2024年3月21日
第13回FC-Cubicオープンシンポジウム

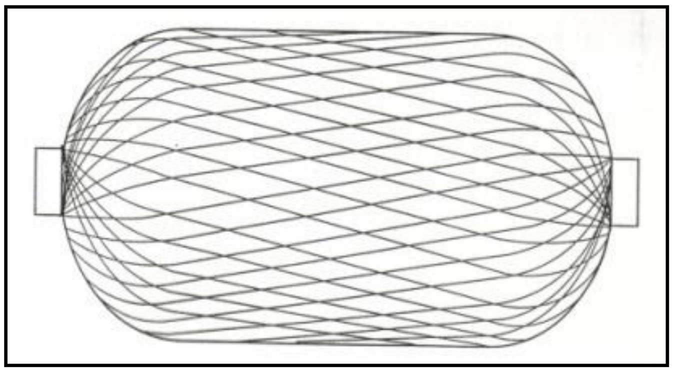
シミュレーションによる水素タンク開発の高度化
- 設計と製造の最適化 -

東京大学 生産技術研究所
吉川 暢宏

最終目標：CFRP製高圧水素タンクの合理的判断に基づく設計および製造の最適化
障　　害：フィラメントワインディング製法により生ずるドーム部の複雑な力学場
解 決 策 ：メゾスケールシミュレーションによる力学場の解明と機械学習による最適解の探索

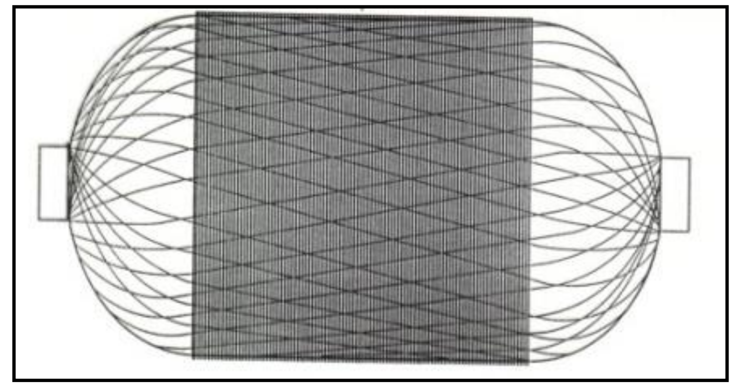
製法に規定される強度発現機構

Dome



Helical winding path

Cylinder



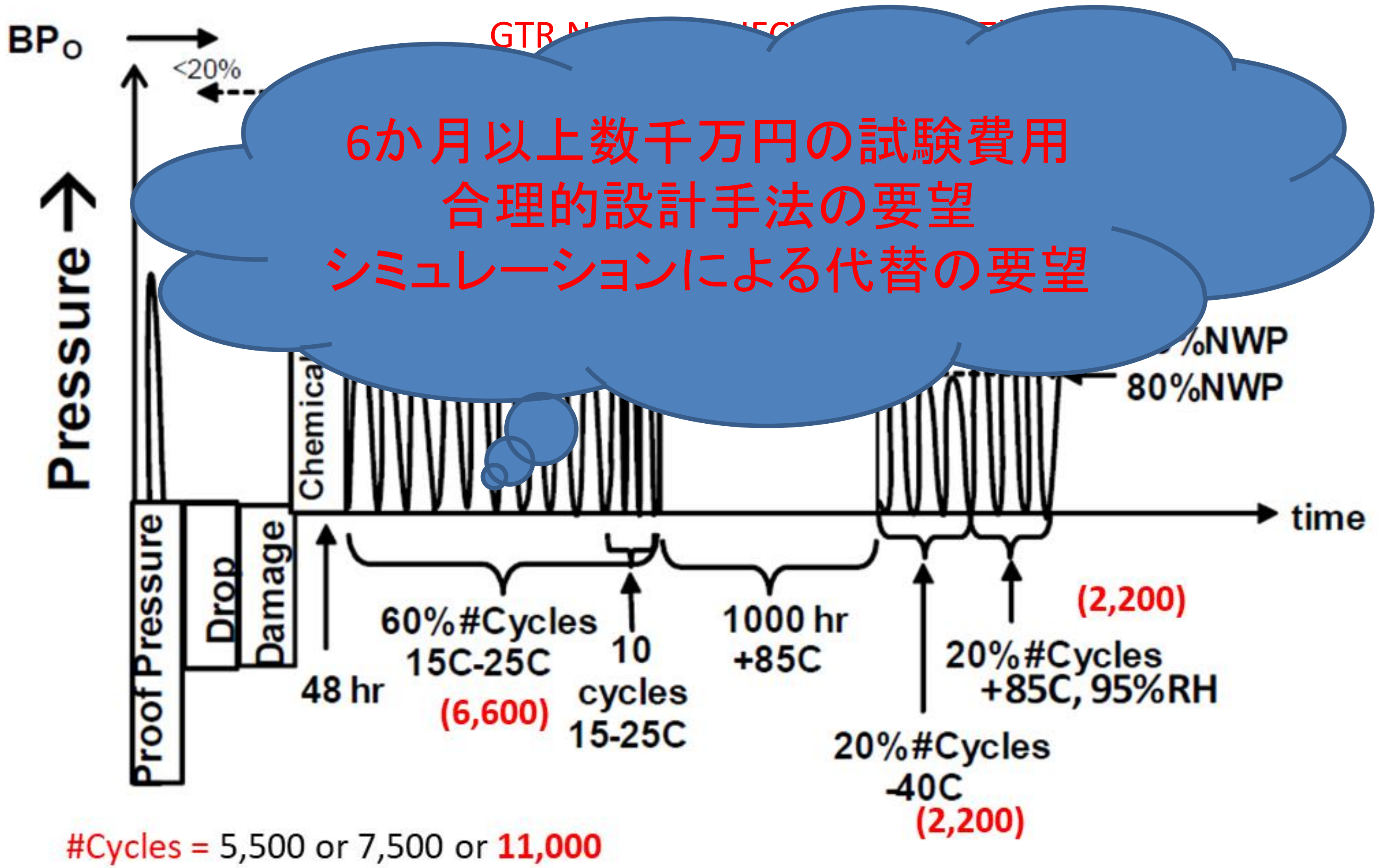
Hoop winding path

- ✓ 直胴部の力学場は長手方向均一性がほぼ成立するがドーム部は炭素繊維束の配向方向やCFRP層の厚さが徐々に変化するため材料モデル化が困難
- ✓ 繊維束の交差による局所的応力・ひずみの上昇が発生
- ✓ ドーム部の形状と最適炭素繊維配向には相関があるため形状とフィラメントワインディング構成の同時最適化が必要

パフォーマンスベースの設計方法論

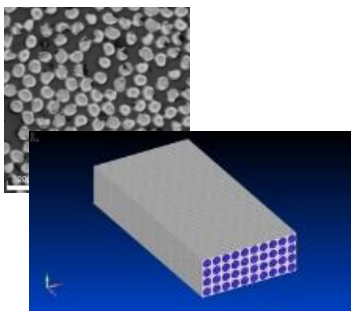
Series Test of UN Regulation

6か月以上数千万円の試験費用
合理的設計手法の要望
シミュレーションによる代替の要望



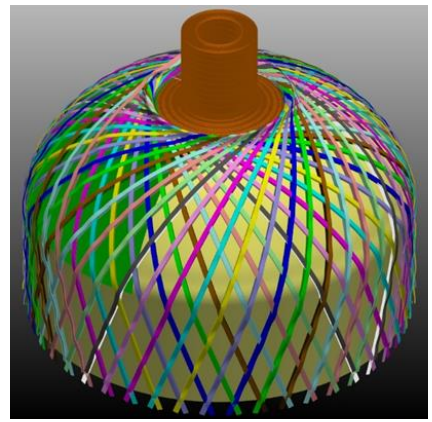
ドーム部の有限要素モデル

Micro-scale



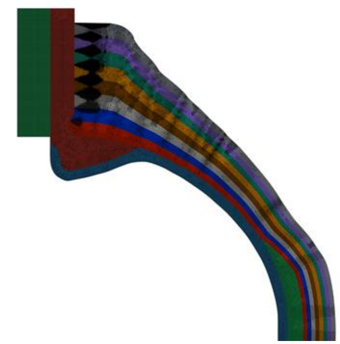
- ✓炭素繊維と樹脂を区分
- ✓炭素繊維：直交異方性弾性体
- ✓樹脂：温度依存等方性非弾性体
- ✓樹脂の強度により支配されるCFRPの強度モデルの検討

Meso-scale



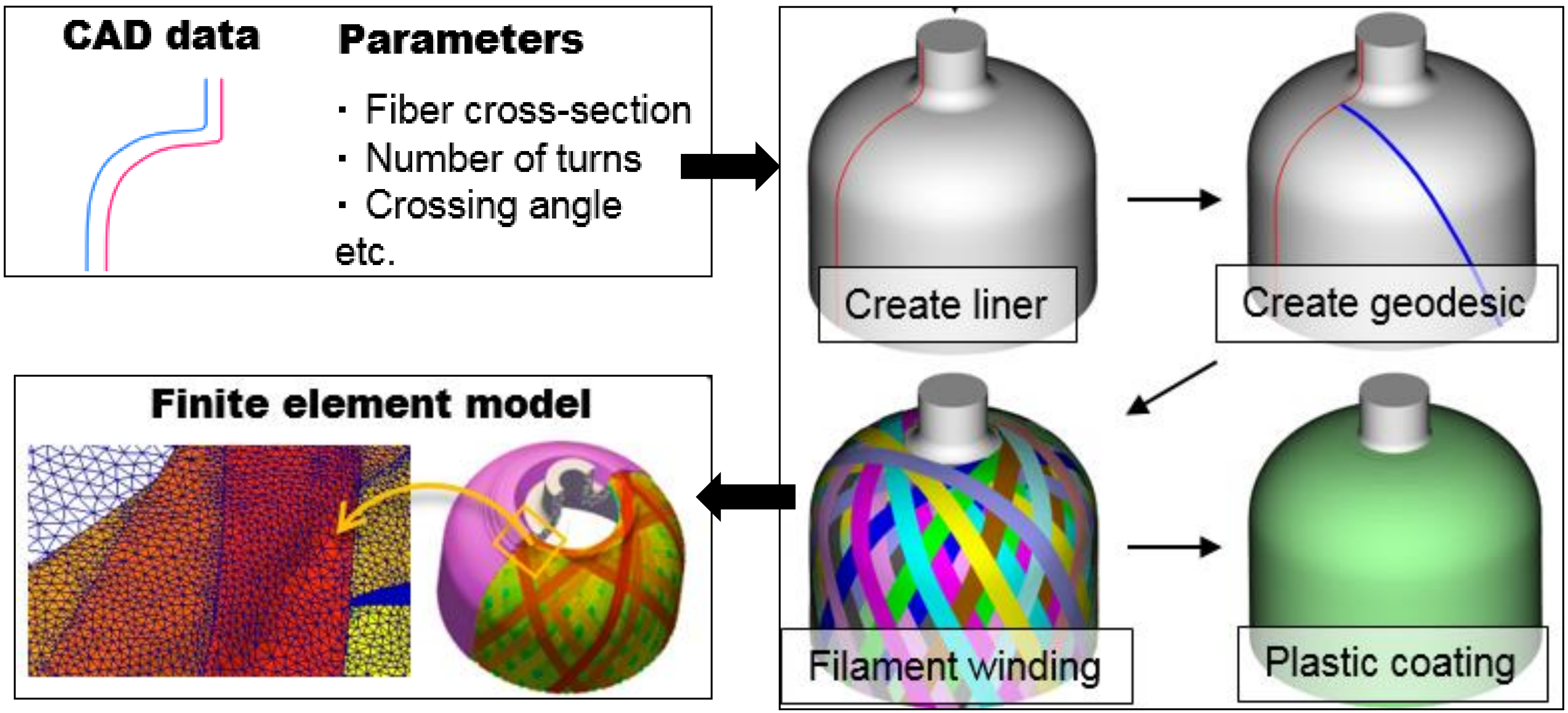
- ✓炭素繊維束と樹脂を区分
- ✓炭素繊維束：直交異方性弾性体
- ✓樹脂：温度依存等方性非弾性体
- ✓樹脂の強度モデルおよび硬化モデルを直接的に導入

Macro-scale



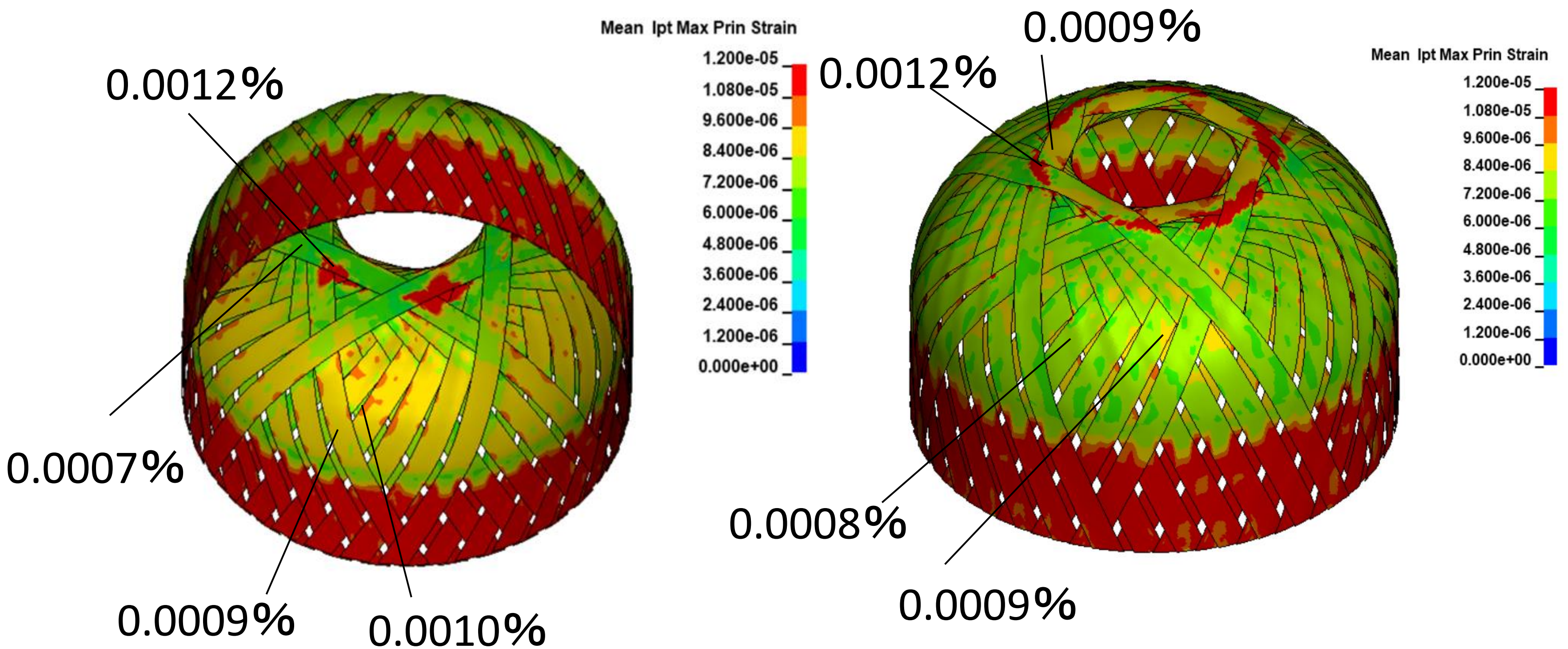
- ✓CFRP部を層状にモデル化
- ✓軸対称直交異方性弾性体
- ✓ドーム部に重大な誤差発生

ドーム部のメゾスケールモデル



- ✓ 有限要素モデルを自動生成するソフトウェアは作成済み
- ✓ 容器全体の解析は非現実的
- ✓ 軸対称モデルを用いたズームアップ解析あるいは材料強度モデル改良に利用

メゾスケールシミュレーションによる炭素繊維束のひずみ解析

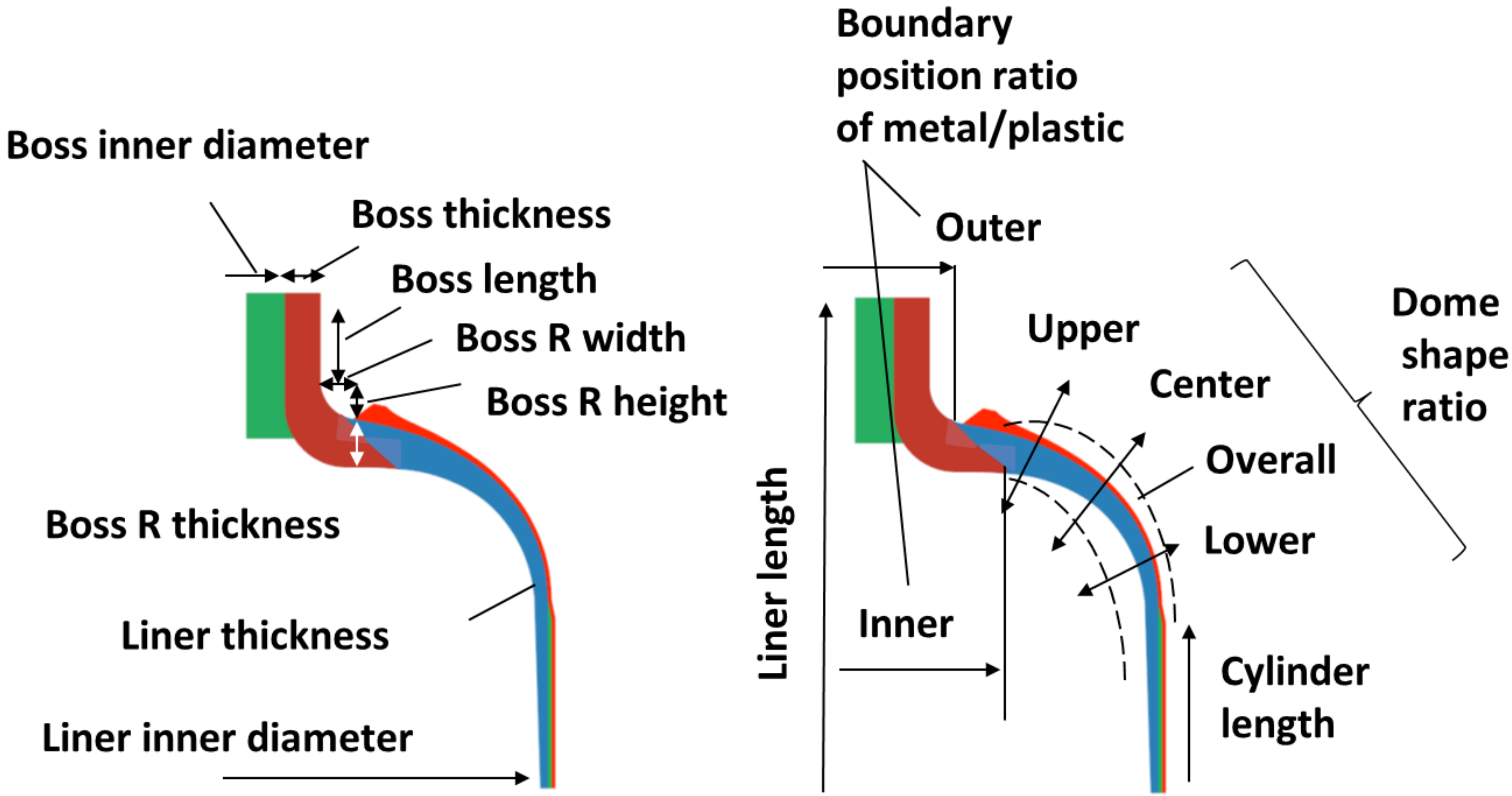


✓ 繊維束の交差部で発生するひずみ上昇や繊維束の回転および金属ボス近傍の力学場を反映させたマクロモデルの改善をNEDOの助成により実施中

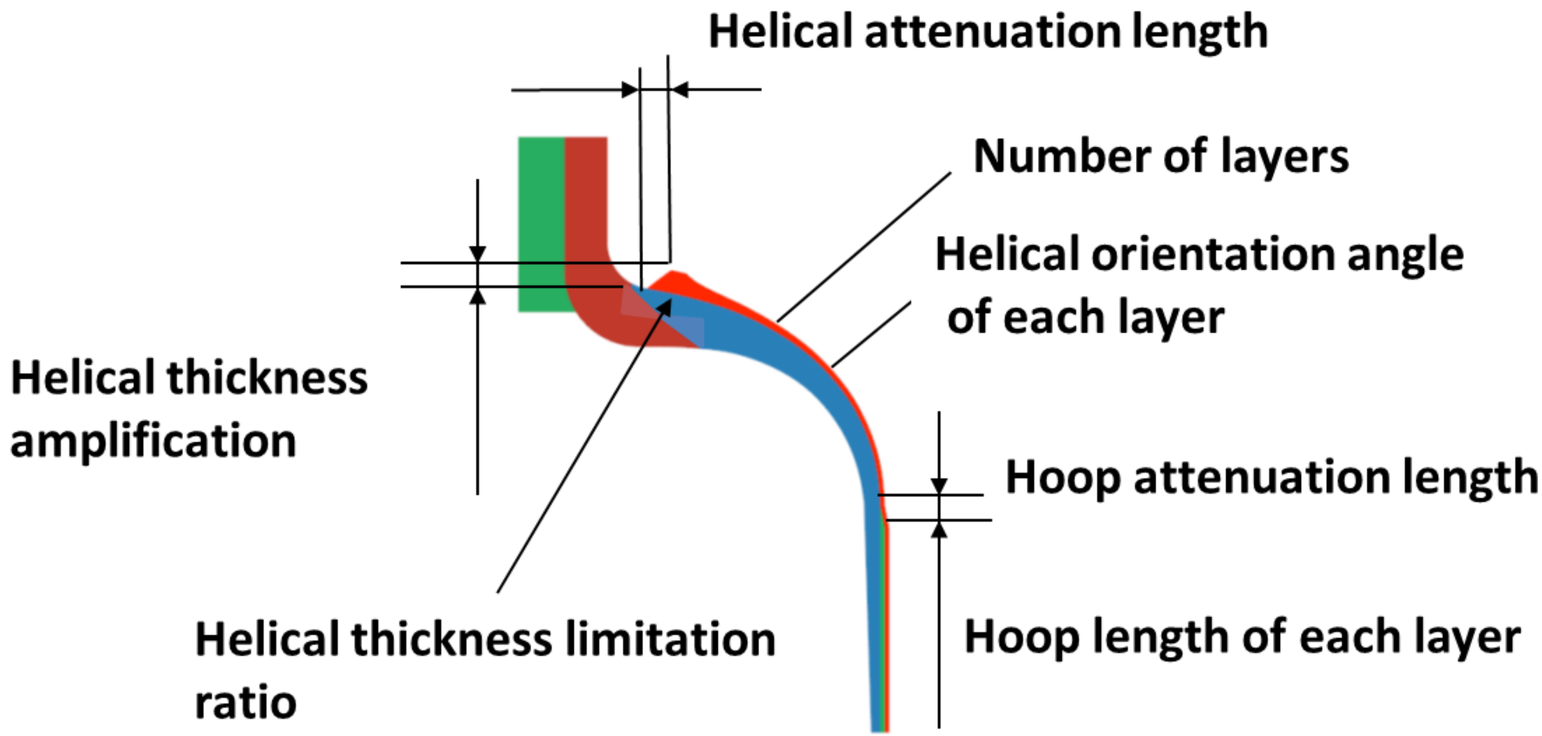
シミュレーションによる設計と製造の最適化

	課題	解決策
設計	• ドーム部の正確な力学場評価 • 膨大な設計パラメータ • ドーム形状とヘリカルワィンディング構成の同時最適化	✓ マクロスケール材料強度モデルの改善 ✓ 機械学習による最適解探索
硬化成形	• 残留応力等の製造欠陥の評価	✓ Two-scale (Macro- and Micro-) モデルによる正確な硬化特性のモデル化

ドーム部形状パラメータ



ヘリカルワインディング構成



Layer No.	Angle (degree)	Layer No.	Angle (degree)	Layer No.	Angle (degree)	Layer No.	Angle (degree)
1	90	6	55	11	90	16	20
2	90	7	90	12	67	17	20
3	90	8	90	13	60	18	20
4	90	9	10	14	54	19	34
5	90	10	58	15	35	20	39

機械学習による最適設計探索

Start : Input of a tank dimension and specification

・Size
・CFRP design parameters range
・Dome shape parameters range

Setting randomly selected tank design parameters

Creation of finite element analysis model of a tank

A finite element analysis of the tank model

Calculation of maximum value of fiber direction strain and CFRP mass per internal volume of the tank

Repetition about 10,000 times (No → back to setting randomly selected tank design parameters)

Yes

Calculation of Pareto frontline from multi-objective optimization

Determination of the convergence

Yes → End : Output of the smallest CFRP mass tank

・CFRP design parameters
・Dome shape parameters

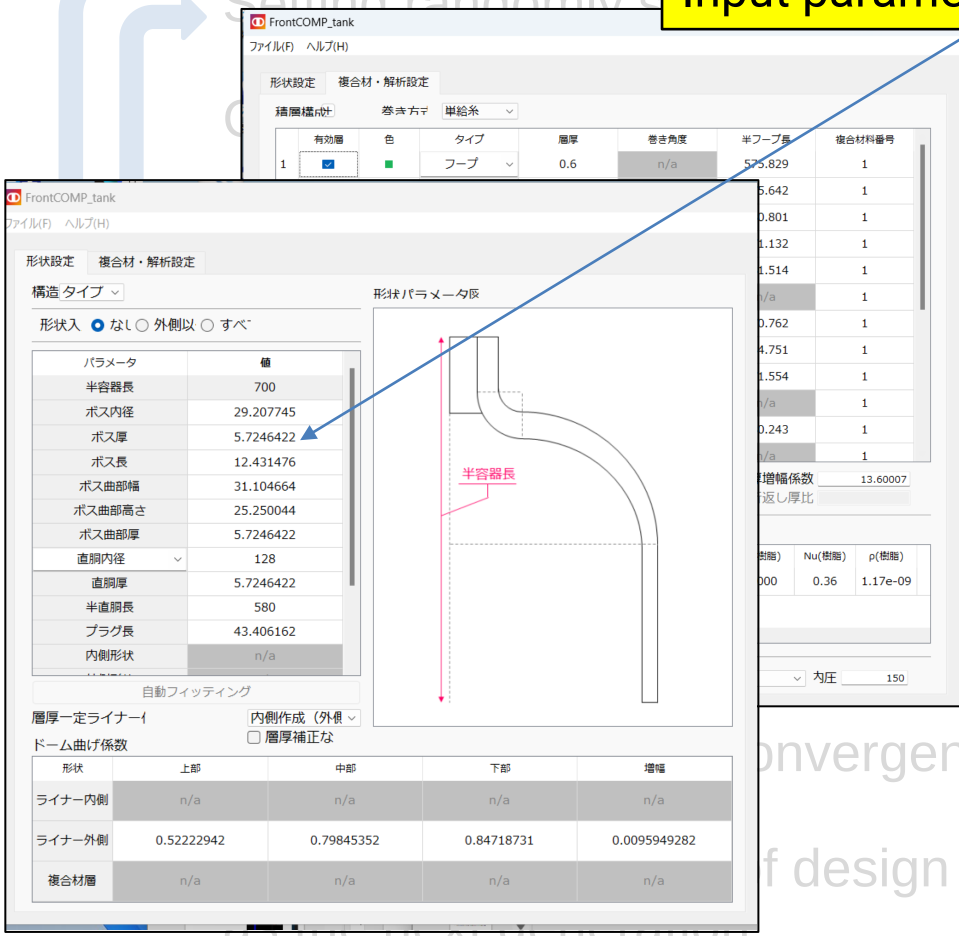
No

Modification of range of design parameters by genetic algorithm as the next generation (→ back to setting randomly selected tank design parameters)

Start : Input of a tank dimension and specification

- Size
- CFRP design parameters range
- Dome shape parameters range

Input parameters on the display or import input file



Specification
- Resistance pressure

Tank size
- Length
- Inner diameter

CFRP parameter
- Number of layer, min. and max.
- Helical layer angle, min. and max.
- Hoop end position, min. and max.
- Thickness of layer
- Overlap volume around boss

Doom shape parameter
- Boss inner diameter, min. and max.
- Boss length, min. and max.
- Boss width, min. and max.
- layer thickness, min. and max.
- Doom axial length, min. and max.
- Doom shape curvature, min. and max.

Start : Input of a tank dimension and specification

- Size
- CFRP design parameters range
- Dome shape parameters range

Setting randomly selected tank design parameters

Creation of finite element analysis model of a tank

A finite ele

Calculatio
and CFRP

No

Repetition

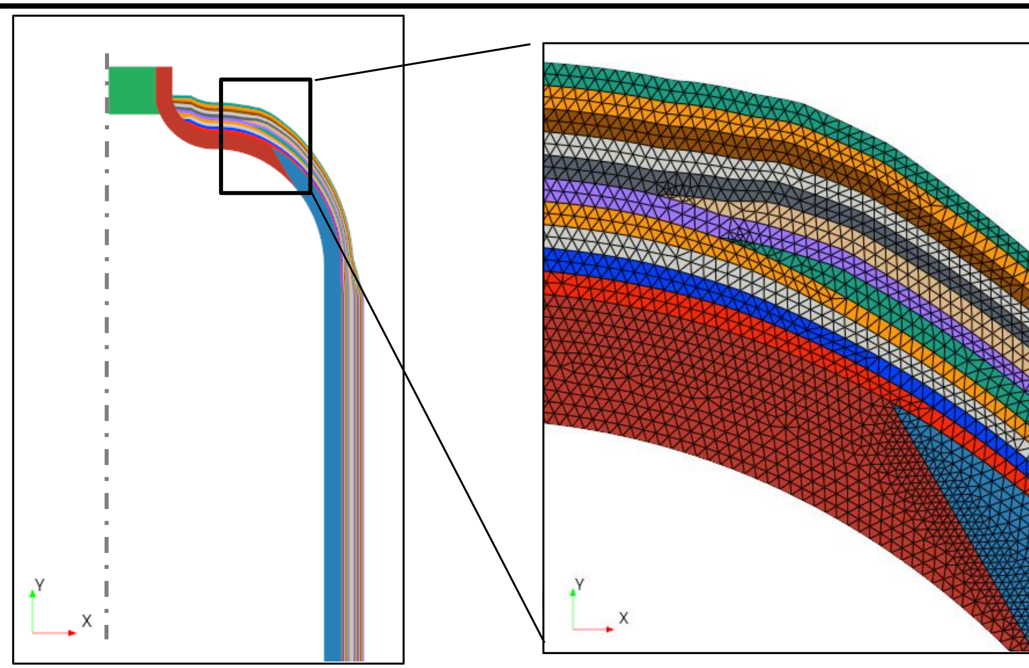
Yes

Calculatio ... tion

Determina

No

Modificatio
by genetic algorithm as the next generation



Finite element analysis model of a tank

Start : Input of a tank dimension and specification

- Size
- CFRP design parameters range
- Dome shape parameters range

Setting randomly selected tank design parameters

Creation of finite element analysis model of a tank

A finite element analysis of the tank model

Calculation of
and CFRP ma

No

Repetition ab

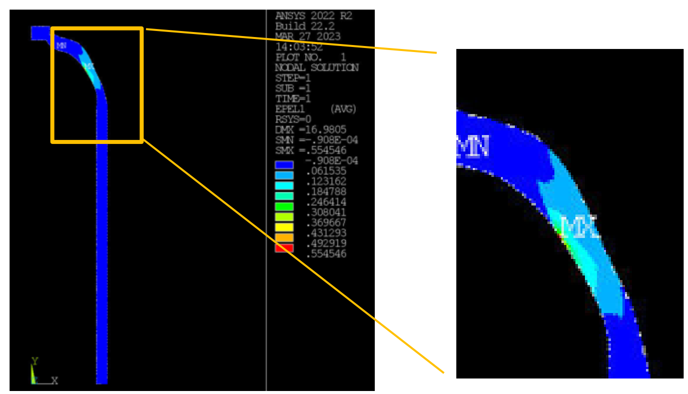
Yes

Calculation of ... imization

Determinatio

No

Modification of range of design parameters
by genetic algorithm as the next generation



Maximum principal strain by analysis

Start : Input of a tank dimension and specification

- Size
- CFRP design parameters range
- Dome shape parameters range

Setting randomly selected tank design parameters

Creation of finite element analysis model of a tank

A finite element analysis of the tank model

Calculation of maximum value of fiber direction strain and CFRP mass per internal volume of the tank

No

Repetition ab

Yes

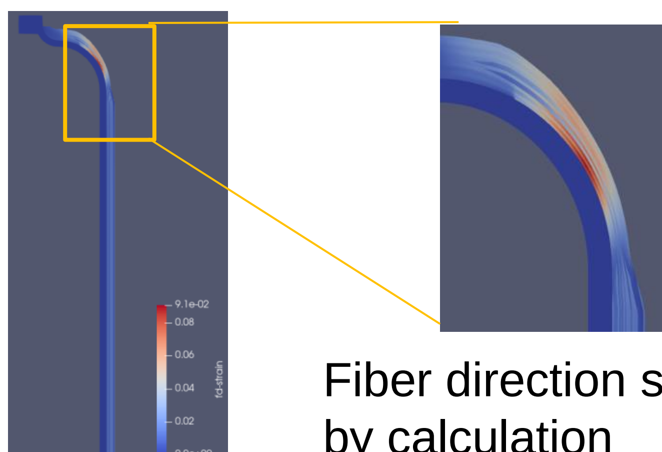
Calculation o … timization

Determinatio

No

Modification c

by genetic al



Fiber direction strain by calculation

Start : Input of a tank dimension and specification

- Size
- CFRP design parameters range
- Dome shape parameters range

Setting randomly selected tank design parameters

↓

Creation of finite element analysis model of a tank

↓

A finite element analysis of the tank model

↓

Calculation of maximum value of fiber direction strain and CFRP mass per internal volume of the tank

↓ No

Repetition about 10,000 times

↓ Yes

Calcula

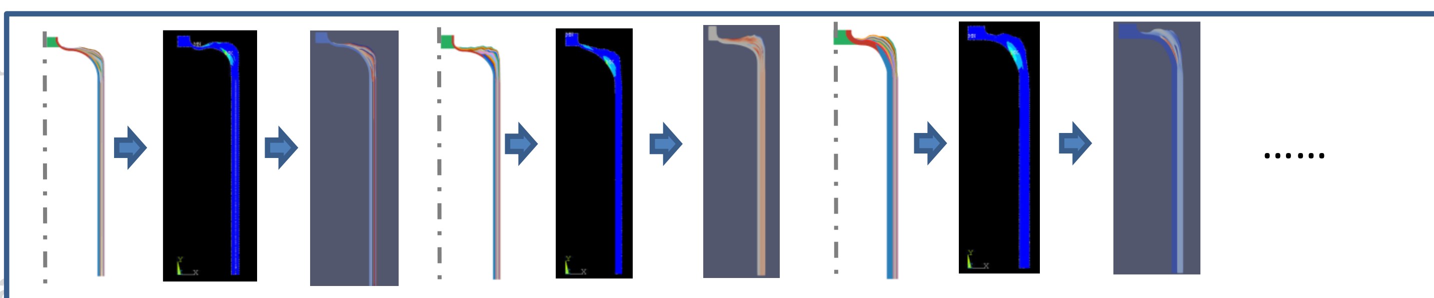
↓

Determ

↓ No

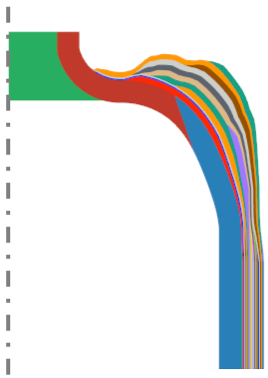
Modifica

as the next generation

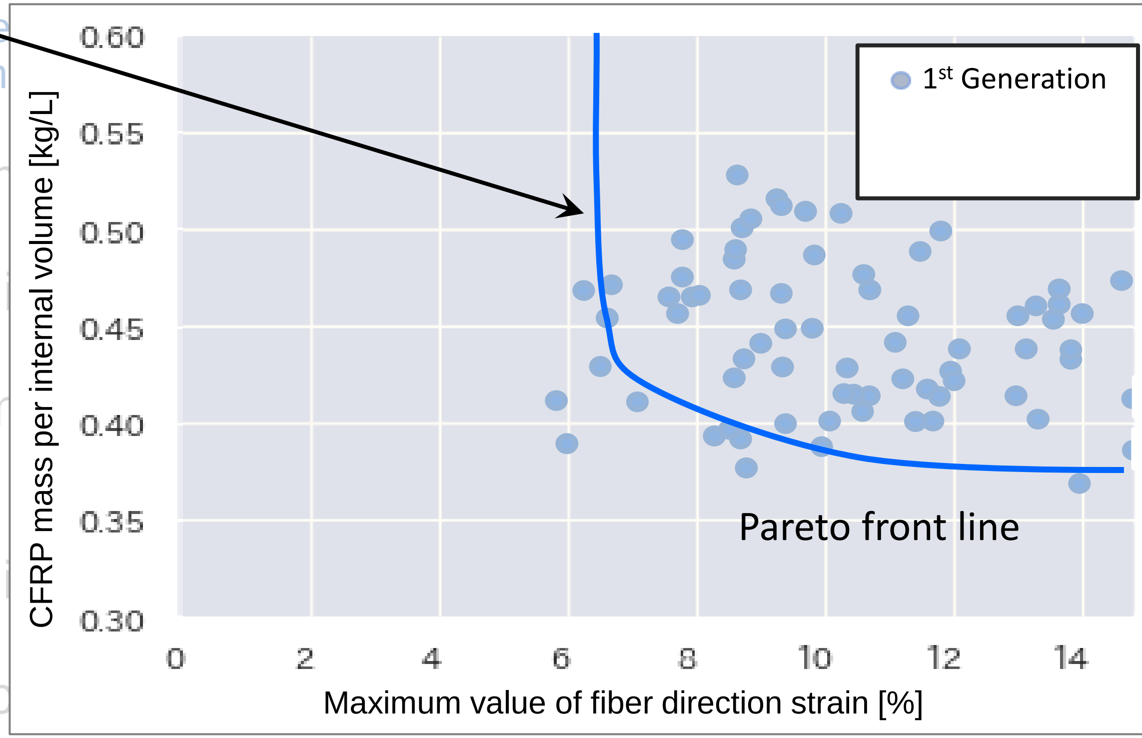


Optimal design flow

Start : Input of a tank dimension and specification



Optimal design tank by the 1st generation



Calculation of
and CFRP wei

No

Repetition abo

Yes

Calculation of Pareto frontline from multi-objective optimization

Determination of the convergence

Yes

End: Output of the smallest CFRP mass tank

- CFRP design parameters
- Dome shape parameters

No

Modification of range of design parameters by genetic algorithm as the next generation

Start : Input of a tank dimension and specification

・Size
・CFRP desi
・Dome shap

Setting randoml

Creation of finite

A finite element

Calculation of m
and CFRP mass

No

Repetition abou

Yes

Calculation of Pareto frontline from multi-objective optimization

Determination of the convergence

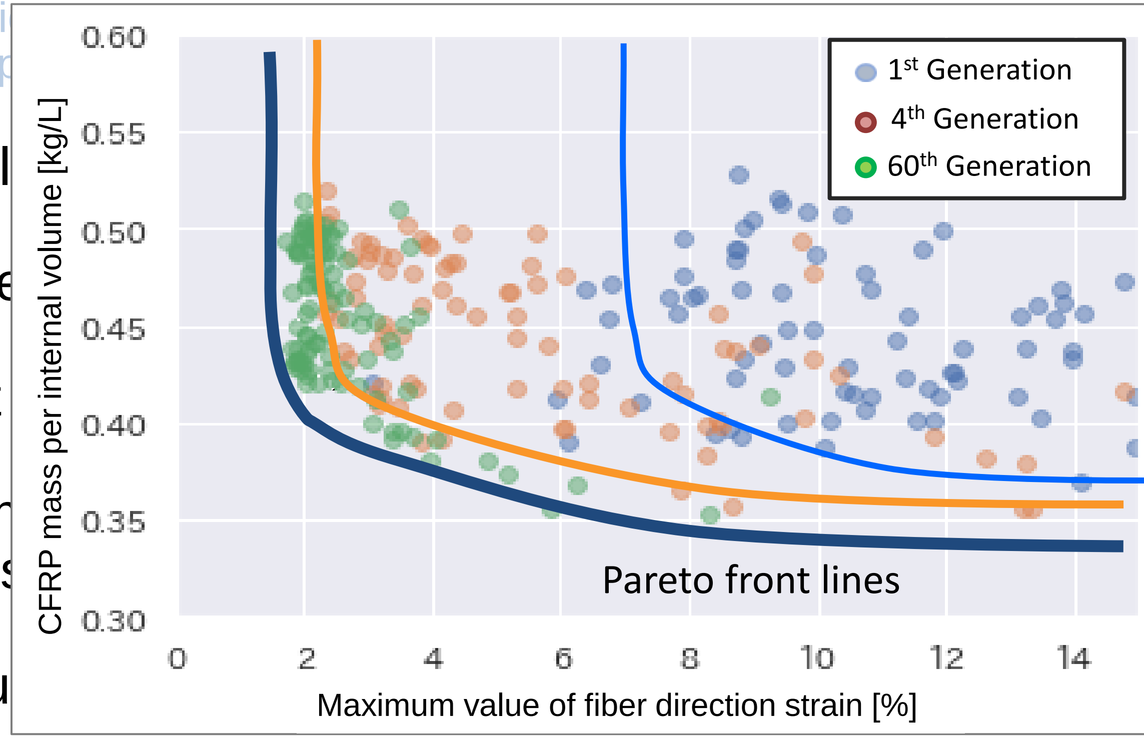
Yes

End: Output of the smallest
CFRP mass tank

・CFRP design parameters
・Dome shape parameters

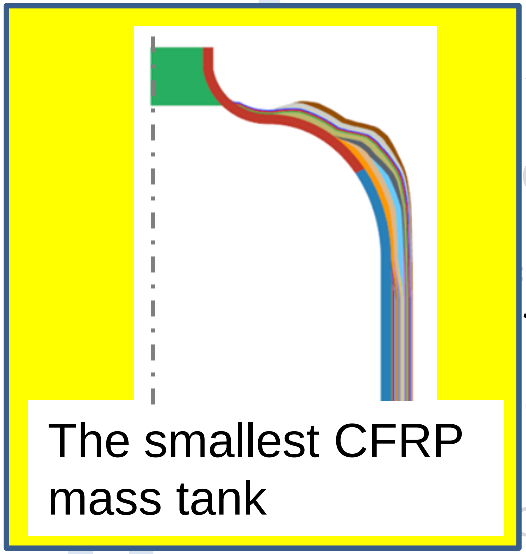
No

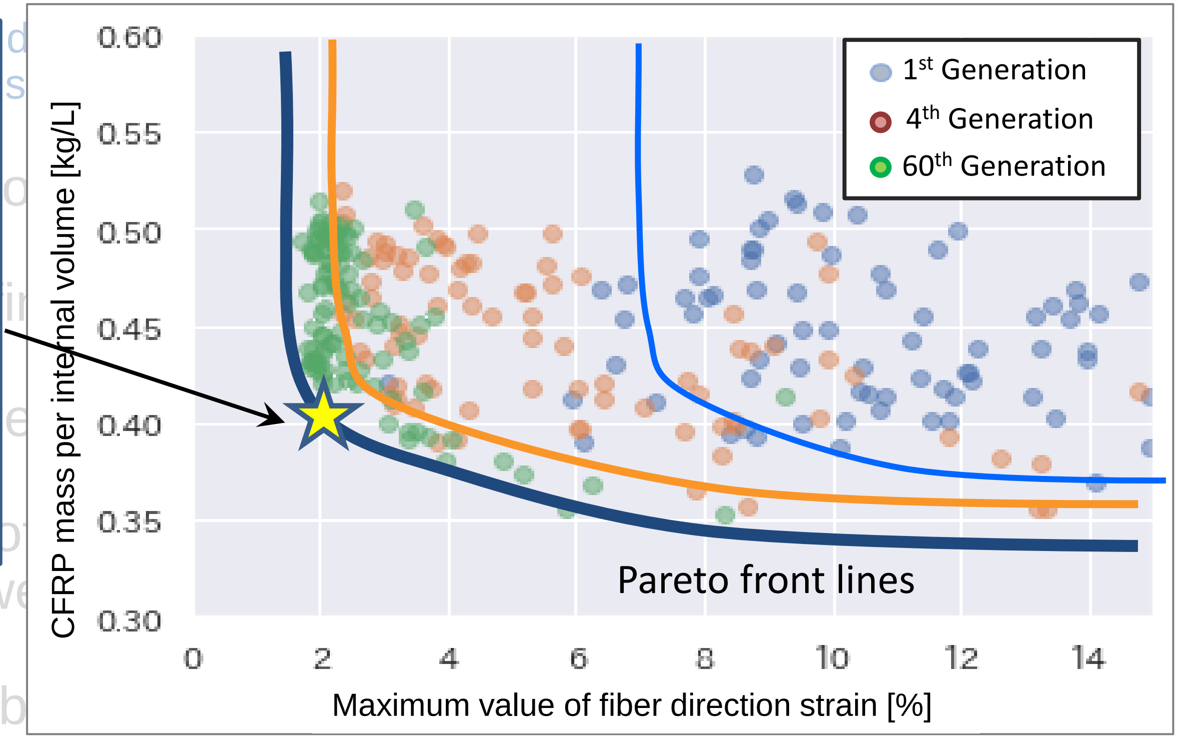
Modification of range of design parameters
by genetic algorithm as the next generation



Start : Input of a tank dimension and specification

・Size





and CFRP we

Repetition ab

Yes

Calculation of Pareto frontline from multi-objective optimization

Determination of the convergence → Yes → End: Output of the smallest CFRP mass tank

・CFRP design parameters

・Dome shape parameters

No

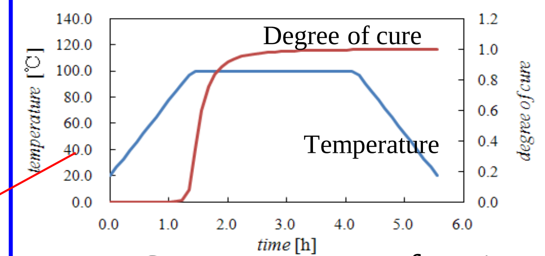
Modification of range of design parameters by genetic algorithm as the next generation

熱硬化性樹脂の材料モデル

Heat conduction analysis with curing heat generation

$$\rho c \frac{\partial T}{\partial t} = k_{xx}\frac{\partial^2 T}{\partial x^2} + k_{yy}\frac{\partial^2 T}{\partial y^2} + k_{zz}\frac{\partial^2 T}{\partial z^2} + \rho \dot{Q}$$

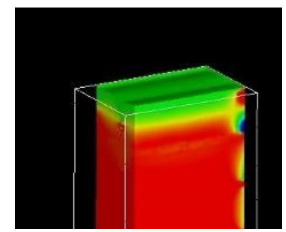
$$\dot{Q} = H_r \frac{da}{dt} = H_r\left(K_1 + K_2 a^m\right)(1-a)^n, \qquad K_i = A_i e^{-(E_i/RT)}$$



Cure property of resin

Strain analysis by temperature and phase change

$$\left(\frac{1}{V_0}\frac{dV}{dt}\right) = \left(\beta_{gel}(T)(1-a) + \beta_{cured}(T)a\right)\frac{dT}{dt} - \lambda_{chem}\frac{da}{dt}$$

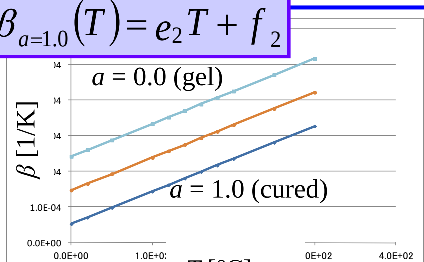

Curing shrinkage

Strain relaxation by viscosity

$$\eta(T,a) = E(T,a)T_g$$

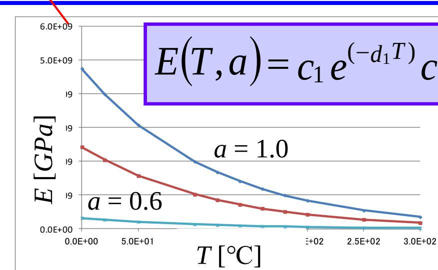
$$\beta_{gel}(T) = \beta_{a=0.0}(T) = e_1 T + f_1$$

$$\beta_{cured}(T) = \beta_{a=1.0}(T) = e_2 T + f_2$$

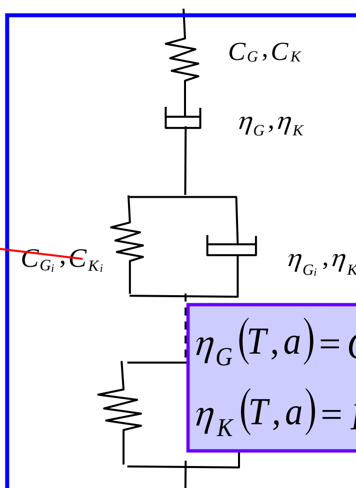


Coefficient of linear expansion

$$E(T,a) = c_1 e^{(-d_1 T)} c_2 e^{(d_2 a)}$$



Young's modulus



$$\eta_G(T,a) = G(T,a)T_G$$

$$\eta_K(T,a) = K(T,a)T_K$$

Voigt model

CFRPの熱硬化マクロモデル

Anisotropic Continuum Modeling

	Longitudinal	Transverse
Thermal Conductivity	$\widetilde{k_L} = k_L^m V_m + k_L^f V_f$	$\widetilde{k_T} = k_T^m \left(\frac{1 + \eta V_f}{1 - \eta V_f} \right), \eta = \frac{\left(k_T^f / k_T^m \right) - 1}{\left(k_T^f / k_T^m \right) + 1}$
Thermal Expansion	$\alpha_L = \{V_f E_L^f \alpha_L^f + V_m E_L^m \alpha_L^m + 2\lambda \left(v_L^m - v_L^f \right) \times V_f V_m \left[\alpha_T^m + v_L^m \alpha_L^m - \alpha_T^f - v_A^f \alpha_A^f \right] \}/E$	$\alpha_T = \left(\alpha_T^f + v_L^f \alpha_L^f \right) V_f + (\alpha_T^m + v_L^m \alpha_L^m) V_m + \frac{\lambda}{2} \left(\frac{1}{k_T^f} - \frac{1}{k_T^m} \right) \times V_f V_m \left[(\alpha_T^m + v_L^m \alpha_L^m) - \left(\alpha_T^f + v_L^f \alpha_L^f \right) \right] - v_L \alpha_L$
Viscoelasticity	$\left[C(t) \right] = \left[C_g \right] \left(1 + \frac{t}{T_g} \right) + \sum_{i=1}^{n} \left[C_i \right] \left(1 - \exp\left(-\frac{t}{T_i} \right) \right)$	$m_{ij} = \frac{1}{2} \int \left(C_{ij}(t) - \bar{C}_{ij} \right)^2 dt$ $\frac{\partial m_{ij}}{\partial C_{aij}} = \int \left(\sum_{b=0}^{n} C_{bij} g_b(t) - \bar{C}_{ij} \right) dt \left(g_a(t) \right) = 0$

粘弾性特性

Generalized Voigt Model by Homogenization Method (Terada et al., 2009)

$$\{\varepsilon(t)\} = [C(t)]\{\sigma(t)\}$$

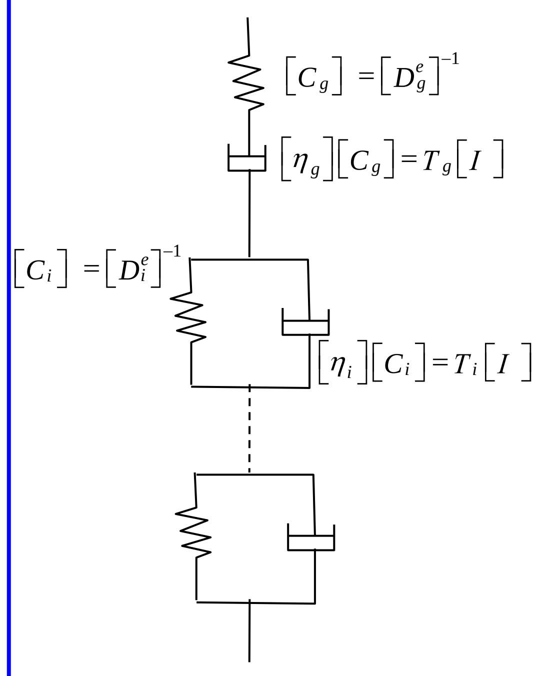
$[C(t)]$: Macro-scale Creep Compliance Matrix

$$[C(t)] = [C_g]\left(1 + \frac{t}{T_g}\right) + \sum_{i=1}^{n} [C_i]\left(1 - \exp\left(-\frac{t}{T_i}\right)\right)$$

$$= \sum_{i=0}^{n} [C_i] g_i(t)$$

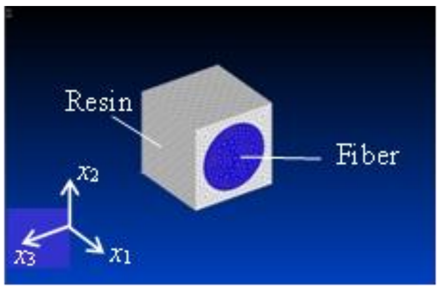
$$[\eta_g][C_g] = T_g[I]$$

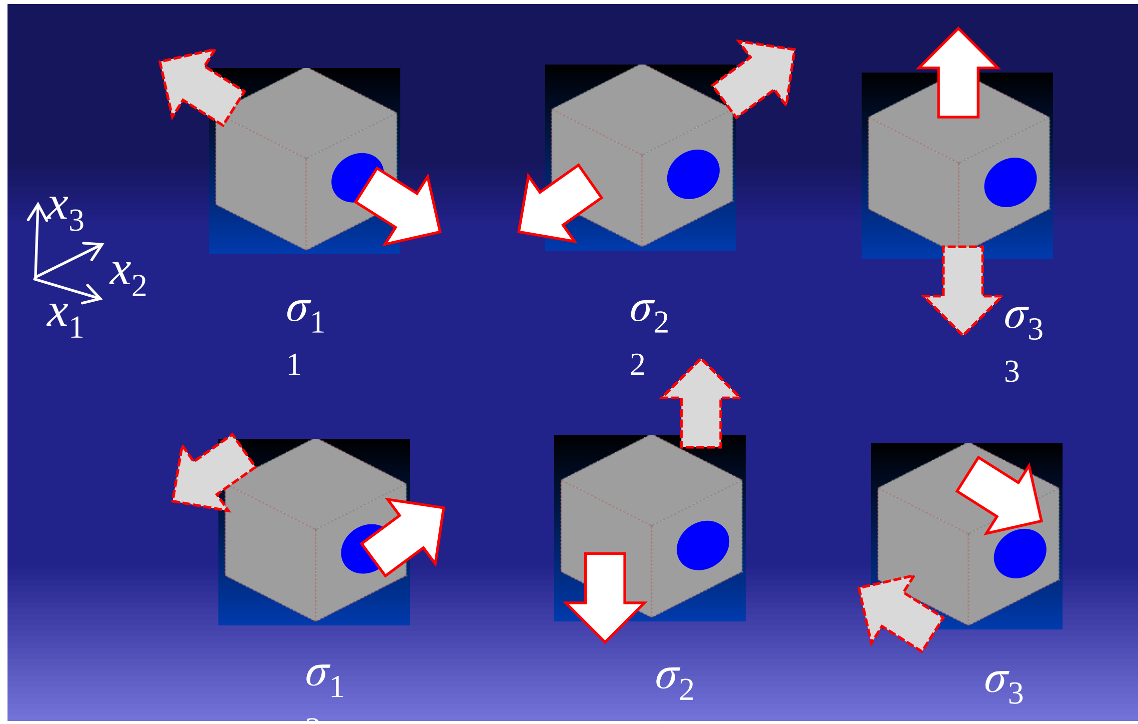
$$[\eta_i][C_i] = T_i[I]$$



ユニットセル解析による
モデル化

Unit Cell Model



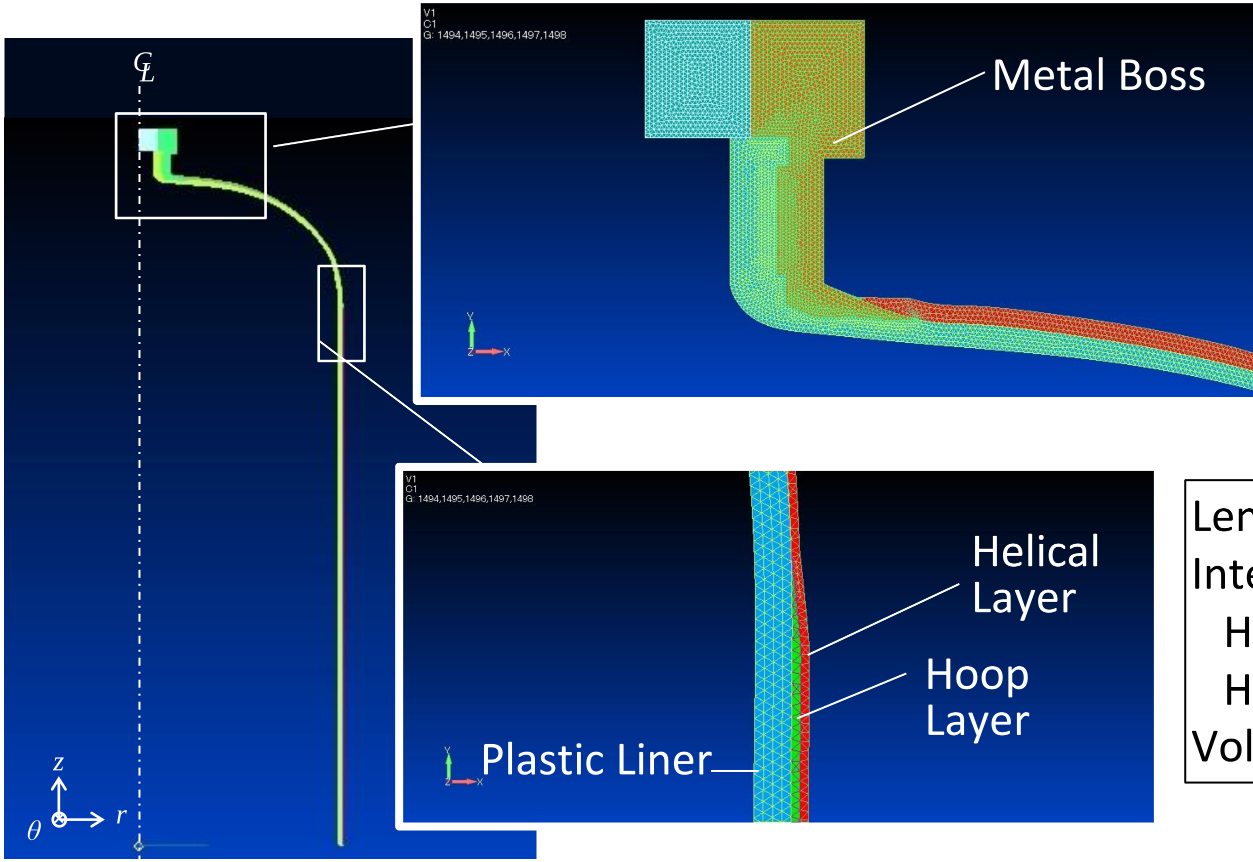


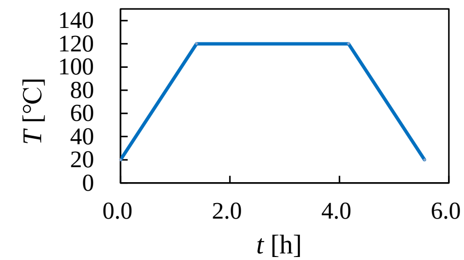
Macro-scale Creep Compliance Matrix $[C(t)]$ is identified through micro-scale analyses of deformation modes by step loading.

22

熱硬化解析例

Finite Element Model





Temperature Time-history

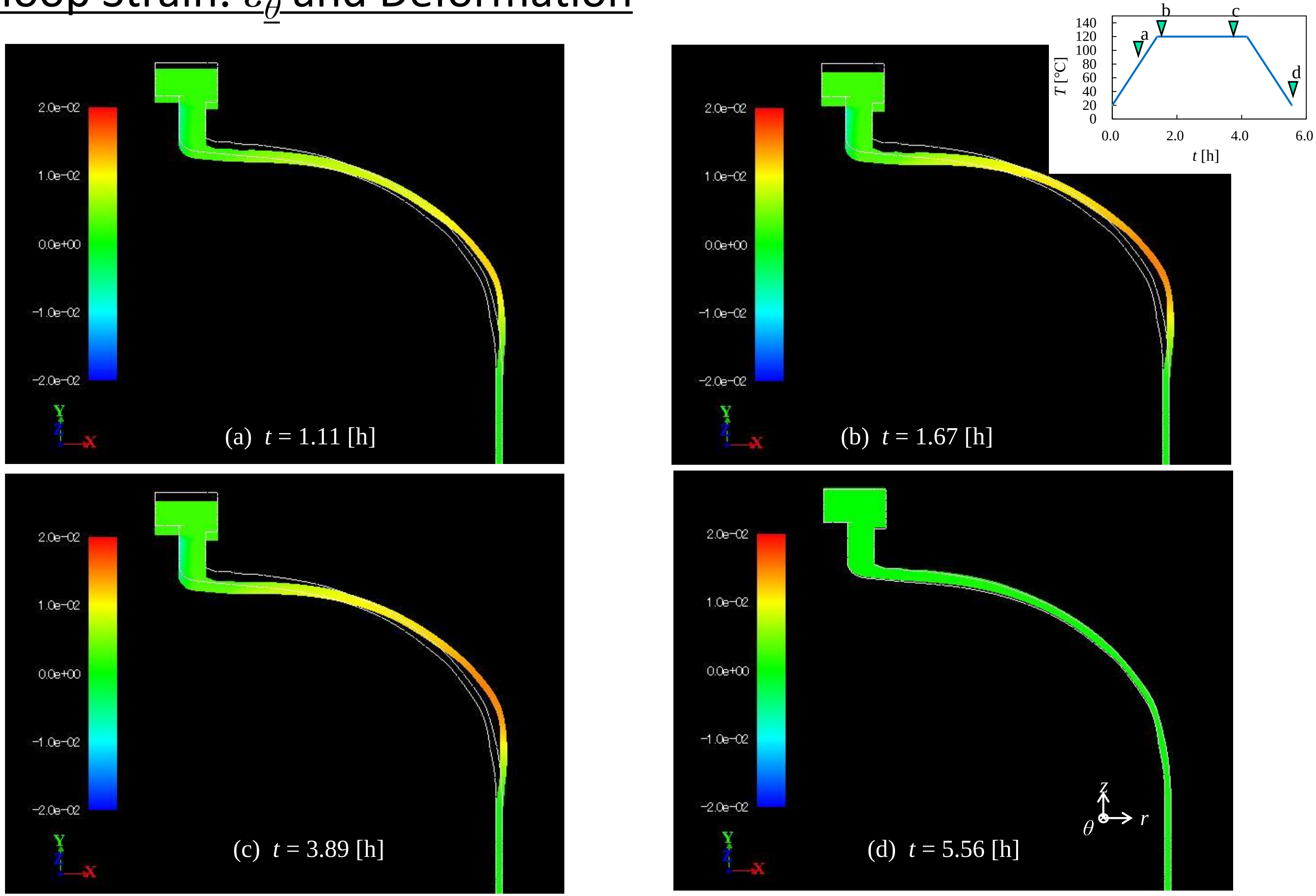
Length: 1055.0 [mm]
Intenar Diameter: 147.0 [mm]
Helical Thickness: 0.45 [mm]
Hoop Thickness: 0.5 [mm]
Volume Flaction: 0.50

Material Property

	Resin	Carbon Fiber	Plastic Liner	Metal Boss
Thermal Conductivity: k [W/(m・K)]	2.60×10^{-1}	8.9 (8.0)	0.48	170
Mass Density: ρ [kg/m^3]	1.22×10^{3}	1.80×10^{3}	9.50×10^{2}	2.70×10^{3}
Specific Heat: c [J/(K・kg)]	1.20×10^{3}	7.10×10^{2}	2.30×10^{3}	9.17×10^{2}

ひずみ解析

Hoop Strain: ε_θ and Deformation



FrontCOMP Software

Dagital Data Processer for CFRP Tank

FrontCOMP_tank	Axisymmetric model by continuum model
FrontCOMP_FW	Single-FW meso-model
FrontCOMP_FW_multi	Multi-FW meso-model
FrontCOMP_FW_shell	Multi-FW meso-model by shell elements
FrontCOMP_wind_multi	CAM data for Multi-FW

Forming Simulation of CFRP

FrontCOMP_cure	Thermoset CFRP
FrontCOMP_TP	Thermoplastic CFRP

WHEEL Server上でのナビゲーション

Local User Sever

INPUT

Design Spec

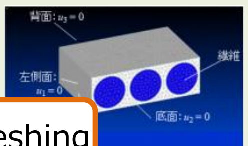
OUTPUT

Optimality Criteria

SHAPE.igs
LAYERS.csv

INPUT

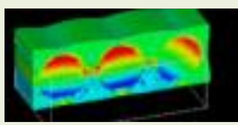
Micro-scale Model



Meshing

OUTPUT

Micro-scale
Mechanical Field



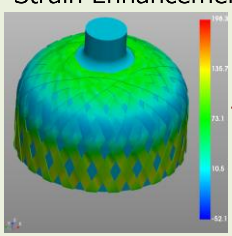
INPUT

Meso-scale Model

FrontCOMP3D

OUTPUT

Strain Enhancement

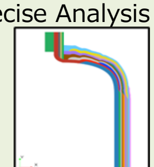


INPUT

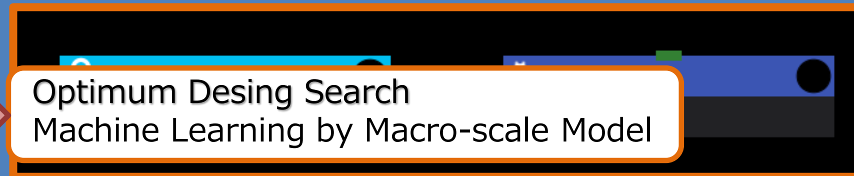
Optimum
Design

OUTPUT

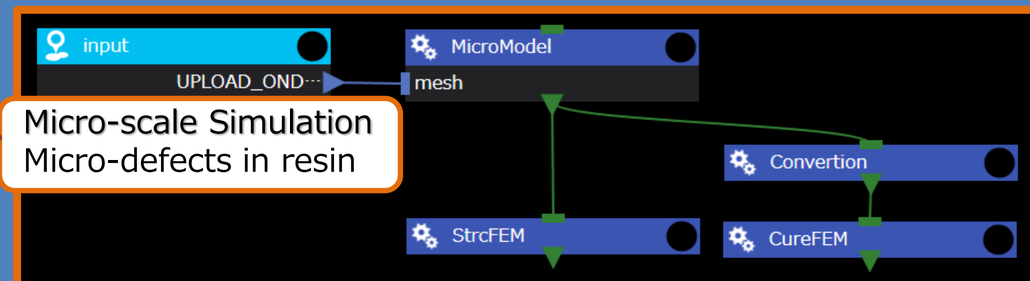
Precise Analysis



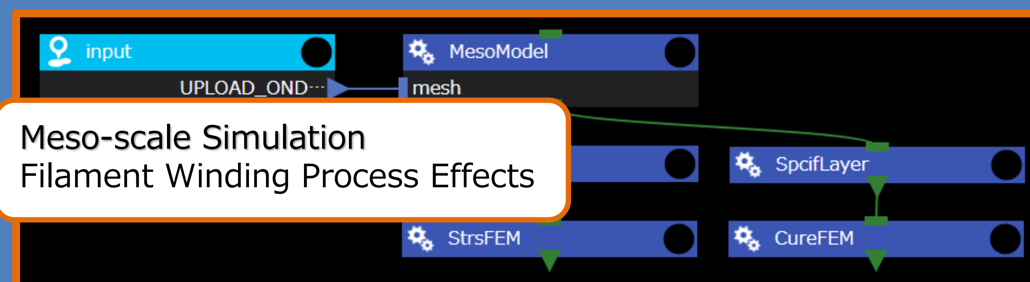
WHELL Server



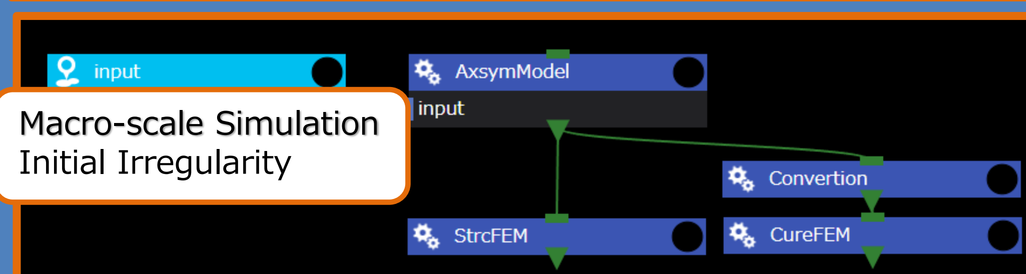
Optimum Desing Search
Machine Learning by Macro-scale Model



Micro-scale Simulation
Micro-defects in resin



Meso-scale Simulation
Filament Winding Process Effects



Macro-scale Simulation
Initial Irregularity

まとめ

最終目標：CFRP製高圧水素タンクの合理的判断に基づく設計および製造の最適化

障　　害：フィラメントワインディング製法により生ずるドーム部の複雑な力学場

解 決 策　：メゾスケールシミュレーションによる力学場の解明と機械学習による最適解の探索

ソフトウェアの開発と
プラットフォーム上での利用環境整備