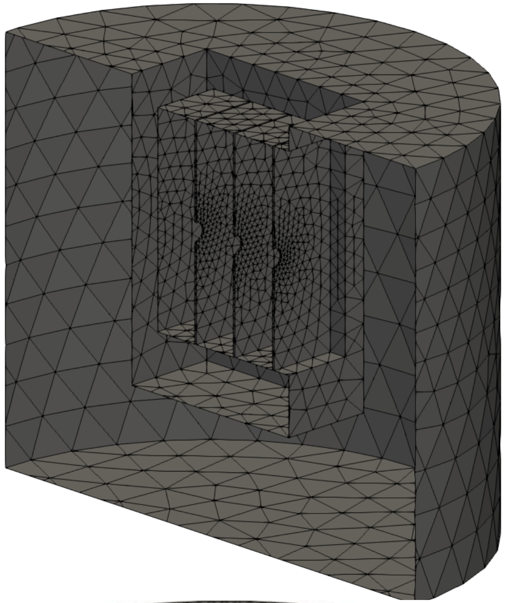
4-Plate BOX Analysis

Overview of 4 Meshes

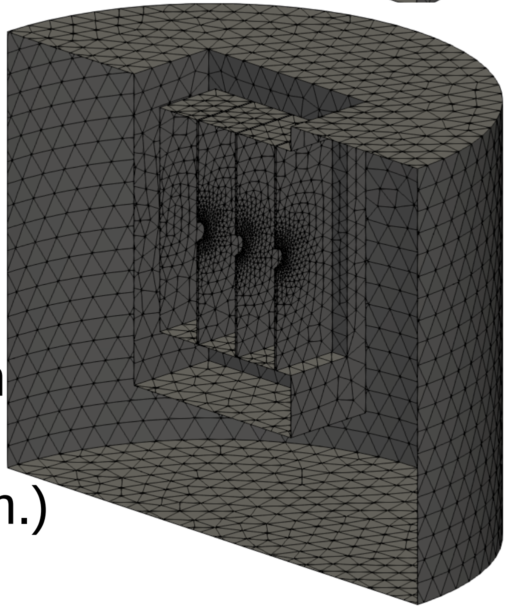
Only the surface meshes are shown.



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



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

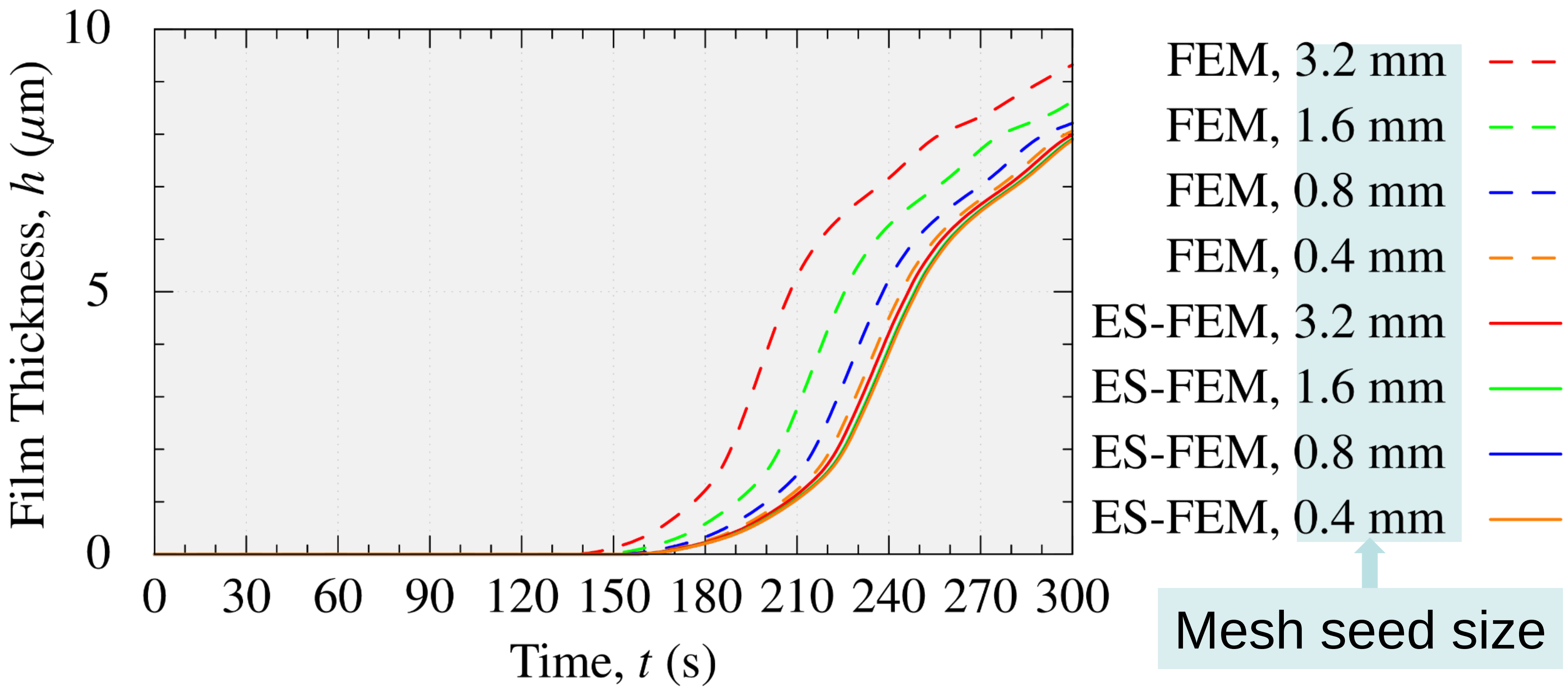


0.8 mm Mesh
Seed Size
(169k T4 elem.)

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

4-Plate BOX Analysis

Film Thickness on Face G (innermost face)

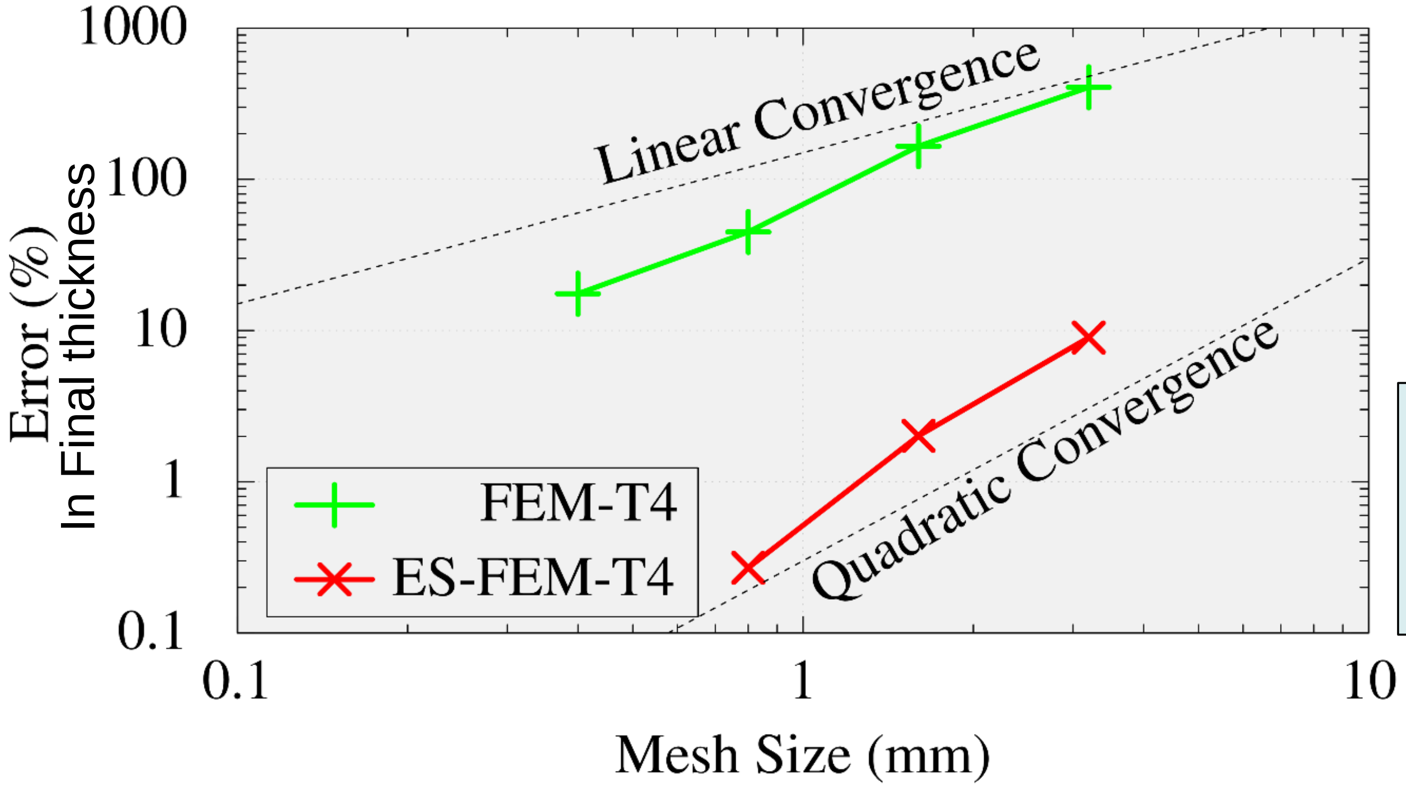


FEM results (dashed lines) have ***large*** errors.

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

4-Plate BOX Analysis

Comparison of Mesh Convergence Rate on Face G (innermost face)



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 Analysis

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

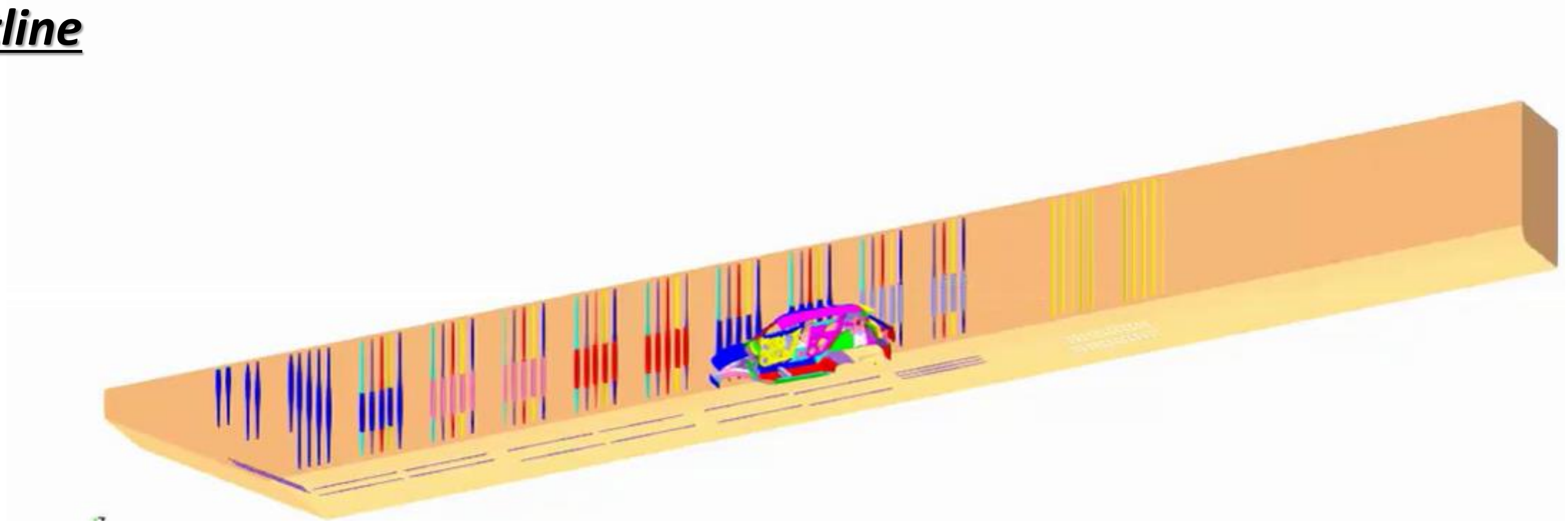
Comparable Accuracy (41 s FEM-T4 at 0.4 mm ↔ 10 s ES-FEM-T4 at 3.2 mm)

- 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 Analysis

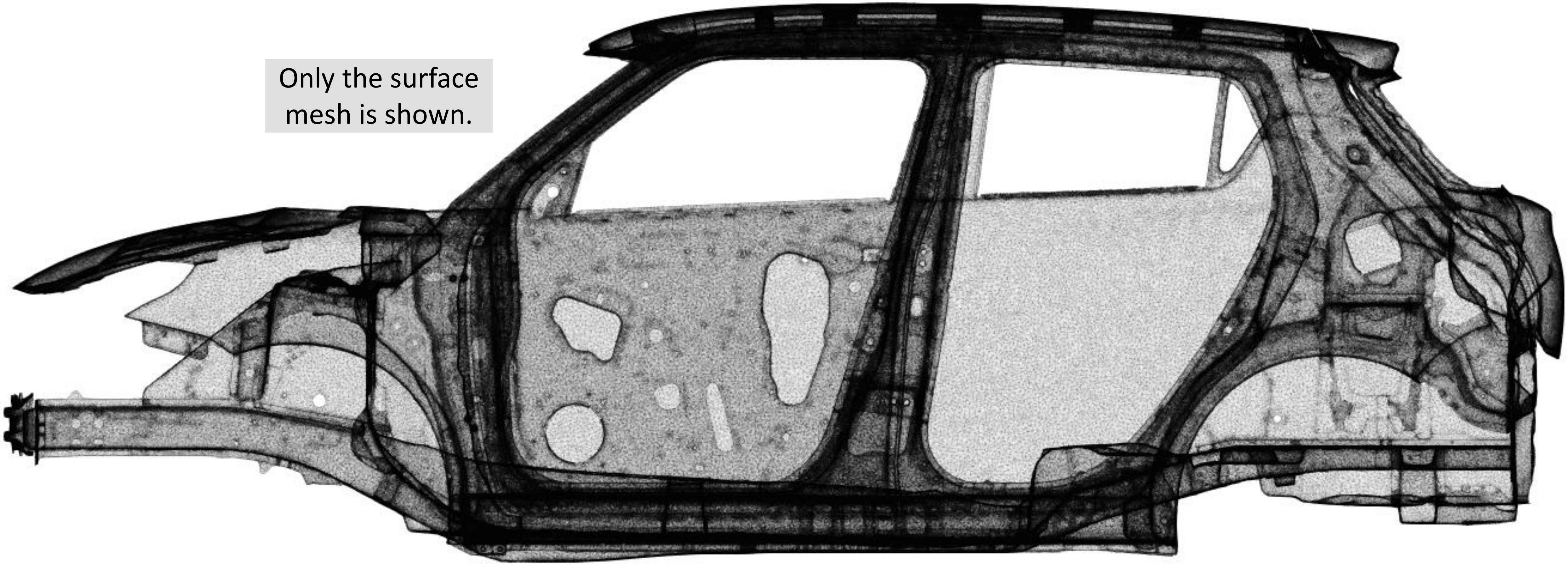
Outline



- **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 distribution is evaluated with **3 different density meshes** using FEM-T4 and ES-FEM-T4.

Actual Line Analysis

Overview of Surface Mesh of 10M Element Mesh

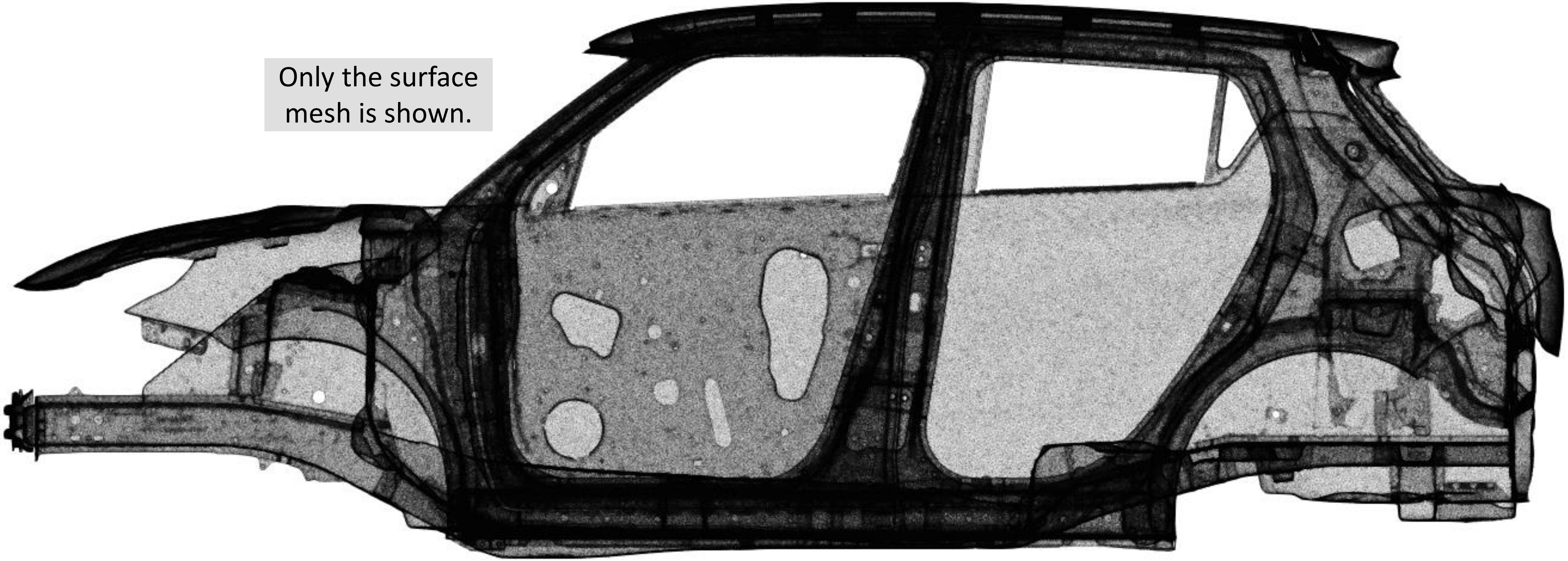


■ There are many **ED holes** around narrow spaces among plates.

Actual Line Analysis

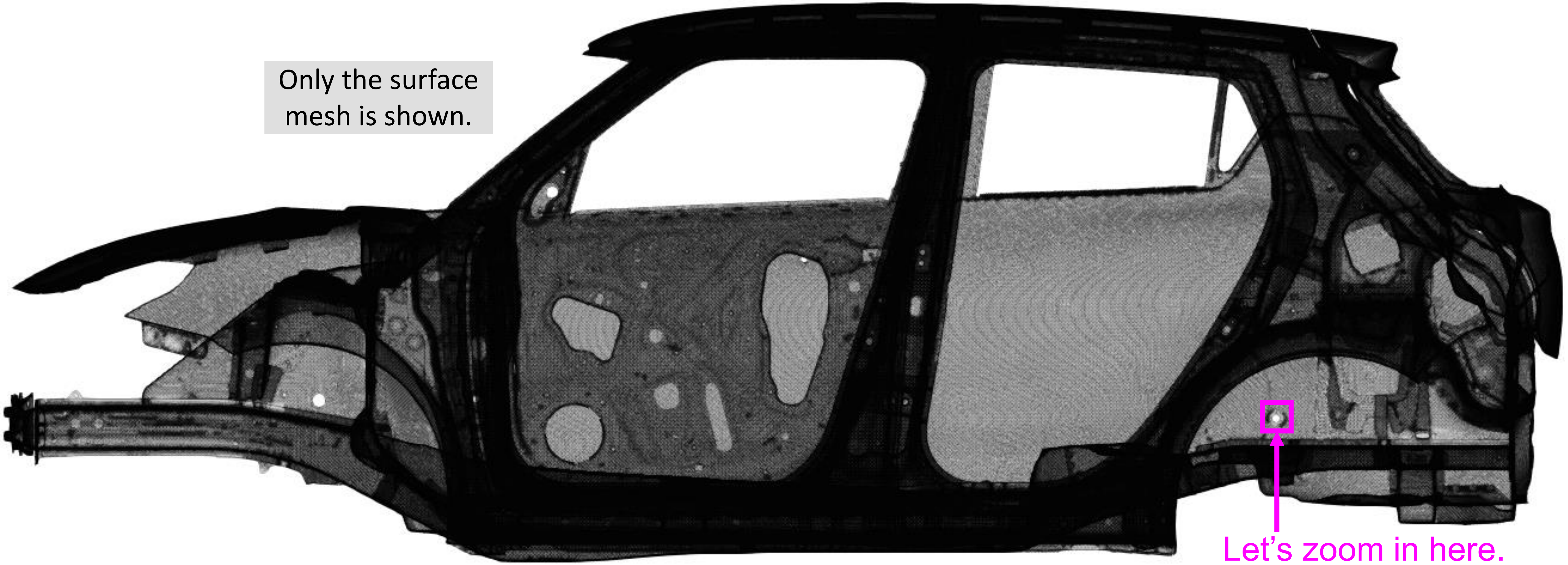
Overview of Surface Mesh of 16M Element Mesh

Only the surface mesh is shown.



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

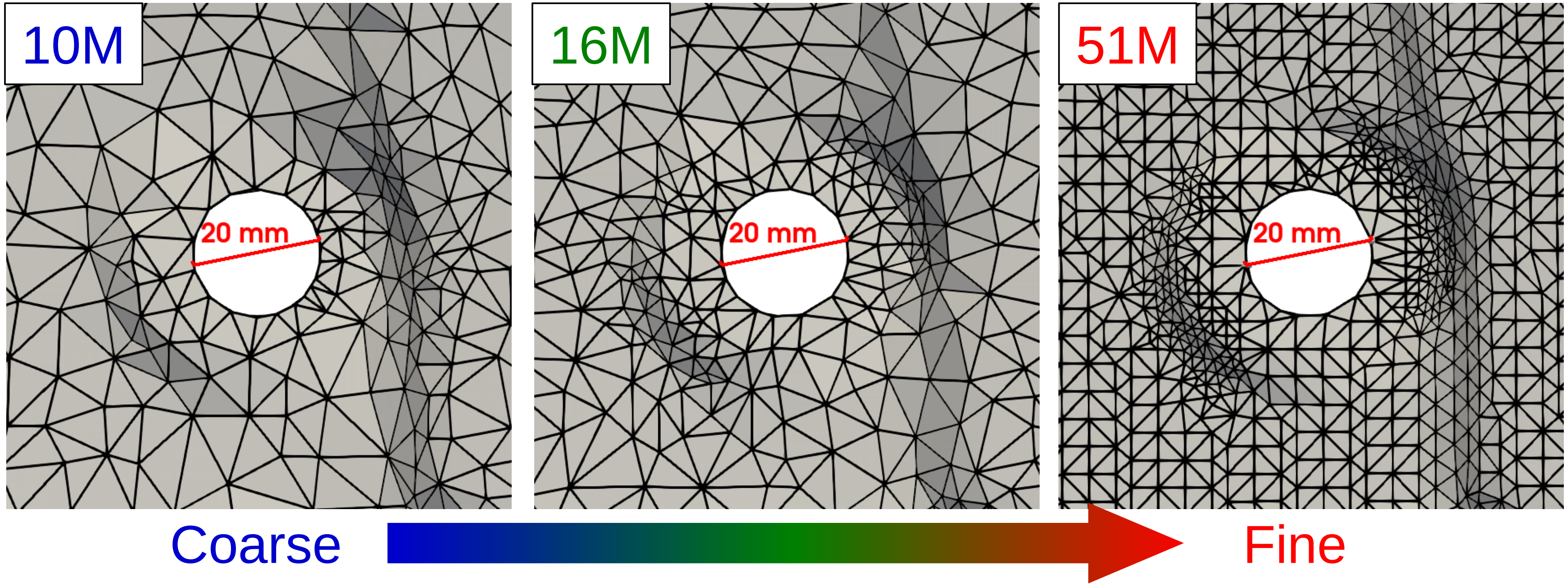
Overview of Surface Mesh of 51M Element Mesh



- 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 Analysis

Zoom in View around the Hole on Carbody

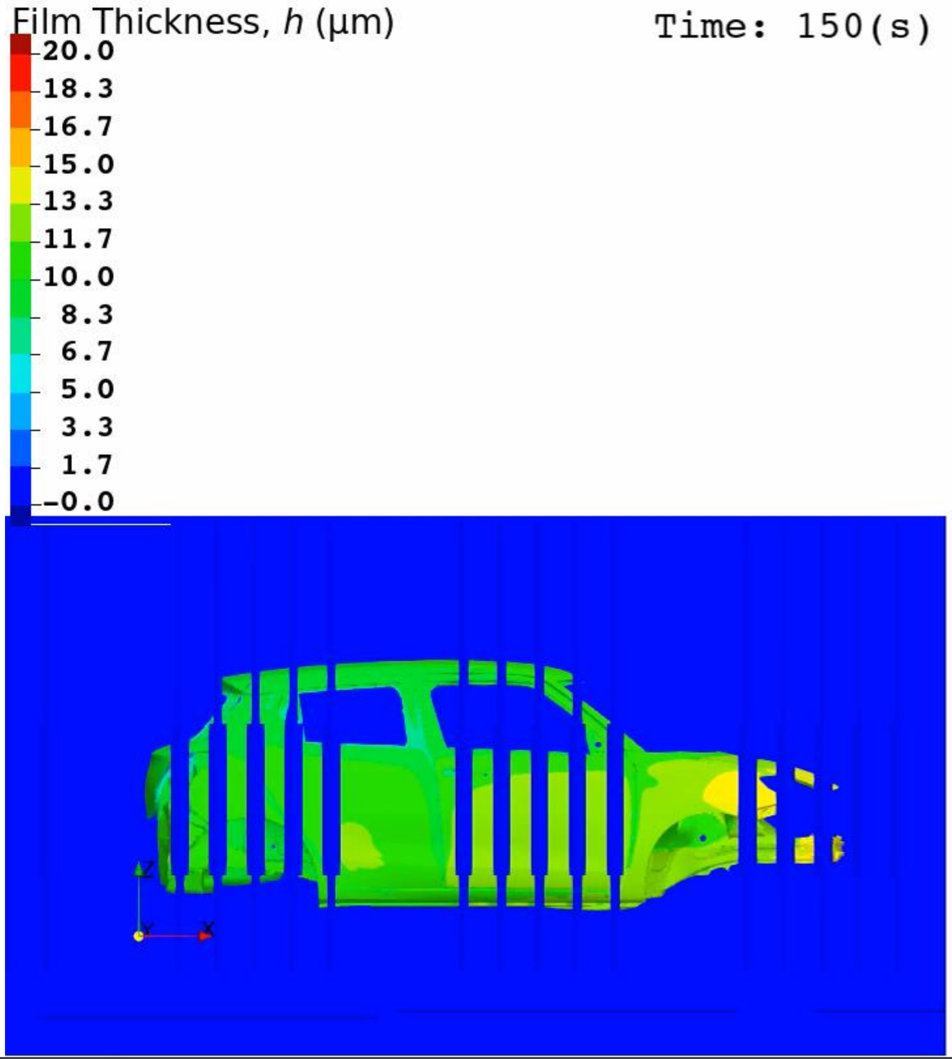


- There are many ED holes around narrow spaces among plates.
- The difference in the mesh can be seen clearly by zooming in around a hole.

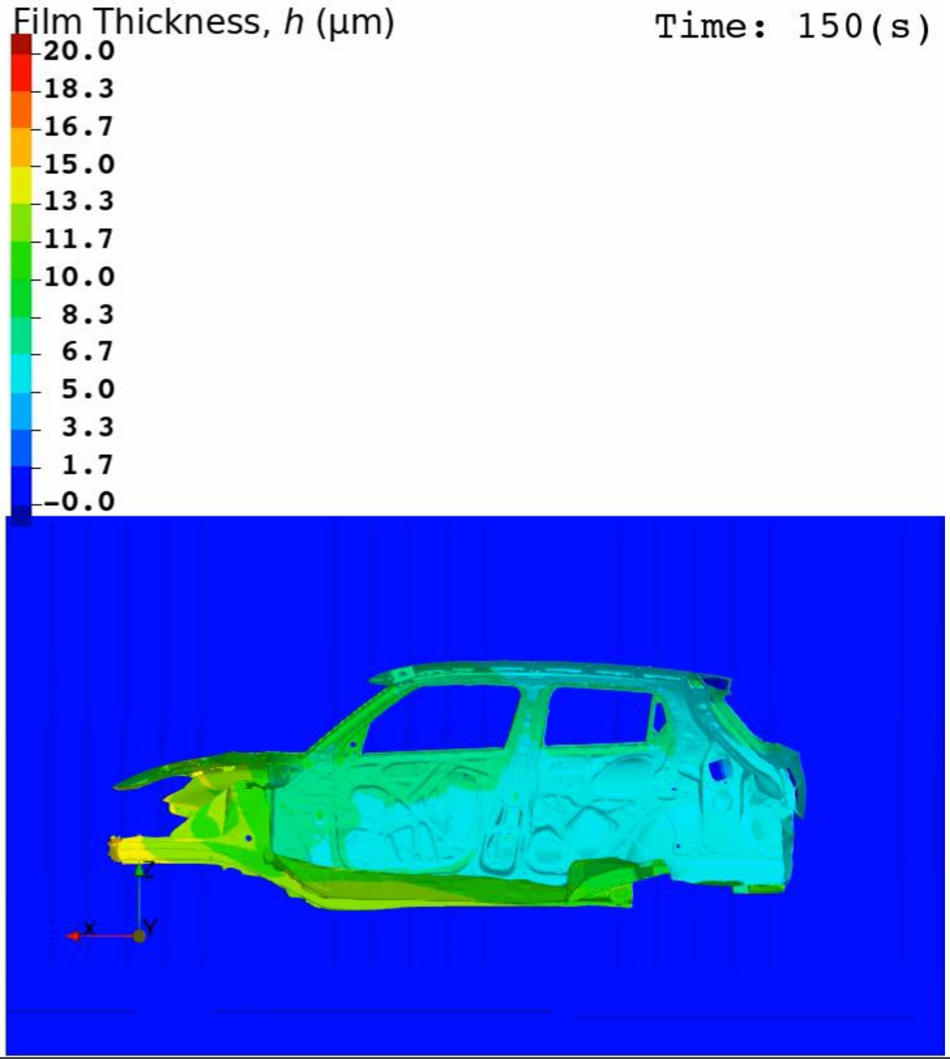
Actual Line Analysis

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

Outer View



Inner View

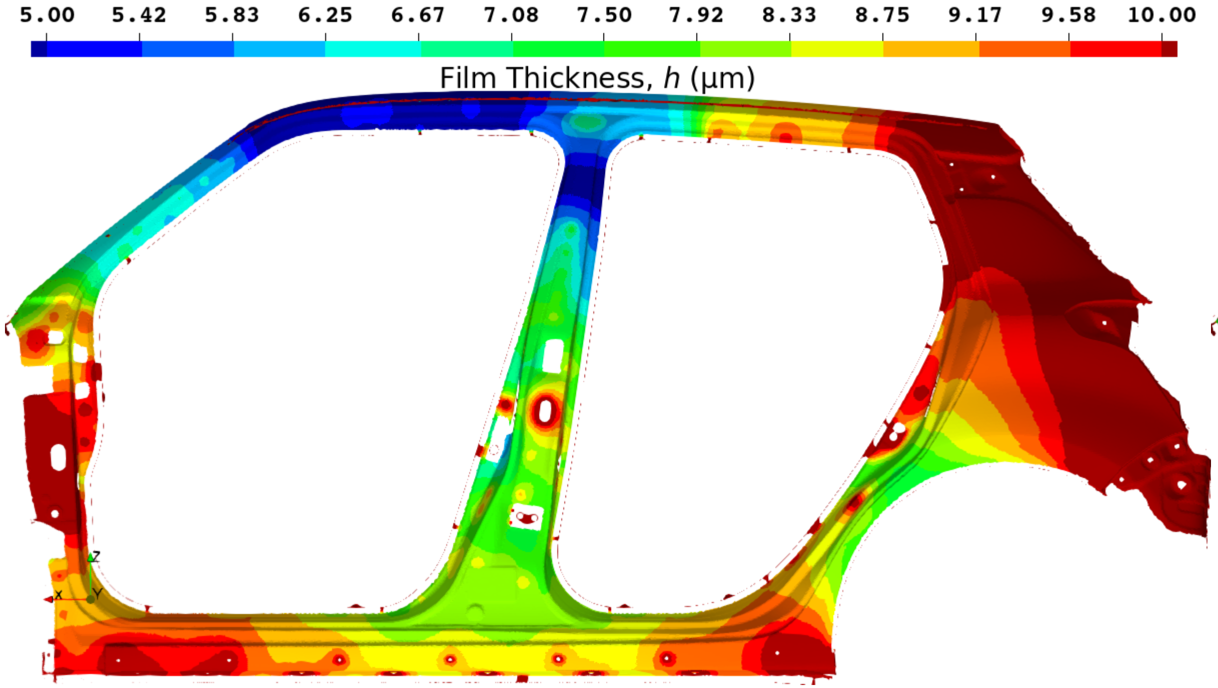


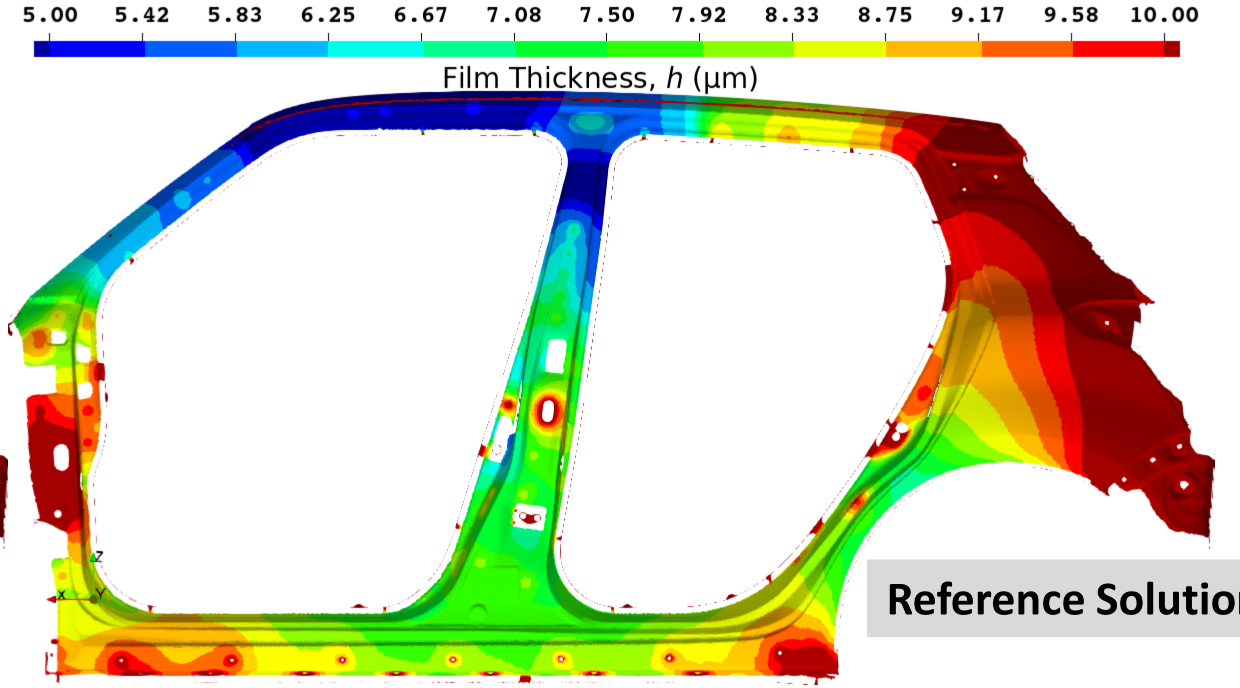
Actual Line Analysis

Final Film Thickness Distribution on the Side Sill Part with 51M Element Mesh

Standard FEM-T4

ES-FEM-T4





Reference Solution

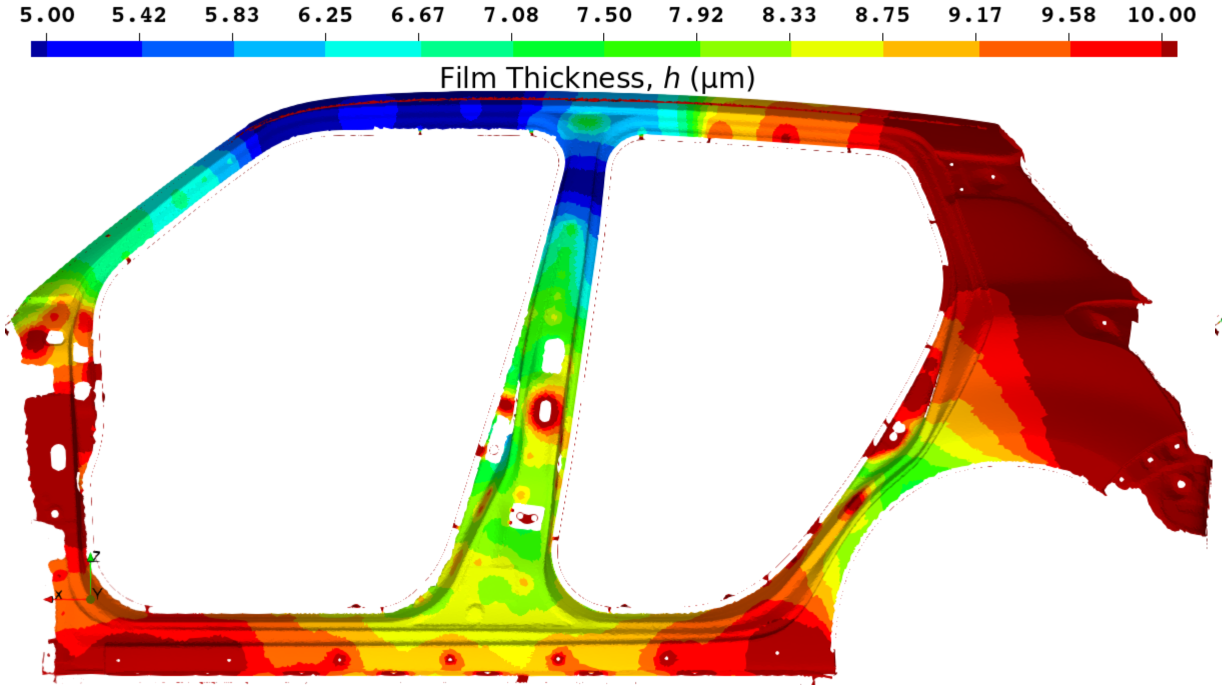
Standard FEM-T4 shows *a little thicker* result.
(The center of the side sill is Yellow.)

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

Actual Line Analysis

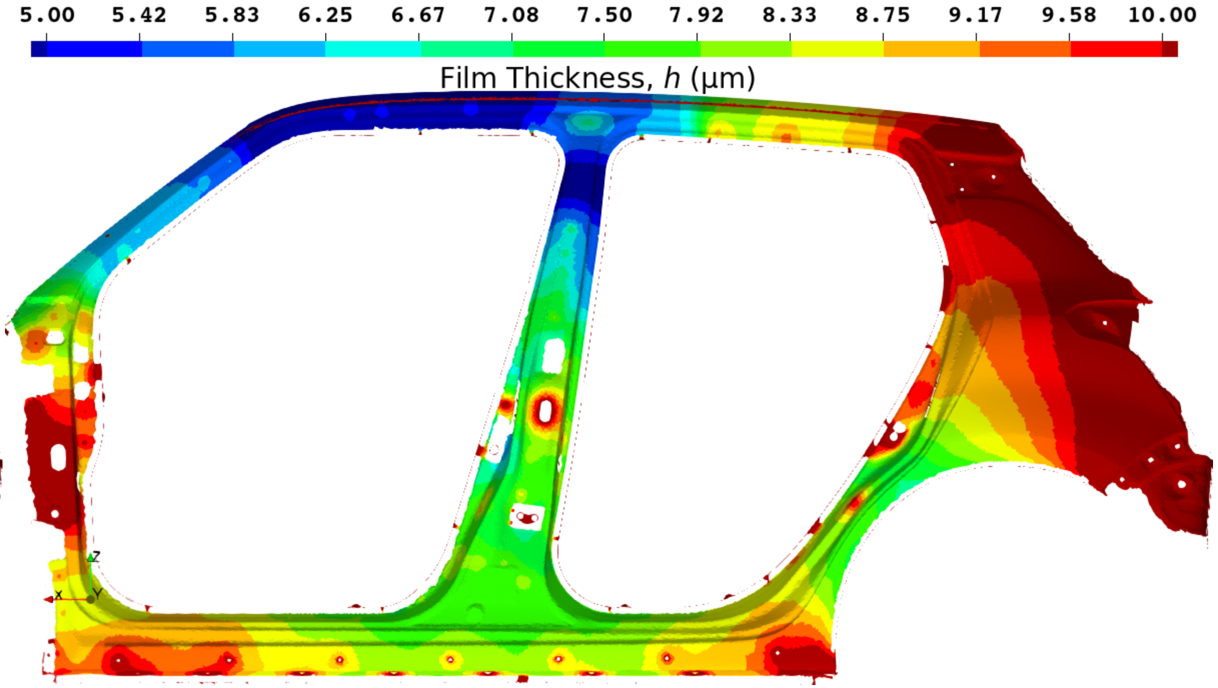
Final Film Thickness Distribution on the Side Sill part with 16M Element Mesh

Standard FEM-T4



Standard FEM-T4 shows *a much thicker* result.
(The center of the side sill is Orange.)

ES-FEM-T4



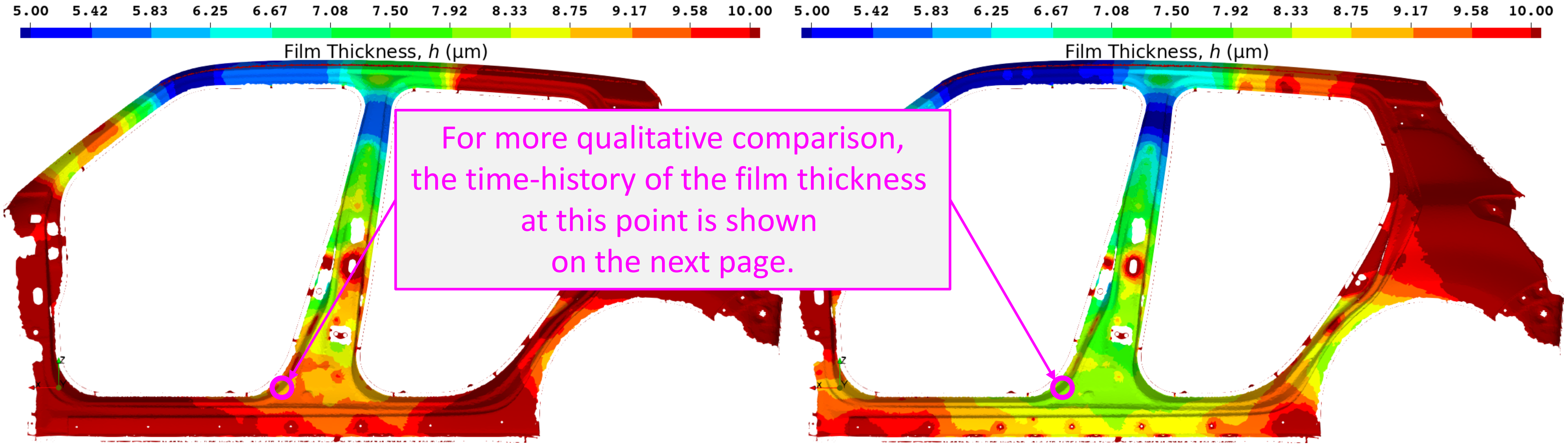
ES-FEM-T4 shows an *accurate* result.
(The center of the side sill is Green.)

Actual Line Analysis

Final Film Thickness Distribution on the Side Sill part with 10M Element Mesh

Standard FEM-T4

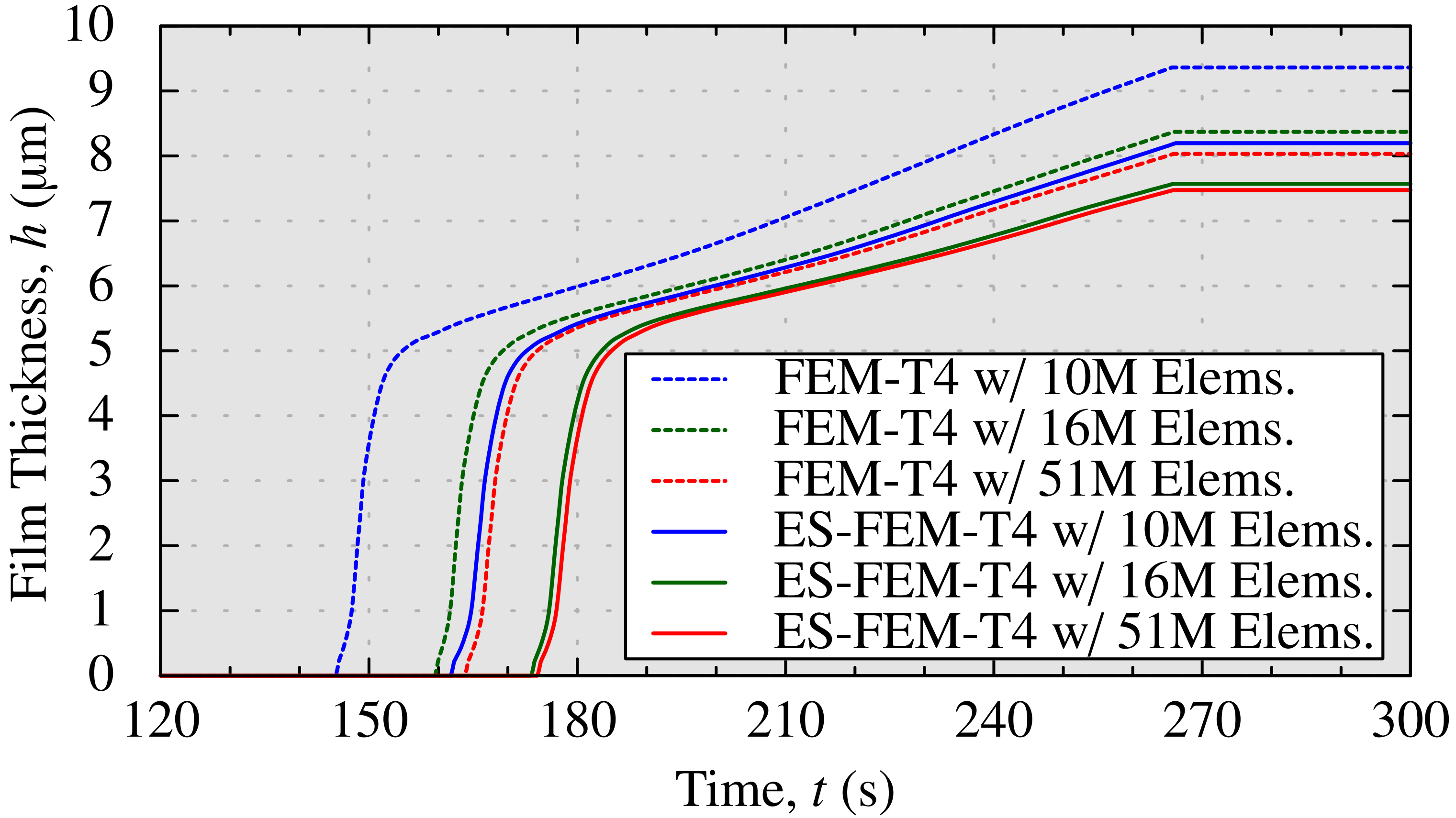
ES-FEM-T4



Standard FEM-T4 shows ***a massively thicker*** result. (The center of the side sill is Red.)

ES-FEM-T4 shows ***a little thicker*** result. (The center of the side sill is Yellow.)

Comparison of Time-histories of Film Thickness at the Sample Point on the 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.

Actual Line Analysis

Comparison of Calculation Time

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

# of Elements	Standard 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

An actual line analysis of a single-body entry takes only a few hours.

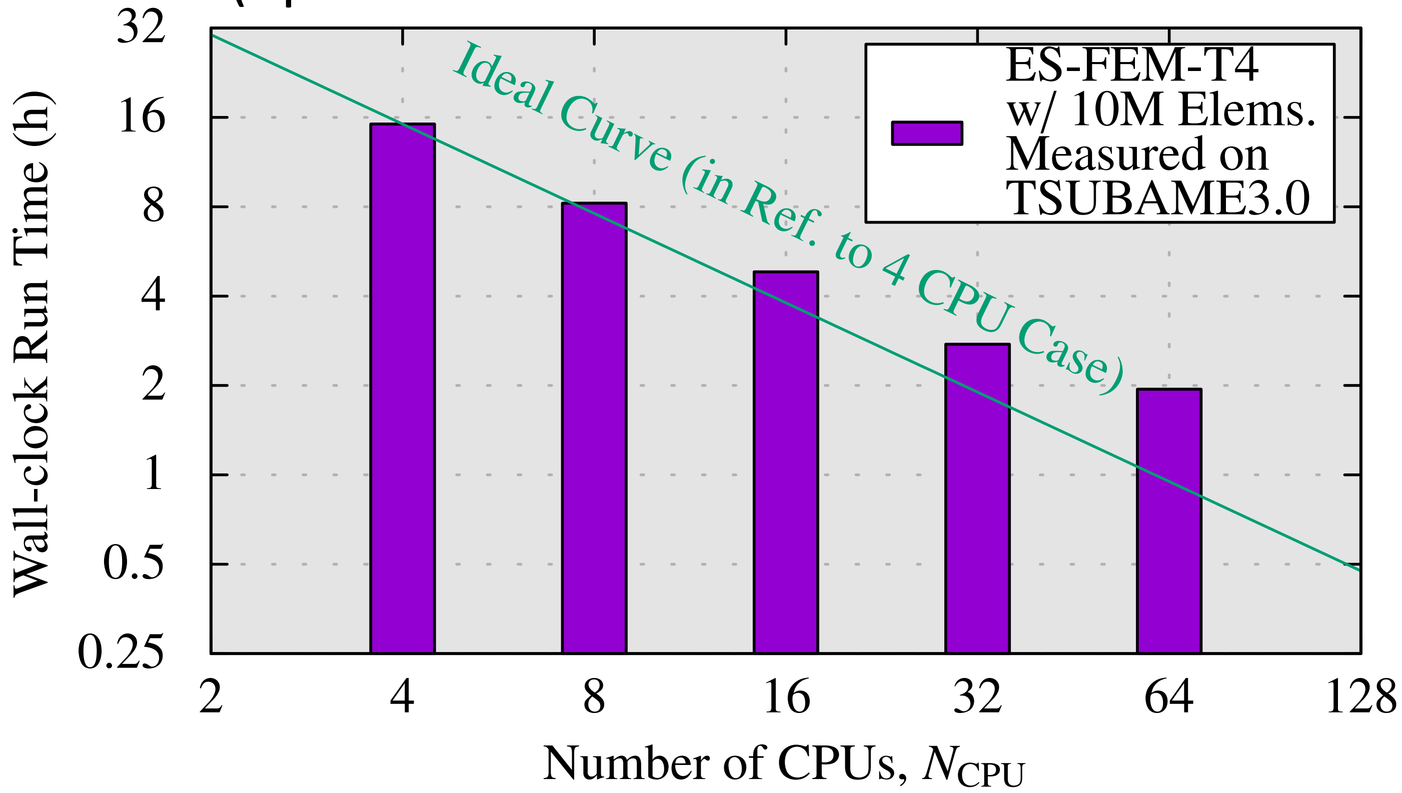
- With the same mesh, ES-FEM-T4 is slower than FEM-T4 by x1.5.
- For the same accuracy, ES-FEM-T4 is faster than FEM-T4 by x3.

For the simulations of actual ED lines with parallel computing, ES-FEM-T4 is much more efficient than FEM-T4.

Actual Line Analysis

Strong Scaling Test (with 10M Element Mesh)

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



Our ES-FEM-T4 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 super-linear (almost quadratic) mesh convergence rate in ED simulation, was confirmed compared to the poor accuracy of the standard 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.
- Further improvement using the edge center-based strain smoothing element (EC-SSE-T4) is our work in the future.
- For more information, please visit our commercial code "**EDESFEM**" official website.

Search	edesfem

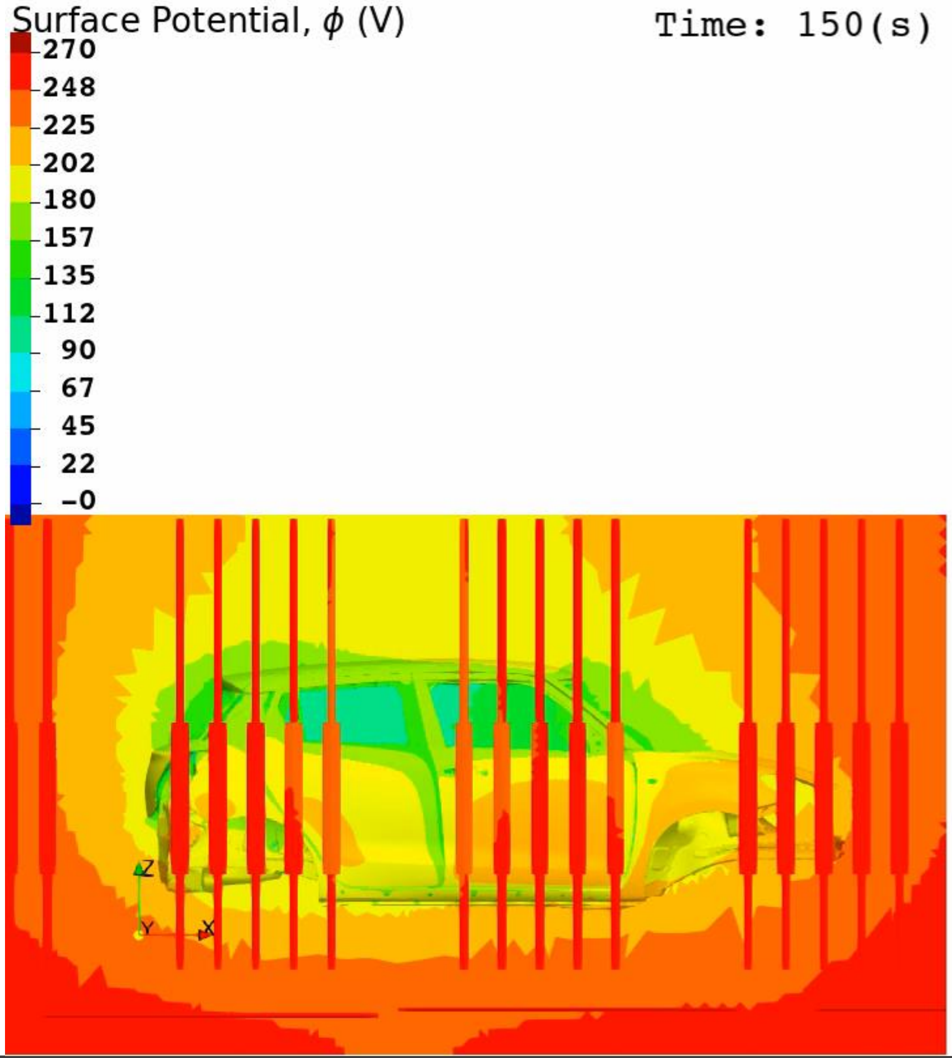
Thank you for your kind attention.

Appendix

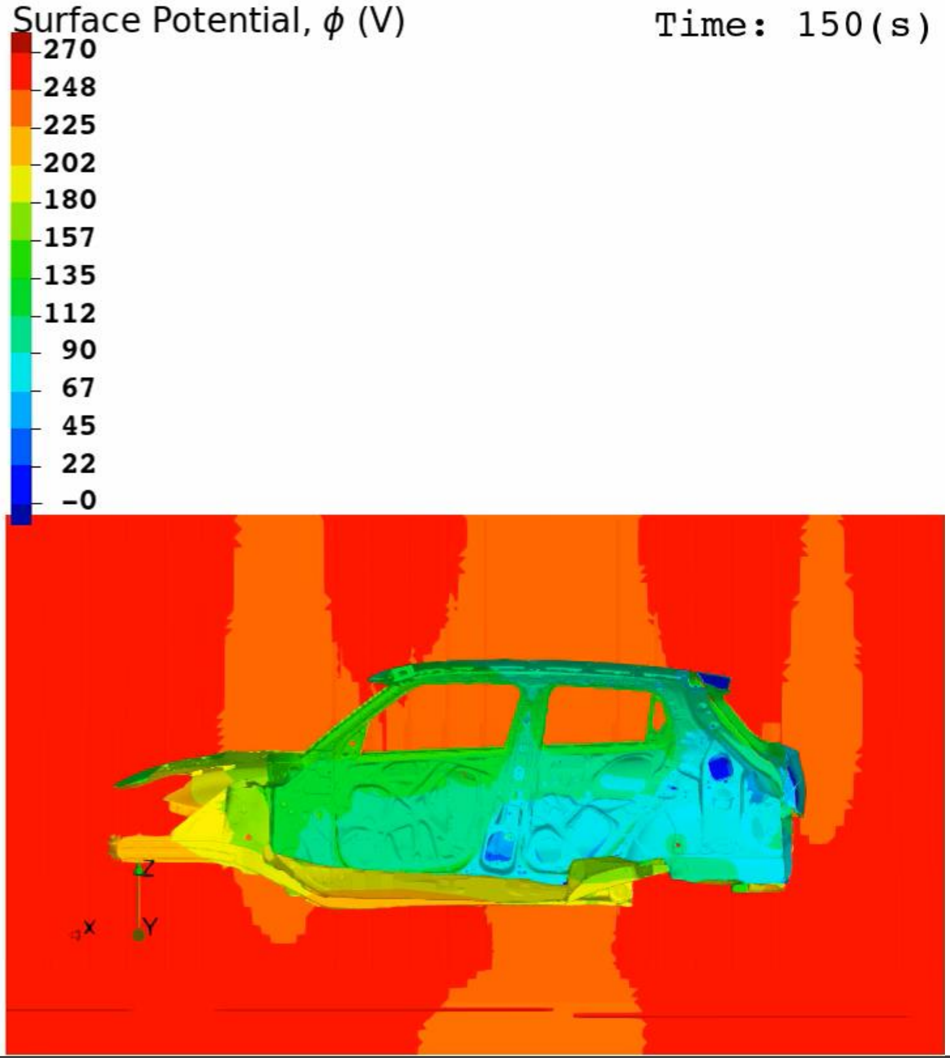
Actual Line Analysis

Animation of Surface Potential (ES-FEM-T4 with 51M Element Mesh)

Outer View



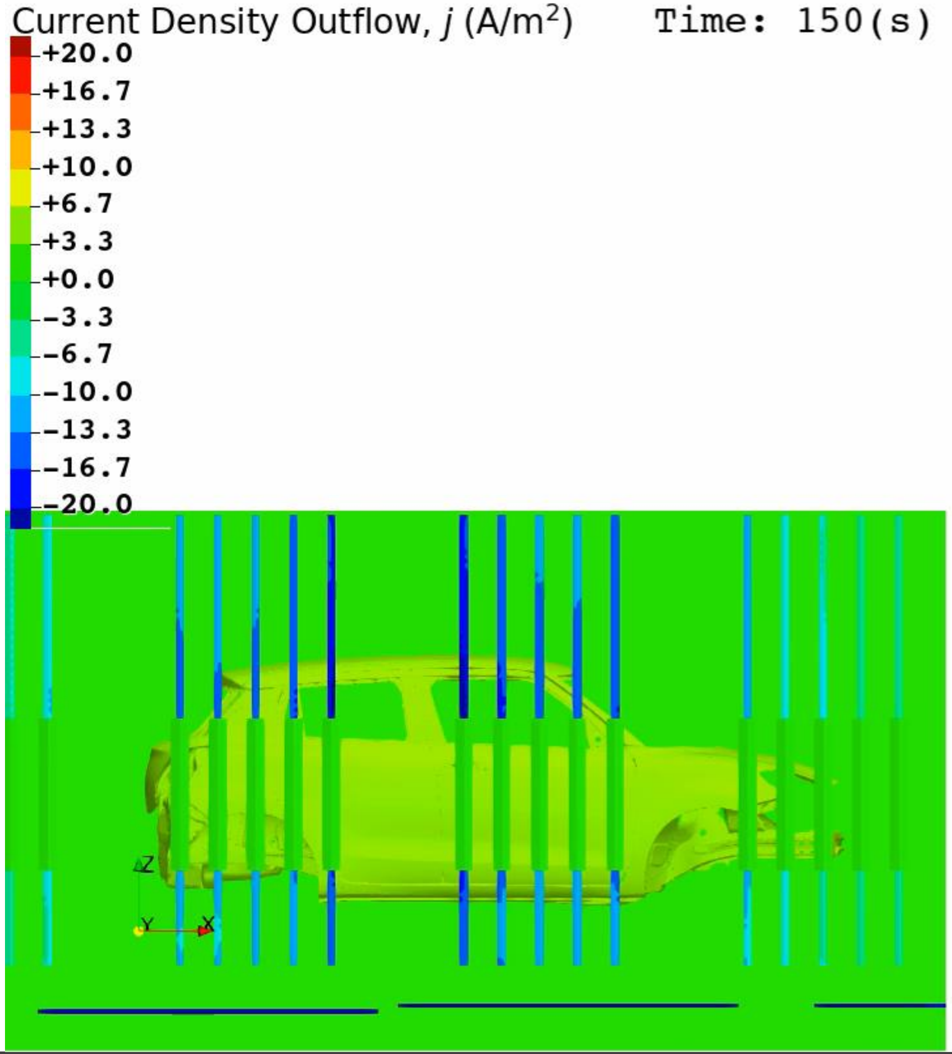
Inner View



Actual Line Analysis

Animation of Current Density (ES-FEM-T4 with 51M Element Mesh)

Outer View



Inner View