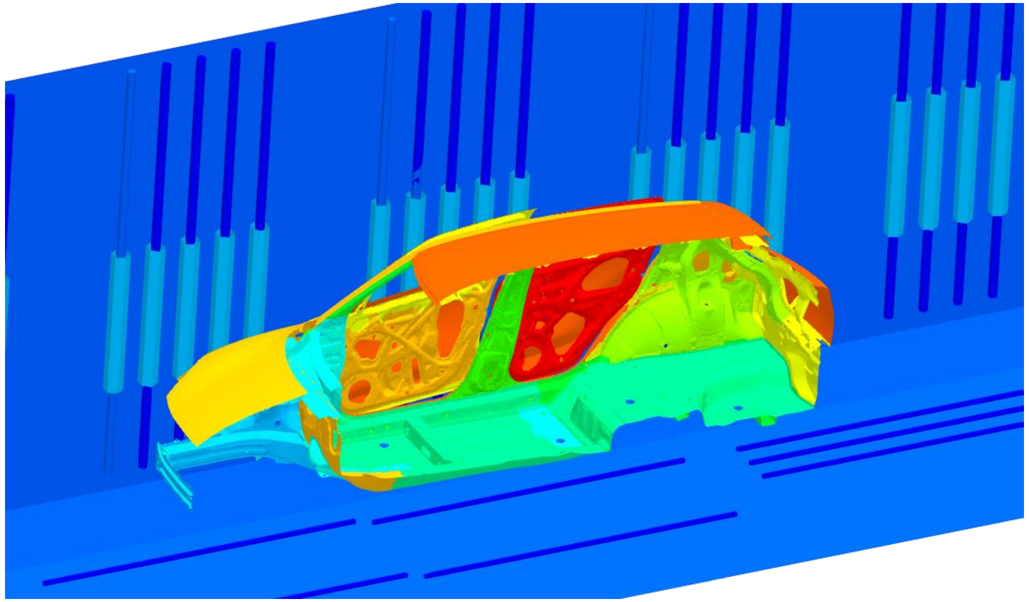
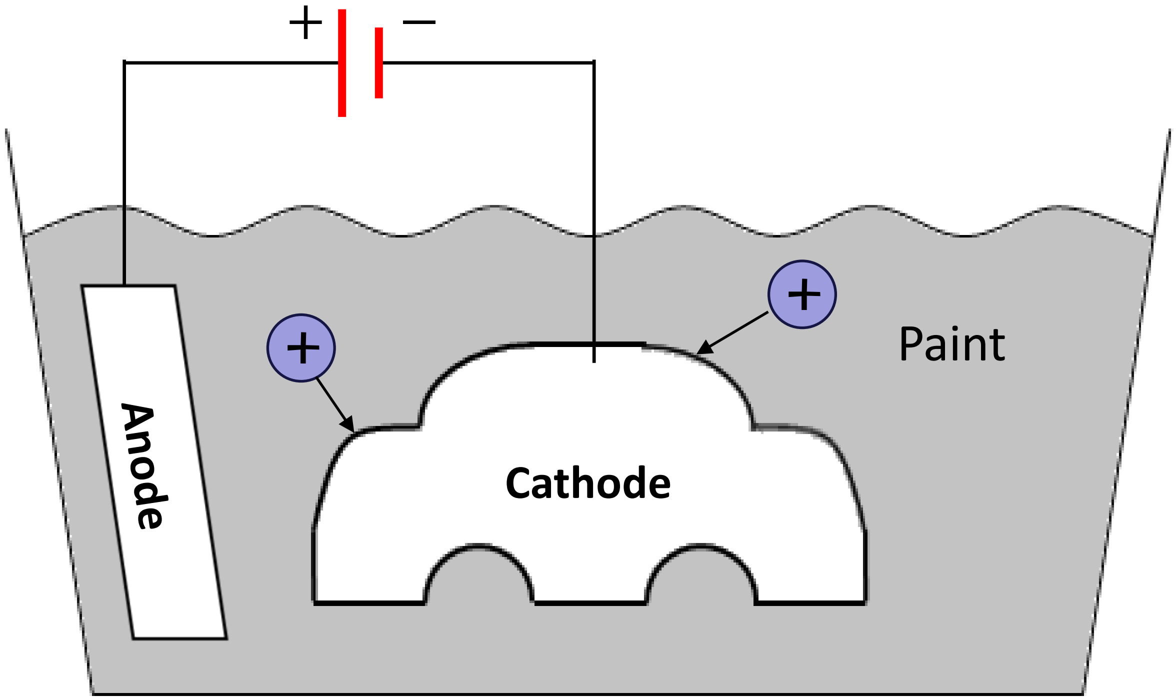
# EDESFEM

# Numerical Analysis Software Specialized for Electrodeposition Coating Simulation



# 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.

# Importance of ED


- Inspections of the safety and structural health of cars (e.g., crash tests) are usually performed with new cars without corrosion.
- However, corrosion significantly reduces the strength and stiffness of a car in reality.
- In other words, corrosion can easily spoil the value of the inspections with new cars.

∴ ED is critical to the safety and structural health of carbodies.

# Impact of ED process on carbody design

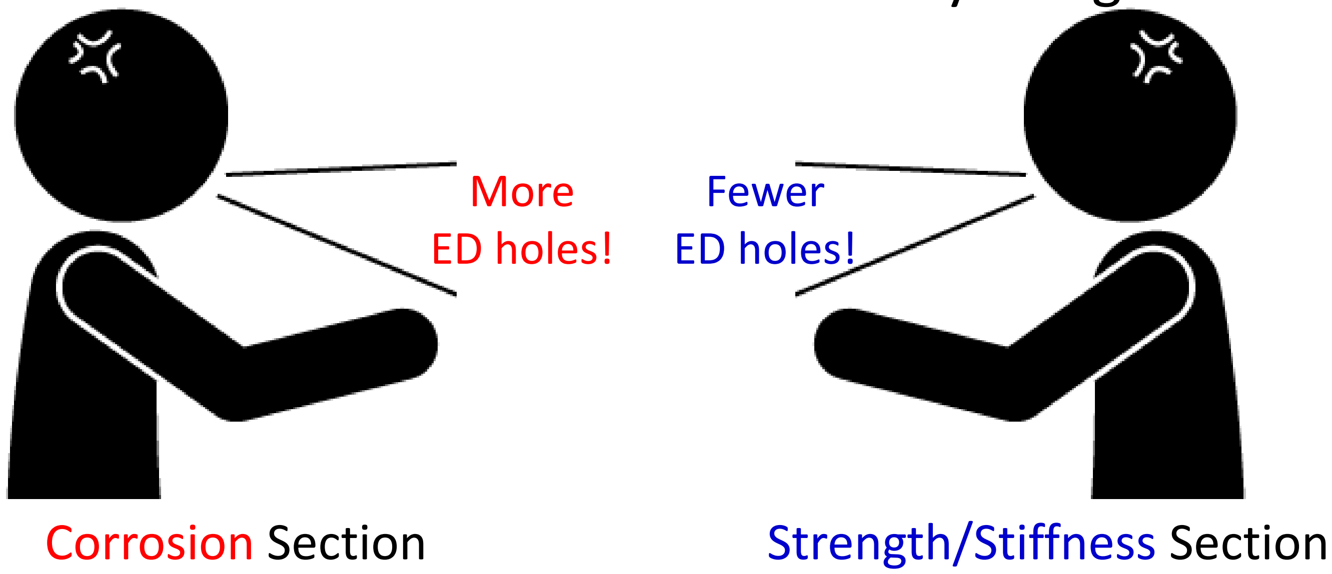


- Undercarriages are exposed to severe corrosive environments.
  (It is even more severe in environments with seawater or snow-melting chemicals.)
- Thus, it is necessary to ensure the ED film thickness is above minimum over the entire surface of the undercarriages.
- Some undercarriage parts (e.g., side sills) have bag-like complex structures with laminated plates, making **some ED holes** as the path for ED current to the inner faces is indispensable.

∴ Understanding and considering the ED process, including the location and size of the ED holes, is essential for carbody design.

# Need for ED Simulation

- ED holes are essential for corrosion protection, while they are unwanted for strength/stiffness.
- Thus, the following conflict occurs in the field of carbody design.

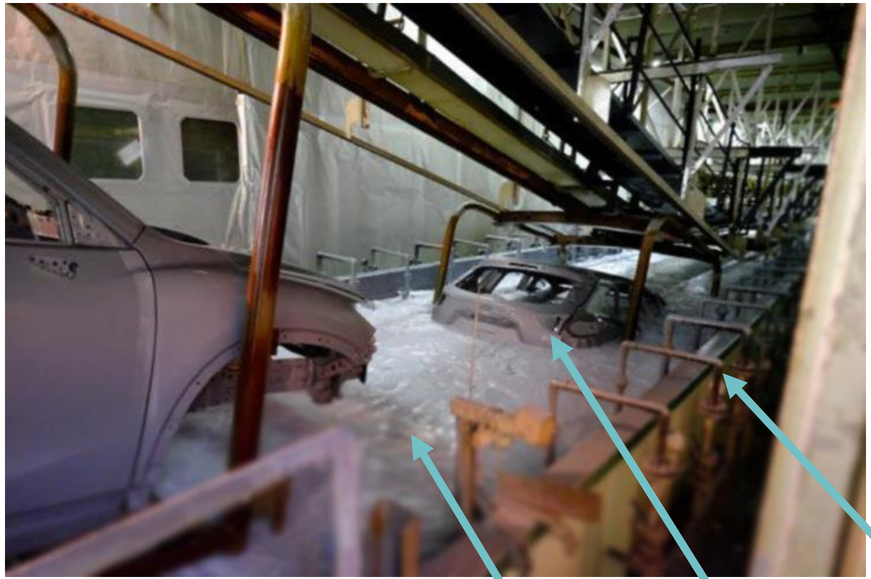



**ED simulation** can resolve such conflicts without any seeds of future trouble and lead to the optimal carbody design.

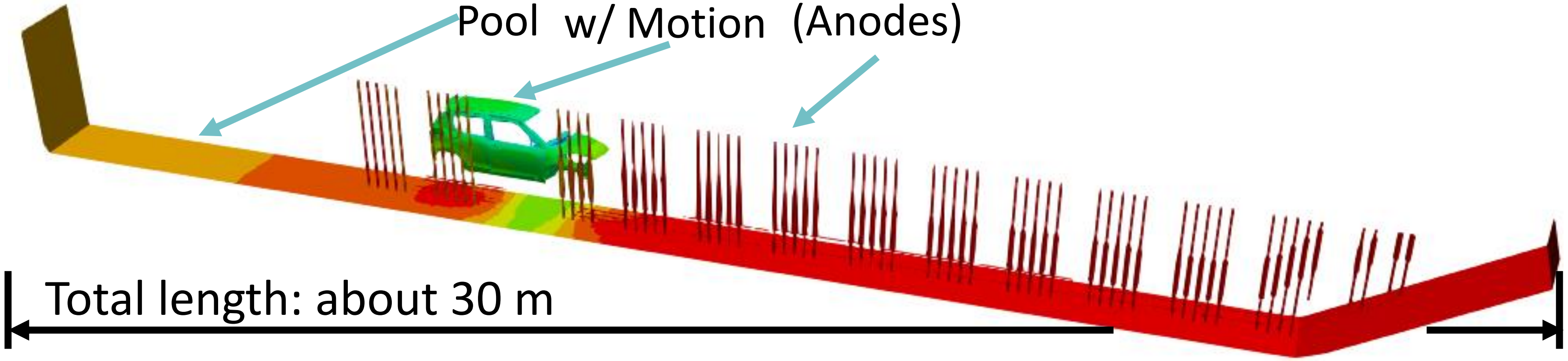
- Of course, ED simulation is also useful for pre-study of the effect of ED condition changes on film thickness, cause finding and quick improvement of insufficient deposition, etc..

# What is ED Simulation?

## *Actual ED Line*



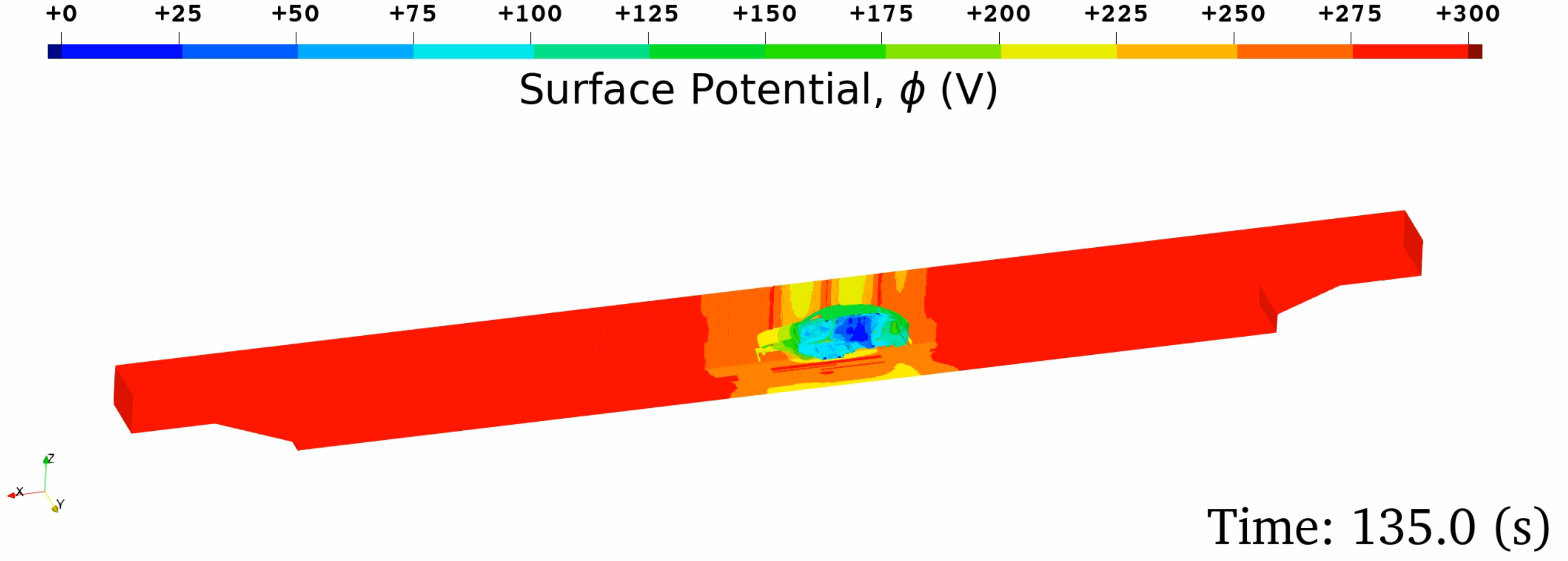
## *ED Simulation*




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

are reproduced in a computer.

# What is ES 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 resistance/growth constitutive model.

Identified via
lab experiments.
↓

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

Final film thickness
← is the main output.

# 4 Features of EDESFEM

# #1: High Accuracy with 4-node Tetrahedral Meshes

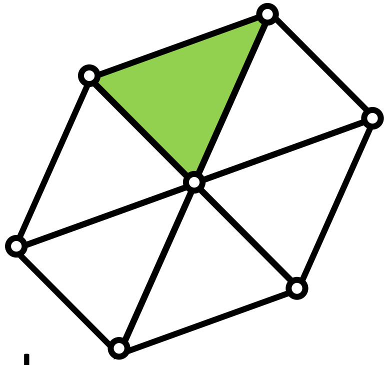
Adopting smoothed finite element method (S-FEM) for numerical formulation

- S-FEM has recently been put to practical use as a next-gen FEM.
- EDESFEM adopts the edge-based S-FEM using 4-node tetrahedral meshes (ES-FEM-T4).

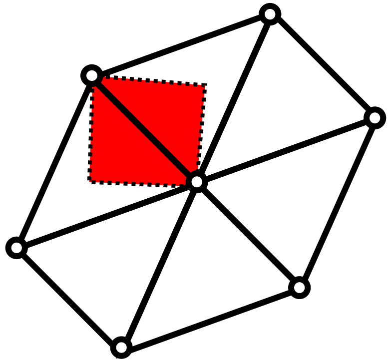
2D example
for simplicity

Standard FEM

Putting
Gauss point
at each element center



ES-FEM

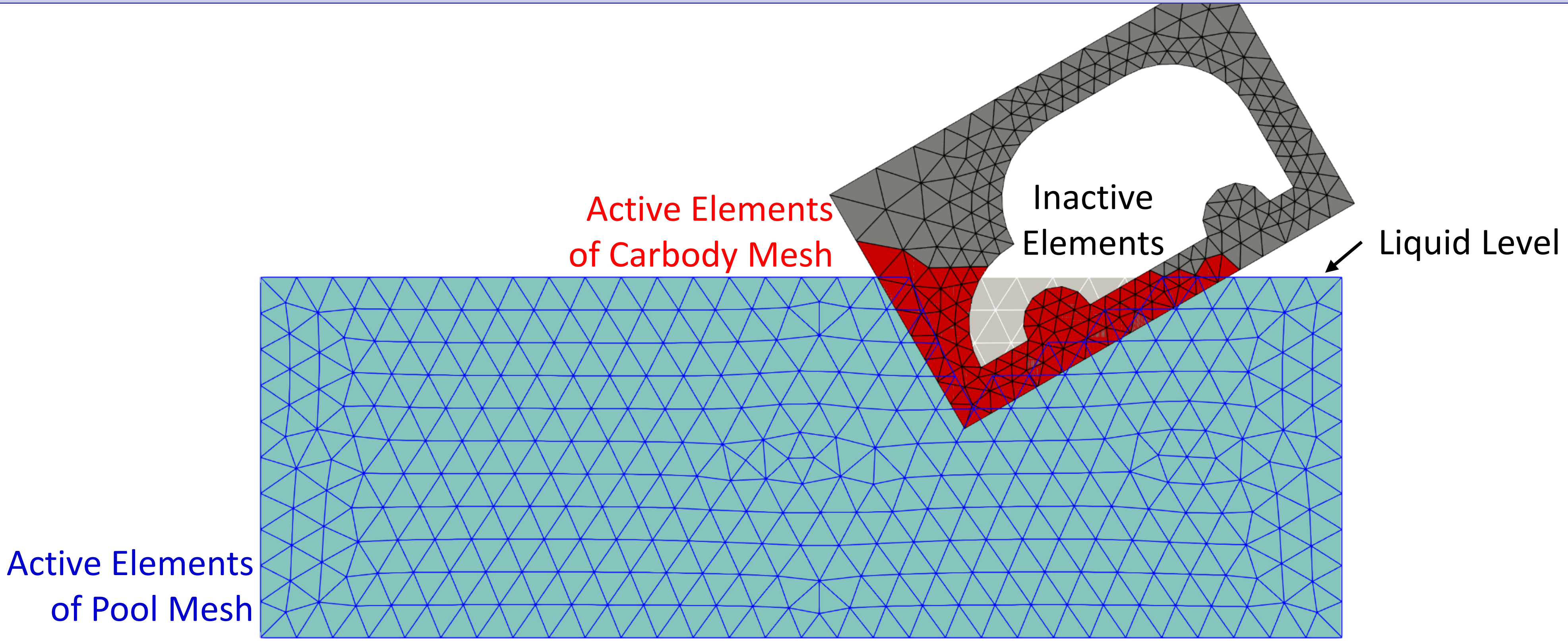


Putting
Gauss point
at each edge center

- Despite the 4-node tet mesh,
  superlinear mesh convergence rate is obtained as fast as the 2nd -order elements.
- 4-node tet meshes enable the analyses with a minimum number of elements,
  even around ED holes, where the quadratic or Cartesian meshes lead to
  a massive increase in elements.

# #2: Support for Moving Boundary Analysis of Multiple Bodies

Enabling moving boundary analysis of multiple carbodies with the overset mesh method



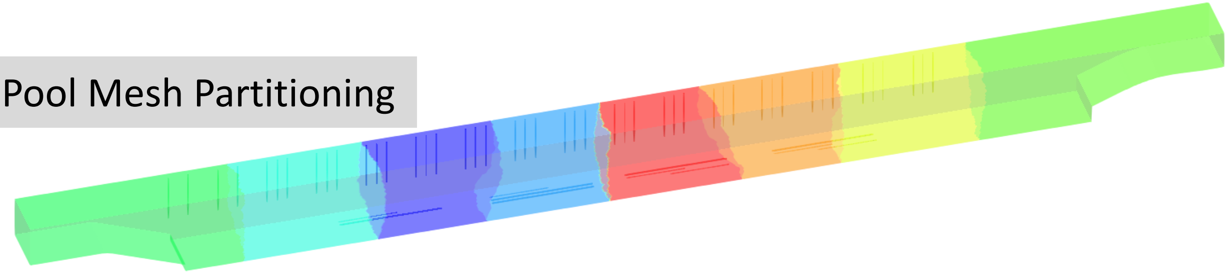

- The user just needs to prepare the pool/carbody meshes and motion tables for each body.
- Using multi-point constraints (MPCs), meshes are automatically connected at interfaces inside EDESFEM.

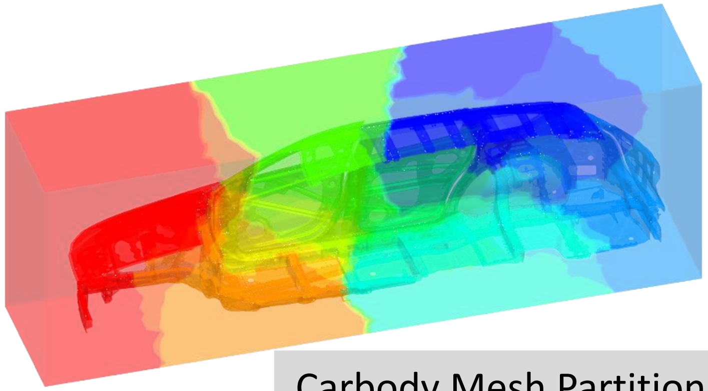
# #3: High Speed with MPI/OpenMP Hybrid Parallelization

Accepting various HPC environments with MPI/OpenMP hybrid parallelization

- EDESFEM can use multi-core CPUs in multi-node HPC environments.
- Calculation steps:
    1. Generating T4 mesh for pool and carbody domains.
    2. Partitioning and reordering each mesh with METIS.

Pool Mesh Partitioning





Carbody Mesh Partitioning

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

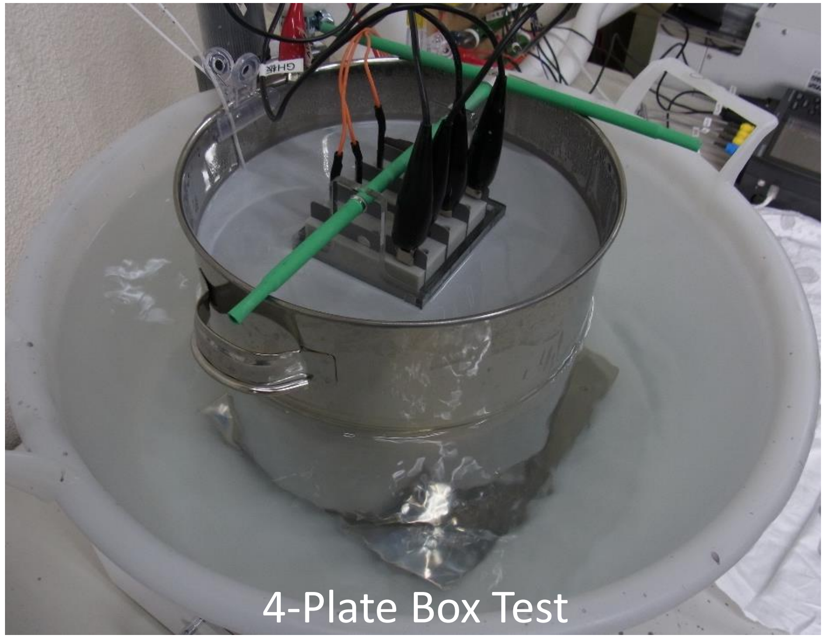
```
orterun –np 64 -bind-to socket -npersocket 1
        -x OMP_NUM_THREADS=8 -x numactl -l edesfem.bin input_file_name.ied
```

# #4: Faithful Reproduction of Deposition Delay on Inner Plates

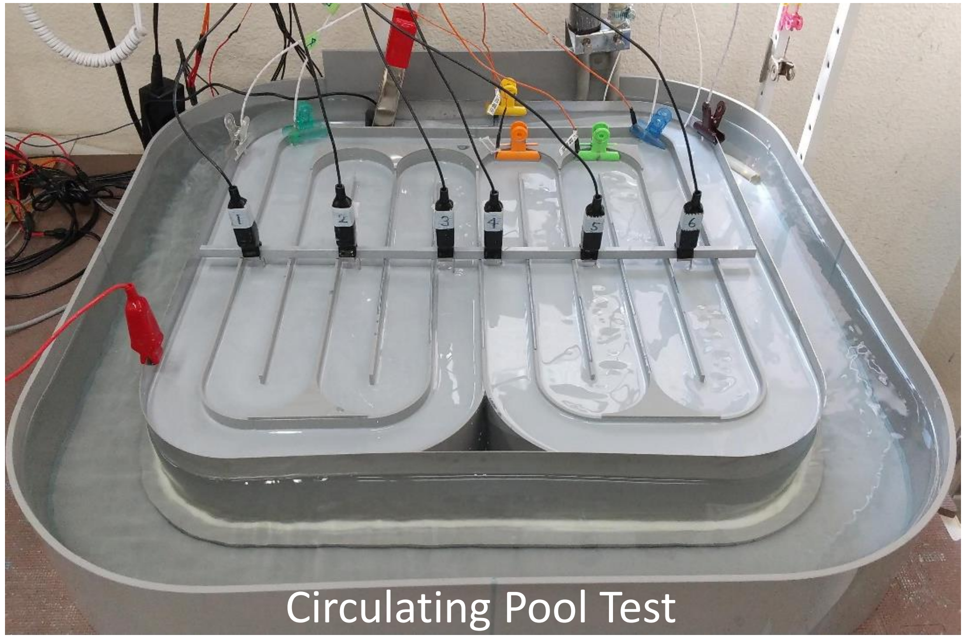
Employing the latest ED numerical model based on detailed lab experiments

- In ED, the film thickness on the inner plates inside the ED holes is important.
- Detailed lab experiments are essential to incorporate the deposition behavior of inner plates into the ED numerical model.

One-Plate Test



4-Plate Box Test



Circulating Pool Test

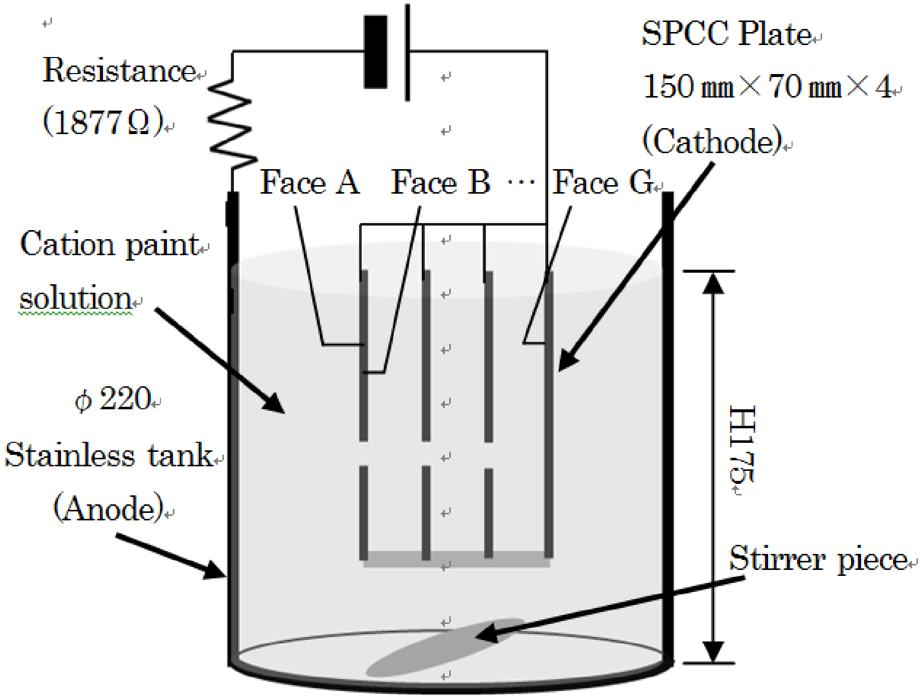
- EDESFEM implements ED numerical models obtained from the latest experimental findings.
- They contribute to the reduction of non-physical "calibration" work.

# EDESFEM
# Verification Example 1

# 4-Plate Box Analysis

# 4-Plate Box Analysis

## ***Outline***




- 4 plates form 3 bags.
- 3rd bag is the most difficult to be deposited.

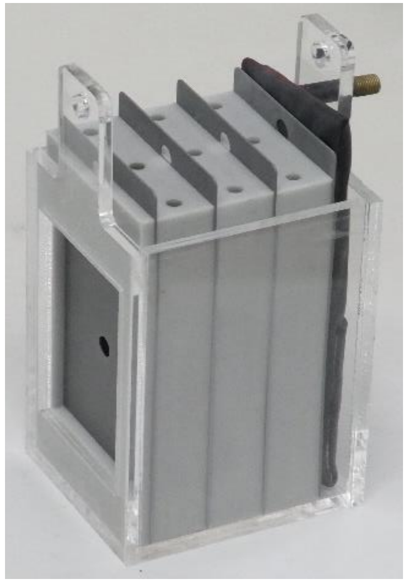
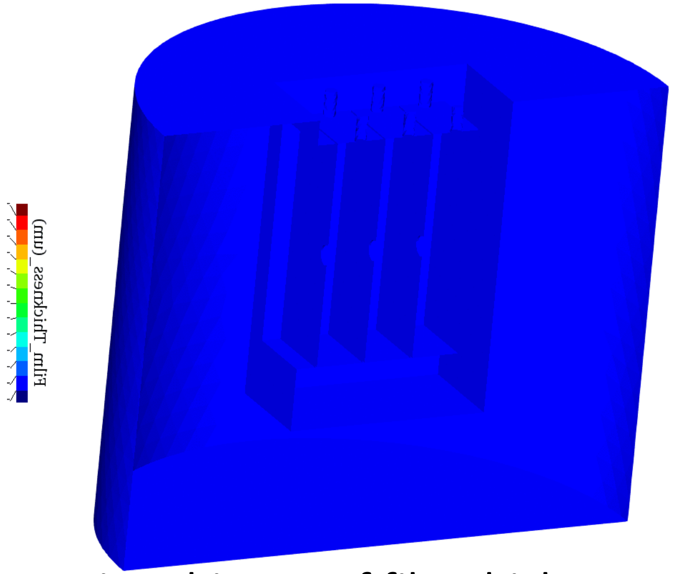


Photo of a 4-plate box



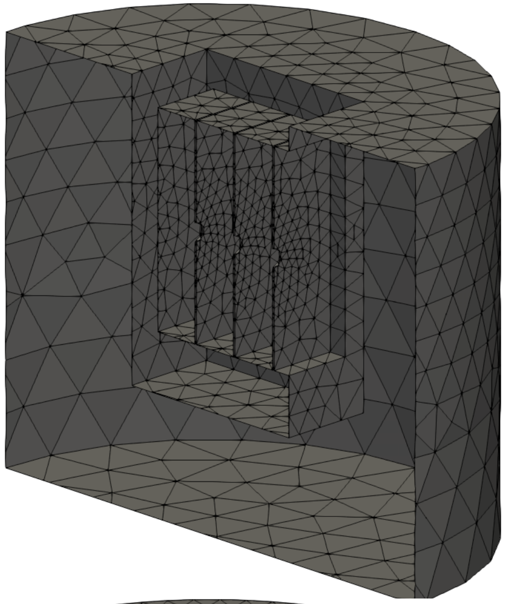
Time-history of film thickness

- 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 on Face G is evaluated with **4 different density meshes** using **FEM-T4** and **ES-FEM-T4.**

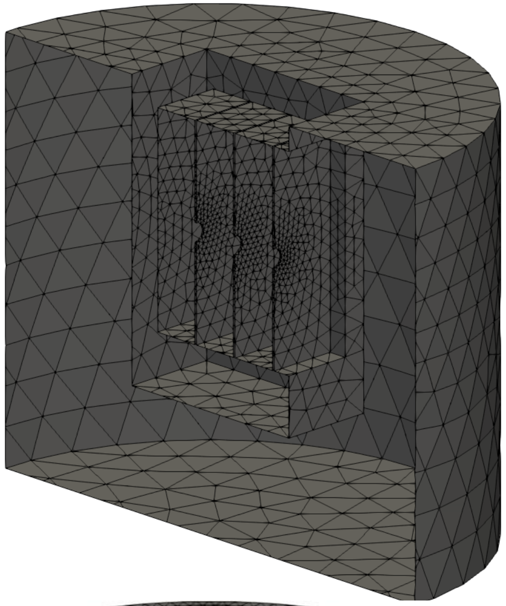
# 4-Plate Box Analysis

## ***Overview of Meshes***

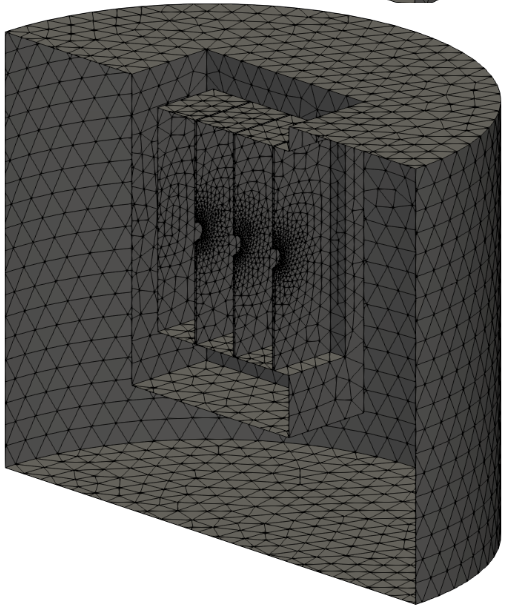
Only the surface meshes are shown.



**3.2 mm Mesh**
(about 31k elements)



**1.6 mm Mesh**
(about 65k elements)

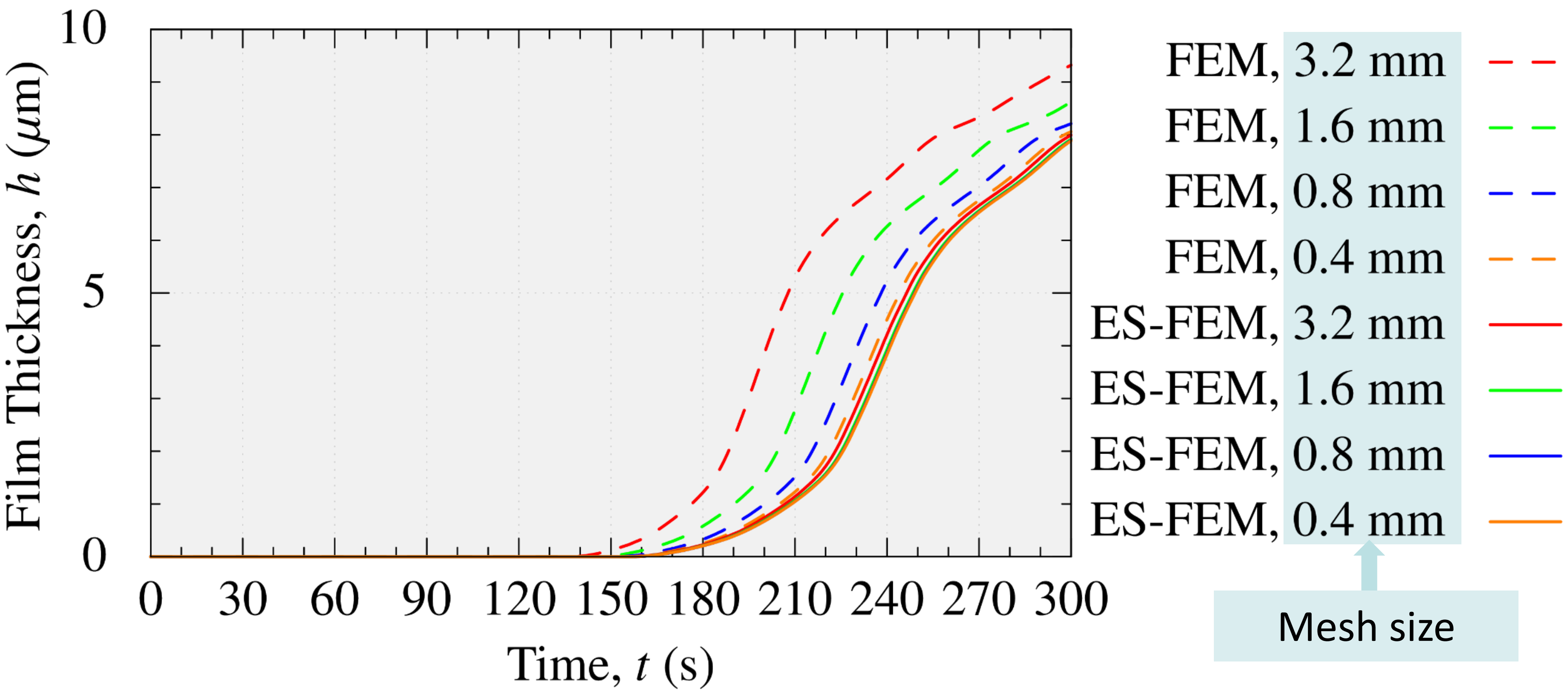


**0.8 mm Mesh**
(about 169k elements)

**0.4 mm Mesh**
(about 716k elements)

# 4-Plate Box Analysis

## ***Film Thickness on Face G (innermost surface)***

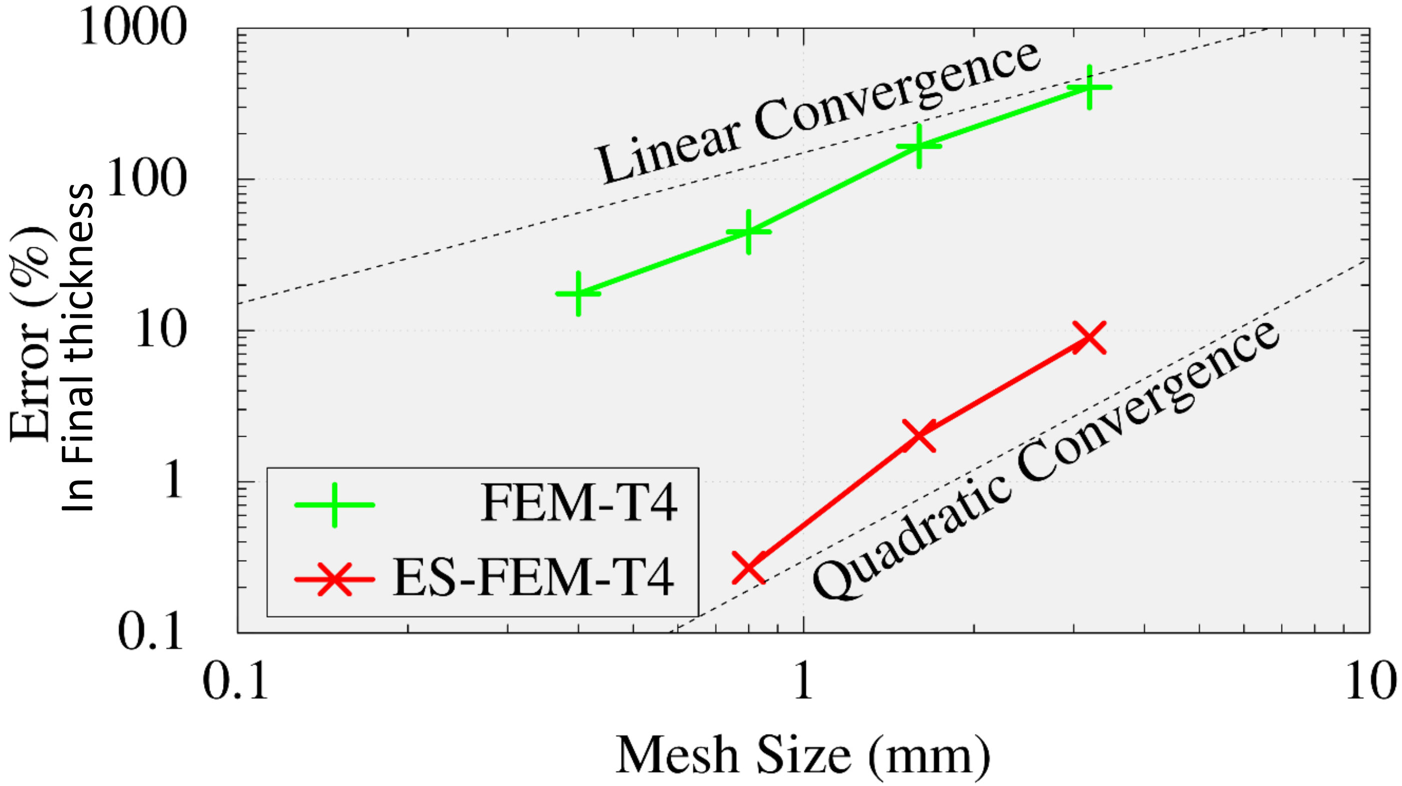



FEM results (dashed lines) have ***significant*** errors.

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 surface)*




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

- FEM-T4 shows a linear convergence.
- EDESFEM (ES-FEM-T4) shows a quadratic convergence.

ES-FEM-T4 adopted by EDESFEM has a much faster mesh convergence rate than the standard FEM-T4.

# 4-Plate Box Analysis

## *Comparison of Calculation Time*

on a PC (only 1 CPU: 16 cores of Intel i9-9960X)

| Mesh Size | Standard FEM (FEM-T4) | EDESFEM (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-T4 is slower than FEM by x2 ~ 3.
- For the same accuracy, ES-FEM-T4 is faster than FEM by x4.

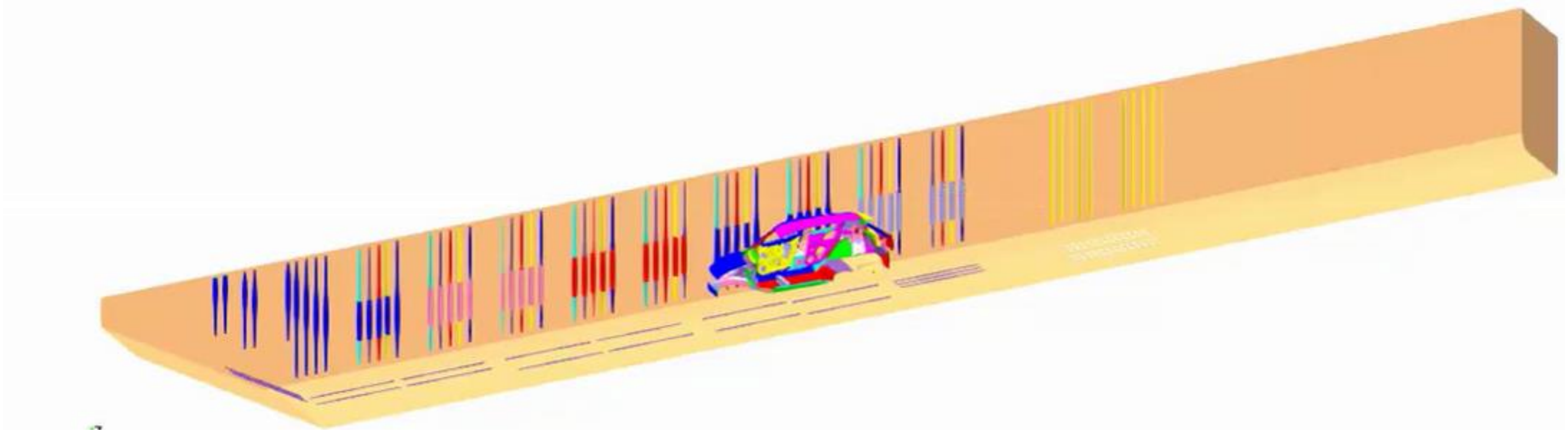
ES-FEM-T4 adopted by EDESFEM is supremely efficient
in comparison to FEM-T4.

# EDESFEM
# Verification Example 2

# Actual Line Analysis

# Actual Line Analysis

## ***Outline***

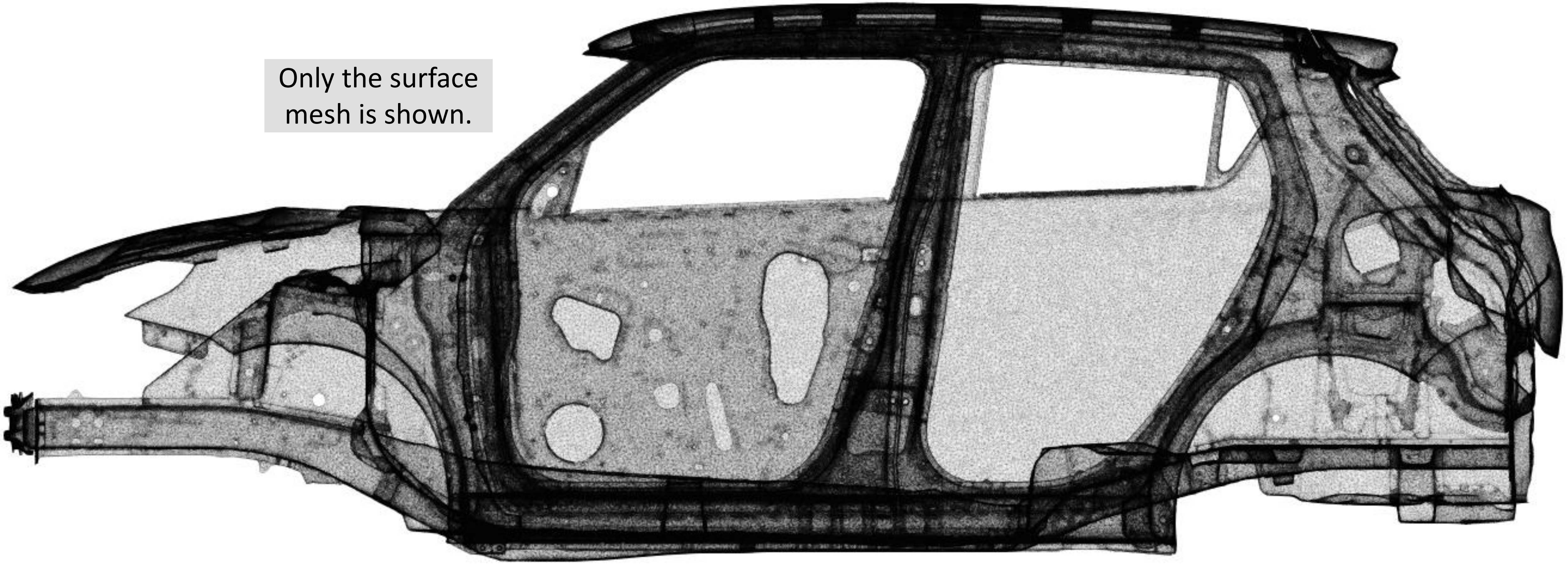


- **Half-body** analysis (only right-hand side).
- Entire line shape, carbody motion, and electrode conditions are faithfully reproduced.
- About 1000 timesteps for 300 s (i.e., average $\Delta t = 0.3$ s).
- The film thickness distribution is evaluated with **3 different density meshes** using FEM-T4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

# Actual Line Analysis

## ***Overview of Surface Mesh of 10M Element Mesh***

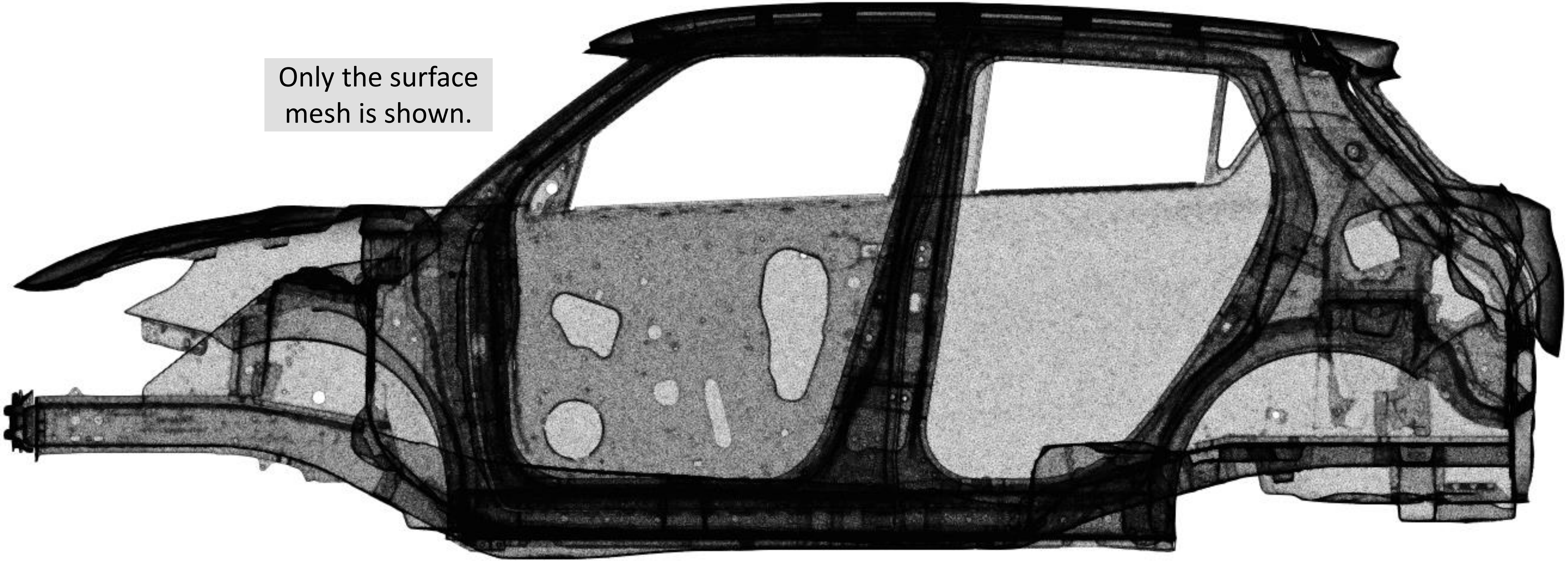
Only the surface mesh is shown.



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

# Actual Line Analysis

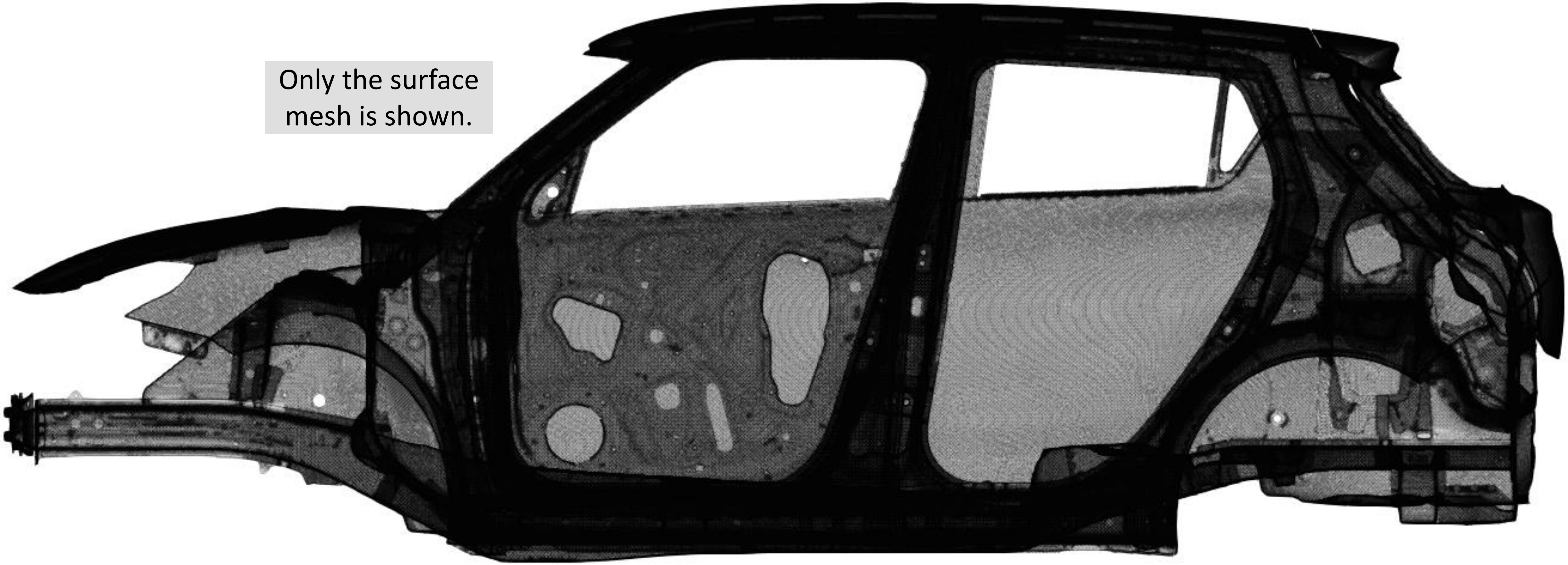
## ***Overview of Surface Mesh of 16M Element Mesh***



Only the surface mesh is shown.

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

## Overview of Surface Mesh of 51M Element Mesh

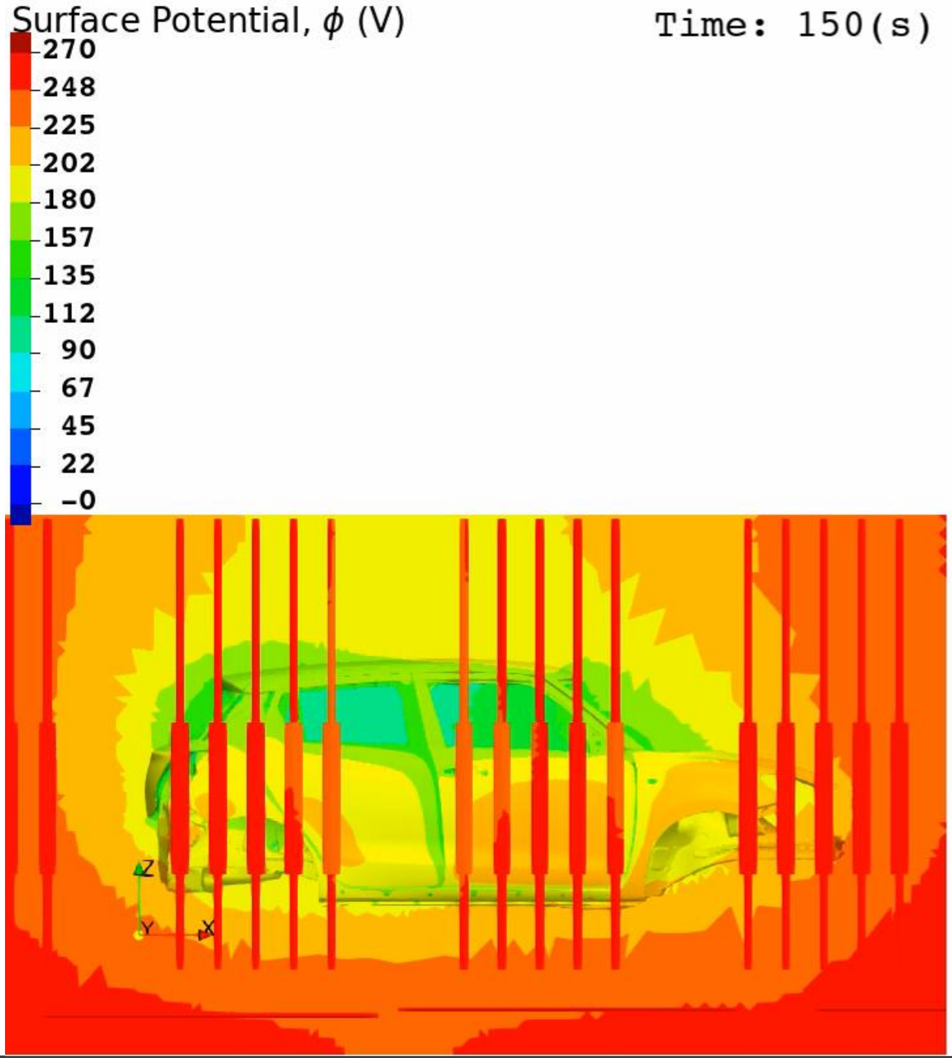



■ There are many **ED holes** around narrow spaces among plates.

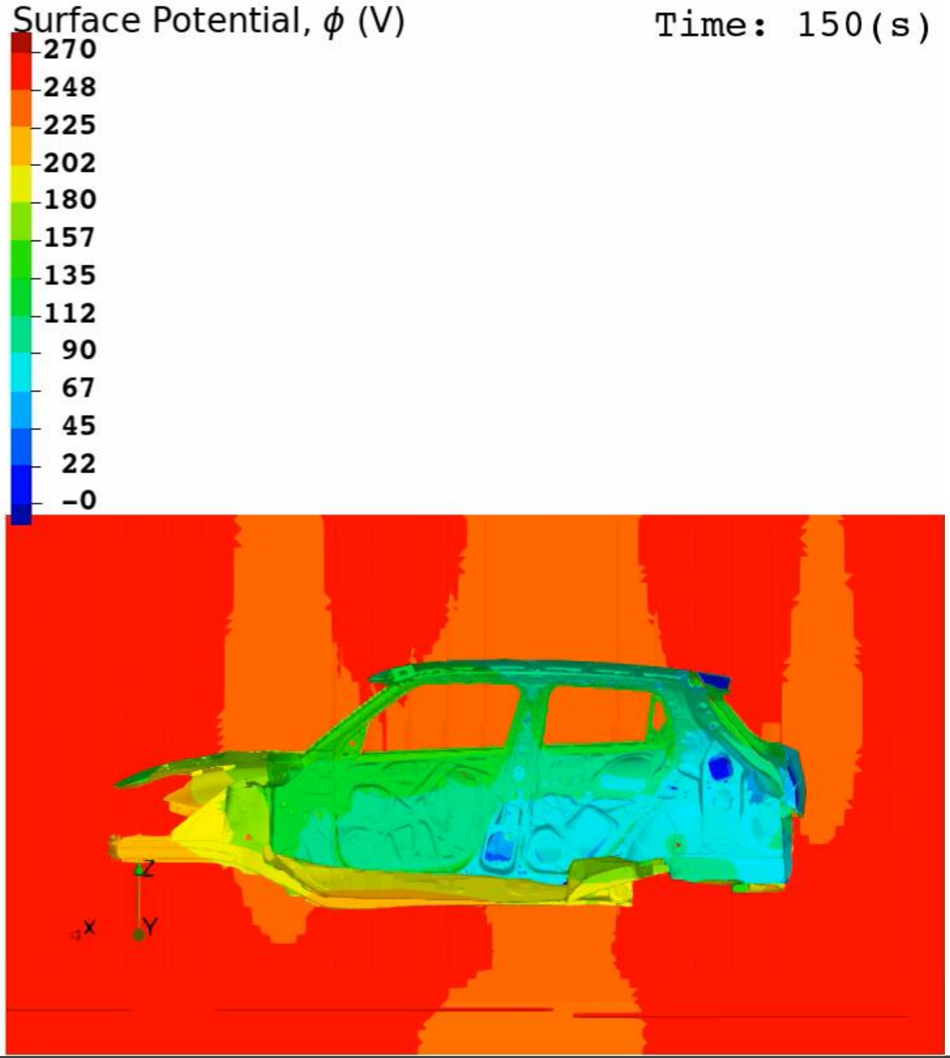
# Actual Line Analysis

## ***Animation of Surface Potential (EDESFEM with 51M Element Mesh)***

**Outer View**



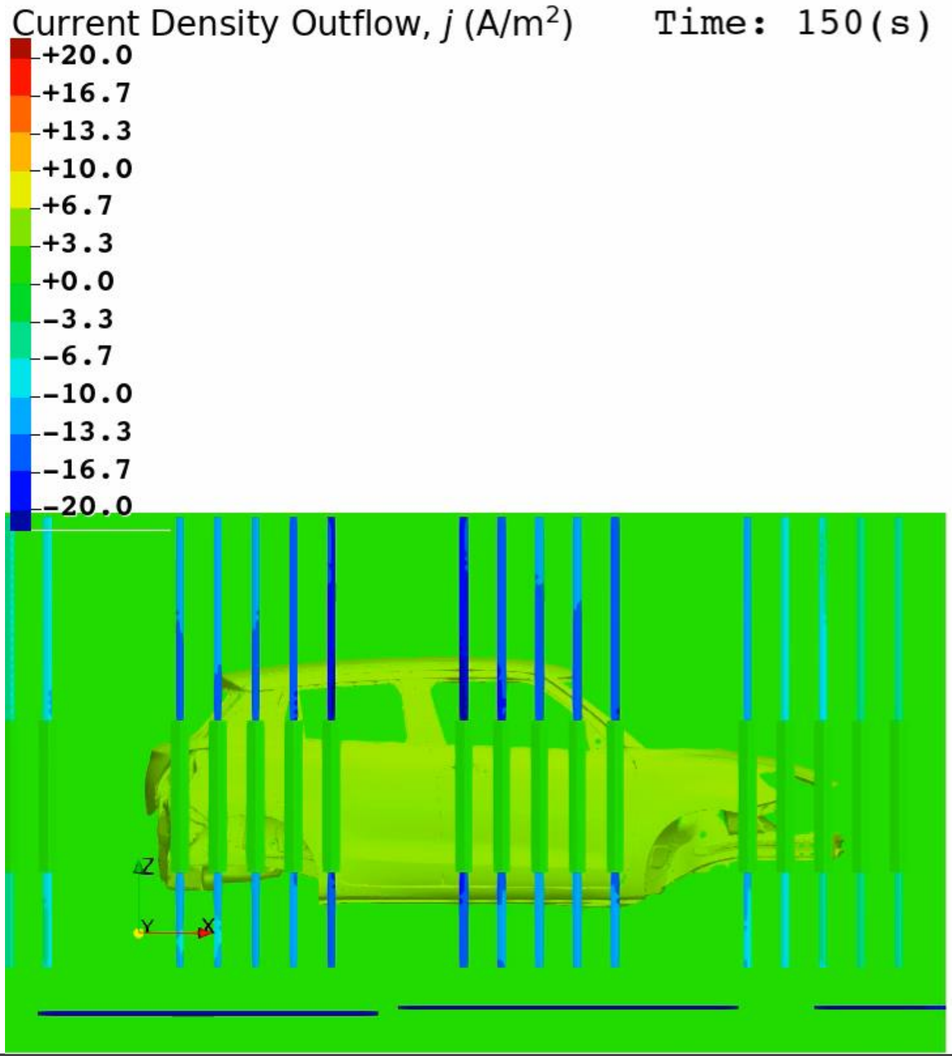

**Inner View**



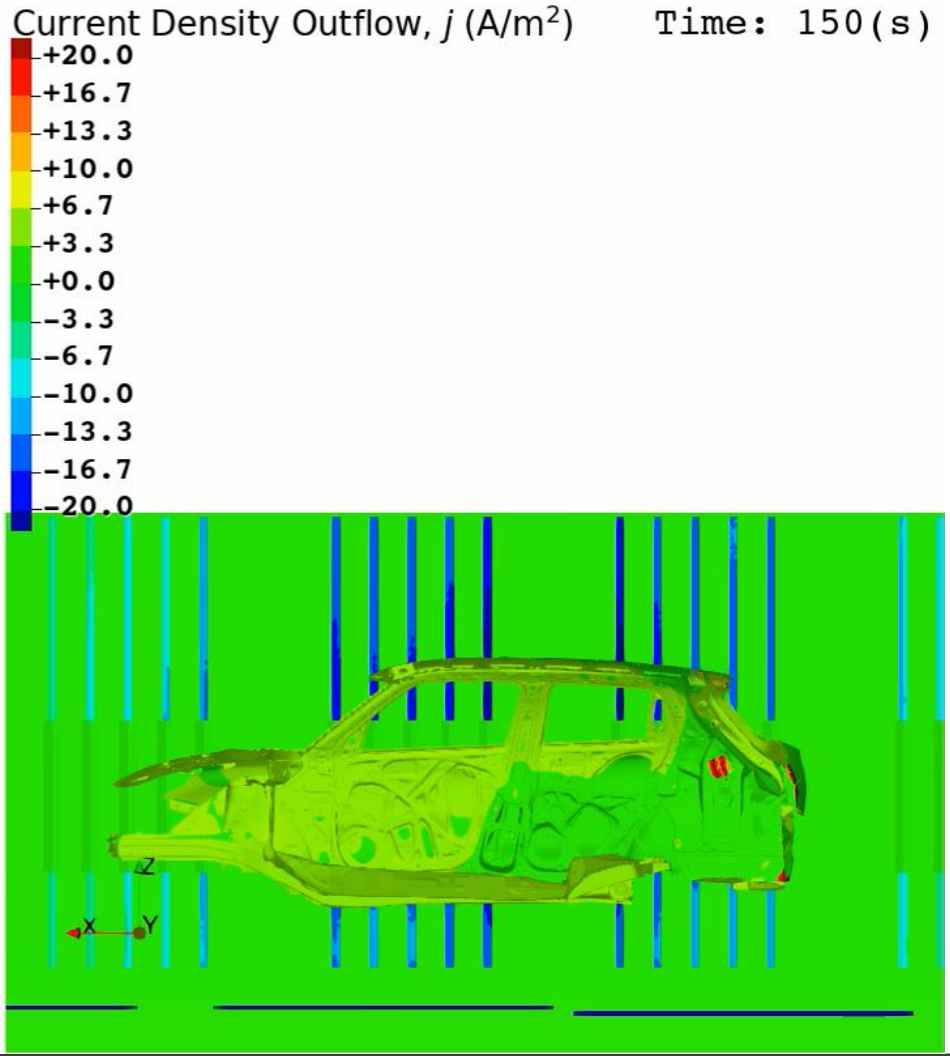
# Actual Line Analysis

## *Animation of Current Density (EDESFEM with 51M Element Mesh)*

**Outer View**



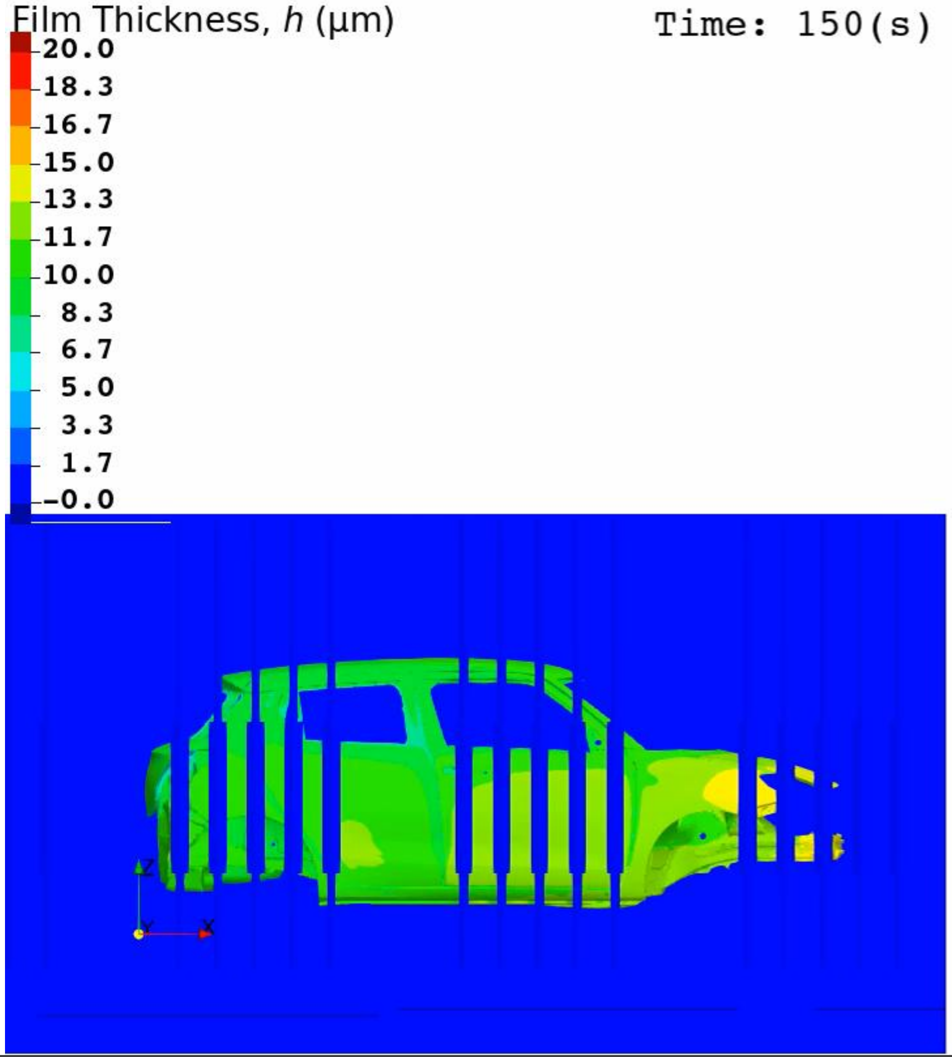

**Inner View**



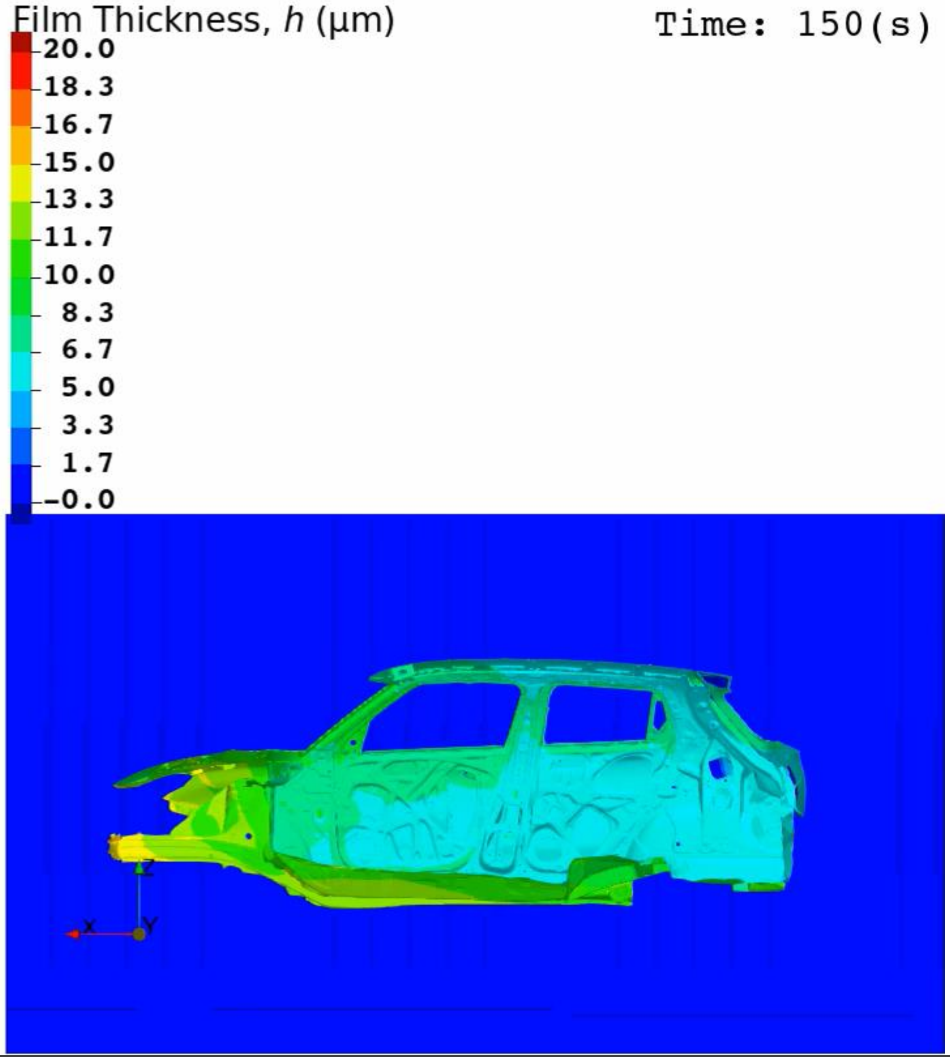
# Actual Line Analysis

## ***Animation of Film Thickness (EDESFEM with 51M Element Mesh)***

**Outer View**



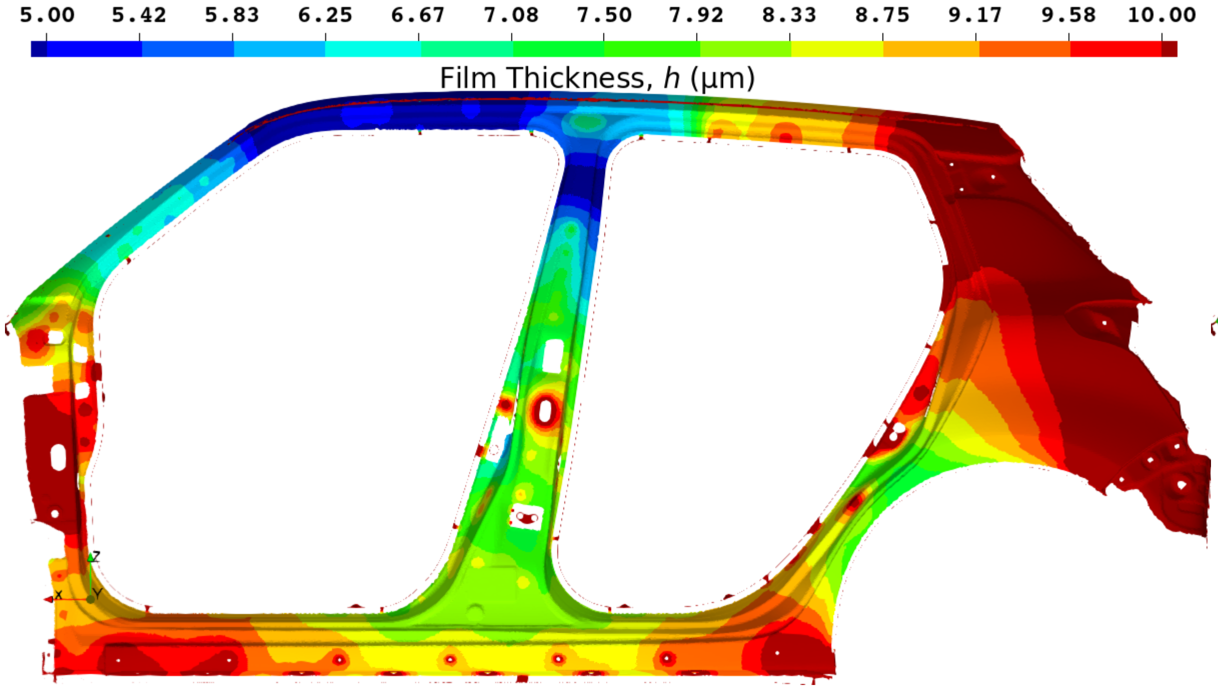

**Inner View**



# Actual Line Analysis

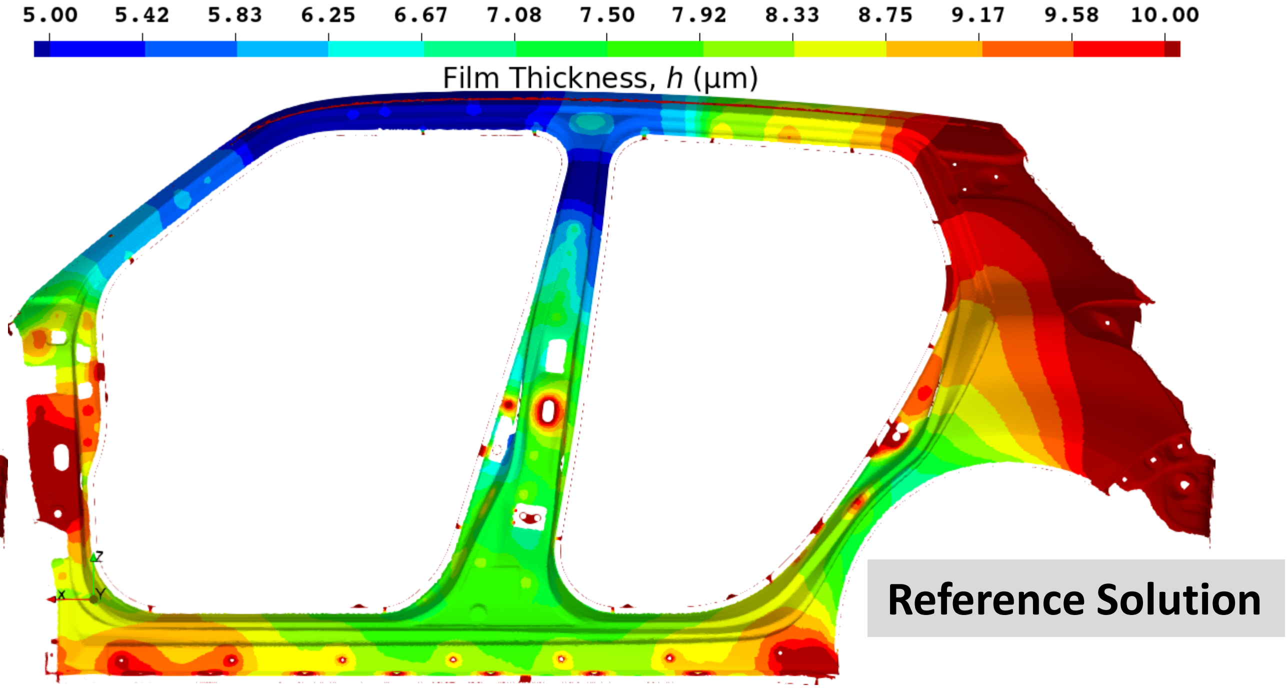
## Film Thickness Distribution on the side sill part with 51M Element Mesh

Standard FEM (FEM-T4)




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

**EDESFEM** (ES-FEM-T4)

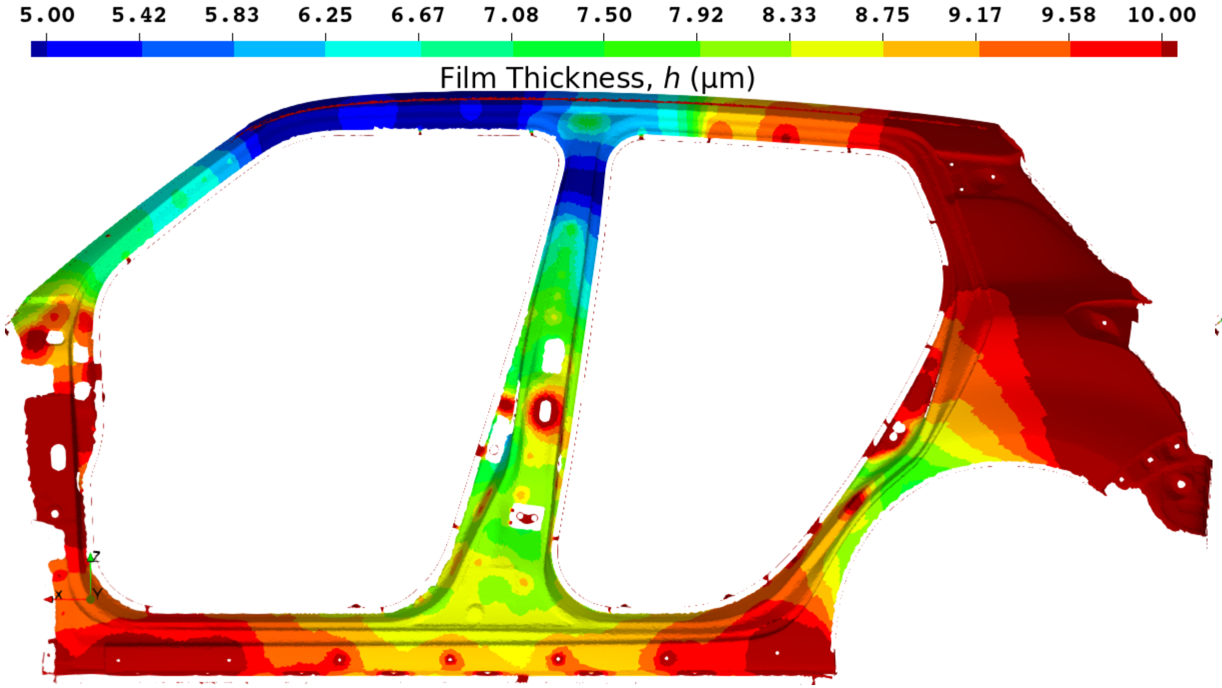



This result is regarded as the *reference* solution.
(The center of the side sill is Green)

# Actual Line Analysis

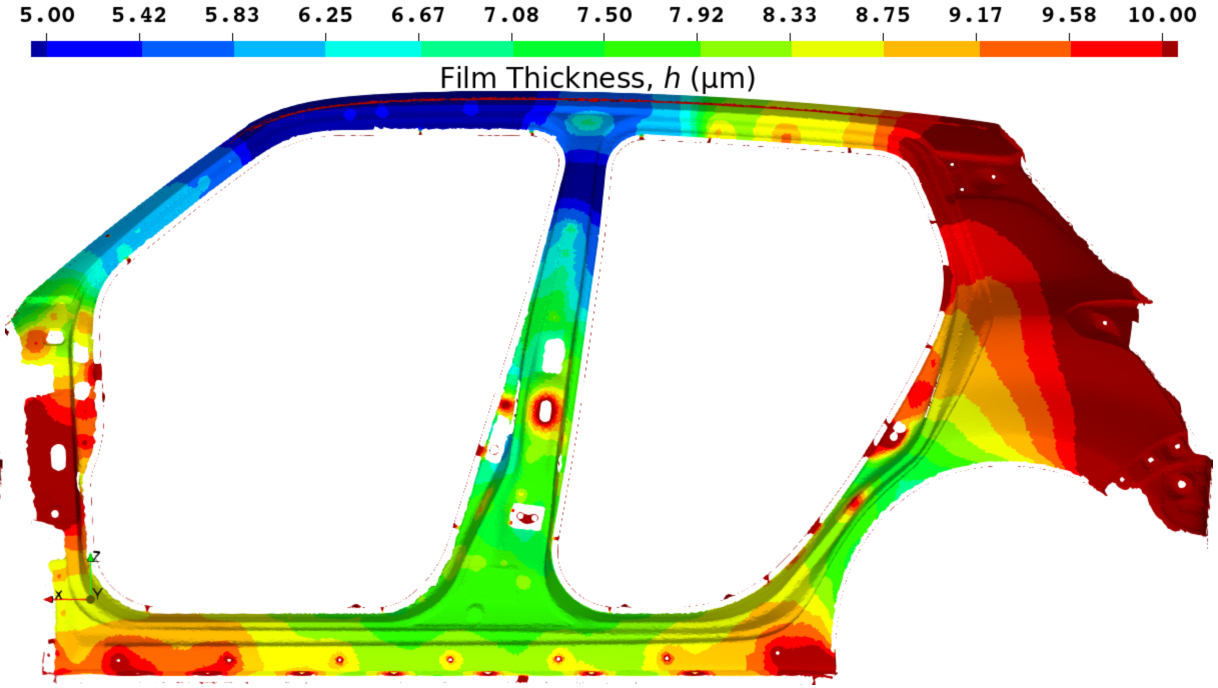
## ***Film Thickness Distribution on the side sill part with 16M Element Mesh***

Standard FEM (FEM-T4)




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

**EDESFEM** (ES-FEM-T4)

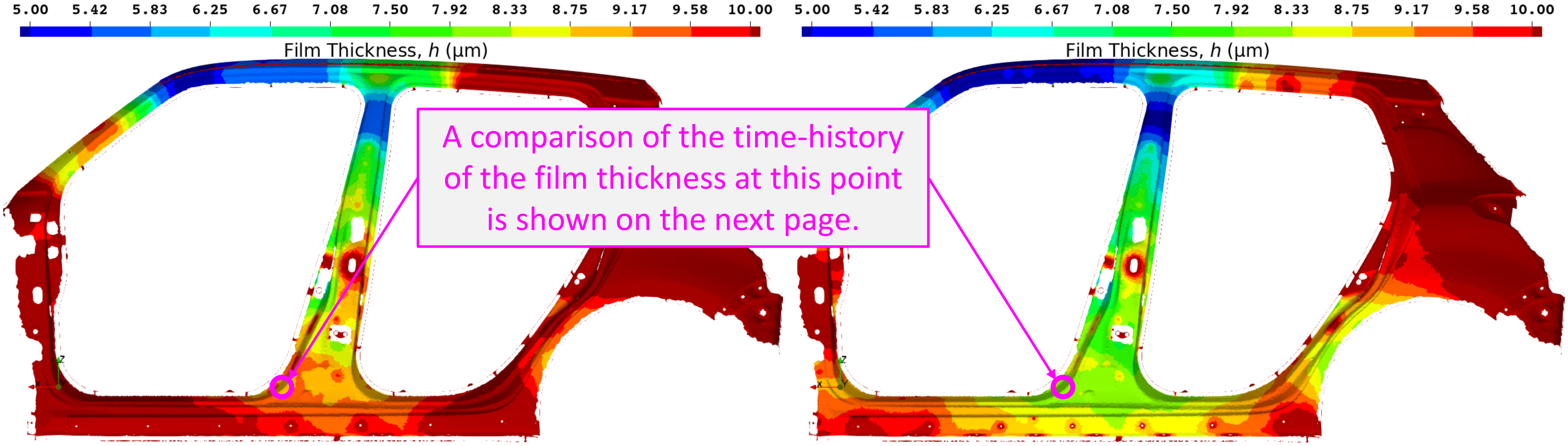



EDESFEM shows an ***accurate*** result.
(The center of the side sill is Green.)

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

Standard FEM (FEM-T4)

**EDESFEM** (ES-FEM-T4)

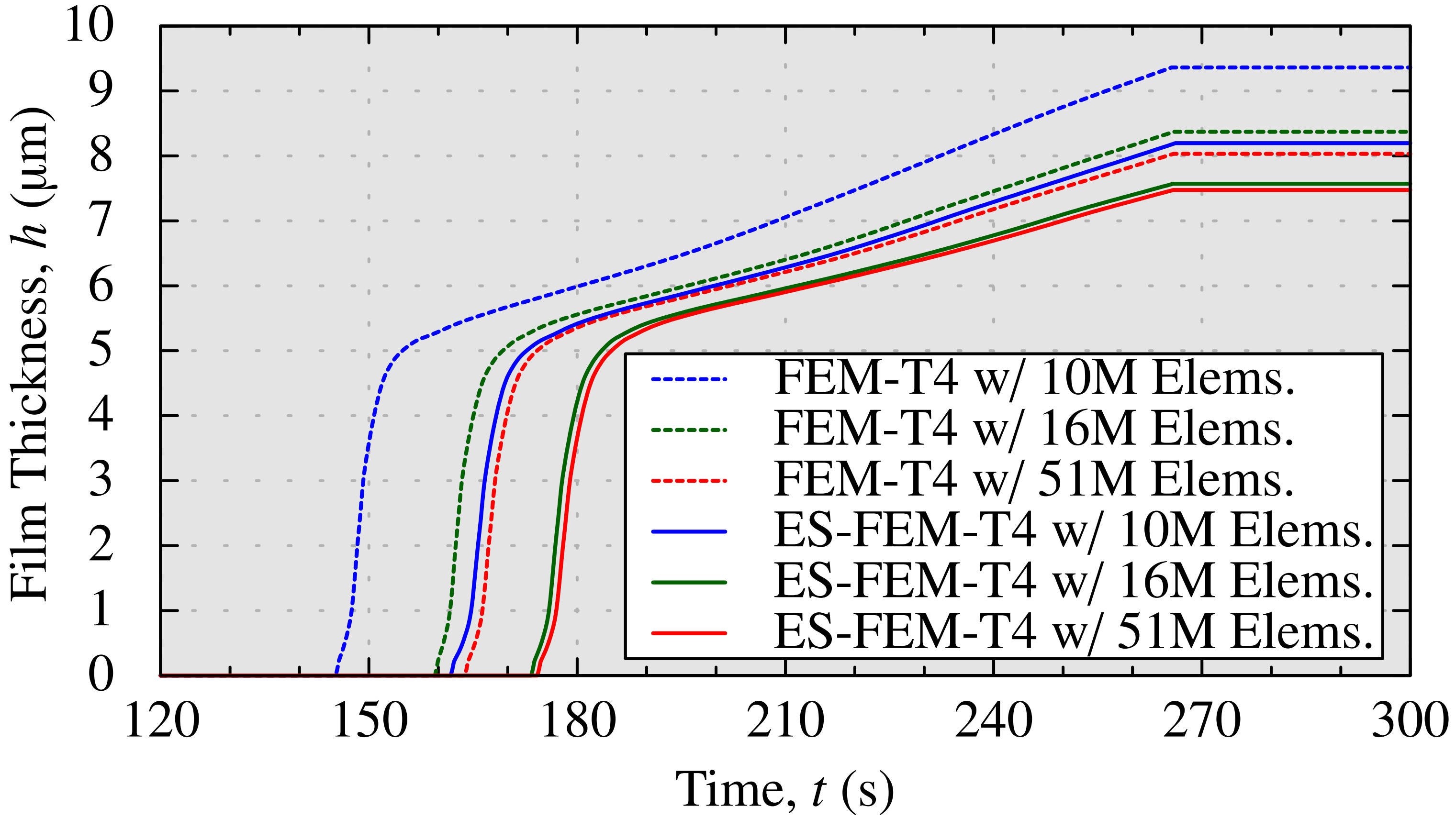



Standard FEM shows ***a massively thicker*** result.
(The center of the side sill is Red.)

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

# Actual Line Analysis

## 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.

# 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 (FEM-T4) | EDESFEM (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.

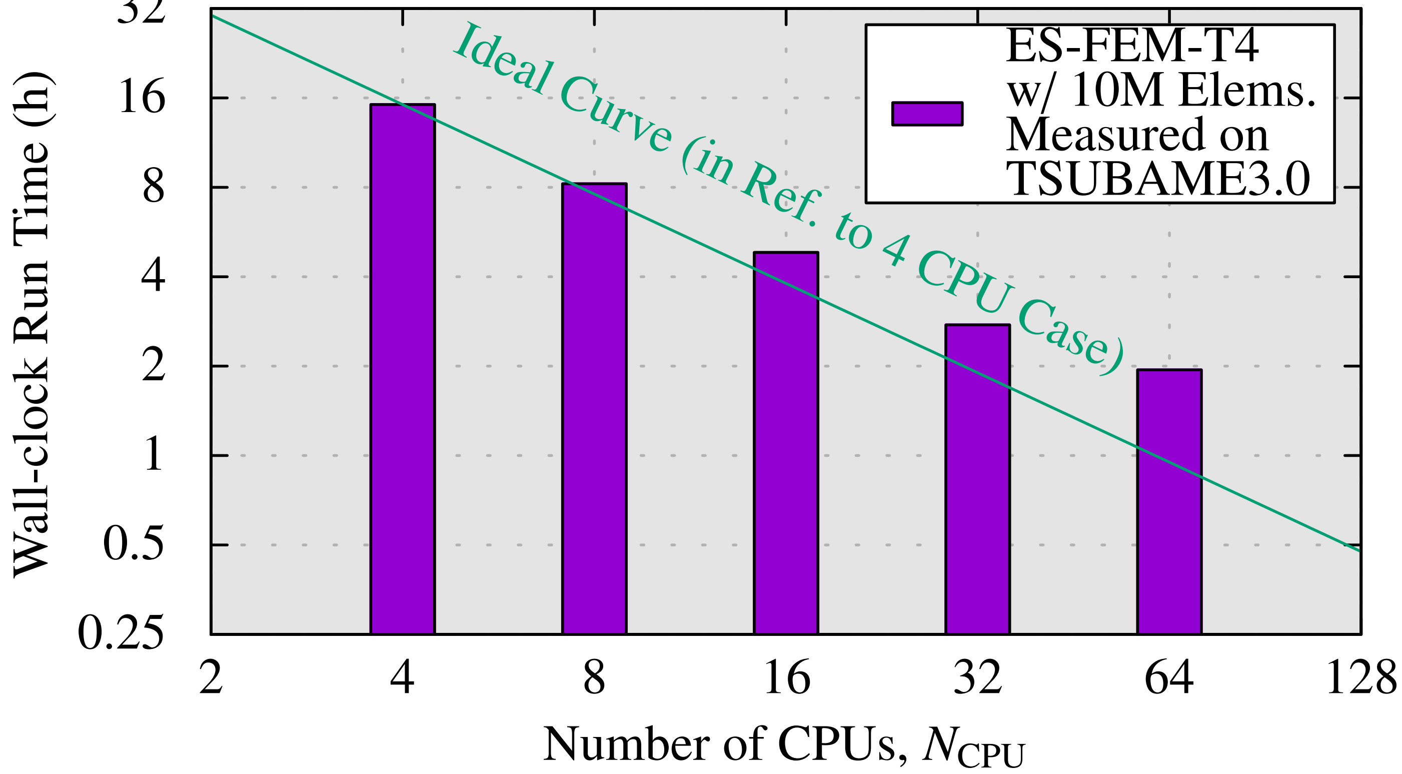
- With the same mesh, ES-FEM-T4 is slower than FEM by x1.5.
- For the same accuracy, ES-FEM-T4 is faster than FEM by x3.

For the simulations of actual ED lines with parallel computing, ES-FEM-T4 adopted by EDESFEM 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)



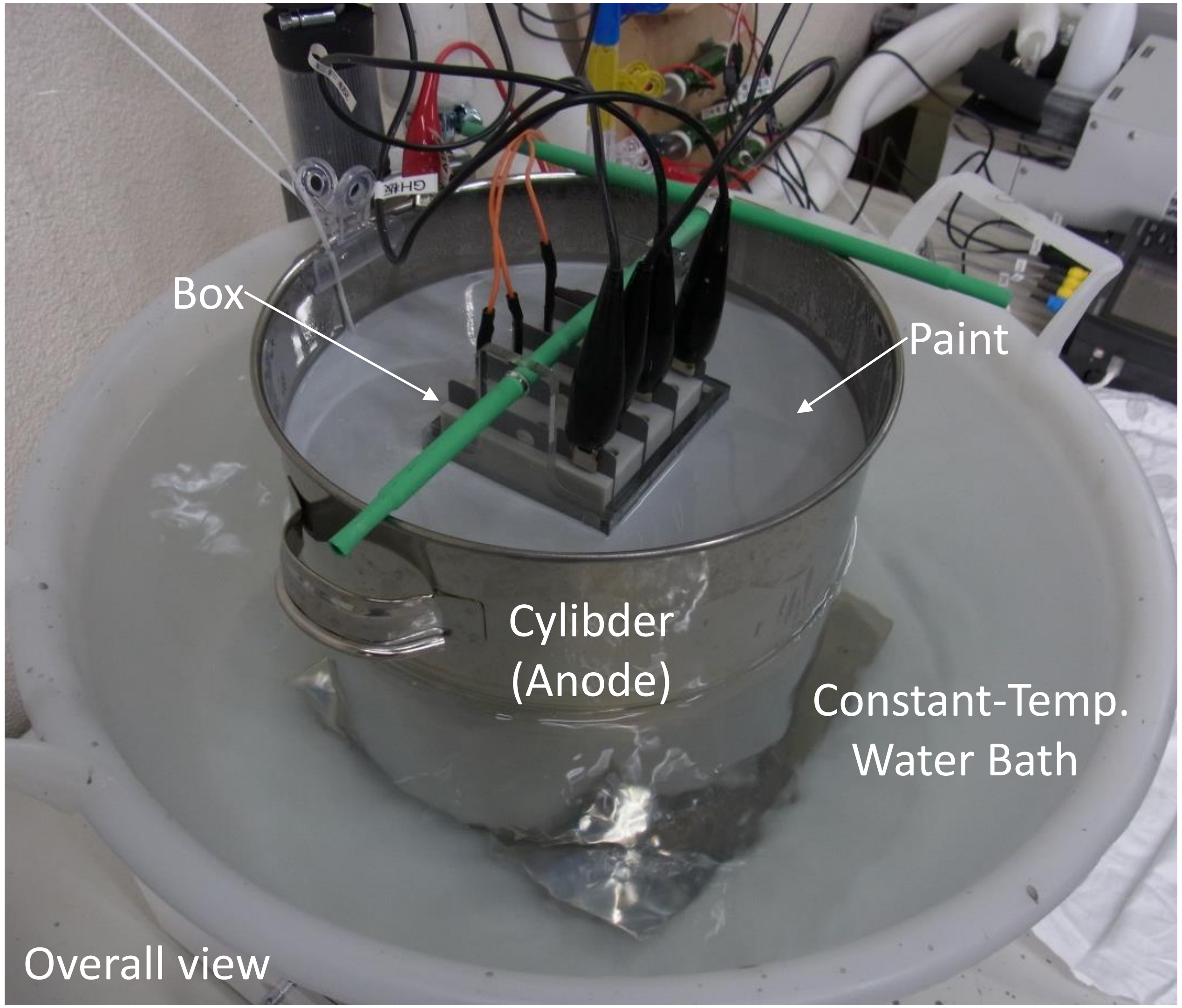

EDESFEM scales to some extent up to 64 CPUs at least.

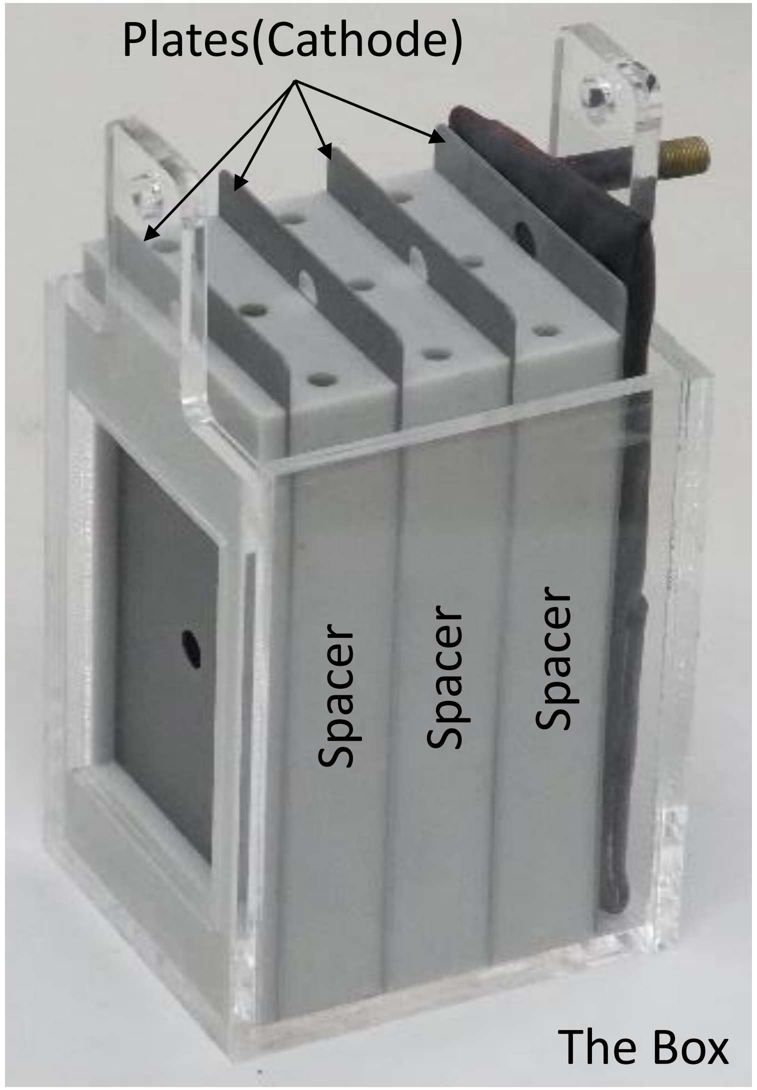
# EDESFEM
# Validation Example 1

# 4-Plate Box Test/Simulation

# 4-Plate Box Test/Simulation

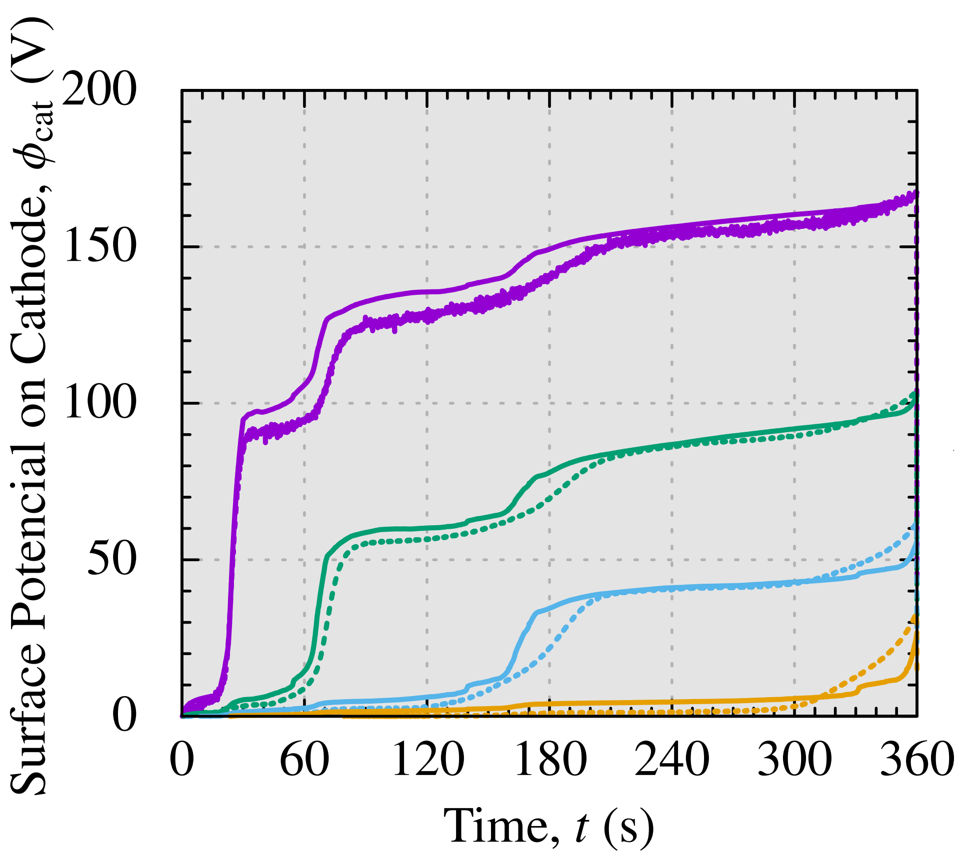
## ***Overview***

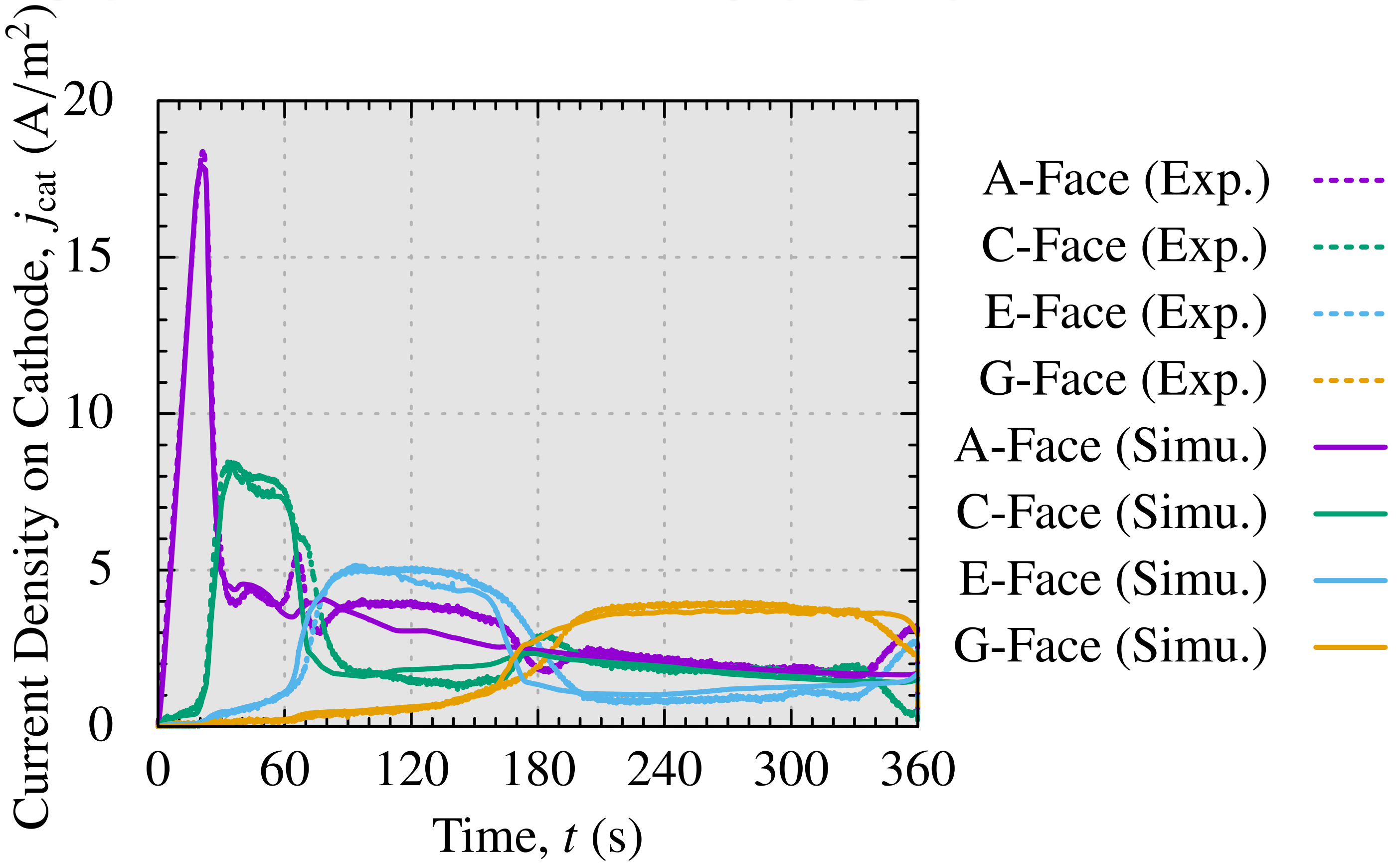


# 4-Plate Box Test/Simulation

## ***Validation of Surface Potential (left) and Current Density (right)***

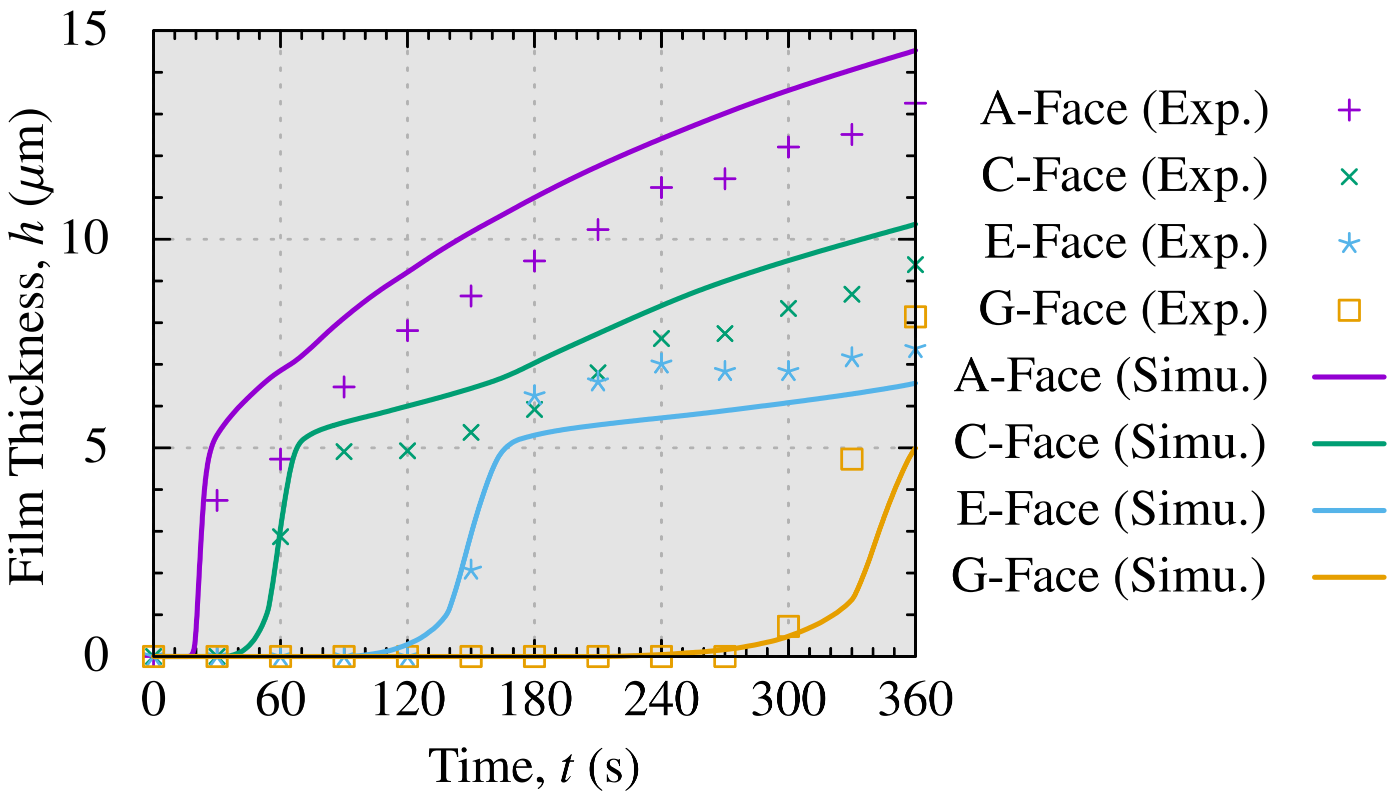



The simulated results are agreed with the experiment results in practical accuracy.

# 4-Plate Box Test/Simulation

## ***Validation of Film Thickness***



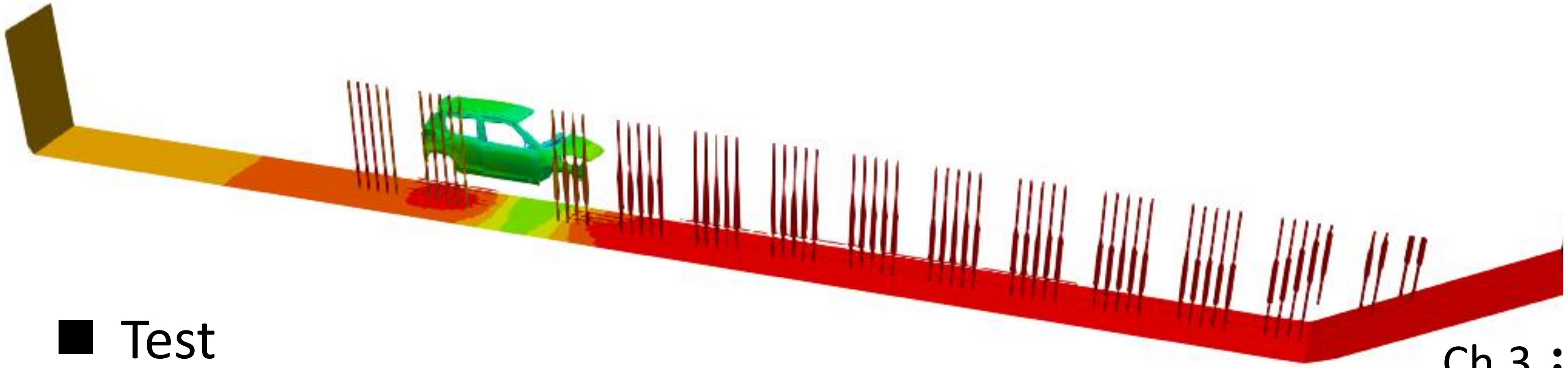

Although the accuracy of the innermost surface (G-Face) remains an issue (maximum error of 3 µm), the accuracy of the other surfaces is practically enough (less than 2 µm error).

# EDESFEM
# Validation Example 2

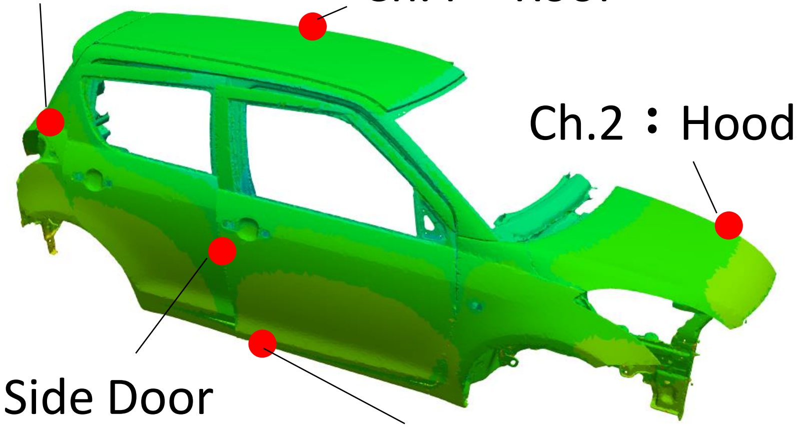
# Actual Line Test/Simulation

# Actual Line Test/Simulation

***Outline***



■ Measured 6 Points




■ Test

- ➢ A surface potential measurement device with 6 probes was mounted on a car running on an actual line to measure surface potential.
- ➢ After baking, the film thickness was measured at the 6 points.

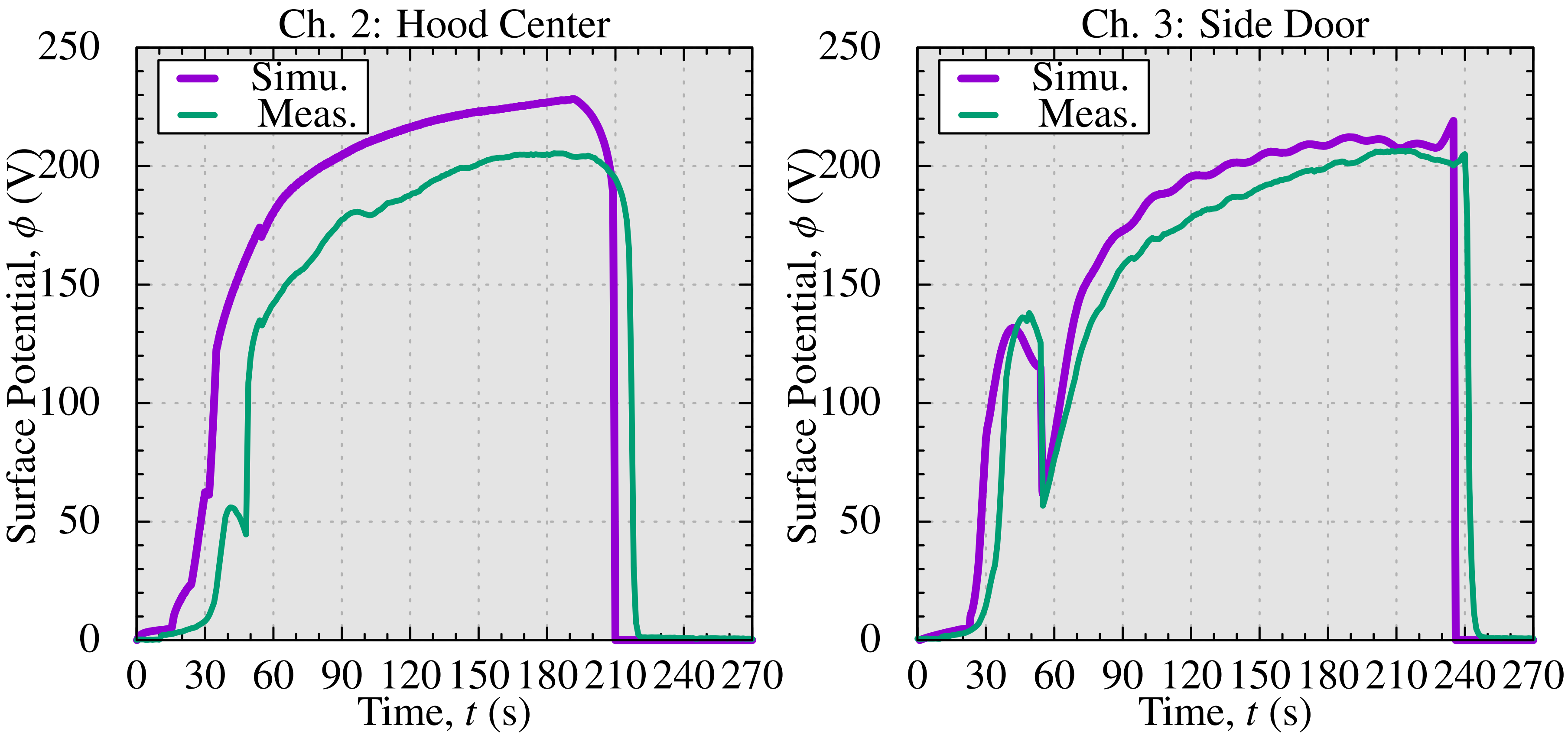
■ Simulation

- ➢ Half-body analysis considering the right-hand side of the pool and car.
- ➢ Shapes of the pool, electrodes, and carbody with motion are reproduced.

Surface potential time histories and final film thickness at the 6 points are compared.

# Actual Line Test/Simulation

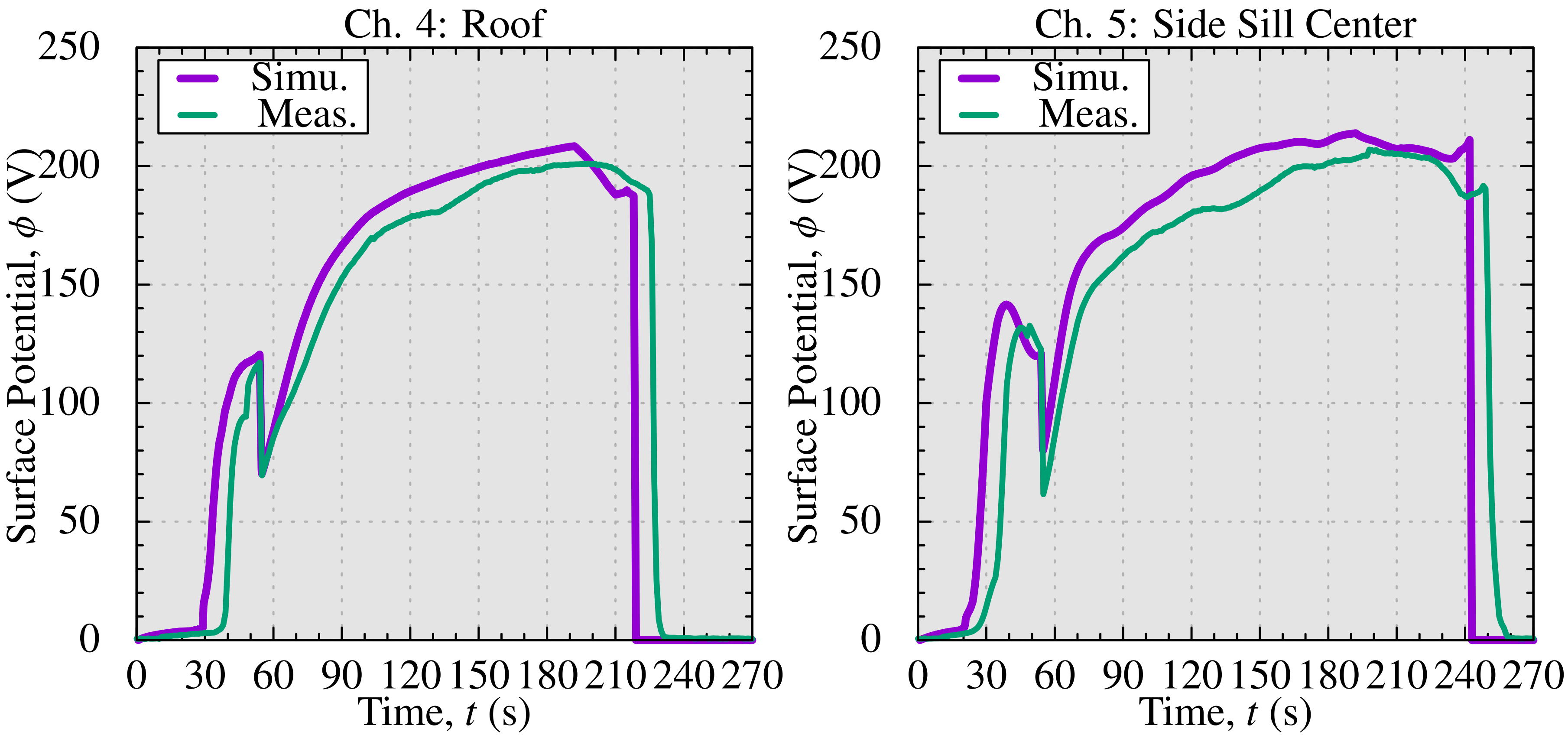
## ***Validation of Surface Potential (Ch. 2 and 3)***




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.

# Actual Line Test/Simulation

## ***Validation of Surface Potential (Ch. 4 and 5)***

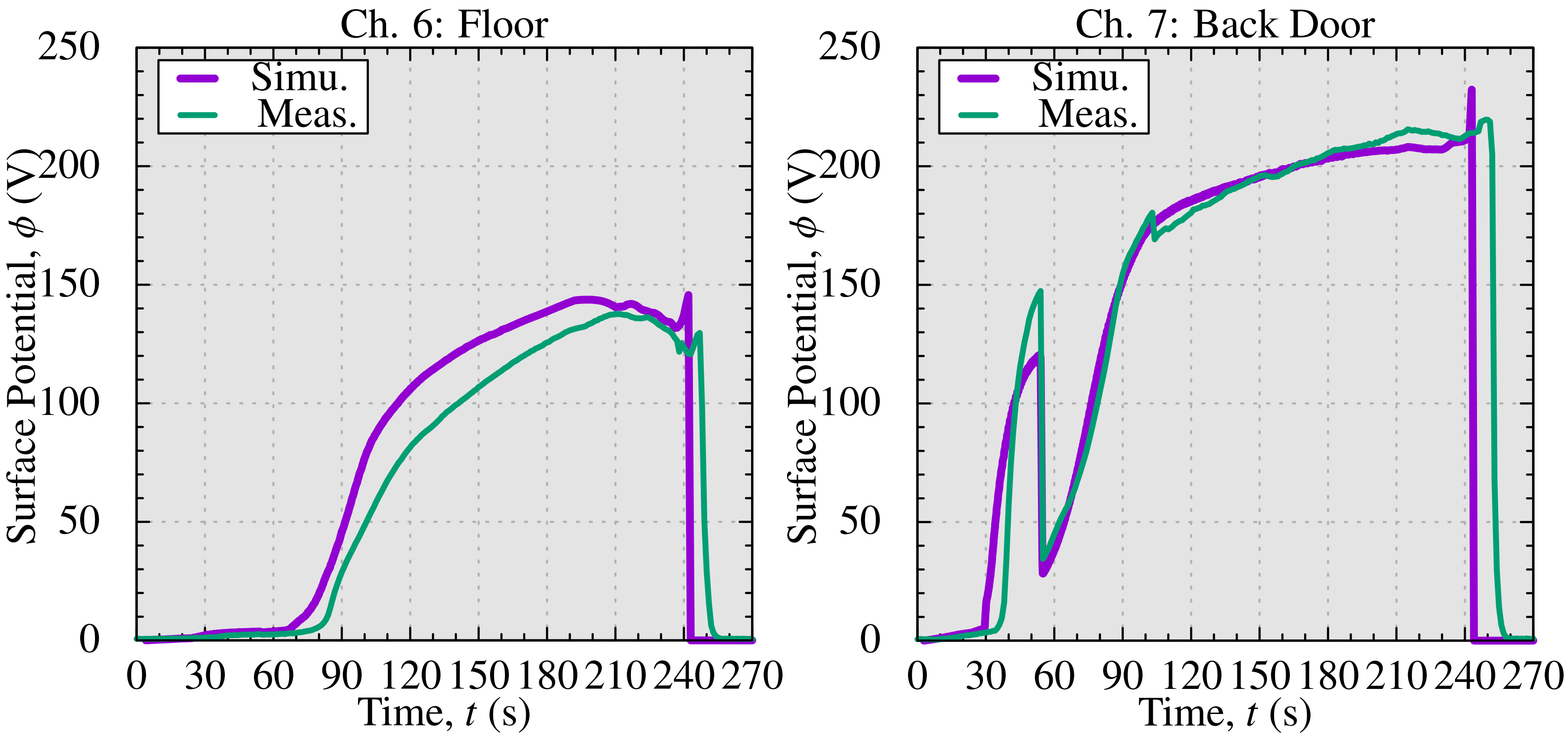



The simulated surface potential is a little high
because the degradation of the membranes of electrodes was not precisely simulated;
yet, the results generally agree with practical accuracy.

# Actual Line Test/Simulation

## ***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.

# Actual Line Test/Simulation

## ***Validation of 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.

# EDESFEM
# Summary

# Summary

- The electrodeposition simulator “**EDESFEM**” is now on sale.
- 4 features of the software were introduced:

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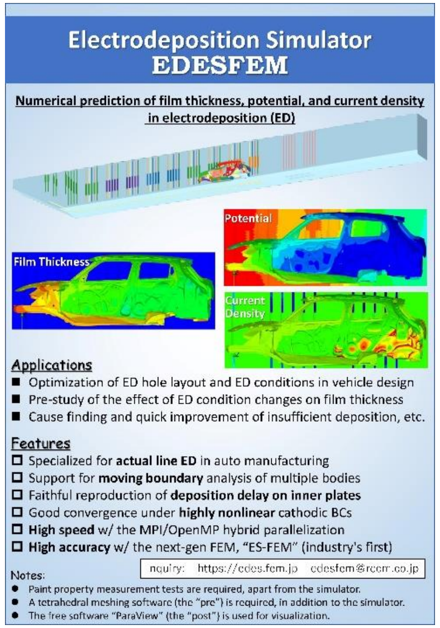
1. High Accuracy with 4-node Tetrahedral Meshes,
2. Support for Moving Boundary Analysis of Multiple Bodies,
3. High Speed with MPI/OpenMP Hybrid Parallelization,
4. Faithful Reproduction of Deposition Delay on Inner Plates.

- V&Vs for the 4-plate box and an actual line were presented.




Leaflet is
also available!

Please feel free to contact us at the following e-mail address
for trial or purchase of **EDESFEM** or for any questions.
We also welcome your inquiries about ED lab experiments and actual line measurements.

**edesfem@rccm.co.jp**